

Investigation of Smartphone Protective Glasses for Use in Emergency Dosimetry

A Dissertation Presented for the
Doctor of Philosophy
Degree

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*To my grandfathers, Eugene “Bud” Morelock and Larry Keith Harrison, who passed away
before the completion of this dissertation.*

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Abstract

The focus of this work was to examine the thermoluminescence (TL), phototransferred thermoluminescence (PTTL), and optically stimulated luminescence (OSL) properties of the protective glasses utilized in modern smartphones and establish the ability to, after a radiation exposure, correlate the absorbed dose measured in a smartphone to that received by an individual carrying it. The primary reason for investigating the protective glasses is that their removal doesn't completely incapacitate the phone, which is not true of methods utilizing other smartphone components, such as the display glass or surface-mount resistors (SMRs), and in the case of OSL, could potentially be used in an in-situ measurement technique. A significant background signal (BGS) contribution that could not be removed was observed during the TL and PTTL analyses, attributed to the use of UV light curing by the manufacturers, that greatly impacted the dose reconstruction process due to significant overlap with the radiation-induced signal (RIS). These results motivated the investigation of the protective glasses by means of OSL, where it was observed that the samples were not encumbered by any such BGS, making it the more encouraging luminescence technique to employ. The only drawback to utilizing an OSL technique is that the signal is susceptible to deterioration or complete erasure from light exposure; however, a recent study has shown that over 75% of smartphone users equip their devices with some form of protection. Therefore, for the devices outfitted with opaque cases or otherwise stored in the dark, utilizing an OSL technique on the protective glasses was shown to be a viable emergency dosimetry method. Previously, the majority of research focused on assessing the dose to the phone component itself, while, in reality, the dose to the individual is the most crucial to performing triage. Therefore, numerous irradiations were performed on an anthropomorphic phantom, equipped with smartphones, to calculate the conversion factors from the phone components (SMRs

and protective back glasses in this study) to the individual carrying them. The resultant factors were observed to be heavily influenced by the phone's location and exposure geometry due to shielding from the body and exposure angle.

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List of Abbreviations

<i>AP</i>	anterior posterior
<i>BGS</i>	background signal
<i>GG</i>	Gorilla Glass
<i>LLAT</i>	left lateral
<i>MDD</i>	minimum detectable dose
<i>OSL</i>	optically stimulated luminescence
<i>PA</i>	posterior anterior
<i>PTTL</i>	phototransferred thermoluminescence
<i>RIS</i>	radiation-induced signal
<i>RLAT</i>	right lateral
<i>ROT</i>	rotational
<i>TL</i>	thermoluminescence

Chapter 1

INTRODUCTION

Following a radiological incident in which members of the public may have been exposed to lethal amounts of radiation, it is of utmost importance to determine the dose to potentially exposed individuals to assist with directing medical response and making public safety decisions. Because exposed persons were unlikely to be outfitted with standardized dosimeters, a retrospective dosimetry method must be employed to estimate the radiation doses, where retrospective dosimetry refers to the determination of dose from materials when conventional detectors were not present at the time of the exposure. The form of retrospective dosimetry of interest in this dissertation is termed emergency (or accident dosimetry) and is characterized by the aim to accurately distinguish between doses > 2 Gy, which require immediate medical attention, and those < 2 Gy, which are less urgent, by the use of ubiquitous, commonplace materials that were present near or on the individual at the time of exposure [1]. The absorbed dose of 2 Gy has been established as the dose cutoff as it initiates the dose range characterized by symptoms of the hemopoietic syndrome (e.g., infection and hemorrhaging) for which moderate-to-urgent care may be required [2]. In addition, this decision is supported by the lack of deaths for absorbed doses below 2 Gy for victims of the Chernobyl incident [3].

The materials best suited for use in this role have favorable characteristics that include high sensitivity to ionizing radiation and the ability to hold the signal for significant amounts of time (i.e., low signal fading) [1]. Locations of such events can be highly unpredictable; therefore, in addition to the material selection, standardized, widely available equipment and methods are also necessary for quickly evaluating and assigning resulting exposures. The urgency in obtaining radiation exposure information imposes a severe constraint on many techniques, such as biological dosimetry, that are invasive or require long sample preparation time [4]. However, because thermoluminescence (TL) and optically stimulated luminescence (OSL) dosimetry are rapid, inexpensive, and reliable methods used widely in industry, medicine, and science [5], they represent the best available techniques with which to establish emergency dosimetry procedures.

For this reason, the last decade has seen a surge in studies on the suitability of various materials for use in emergency luminescence dosimetry. Research has been conducted on items such as vitamins [6], salts [7], and fabrics [8]; however, the most encouraging was on

the components [e.g., resistors [9], inductors [10], display glasses (LCDs) [11], and protective glasses [12]] of portable electronic devices, specifically smartphones, due to their prevalence and proximity to the user. One component of particular interest is the protective glasses, as their removal represents the only component readout method that does not render the phone inoperable. This fact is an important consideration when working with individuals who have just experienced a major event and would have a high attachment to these devices for communication purposes.

Nevertheless, prior to embarking on the research for this dissertation, there had only been two studies to examine the luminescence properties [TL [12] and phototransferred thermoluminescence (PTTL) [13], respectively] of the protective glasses located on modern smartphone devices. Therefore, the aim of this dissertation was to expand the TL and PTTL research of the protective glasses and initiate the investigation of their OSL properties for use in emergency dosimetry.

OSL and TL both represent mature fields with applications in the food industry, geological dating, and nuclear forensics, as well as in medical, space, and personnel dosimetry; however, regardless of their application, the governing physics stays the same. This process involves a host material that stores energy from incident radiation within defects located inside its structure [5]. Upon heating or exposure to light, for TL and OSL, respectively, the material releases light proportional to the amount of radiation to which it was exposed. While a complete review of these physical processes is outside the scope of this dissertation, a brief overview is warranted.

Theory

As mentioned, the common phenomenon behind OSL and TL is the process of light emission after external stimuli (heating for TL and light exposure for OSL), where the light emitted is proportional to the amount of radiation previously incident on the material. This is possible due to defects in the material that trap excited electrons and holes in a metastable-like state. These defects are of various types including interstitial defects, where an atom is located in a lattice position that it is not normally present; substitution defects, where an impurity

atom has replaced an atom located in the lattice; and vacancy defects, where an atom is missing from a lattice position in which it would normally be located. The consequence of these defects is the creation of localized energy levels that allow for electrons to possess energies that are otherwise not possible (i.e., forbidden) in a perfect crystal. The localized energy levels are best discussed within the framework of the energy band model. It should be noted that while the discussion will focus on crystalline materials, the process applies to any material having metastable states that can produce luminescence upon relaxation to the ground state [5, 14].

When many atoms are grouped together in a crystalline lattice, the valence electrons that were previously confined to discrete energy levels within a single atom are now connected in continuous energy bands that extend throughout the entire crystal. The highest filled energy band is called the valence band and the conduction band is the first empty band above it. The two bands are separated by an energy gap, which is where the defect-created energy levels are located [5, 14].

When exposed to ionizing radiation, electrons absorb enough energy to overcome the band gap and migrate to the conduction band, leaving behind vacancies, or holes, that can now be thought of as units of positive charge that move through the valence band. The defects in the crystal introduce a local electric field which may capture an electron from the conduction band or a hole from the valence band. Once trapped, the electrons will remain at these defect sites until enough energy is absorbed to overcome the energy difference between the localized energy state and the conduction band. After which, the electron may travel through the crystal, either recombining with a trapped hole or becoming retrapped. If recombination occurs, the resultant energy release can be either radiative (photon emission) or non-radiative (lattice vibrations) [5, 14].

If a trap first captures an electron or hole, and then subsequently captures the opposite charge carrier causing recombination, it is referred to as a recombination center. A recombination center is distinguished from a trapping center based on the higher probability that the trapped charge carrier will recombine with the opposite charge carrier at the site as opposed to the trapped charge carrier being stimulated back to the delocalized bands. For

this reason, the recombination centers are located towards the center of the band gap, while traps are located at the boundaries [5, 14].

There are two avenues in which an excited electron can recombine with a hole. The first path is through direct recombination, also known as band-to-band recombination, where the electron crosses the band gap and recombines with a hole in the valence band; this process involves only the delocalized bands. The second option is indirect recombination, which is more common in wide band-gap materials and can be either band-to-center or center-to-center recombination. The indirect recombination occurs through the localized energy levels via the trapped electrons (or holes). The described trapping process and subsequent recombination pathways are illustrated in Figure 1.1. The figure presents the luminescence process starting with the initial radiation exposure that excites the electrons to the conduction band (a), which subsequently become trapped (b). This process leaves behind vacant holes that are also trapped (c, d). After stimulation (heating or light exposure), the electrons are excited out of the traps (e, f) into the conduction band where they can either be retrapped (f), recombine with holes via band-to-band transitions (g), or recombine at the recombination center via band-to-center transition (h). Alternatively, the recombination can occur directly through a center-to-center transition (i). For all recombination processes, the emission of light is a possible route of energy dissipation [5, 14].

Of interest to luminescence dosimetry is the stability of these trapped carriers and the process of releasing them during readout. For TL, the probability that the trapped electron will be released from its trap is described by the following relation:

$$\rho = s \cdot \exp(-E/kT), \quad (1.1)$$

where s is the frequency factor, E is the energy depth of the trap, k is the Boltzmann constant, and T is the temperature. From this relation, it can be deduced that as the temperature rises so will the probability of detrapping. This is evident in a typical light output vs temperature (glow curve) plot which is represented by a steady rise in light output up to a maximum that is followed by a decline as the traps are depleted, producing distinct peaks. This process can be repeated within the same material as the temperature stimulates

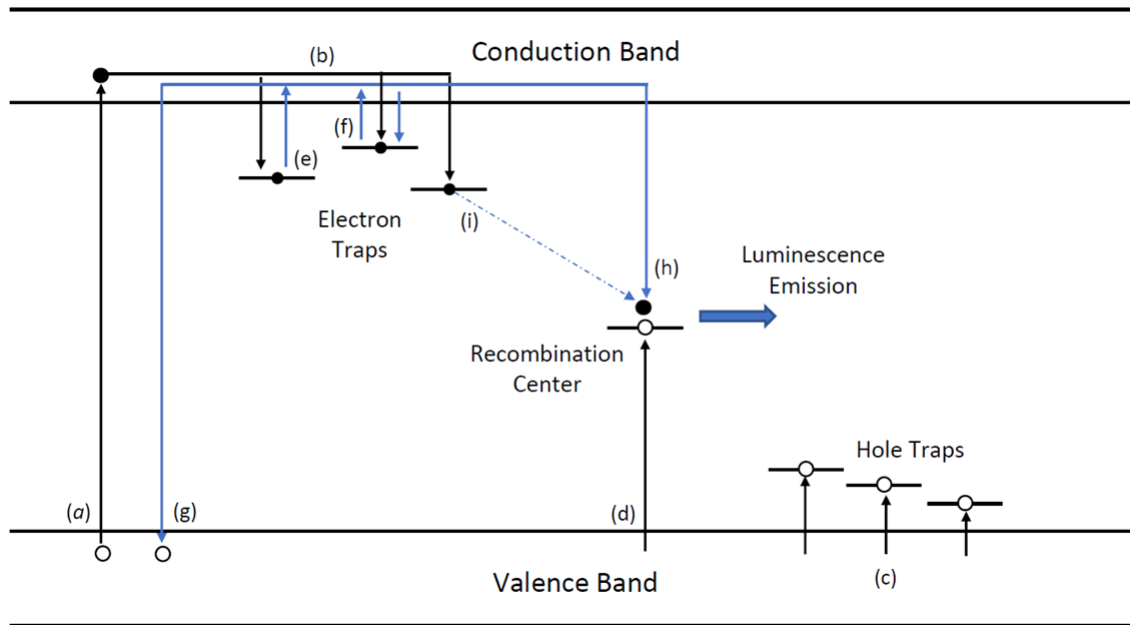


Figure 1.1: Band model illustrating the process of stimulated luminescence. The black lines represent the initial radiation exposure that leads to the subsequent trapping of the electrons and holes, whereas the blue lines represent energy absorption by the trapped electrons via heating or light exposure that leads to recombination and luminescence emission.

deeper and deeper traps, resulting in the formation of multiple glow curves peaks in one glow curve plot [5, 14].

For OSL, the probability that an electron will be detrapped is a function of the incident photon flux, Φ , and the photoionization cross section, σ :

$$\rho = \Phi\sigma. \quad (1.2)$$

In the same manner that the probability increases with temperature for TL, the probability of detrapping an electron increases for OSL with the amount of light incident on the material. The resulting light output vs time plots (decay curves) are represented by a large initial light output that decays quickly as traps become depleted. The resultant graph is different than TL in that the stimulation intensity is constant, emptying all OSL sensitive traps at the same time, whereas TL is characterized by a constant heating rate that stimulates higher energy traps as the temperature is elevated [5, 14].

Organization of the Dissertation

This dissertation is composed of several independent chapters:

Chater 2 The second chapter is a comprehensive literature review of the previous analysis performed on both the display and protective glasses from smartphones. The review thoroughly documents the previously established TL, PTTL, and OSL characteristics of both glass types.

Chapter 3 The third chapter characterizes the TL and PTTL properties of protective glasses. This includes an in-depth investigation of the glow curves shapes and intensities from different version of protective glasses, and an extensive analysis of the background signals (BGSs), including their formation, uniformity, removal, and re-creation.

Chapter 4 The fourth chapter investigates the OSL properties of protective glasses, including their sensitivity to radiation, signal reproducibility, dose response, and signal

stability. This information is utilized in a dose-reconstruction test performed on the protective glass from the back of a smartphone after 5 days.

Chapter 5 The fifth, and final chapter, culminates the project by developing dose conversion factors from the dose in protective glasses (and resistors) to that in the individual organs of an anthropomorphic phantom. The conversion factors are developed based on variations of the exposure geometry and phone position on the phantom.

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Chapter 2

LITERATURE REVIEW

A version of this chapter was written by J. R. Chandler and originally included in the publication by S. W. S. McKeever et al.:

McKeever S. W. S., Sholom S., and Chandler J.R. "Developments in the use of thermoluminescence and optically stimulated luminescence from mobile phones in emergency dosimetry". *Radiation Protection Dosimetry*. 192(2) (2020), pp. 205-235.

2.1 TL and OSL From Smartphone Glasses

Glasses have long been known to exhibit the necessary properties for use as retrospective/emergency dosimeters; this holds true of the glasses found in earlier-generation mobile phones as well as in modern-day smartphones. In fact, glasses have a few advantages over other phone components in their use as fortuitous dosimeters. The most obvious being the amount of sample available for measurement; while phones, and therefore glasses, continue to get larger, the internal components continue to decrease in size and number. Another advantage is that the glass removal process is the least time consuming and least destructive; this aspect is closely associated with the repair process that is the most feasible and economical for glasses.

There are two distinct categories of glass associated with phones. The first consists of those that are integrated into the phone's display unit (display glasses) as substrates on which the display technologies are built; these are found in both older mobile phones and modern smartphones. The second category is comprised of glasses that are utilized as an element of the phone's outer protective layer (protective glasses); these glasses are only found on modern smartphones due to the emergence of the capacitive style touchscreens.

An important fact to consider when dealing with smartphone technology is that it has progressed rapidly over the last decade and will continue to do so in the future. These developments are occurring not only in the components that increase the phone's performance but also in the materials used in making the body as well as the glue that holds it all together. This means that, where smartphones are concerned, there is an ongoing need to not only investigate alternative solutions but to continue research into those previously studied. A prime example of this perpetual change can be observed in the glass that arrived

on the front of smartphones in 2007 [Corning’s Gorilla Glass (GG)] [1]. Since first appearing on the iPhone, it has undergone numerous overhauls and is now in its seventh generation.

This section will review the studies of smartphone (and mobile phone) glasses, focusing on those that analyzed their luminescence properties, i.e., thermoluminescence (TL), phototransferred thermoluminescence (PTTL) and optically stimulated luminescence (OSL), and discuss how the ever-changing smartphone landscape has affected their dosimetry properties.

2.2 Display glasses

Display glasses are associated with the smartphone’s display unit, of which modern smartphones employ both liquid crystal (LCD) and light-emitting diode (OLED) display types. There are technical differences between the two display types, but of most importance is that each traditionally utilize glass as the substrate material in its design. These substrates are usually made from variations of borosilicate and aluminosilicate glass that have been optimized for the application of thin-film transistors (TFTs). It should be noted that both display types have two substrates stacked on top of one another. The substrates are made of the same glass; however, the glass furthest away from the front of the device is the one used in all studies due to having, on average, a lower BGS as well as more protection from light exposure.

The first mobile phones used both monochrome and color LCD displays (with OLED appearing in 2008), with some models including resistive-style touchscreens. The first smartphones appeared in 2007 and have since become the technology standard; however, basic feature phones are still important to emergency dosimetry as there is still a large audience for them, especially in less-developed nations. For this section, all non-smartphone devices will be referred to as mobile phones.

2.2.1 TL studies

Display glasses exhibit several favorable TL properties, e.g., good sensitivity to ionizing radiation, a linear dose-response and good signal reproducibility. However, glasses have

been shown to possess disadvantageous properties as well; these include signal fading, susceptibility to light and the presence of a BGS that interferes with the determination of the RIS. These sections will examine the favorable properties and delve into the strategies employed to overcome the glasses' negative aspects.

2.2.1.1 TL glow curves

There have been several studies that have reported the different aspects of the radiation induced signal (RIS) glow curves in display glass [2–8]. Each research group uses different measurement techniques, i.e., heating rate and filter set, and it is impractical to try to directly compare the glow curve shapes, intensities and peak positions between studies. Nevertheless, there are some overarching conclusions that can be made, the main one being that there are four distinct glow curve groups, three of which produce well-formed TL peaks, maxima ranging from approximately 100–300 °C (Figure 2.1) [2, 3]. The fourth group has low or no sensitivity to ionizing radiation. This has been attributed to devices with old monochrome displays [3]. A lack of sensitivity has also been observed in mobile phones with color displays and even in smartphones with model years as late as 2018 [8]. Two of the radiation-sensitive groups feature either a single symmetric or asymmetric curve, while the third is notable for having two distinct peaks. The glow curve shapes are attributed to the different glass types used in the display. Those having a sensitivity to radiation were characterized as lime aluminosilicate and boron silicate glasses, with the former exhibiting greater sensitivity to ionizing radiation [3].

2.2.1.2 TL emission spectra

Determining the emission wavelength of the display glasses is critical for selecting the proper detection window (filter set) for use in measurement. If the incorrect filter is applied, a large portion of the spectrum of the display glass may be cut off which can severely limit the intensity of signal detected. This in turn could be an issue when dealing with low-sensitivity glasses or exposure to small doses. It should be noted that application of different filter sets will change the shape and intensity of the resultant TL glow curves.

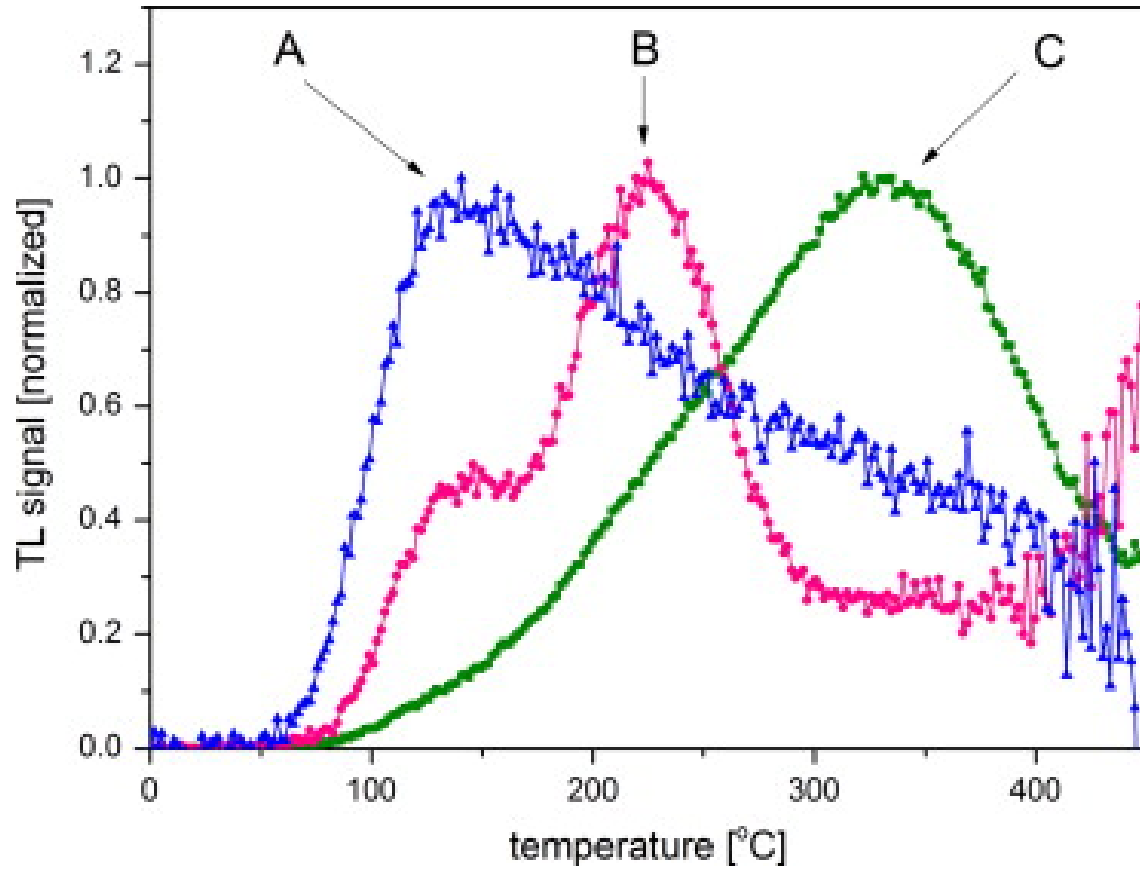


Figure 2.1: Classification of typical TL glow curves of glass samples coming from different mobile phone producers classified according to their TL glow curve shapes (Groups A, B, and C). (Adapted from Mrozik et al. [2].)

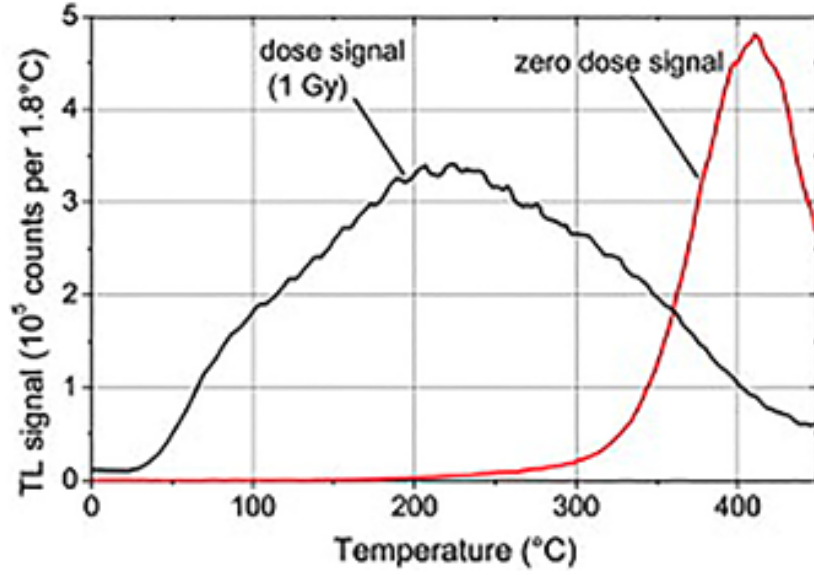
Display glass TL emissions have been observed in the 340–680 nm range with lime aluminosilicate glasses exhibiting two peaks at around 380 and 465 nm, whereas boron silicate glasses had a single peak at around 605 nm [7, 9]. The results indicate that the selection of the detection window is glass specific.

Of note, the same TL emission results seen in older mobile phones were also observed in more modern smartphones, up to the 2015-y models [7].) This is indicative that smartphone displays are still using the same basic glasses found in older style mobile phones, which is beneficial for emergency dosimetry applications.

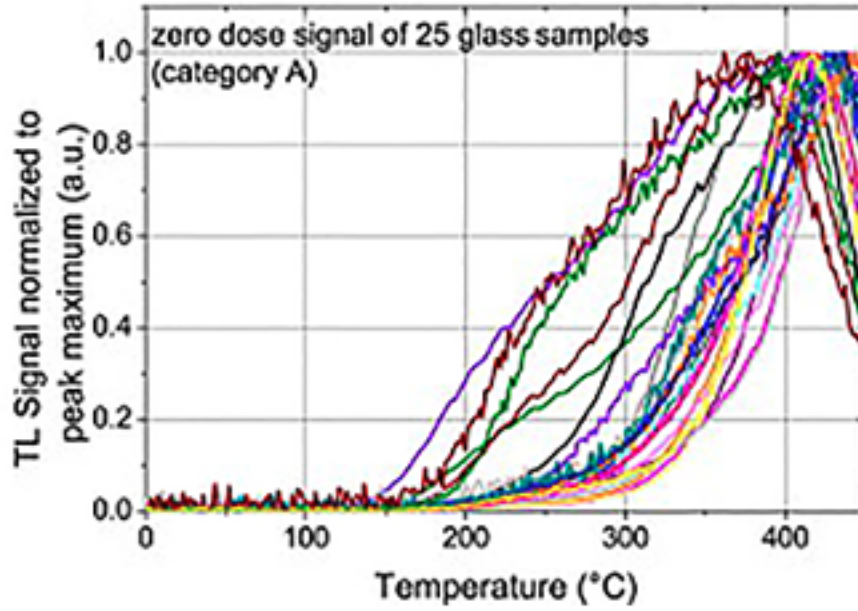
2.2.1.3 Background signal

All display glasses with sensitivity to ionizing radiation display a BGS, which is removed by the first TL readout. The BGS varies in intensity and shape even among glasses of the same type [2–4, 6]. In comparison to the RIS glow curves, the BGS glow curves are noticeably more narrow with peaks at higher temperatures ($> 350^{\circ}\text{C}$) in all detection windows, as shown in Figure 2.2. Even with noticeable differences between the glow curves, the BGS and RIS overlap is still considerable; thus, to account for this, the integration window has been restricted to 100–250 $^{\circ}\text{C}$, which is a compromise between thermal stability and minimizing the influence of the BGS [3].

It has been surmised that the BGS originates from UV exposure during the TFT application process; however, efforts to reproduce this signal with exposure to 366 and 254 nm UV were unsuccessful [3]. For older mobile phones, the intensity of the BGS, in terms of dose, was observed to be equivalent to $< 200\text{ mGy}$ for the majority of lime aluminosilicate samples, with the exception of a few that were as high as 800 and $< 600\text{ mGy}$ for the boron silicate glasses with a few over 1000 mGy. A sufficient degree of homogeneity of the BGS was found across the display glass [3]. Likewise, as illustrated in Figure 2.3 for smartphone displays, no particular pattern could be identified for the distribution of the BGS on the glass as a whole; however, it was determined that these displays do exhibit high variation of the BGS in some glasses [7]. To account for this variation, it is recommended that as many aliquots as possible should be used to ensure an accurate account. The minimum detectable dose (MDD) for both glasses, without any glass treatment, were similar with reported values



(a)



(b)

Figure 2.2: (a) Zero-dose BGS in comparison with the RIS (after 1 Gy). The heating rate was 2°C/s for each measurement. (b) BGSs of 25 different glass samples (lime aluminosilicate) to illustrate the degree of variability in shape. The glow curves were normalized to the peak maximum. All measurements were in the blue (300–580 nm) wavelength range. (Adapted from Discher and Woda [3].)

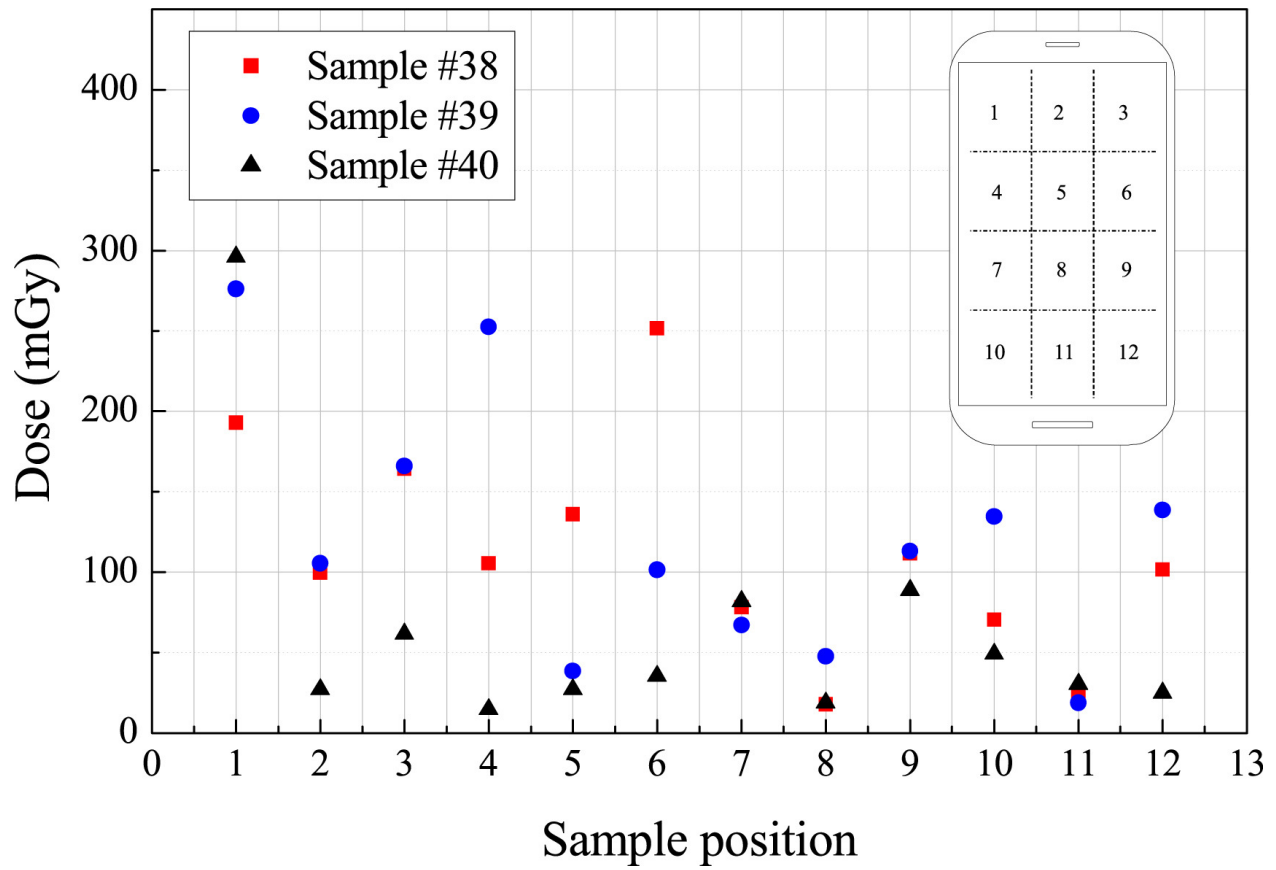


Figure 2.3: Distribution of the zero-dose BGS according to the position on the glass for three mobile phone samples. (Adapted from Kim et al. [7].)

of 150 mGy for older devices and 190 mGy for smartphones [3, 7]. These MDD values are more than acceptable for emergency dosimetry, where 1 Gy is acceptable for triage purposes.

2.2.1.4 Background signal mitigation

Three different techniques have been proposed to mitigate the effects of the BGS on dose reconstruction; these include subtracting an average BGS value from the total RIS, using various filter setups to block the BGS or to remove the BGS from the sample.

The first technique, subtraction of an average BGS value from the total calculated dose, was utilized after recognizing that the recorded distribution of the BGS comes from a normally distributed population [3]. In a dose recovery test, its application has led to an average reconstructed dose that was $\sim 10\%$ lower than the delivered dose. For phones that do not exhibit a large variation in the BGS from one phone to another or across the display of a single phone, this technique could be used for triage purposes.

The second technique, blocking the BGS through selective filter selection, was determined to be impracticable through the analysis of the TL emission spectra where the BGS was found to emit in similar wavelengths as the RIS [9].

The third technique is by far the most effective. The premise behind this strategy is that the BGS arises from the surface layers of the glass only and therefore it may be removed by chemical etching or mechanical grinding of the glass surface [5, 6]. The method was able to reduce the BGS, in some samples, by $> 95\%$ (in the 100–250 °C integration region; see Figure 2.4). As illustrated in Figure 2.5, neither removal technique created any adverse signals and, in both cases, greatly reduced the BGS while leaving the weight-normalized RIS intact. Application of this technique results in significantly lowered MDD values, with reductions in pre-bleached samples from 340 to 76 mGy and from 1370 to 210 mGy for lime aluminosilicate glasses and boron silicate glasses, respectively.

The chemical etching method was further optimized by testing the effects of different acids and etching times on the BGS efficacy [2]. In doing so, it was discovered that some glasses are more sensitive to pure HF acid, while others reacted better to an acid mixture. The optimal etching time is dependent on the thickness of the glass, but 4 min appeared

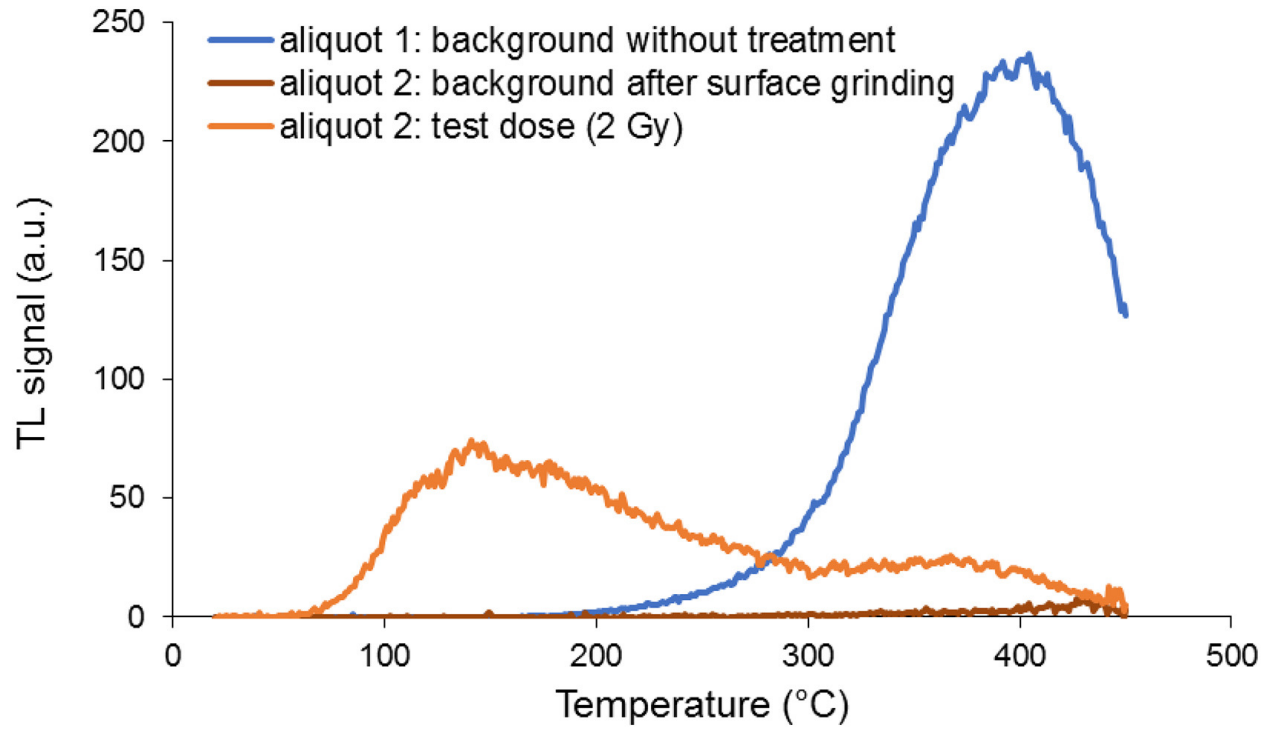


Figure 2.4: BGSs measured for NOKIA 6021 mobile phone glass. Aliquot 1 was untreated, while the surface of aliquot 2 was ground before measurement. A TL RIS following 2 Gy irradiation is also shown for aliquot 2. (Adapted from Bassinet et al. [6].)

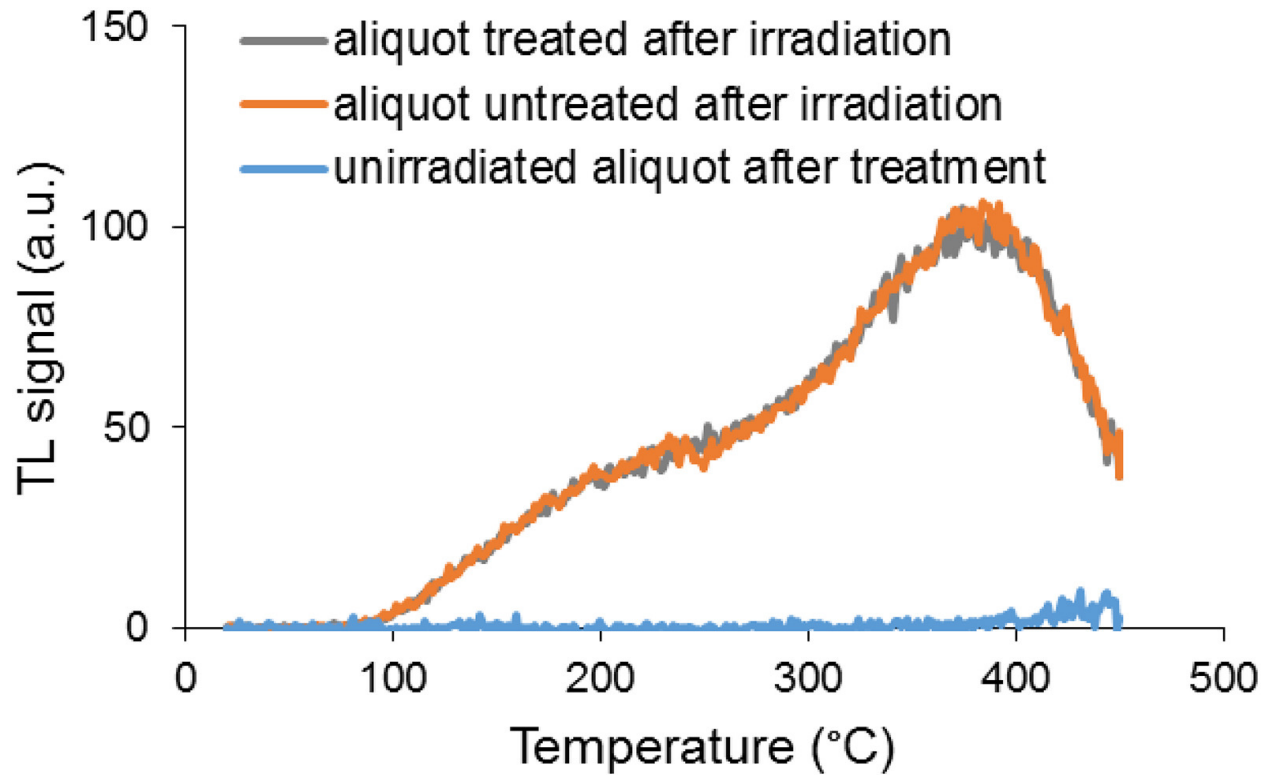


Figure 2.5: Glow curves from a NOKIA 3109c mobile phone glass aliquot. A glow curve was measured after applying a surface grinding process on the irradiated aliquot (2 Gy). The other one was measured on the same aliquot irradiated a second time with the same dose (same time delay between irradiation and TL measurement, no additional grinding process). The mechanical treatment affected neither the intensity nor the structure of the glow curve. The glow curve of an unirradiated aliquot recorded after signal surface process is also shown. No TL signal was created by grinding. (Adapted from Bassinet et al. [6].)

to be the best selection for most samples for optimizing the BGS reduction while retaining sufficient sample mass for analysis.

2.2.1.5 Optical stability

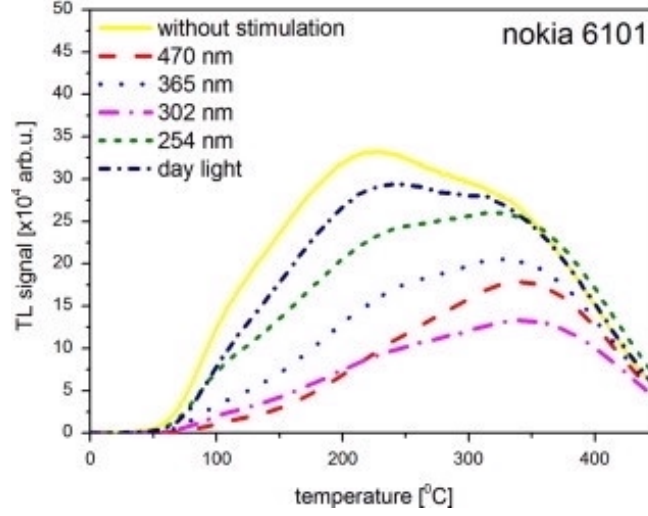
Several studies have observed that the RIS in display glasses is bleachable through light exposure [2–4, 6], the degree of which is dependent on the light source intensity and wavelength and the light exposure duration. If a sample is exposed to environmental light and the bleached signal is not taken into consideration, a large underestimation in the reconstructed dose could arise. One study showed that, in comparison with an equivalent sample stored in the dark, a loss in TL signal of up to 55% is incurred in samples that are used normally (exposure to indoor and outdoor light) for 5 d [3].

In a test of TL signal bleaching effectiveness, the largest TL loss incurred over 500 s, due to direct sunlight exposure, with approximately 14% of the original signal still intact. The second most effective bleaching was with blue light, leaving about 22% of the signal intact [3]. During normal use, the rear display glass is protected from direct sunlight exposure by the extra layers of glass and filters. The light bleaching sources most likely to be encountered, i.e., indoor light, diffuse sunlight and self-illumination, can have their exposures simulated with blue light. The blue light exposure has the effect of isolating a more stable signal by preferentially removing the less stable, low-temperature portion of the glow curve. With 500 s determined to be the optimal duration, applying the pre-bleach treatment results in around 80% signal removal.

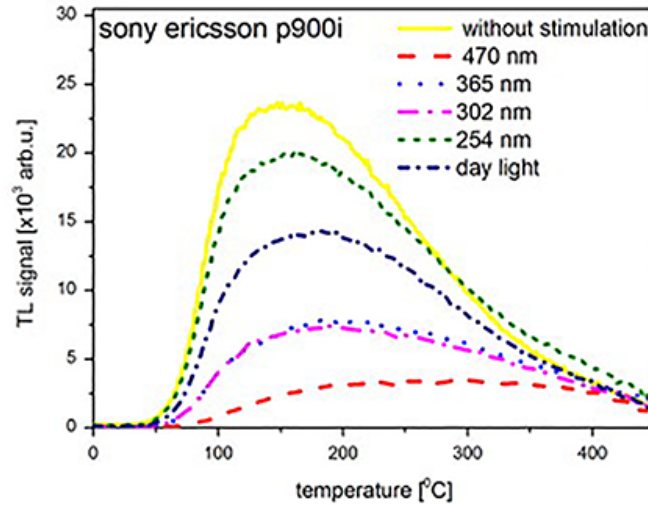
In a subsequent study [2], several light sources were tested for their use in a proposed pre-bleaching protocol; these included blue light (470 nm) as well as 254, 302 and 365 nm UV light. The results showed that various glasses can be more susceptible to different light sources (Figure 2.6). In particular, the best bleaching effect was obtained with the blue light for one glass sample, whereas the 302 nm UV was the most effective for another.

2.2.1.6 Fading

All display glasses have been shown to experience anomalous signal fading with increased storage time, with fading rates specific to each glass type. Where lime aluminosilicate



(a)



(b)

Figure 2.6: TL signal of glass extracted from mobile phone Nokia 6101 (a) and Sony Ericsson p900i (b), both irradiated with a dose of 2 Gy ($^{90}\text{Sr}/^{90}\text{Y}$ beta source) and then bleached with different wavelengths: 470, 365, 302 and 254 nm (UV lamp), day light and without exposure to light before the TL readout. The glow curves were normalized to the mass of the samples. (Adapted from Mrozik et al. [2].)

glasses retain approximately 50% of their original signal after 1000 h, boron silicate glasses retain only half that amount [3, 9]. The reproducibility of the fading signal for the lime aluminosilicate glasses was within 7% for older mobile phones and less than 2% for smartphones. This is in contrast to the boron silicate glasses, shown in Figure 2.7, which experienced an increased dispersion, up to 27%, for longer fading times [7]. Another distinction between the two glass types was that the proposed pre-bleach protocol (mentioned above) improved the fading rate for lime aluminosilicate glasses but had no effect on fading in boron silicate glasses. While signal fading is an unfavorable attribute, it can be accounted for by fitting to a logarithmic decay function [9]. Assuming the storage time is known, this allows for a fading correction factor to be applied in the final dose evaluation. While not appropriate for long-term retrospective dosimetry, the stability of the RIS in display glass is sufficient for emergency dosimetry purposes, where results would be calculated in a matter of days.

2.2.1.7 Dose–response characteristics and reproducibility

The dose–response relationship for both glass types has been reported to be linear in several studies [3, 6]. This includes the 10–20 Gy range in both the UV and blue detection windows for older mobile phones as well as up to 10 Gy in smartphones. It is also been observed that the glasses that undergo a pre-bleach or BGS removal, through chemical etching or grinding, also remain linear over the tested dose ranges [10].

The reproducibility of the signal for repeated cycles of irradiation and measurement has been reported as $< 10\%$ for 10 cycles of older mobile phones [10], with another group reporting within 3% for the same style phones [3]; whereas, smartphones demonstrated a reproducibility within 11% for five cycles [8]. These results illustrate that the sensitivity of the sample does not change with repeated exposures to radiation or high temperatures; this is an important detail for dose reconstruction where a change in radiation sensitivity would need to be taken into account, complicating the reconstruction process.

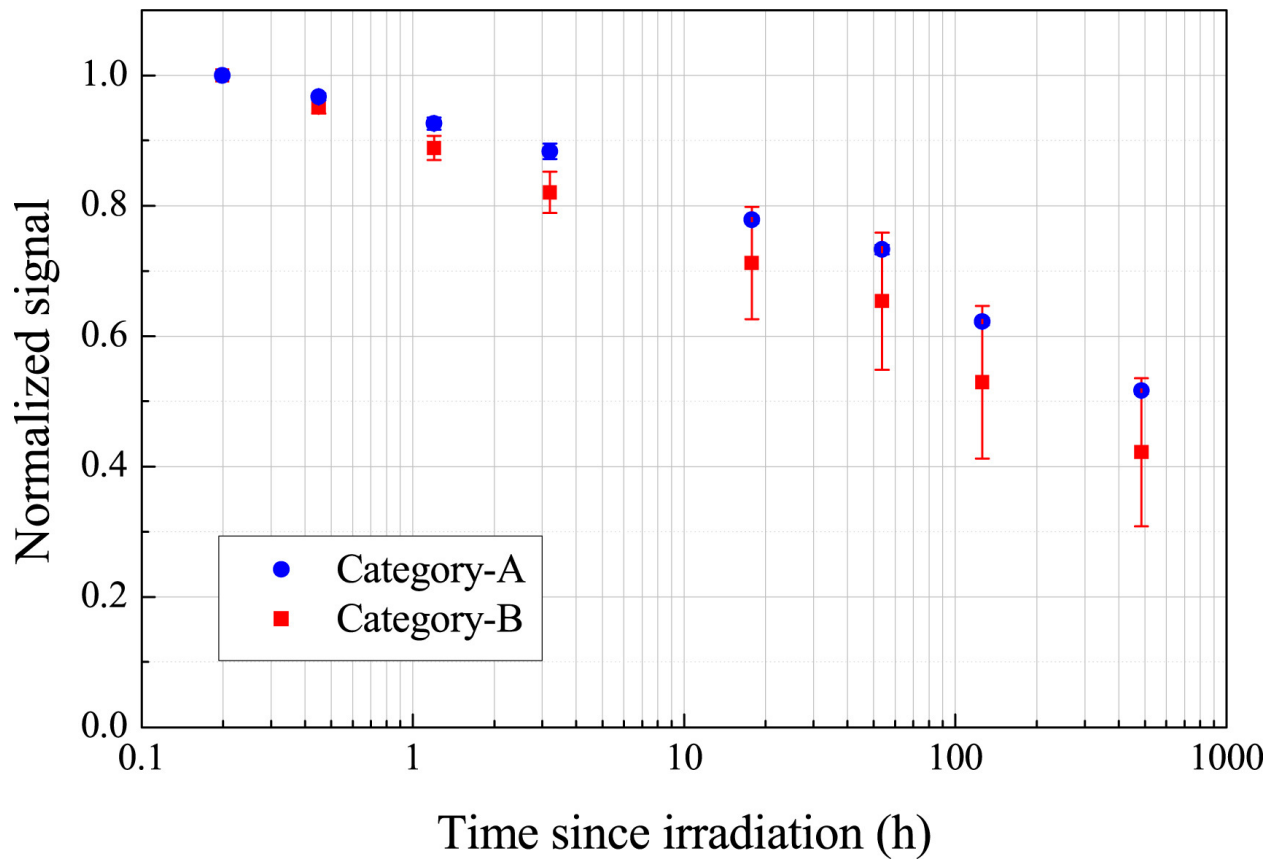


Figure 2.7: Fading of TL signals up to 5 d for the 22 AMOLED substrate glasses (15 lime aluminosilicate glasses and 7 boron silicate glasses). (Adapted from Kim et al. [7].)

2.2.1.8 Energy–response characteristics and angle dependence

The position in which a phone is exposed and the source it was exposed to could play a major role in dose reconstruction. Fortunately, the display glass has been investigated for both its possible angle and energy dependences [6, 8].

For the photon energy dependence, two studies [6, 11] showed that the observed responses were in good agreement with the theoretical calculations, with each showing an over-response varying from 5 to 11% when compared to the response to a reference energy > 500 keV. The responses were similar for both the lime aluminosilicate glasses and boron silicate glasses, with no differences seen whether the glass was from an older mobile phone or from a smartphone. For the angle dependence, using free-in-air exposures, a strong shielding effect was observed between 90 and 270° for low energies, with the variation in angle response ranging from 13% for ^{137}Cs to 51% for 118 keV photons. These results illustrate that, especially when exposed with low-energy photons, correction factors will need to be applied to account for shielding to be able to accurately determine the received dose.

2.2.1.9 Dose reconstruction tests

Experiments have been performed with the glass samples both intact and previously extracted from the displays [5, 10]. The results showed good correlation with the given doses; however, for the intact experiment, the results did slightly overestimate the administered doses by 5.8–22.2% [10]. In comparison to the alumina resistors, with accuracy within 5% for all but one sample, the method performed worse; however, the display glasses do have the advantage of easier sample preparation and lower fading rates.

There has been one interlaboratory comparison that has assessed the applicability of a TL protocol on display glasses [12], which was organized by a joint effort between Running the European Network of Biological and Retrospective Physical Dosimetry (RENEB) and the European Radiation Dosimetry Group (EURADOS). The protocol called for the application of a pre-bleach and a chemical etching treatment. Each group was given three samples irradiated to doses of 0.6, 1.5 and 2.5 Gy. The results showed that the reconstructed doses were all within the 95% confidence interval and no significant dose underestimation was

observed. This implies that the prescribed protocol successfully accounted for the signal fading and optical bleaching incurred by the sample. In addition, no systematic differences in the quality of results could be seen between the laboratories that participated in a sample preparation and measurement training exercise and those that received detailed written instructions.

2.2.2 PTTL properties

PTTL is a luminescence method that seeks to overcome some of the complications associated with the TL method by taking advantage of deeper, more stable radiation-sensitive traps that demonstrate a slower fading time with less sensitivity to light exposure. The glass is first heated to temperatures $> 350^{\circ}\text{C}$, then cooled to room temperature and exposed to a light source to stimulate the transfer of electrons from the deeper traps into the traps that were just emptied during the initial heating. When the signal is reheated a second time, the emitted signal is now PTTL. To date, there has been only one study of PTTL from display glass [13]. The research was performed on two lime aluminosilicate display glasses, one from an older mobile phone and the other from a more modern smartphone. The aim of this study was to analyze various aspects of a potential PTTL protocol, such as selecting the appropriate filter set, optimizing the preheat temperature and hold time and determining the most suitable phototransfer source. It was determined that the optimized parameters were a preheat at 400°C and a hold time of 10 s.

The choice of detection window was based on the ratio of the RIS to the non-radiation-induced signal (nRIS) measured by integrating the signals between 200 and 300°C [13]. The results, shown in Figure 2.8, revealed that the best RIS/nRIS ratio was achieved by a filter set with a detection window centered at a wavelength of 340 nm with a full-width half-maximum value of 30.2 nm. In a similar fashion, the selected light exposure source was determined by examining the RIS/nRIS ratio produced by each source integrated between 200 and 300°C . The experiment was conducted using 254, 302, 365, 385 and 405 nm light sources. In general, the results indicated that the intensity of both the RIS and nRIS PTTL signal increases with decreasing stimulation wavelength. However, shorter wavelengths produced their own TL signals. Therefore, the optimal choice of light source to use is a compromise between

the PTTL intensity and the prevention of an nRIS signal generated by the source itself. The RIS/nRIS ratio suggests that any of the sources with wavelengths $> 302\text{ nm}$ would be appropriate for use.

The reproducibility of the PTTL protocol was tested by performing five cycles of irradiation, preheat, light exposure and final readout; the results were observed to be within 10% of the original readout for each cycle. In addition, the PTTL dose-response was found to be linear over the 0.24–11.8 Gy dose range with no discernible differences between the smartphone and mobile phone displays.

The PTTL signal was confirmed to exhibit an improved signal stability in comparison to that of a standard TL signal. Over a 254-h storage period, the PTTL signal experienced a signal loss of $< 10\%$. Furthermore, the PTTL signal was found to be virtually stable over a 20-h period, whereas the TL signal had lost 20% of its original signal over the same time. These observations demonstrate that, unlike a TL protocol, the application of fading corrections maybe unnecessary for PTTL.

2.3 Built-in protective glasses

Protective glasses can be subdivided into those built into the device at the time of manufacture and those added after the phone has been purchased by the consumer. The built-in protective glass is located on both the front and back of the device. On the front (screen side), it is commonly referred to as a touchscreen glass and is responsible for protecting the display underneath while also facilitating the phone’s capacitive touch interactions. It is predominately made of Corning’s GG; however, there are other chemically strengthened glasses in use (e.g., Dragontrail glass manufactured by AGC Inc.). GG is also found on the back of many modern smartphones, and its role here is to protect the phone’s internal components while simultaneously enabling the phone’s wireless charging capability.

The following sections analyze the TL, PTTL and OSL properties of built-in protective glass. Throughout this section, both styles of built-in protective glasses will be referred to as touchscreen glasses, and all data are specific to the GG brand of chemically strengthened glasses.

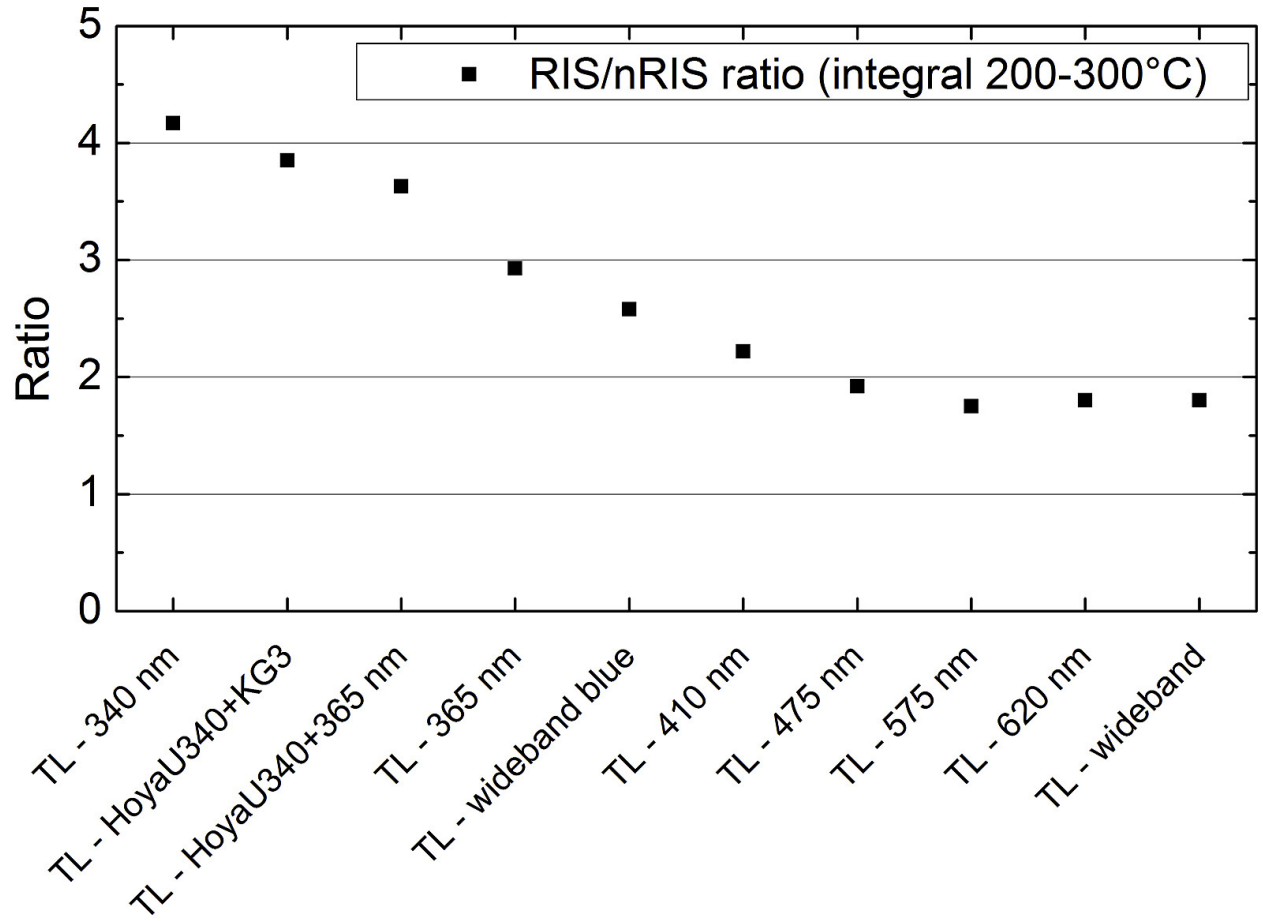


Figure 2.8: Calculated RIS/nRIS ratio of the radiation-induced and the non-radiation-induced PTTTL signals. The results are shown in descending order. (Adapted from Discher et al. [13].)

2.3.1 TL studies

2.3.1.1 TL glow curves

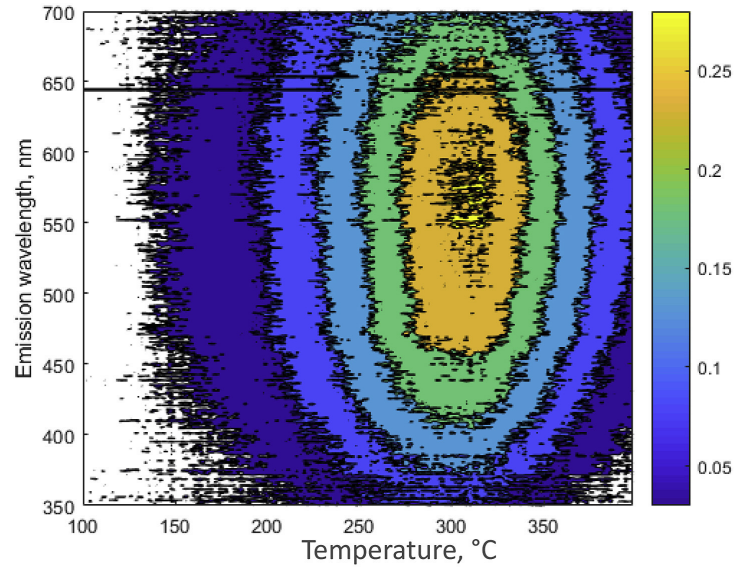
Unlike the display glasses, touchscreen glasses do not fall into characteristic categories. Instead, they all belong to the same group since they are all made of the same alkali-aluminosilicate glass. Although this minimizes the variations between samples, it does not signify a consistent set of properties. In fact, while the same general glow curve shape persists, the peak position, signal intensity and glow curve width all vary with the different generations of GG [14, 15].

2.3.1.2 TL emission spectra

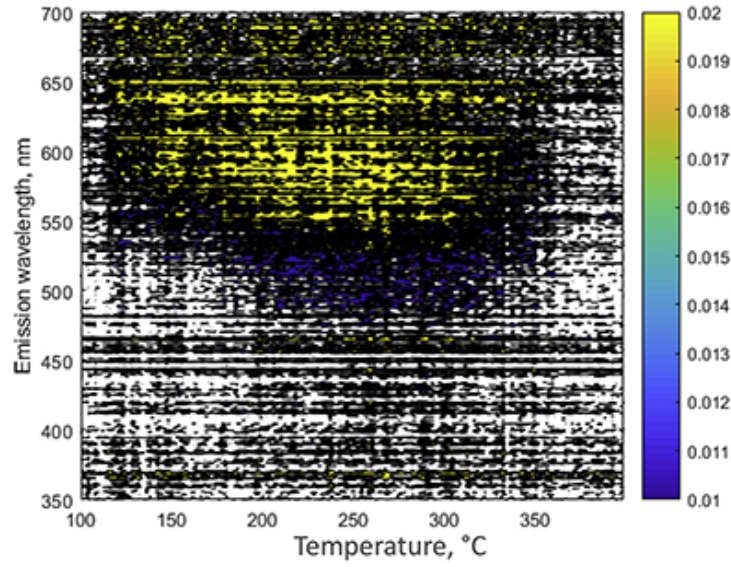
While the RIS glow curves from the lime aluminosilicate display glasses most resemble that from the touchscreen glass, the TL emission wavelengths correlate more closely to those from the boron silicate display glasses. The emission wavelengths for the touchscreen glasses extend into the 650–750 nm range (Figure 2.9) [16]. The choice of the transmission window should be taken into consideration based on the emission wavelength of the sample so as not to cut off a portion of the spectrum. An appropriate filter choice for touchscreen glasses should extend into the visible region.

2.3.1.3 Background signal

The characteristics of the BGS, like those of the RIS, are observed to fluctuate in shape and intensity with the GG generation. The BGS glow curves peak at temperatures of 25–50 °C higher than that of the RIS, begin at approximately 150 °C and can extend past 450 °C. The observed overlap of the BGS and RIS is more severe for touchscreen glasses than for display glasses, thus, further restricting the possible integration window to between 100 and 175 °C [14]. The intensity of the BGS glow curves from the earliest generation of GG is minimal (corresponding to a dose between 141 and 252 mGy); however, the BGS intensity increased steadily, to the equivalent of tens of Gy, with the subsequent generations [14, 15].



(a)



(b)

Figure 2.9: TL emission spectra from two samples of different radiation sensitivity (a, b). The samples were irradiated to a beta dose of 20 kGy and the heating rate was 2 °C/s. All spectra were corrected for the system wavelength response. (Adapted from Sholom et al. [16].)

For touchscreen glasses made of later generation GGs, the BGSs are not homogenous across the display. In fact, one study observed an increased BGS for aliquots taken from the edge compared to those taken from the center was encountered in another [15].

2.3.1.4 Background signal mitigation

The BGS mitigation technique employed for display glasses, in which the surface of the glass is removed, was also found to be successful for touchscreen glasses [14]. The glass was removed through mechanical abrasion using a grinding pencil, with approximately 200–500 nm removed from each side. The mechanical treatment resulted in a reduction of the BGS between 75% and 82%, with the abrasion process itself not generating any erroneous signals [14].

2.3.1.5 Optical stability

The optical stability of touchscreen glasses was examined by exposure to varying durations of blue light [14]. The results show a strong reduction in TL intensity with increasing exposure time. For display glasses, that are partially protected from light exposure by layers of glass and filters, the use of a pre-bleaching was able to account for any light exposure that would occur during normal use. However, touchscreen glasses that were exposed to 2 h of direct sunlight and 16 h of indoor light had reconstructed values of 51 and 57% of the given dose for annealed and unannealed samples, respectively [14]. The underestimation is a consequence of the higher bleaching efficiency of sunlight (compared to blue light) combined with the lack of protection from it for the touchscreen glasses.

2.3.1.6 Fading, dose–response characteristics, and reproducibility

The dose–response characteristics of touchscreen glass are linear over the investigated range of 0.1–5.5 Gy, with a reproducibility within 6% for 10 cycles of irradiation and measurement [14]. Fading was studied over a 51-d period, with results varying between the touchscreen glasses from the same smartphone model [14]. The samples were observed to fade by approximately 30 and 50% over 1-d and 10-d storage periods, respectively. Fortunately,

the results can be approximated by a logarithmic function which allows for corrections to be made to recovered doses.

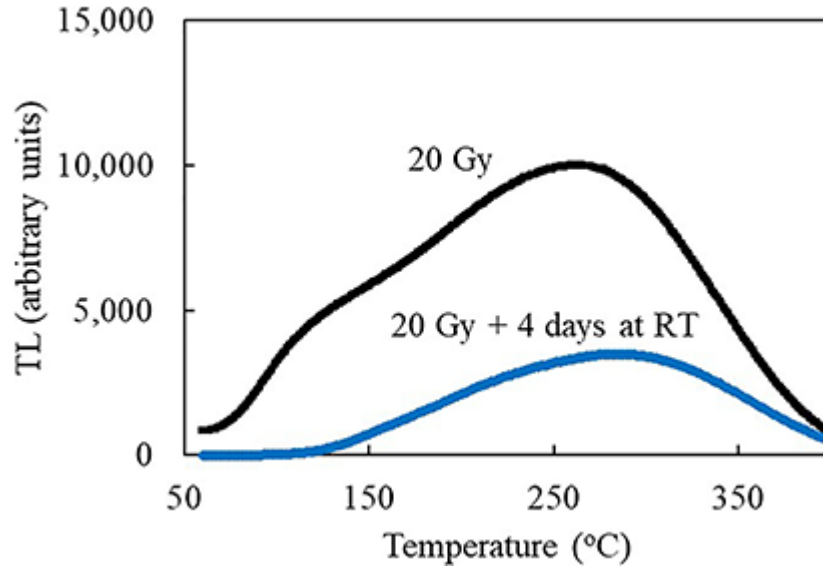
2.3.2 PTTL studies

The initial PTTL study of touchscreen glasses [17], utilizing first-generation GGs, observed that the best signal was obtained when integrating between 250 and 350 °C to avoid the UV-induced TL signal and using a preheat temperature ranging from 350 to 400 °C, depending on the sample. The optimal stimulation wavelength was observed to be 365 nm, as this wavelength allowed for adequate signal intensity while also limiting the UV-induced TL. Using these parameters, the PTTL dose–response exhibited a linear dose–response from 1 to 20 Gy. In addition, the RIS was found to have excellent fading characteristics, with minimal signal loss over a 20-d storage period (Figure 2.10). The method was able to perform comparably well alongside surface mount resistors, integrated circuits and display glasses during dose recovery tests.

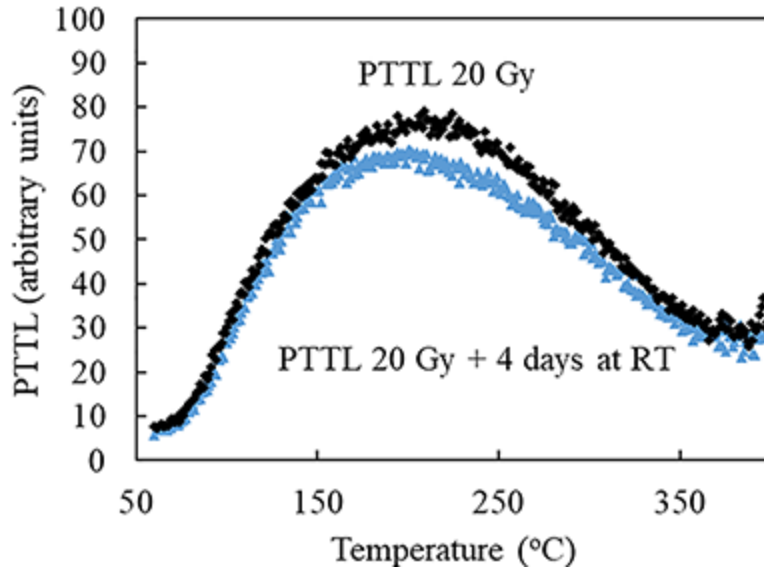
2.3.3 OSL studies

The most recent smartphones have a glass backing to enable wire-free charging. The opportunity for utilizing OSL as a dosimetry method with smartphones is due to the majority of people protecting their smartphone by installing it in a case. In doing so, and assuming the case is opaque, the back glass is protected from any exposure to light.

The OSL BGS was observed to be exceedingly small, to non-existent, with MDDs between 2 and 100 mGy for the tested samples (Figure 2.11) [16]. The RISs showed significant differences in both shape and intensity between different glasses but could be divided into two major groups. The first group consisted of the higher sensitivity samples that demonstrated slower OSL decay, whereas the second group was made up of lower sensitivity samples exhibiting a faster OSL decay. When comparing the two groups, the OSL intensity and decay time of Group 1 samples was about one order of magnitude and two times longer, respectively, than their Group 2 counterpart. The OSL dose–response was observed to be

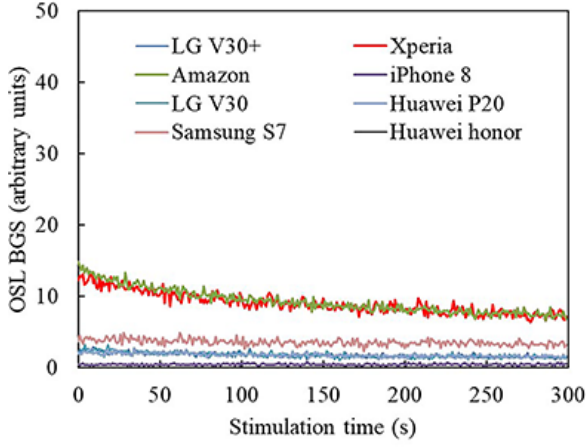


(a)

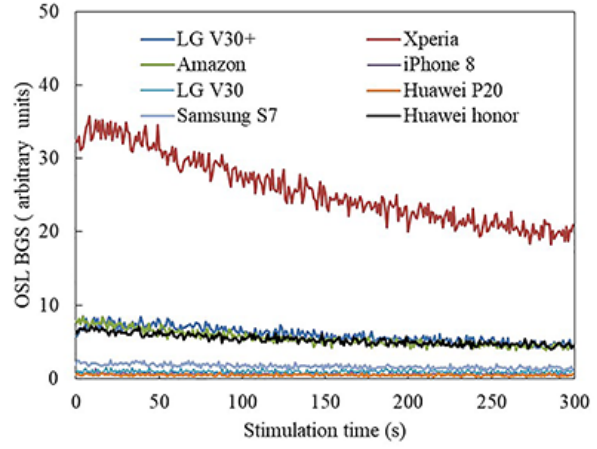


(b)

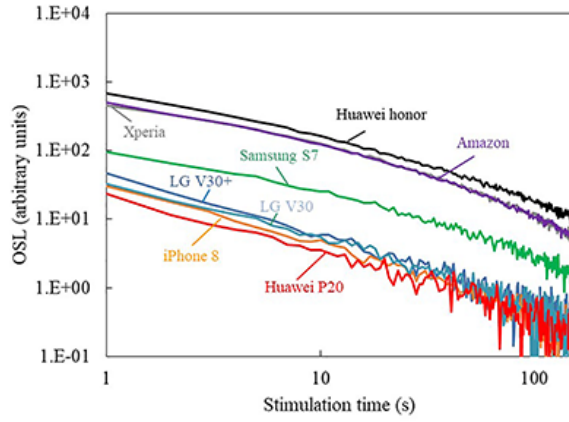
Figure 2.10: Changes to the glow curves due to fading (4-d storage under ambient conditions at room temperature (RT)) for: (a) the TL signal and (b) the PTTL signal. The PTTL signals were obtained following a 400 °C preheat and 365 nm exposure for 20 min. The initial delivered beta dose was 20 Gy. (Data from McKeever et al. [17].)



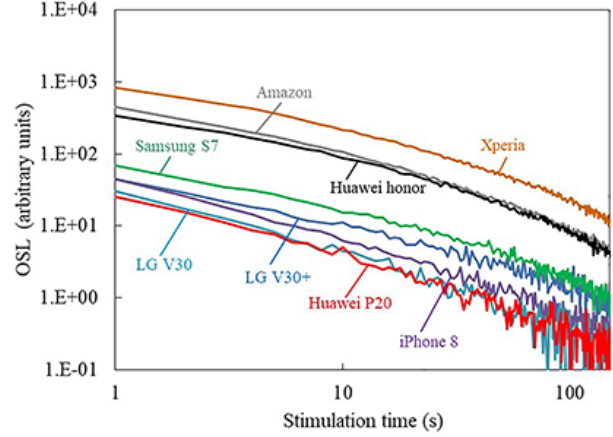
(a)



(b)



(c)



(d)

Figure 2.11: BGS (a, b) and 0.8 Gy RIS (c, d) OSL signals from the back (a, c) and corresponding front (b, d) glasses, tested using continuous wave OSL. The OSL signals were stimulated with 470 nm light at RT and within 2 min after exposure. (Adapted from Sholom et al. [16].)

linear up to 10 Gy and lost around 82 and 88% of the original signal over the course of 1 week for Group 1 and Group 2 glasses, respectively [16].

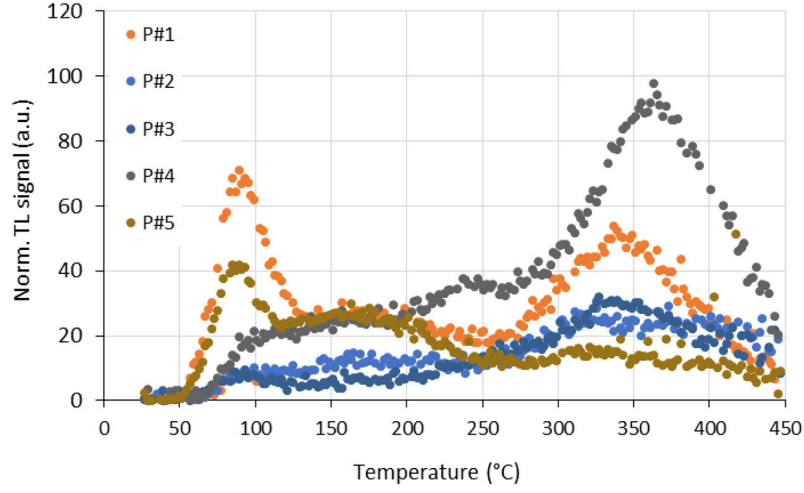
A pulsed OSL (POSL) technique was tested with the aim of allowing for fiber-optic, non-destructive measurements [16]. The premise behind the technique is that the glass could remain intact on the device and an OSL reader outfitted with a fiber-optic attachment could be placed on the glass when performing measurements. Using this setup, the dose-response was found to be linear for doses < 7 Gy with estimated MDD values in the range of 0.5–30 Gy, depending on the sample. Utilization of this POSL technique would have the fastest possible result turnaround time as no sample preparation is necessary; however, more work is required to optimize the method.

2.4 Screen protectors

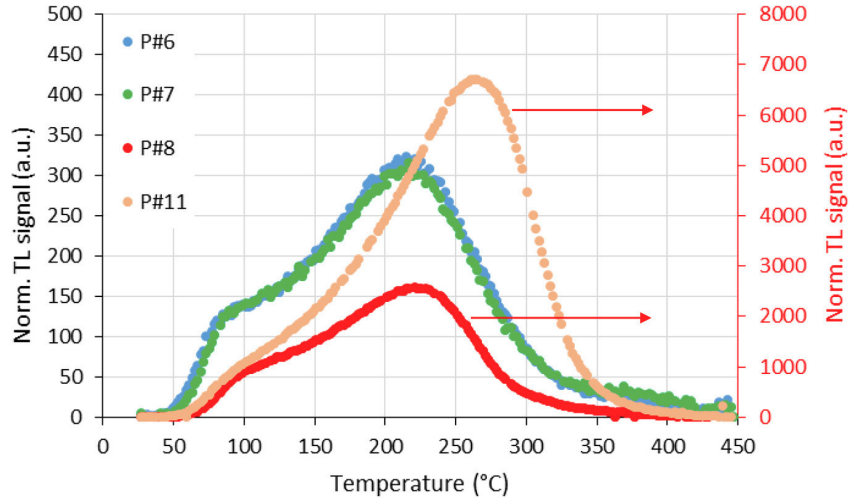
The second group of protective glasses is known as screen protectors. Commonly, they are made of tempered soda-lime glass, where tempered glass is one that has been strengthened through a heating and rapid cooling process. The screen protectors are purchased aftermarket and placed by the consumer on top of the touchscreen glass as an extra layer of protection against scratching. There are many brands in this competitive market (e.g., Zagg, Tech Armor, Spigen and others).

At the onset, screen protectors have the advantage of a simpler sample preparation when compared to both touchscreen and display glasses as the screen protectors are only lightly adhered to the front of the device and their removal causes no damage. An initial study of screen protectors, recently completed on 20 different models of glass screen protectors, examined several of their dosimetry properties [18].

The TL signals from the screen protector glass were seen to vary from sample to sample in shape and intensity; however, they could be grouped into two distinct categories while using a wideband blue detection window (Figure 2.12). The first category's TL glow curve is comprised of three separate peaks; the first peak appears at approximately 90 °C, the second at around 350 °C and at least one peak in the 150–250 °C range. The second category has its



(a)



(b)

Figure 2.12: Radiation-induced TL signals from the screen protector glass. Two categories of glasses are identified: (a) Category 1 and (b) Category 2. The glass was previously annealed by heating as in a normal TL measurement. The TL signals (after a dose of 5 Gy) are normalized to the aliquot mass. (Adapted from Bassinet et al. [18].)

main peak in the 200–300 °C range, with another prominent peak located at around 100 °C. The RIS intensity was observed to be higher for the Category 2 glasses.

Every screen protector glass possessed a BGS that varies in shape and intensity from one screen protector to another. The BGS, after employing the same etching strategy used for display glasses, could be largely eliminated. Due to its interference with the RIS, the integration window must be restricted to between 100 and 150 °C.

The RIS signal was found to be sensitive to light; however, a pre-bleach with blue light allowed measurements of the hard-to-bleach components. Using this protocol, the reproducibility for five cycles was observed to be within 4% of the original value. In addition, the dose–response was linear up to 20 Gy. Lastly, a fading study on previously annealed aliquots showed that fading of the RIS was negligible within the first 100 h and experienced only around 20% fading after 12-d. An initial dose recovery test observed good agreement between the reconstructed and administered dose [18].

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Chapter 3

THERMOLUMINESCENCE AND PHOTOTRANSFERRED THERMOLUMINESCENCE DOSIMETRY ON MOBILE PHONE PROTECTIVE TOUCHSCREEN GLASS

A version of this chapter was originally published by J. R. Chandler et al.:

Chandler, J.R., Sholom, S., McKeever, S.W.S, and Hall, H.L. "Thermoluminescence and phototransferred thermoluminescence dosimetry on mobile phone protective touchscreen glass". *Journal of Applied Physics* 126 (7) (2019), p. 074901

Abstract

Thermoluminescence (TL) and phototransferred thermoluminescence (PTTL) measurements of protective glass from smartphones are described. Samples of Gorilla Glass (GG) were examined from nine different manufacturers and 40 different phone models. Additionally, 12 glasses believed to be original equipment manufacturer replacements, as well as three glass samples from U.S. finishers, were also studied. Altogether, 99 different GG samples were examined. The radiation-induced thermoluminescence signal (RIS) produced glow curve shapes specific to the GG generations and could be used to distinguish between them. A background TL (and PTTL) signal was found in all unirradiated samples. Its intensity and shape were found to be dependent on the GG generation, phone manufacturer, and phone model. The background signal (BGS) was demonstrated to be produced by ultraviolet (UV) light exposure; the shape of the BGS was reproduced by the combined exposure to a broad-spectrum solar simulator and a 302 nm UV light source. The BGS intensity was found to vary with the location from which it was taken on the glass. It was also found to be dependent on the depth within the GG due to absorption of the UV light as it traversed the medium. Removal of the glasses' surface layers was found to be an inadequate method for removing the BGS. In some samples, the BGS intensity was large enough to significantly contribute to the total TL (and PTTL) signal; therefore, a matrix deconvolution method was introduced to separate the BGS and RIS. This method was found to enable dose reconstruction using the RIS alone.

3.1 Introduction

During the course of a radiological incident, due to either an accident or a deliberate act of nuclear terrorism, many individuals may be exposed to varying degrees of radiation. It is critical in such circumstances that the doses to potentially exposed individuals be determined as quickly as possible after the event for purposes of triage, initial medical management, and public safety decisions. Exposed individuals are unlikely to have standard dosimeters on their person; consequently, methods of retrospective dosimetry must be developed in order to estimate the received radiation doses. In addition to biodosimetry, several physical dosimetry methods have been proposed that make use of fortuitous and ubiquitous materials that may be located near to or on the individual at the time of exposure [1, 2].

Retrospective dosimetry of this nature is termed accident or emergency dosimetry, and its aim is to make use of materials with low signal-fading characteristics that have the capability of easily distinguishing between doses > 2 Gy, which require immediate medical attention, and those < 2 Gy, which are less urgent [1]. There exists extensive literature on the suitability of varying materials in this role. Materials investigated for luminescence dosimetry have included items such as vitamins [3], tooth enamel [4, 5], business cards [6], banknotes [7], insect wings [8], fabrics [9], and colored pencils [10]. However, the research that has garnered the most interest has been on the applicability of different components found in portable electronic devices, most notably smartphones due to their pervasiveness and proximity to the user.

Initial efforts focused on optically stimulated luminescence (OSL) from internal, surface-mount resistors [11]. To date, this is the leading candidate for physical dosimetry from electronic devices [12]. Glass from phones has also been the subject of several studies. It can be found within a phone as part of the display (e.g., liquid-crystal displays) and on the exterior of the phone as part of its protective structure. The specialized protective type of glass first made its appearance on the market in 2007 with Corning's Gorilla Glass (GG) on the Apple iPhone [13]. Its emergence came as smartphones transitioned from physical keyboards to capacitive touchscreens.

Both display and protective glasses have been tested as possible emergency dosimeters; however, protective glass has an important advantage that its sample preparation procedure avoids the need to irreversibly damage the phone. This is a major issue, especially when communication between individuals during an emergency is considered to be vital and attachment to these devices would be at its highest [14].

While other similar glasses are available for this application, GG still dominates the market and has, therefore, been the focus of considerable research in this area. GG has previously been investigated using electron paramagnetic resonance (EPR) [15–18], thermoluminescence (TL) [18–20], and phototransferred thermoluminescence (PTTL) [21].

In one of the first EPR studies, utilizing preprepared GG from 22 identical (undisclosed) model smartphones, Fattibene et al. (2014) [15] conducted an interlaboratory comparison among 13 participants. The participants were divided into two groups with one group’s samples consisting of a homogeneous mixture of crushed glass, each irradiated to unknown (i.e., blind) doses, while the other group utilized glass from independent phones. Another element of the study involved an assessment of how storage conditions affected the results. The first group’s mixture was stored under consistent laboratory conditions, whereas the second group’s phones were stored in variable daylight conditions.

The results showed that the participants from the first group were able to satisfactorily (within a 95% confidence interval) determine the blind doses, while members of the second group struggled to correctly identify the doses. These findings suggest that the variability between samples, influence of environmental conditions, or both could be a detriment to this approach.

Subsequent EPR studies [16–18] demonstrated a large variability in the signals not only between glasses from different phones but also between different aliquots obtained from the same phone. These authors suggested that the large signal variability was caused by ultraviolet (UV) light exposure during the phone manufacturing process.

Discher et al. (2016) [20], employing a TL method and using glass from five iPhone 4 devices (2010 production year), found a linear dose-response relationship over the range of 0.1 Gy to 5.5 Gy with a reproducibility within $\pm 6\%$. It was discovered that the samples had an elevated background signal (BGS) in the dose range equivalent to 140 mGy–250 mGy. A

diamond grinding bit was used to remove 200 μm to 500 μm from the glass surface layers. This treatment resulted in a relative reduction of the BGS intensity by approximately 80%. Unfortunately, while corrections for long-term fading in ambient storage conditions could be approximated by a logarithmic function, the methods described by Discher et al. (2016) [20] were unable to account for the effects of light exposure. Samples that were exposed to direct sunlight drastically underreported the test dose during the dose-reconstruction test.

The latest TL study (McKeever et al., 2018) [18]—conducted on several different GG samples—revealed a larger impact of the TL BGS, which for some samples, was found to be equivalent to a dose as high as several tens of gray. In addition, these authors showed a strong correlation between the TL and EPR BGS.

To avoid some of the complications associated with the TL method, McKeever et al. (2017) [21] explored the use of PTTL. In comparison with TL, PTTL dose reconstruction uses deeper, more stable radiation-sensitive traps that demonstrate a slower fading time with less sensitivity to sunlight. For the five different smartphones used in the McKeever et al. (2017) [21] study [iPhone 3GS (2009), iPhone 4S (2011), HTC Hero (2009), Samsung Galaxy S II (2011), and a ZTE Obsidian (2015)], a linear dose PTTL relationship was found from 1 to 20 Gy, as well as excellent fading characteristics. A BGS of varying strength was also seen, which severely affects the variability in the minimum detectable dose (MDD). Additionally, a large disparity in sensitivity between the samples was observed; however, the method was able to perform quite well in a 2-Gy dose-reconstruction test when compared to other methods (TL, OSL), albeit with somewhat greater uncertainty. (The calculated standard deviations from this dose-reconstruction test were ± 0.038 Gy, ± 0.11 Gy, and ± 0.45 Gy for OSL of surface-mount resistors, TL of display glass, and PTTL of protective glass, respectively.)

The focus of the current work was to continue the investigation of the TL and PTTL properties of protective glass from modern smartphones. Specifically, a much larger sample size and variety of phone models were used than had previously been examined. An extensive analysis was completed on the BGS and the TL emission spectra. In addition, a potential deconvolution method to separate the BGS and the radiation-induced signal (RIS), for purposes of dose reconstruction, was also tested.

3.2 Materials and Methods

Eighty-four smartphones were used in this study. The protective glass of these phones was known or widely accepted to be GG. In addition to the glass samples detached from the phones, GG samples were ordered directly from three glass finishers located in the United States. The finishers receive bulk glass from Corning and complete the ion-exchange strengthening process in-house. Additionally, 12 glasses believed to be original equipment manufacturer replacements were obtained from four online vendors. This totaled 99 samples, spanning five generations of GG from nine manufacturers and 40 models. Tables 3.1 and 3.2 provide additional information on the selected samples. (Note that Apple does not disclose information on the glass used in its devices, so the information listed is speculative. The latest generation of GG available at the time of production was assumed in each case.)

Preparation of the samples included removal from the smartphone (where applicable) and cleaning with ethanol to remove any excess glue. Several $5.5 \times 5.5 \text{ mm}^2$ aliquots were then cut from each sample using a Buehler Isomet 1000 precision sectioning saw equipped with a diamond wafering blade and water cooling. This aliquot size is compatible with the Risø stainless steel sample disks that were used with a Risø DA-15 TL/OSL reader for collection of all TL and PTTL glow curves. TL and PTTL measurements were carried out with a BG-39 filter in a nitrogen atmosphere using a 2°C/s heating rate. The maximum heating temperature was sample dependent and in the range of $450\text{--}600^\circ\text{C}$. Additionally, blackbody background subtraction was used for all TL and PTTL measurements.

Sample irradiations were performed using one of the two $^{90}\text{Sr}/^{90}\text{Y}$ beta sources: Risø's built-in source and an external source delivering 80 mGy/s and 250 mGy/s , respectively. Both sources were calibrated to absorbed dose in water using a secondary standard ^{60}Co source from the National Institute of Standards and Technology (NIST).

For experiments employing UV exposure, two sources were used: a UVP 3UVTM (4 W) multi wavelength UV lamp and an Oriel LCS-100 solar simulator. The irradiance of each of these sources was: 1.6 mW/cm^2 , 1.52 mW/cm^2 , 1.51 mW/cm^2 , and 7.756 mW/cm^2 for the 254 nm, 302 nm, 365 nm, and the solar simulator, respectively. TL emission spectra were acquired using an Ocean Optics USB2000 spectrometer. The spectra were corrected for the

Table 3.1: Summary of GG samples removed from smartphone devices used in this study.

Manufacturer	Model	Production Year	GG Generation	# of Samples
Apple	iPhone 4	2010	1	Three
Apple	iPhone 4S	2011	1	Three
Apple	iPhone 5	2012	2	Five
Apple	iPhone 5C	2013	3	Six
Apple	iPhone 5S	2014	3	One
Apple	iPhone 6	2014	3	Seven
Apple	iPhone 6 Plus	2014	3	Four
Apple	iPhone 6S	2015	4	Two
Apple	iPhone 6S Plus	2015	4	Two
Apple	iPhone 7	2016	5	One
Apple	iPhone 7 Plus	2016	5	Three
Samsung	Galaxy S	2010	1	Two
Samsung	Galaxy S II	2011	1	Four
Samsung	Galaxy S III	2012	2	Three
Samsung	Galaxy S4	2013	3	One
Samsung	Galaxy S5	2014	3	Three
Samsung	Galaxy S6	2015	4	Three
Samsung	Galaxy S7	2016	4	Three
Samsung	Galaxy S8	2017	5	Three
Samsung	Galaxy Note 3	2013	3	Three
Samsung	Galaxy Note 4	2014	4	Two
Samsung	Galaxy Note 5	2015	4	One
LG	G2	2013	2	One
LG	G3	2014	3	Four
LG	G4	2015	3	One
LG	K10	2016	3	One
LG	G Stylo	2015	3	One
Motorola	Droid RAZR M	2012	1	One
Motorola	DROID RAZR MAXX	2012	1	Two
Motorola	DROID Ultra	2013	1	One
Motorola	DROID Mini	2013	1	One
Motorola	Moto Z Play	2016	3	One
HTC	Windows Phone 8X	2012	2	One
ZTE	Grand X Max+	2015	3	One
Huawei	Nexus 6P	2015	4	Two
Windows	Lumia 640	2015	3	One

Table 3.2: Summary of GG samples obtained from online vendors or GG finishers used in this study.

Manufacturer	Model	Production Year	GG Generation	# of Samples
Retailer 1	Nokia Lumia 1320	N/A	3	One
Retailer 1	Nokia Lumia 925	N/A	2	One
Retailer 1	Nokia Lumia 900	N/A	1	One
Retailer 1	Galaxy A7	N/A	4	One
Retailer 1	iPhone 4	N/A	1	One
Retailer 1	iPhone 5	N/A	2	One
Retailer 1	iPhone 6 Plus	N/A	3	One
Retailer 1	iPhone 7	N/A	5	One
Retailer 2	Galaxy S8	N/A	5	One
Retailer 3	iPhone 6 Plus	N/A	3	One
Retailer 3	iPhone 7	N/A	5	One
Retailer 4	Galaxy S7	N/A	4	One
Finisher 1	Abrisa	N/A	3	One
Finisher 2	Cat-I-Glass	N/A	3	One
Finisher 3	Stemmerich	N/A	3	One

response characteristics of the spectrometer using a NIST-calibrated lamp standard. Optical absorption data were collected using a Cary 5000 spectrophotometer.

3.3 Results and Discussion

3.3.1 TL emission

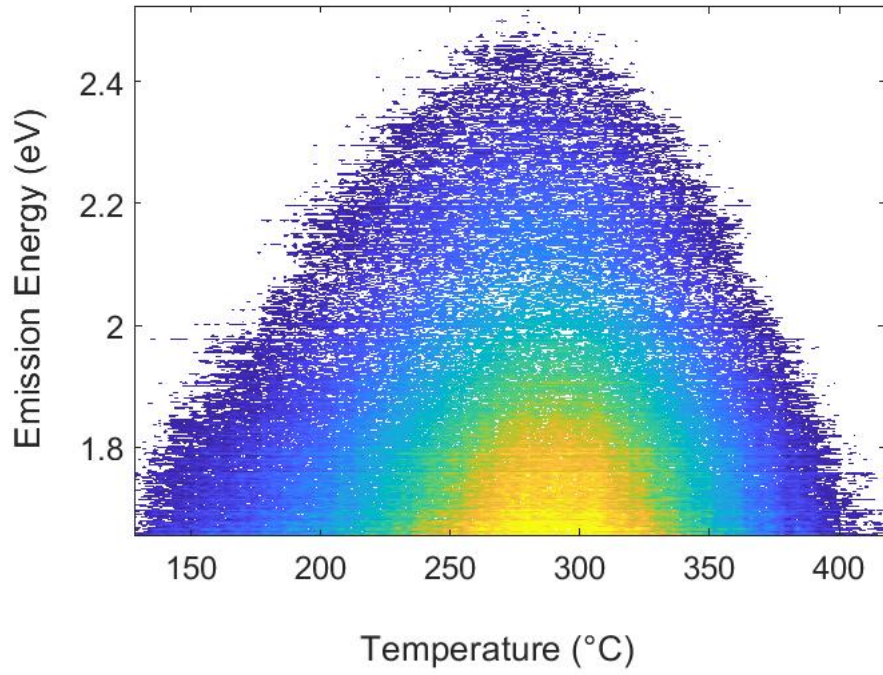
Figure 3.1 shows example TL emission spectra from GG samples after irradiation with a dose of 20 kGy. The emission intensity peaks at a temperature between 250 °C and ~300 °C. The emission band is broad with a maximum energy at ~1.65 eV. This corresponds to an emission wavelength that is longer than that observed by Discher and Woda (2014) [22] or by Kim et al. (2019) [23] for boron-silicate glasses (~600 nm wavelength) and lime aluminosilicate glasses (~380 nm wavelength). With these results in mind, a BG-39 filter, with a 300–700 nm detection window, was used for all TL and PTTL measurements.

3.3.2 TL glow curve measurements and analysis

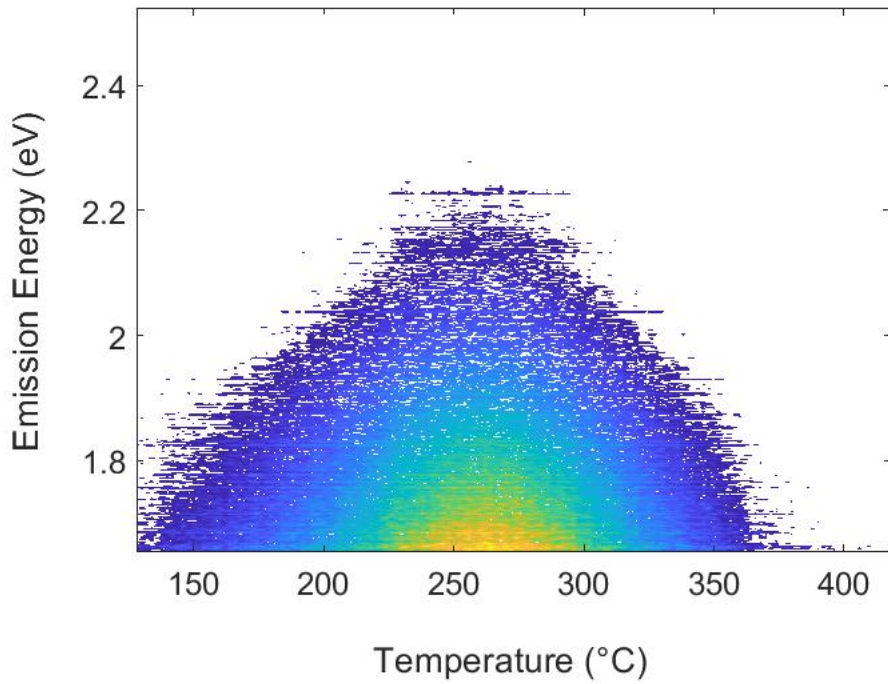
TL measurements were performed on each of the samples for three different signals: the BGS, RIS, and the signal from samples that still had their BGS intact, or as received (ARS), that were then irradiated. This signal is comprised of both the BGS and RIS. To obtain these signals, a few of the samples were first heated to 475–525 °C (the required temperature to deplete all traps was sample dependent), creating the BGS glow curves. These samples were then irradiated to generate the purely RIS glow curves. In addition, other samples were irradiated without removing the BGS, producing the ARS. These signals correlate with the subsequently generated curves presented in the following sections: 1 (blue) is the ARS, 2 (red) is the RIS, and 3 (black) is the BGS. This convention is exhibited in Fig. 3.2 for the iPhone 4S.

3.3.2.1 Radiation-induced TL glow curves

RIS glow curves for GG are characterized by a variety of shapes with the peak temperature position varying within the range of 250–350 °C, and while some glow curves



(a)



(b)

Figure 3.1: TL emission spectra for (a) an LG G4 and (b) an iPhone 4S after receiving a dose of 20 Gy. The emission intensity peaks between 250 and 300 °C with a broad emission band peaking at an energy of ~ 1.65 eV for each device. Concerning the figure colors, the warmer the color the higher the emission intensity.

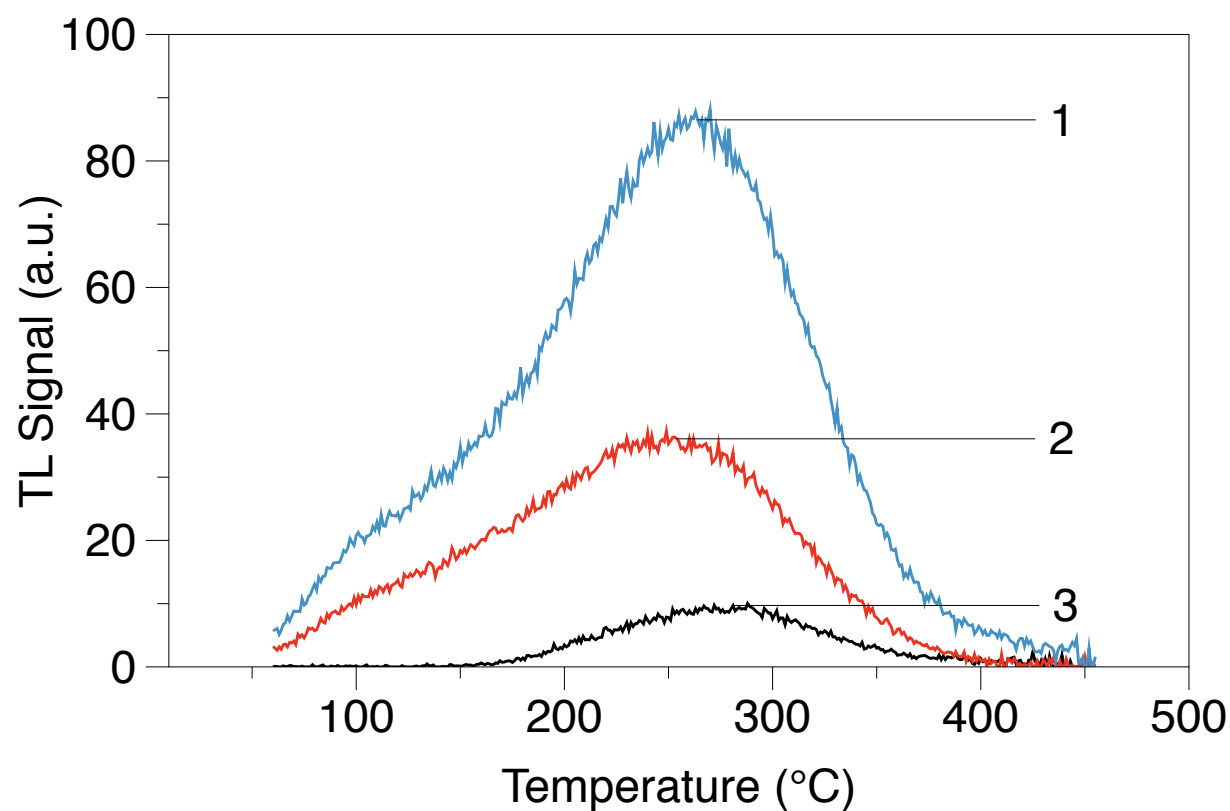


Figure 3.2: TL glow curves for samples of GG from an Apple iPhone 4S device. The glow curves represent the ARS (1) after receiving a dose of 5 Gy, the RIS(2) after receiving a dose of 5 Gy, and the BGS (3).

are symmetrical, others feature the addition of a small shoulder corresponding to a low-temperature TL signal. In addition, it was observed that no RIS TL occurs above 450 °C.

Corning has currently produced six generations of GG and has adjusted the composition of each generation. These modifications appear to be responsible for the glow curve differences noted above. Figure 3.3 depicts these changes through the evolution of a single smartphone series, the Samsung Galaxy S, generation 1 through generation 5.

The Samsung Galaxy S1–S8 models correspond to GG generations 1–5. The RIS TL glow curve shapes and positions appear to correlate well with the phone’s GG generation. In fact, when replotted as normalized TL curves, the phones naturally group together as follows: S1, S2, and S3; S4 and S5; S6 and S7; and S8. These groupings correspond to GG1 and GG2, GG3, GG4, and GG5, respectively.

The most distinct variation among the RIS curves is the presence of low-temperature TL near 75–100 °C. TL in this region is prominent for the earliest GG generations but gradually recedes as the peaks become narrower and more symmetrical with later generations. This trend continues until the introduction of generation 5 [Fig. 3.3(h)], where the main peak area has broadened and encompassed the lower-temperature TL region. It should be noted that the manufacture of generation 5 glass included a new two-stage ion-exchange strengthening process [24]. As can be implied from Fig. 3.3(h), this may have affected the glow curve shape and its TL sensitivity to ionizing radiation.

While the change from generation 4 to generation 5 is the most pronounced example of sensitivity change between generations (a decrease by a factor of five), there exist clear intergenerational and intragenerational sensitivity differences for all GG. This is evident when comparing the y axis of the individual graphs in Fig. 3.3. Furthermore, even aliquots from the same smartphone can have different sensitivities, as shown in Fig. 3.4 for ten thermally annealed aliquots of an LG G4 device measured after exposure to 20 Gy. These results indicate that an over- or underestimation of as much as 40% can occur in dose estimation if individual aliquot sensitivities are not taken into consideration.

The disparity in the sensitivities and glow curve shapes between samples is presumably caused by a difference in the elemental composition of the glasses themselves. This assumption is supported by Seyfang et al. (2015) [25], who were able to differentiate

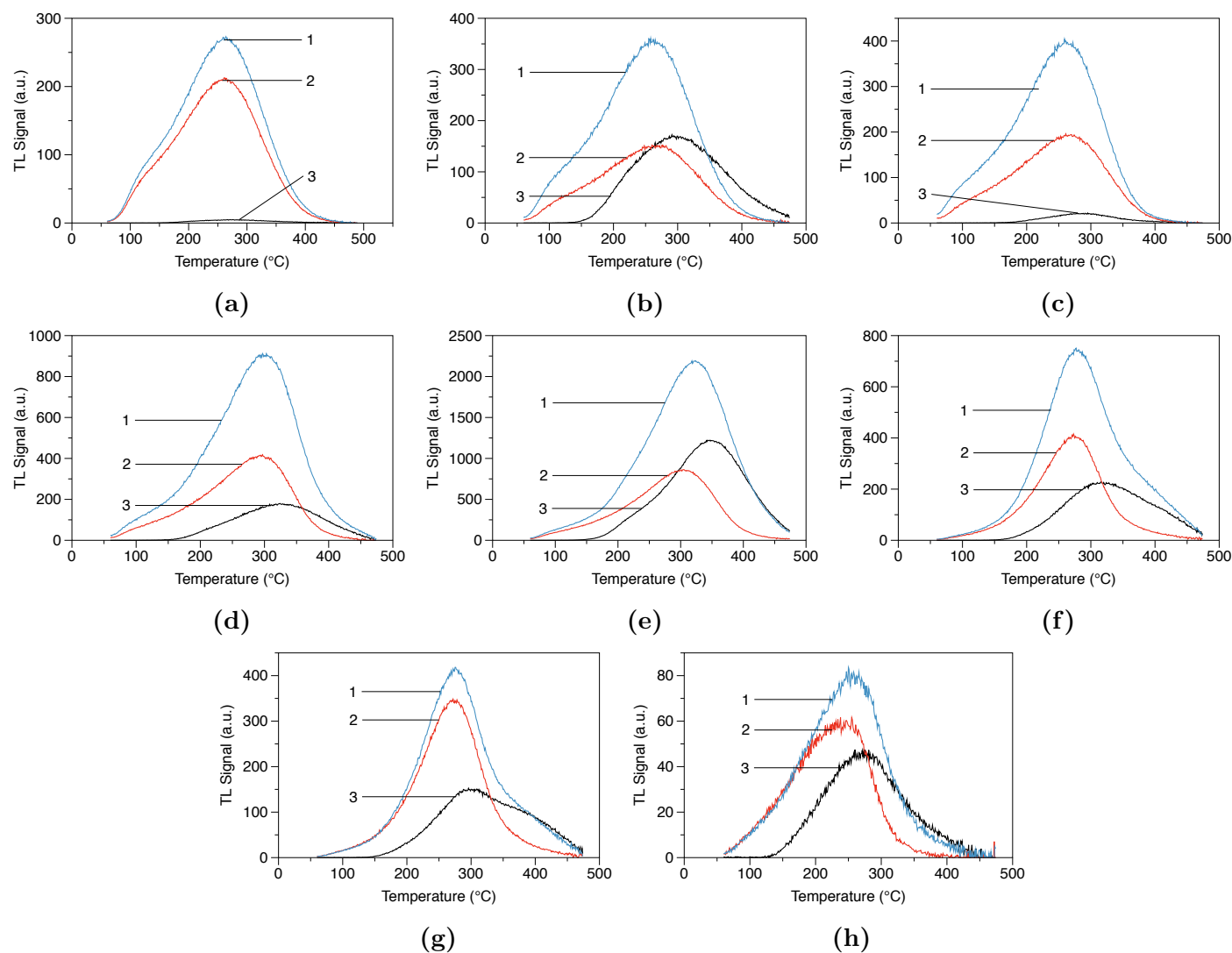


Figure 3.3: TL glow curves for samples of various GG generations from the Samsung Galaxy S series of devices. (a)–(h) represent the Samsung Galaxy S1, S2, S3, S4, S5, S6, S7, and S8, respectively. In each figure, the glow curves represent the ARS (1) after receiving a dose of 20 Gy, the RIS (2) after receiving a dose of 20 Gy, and the BGS (3).

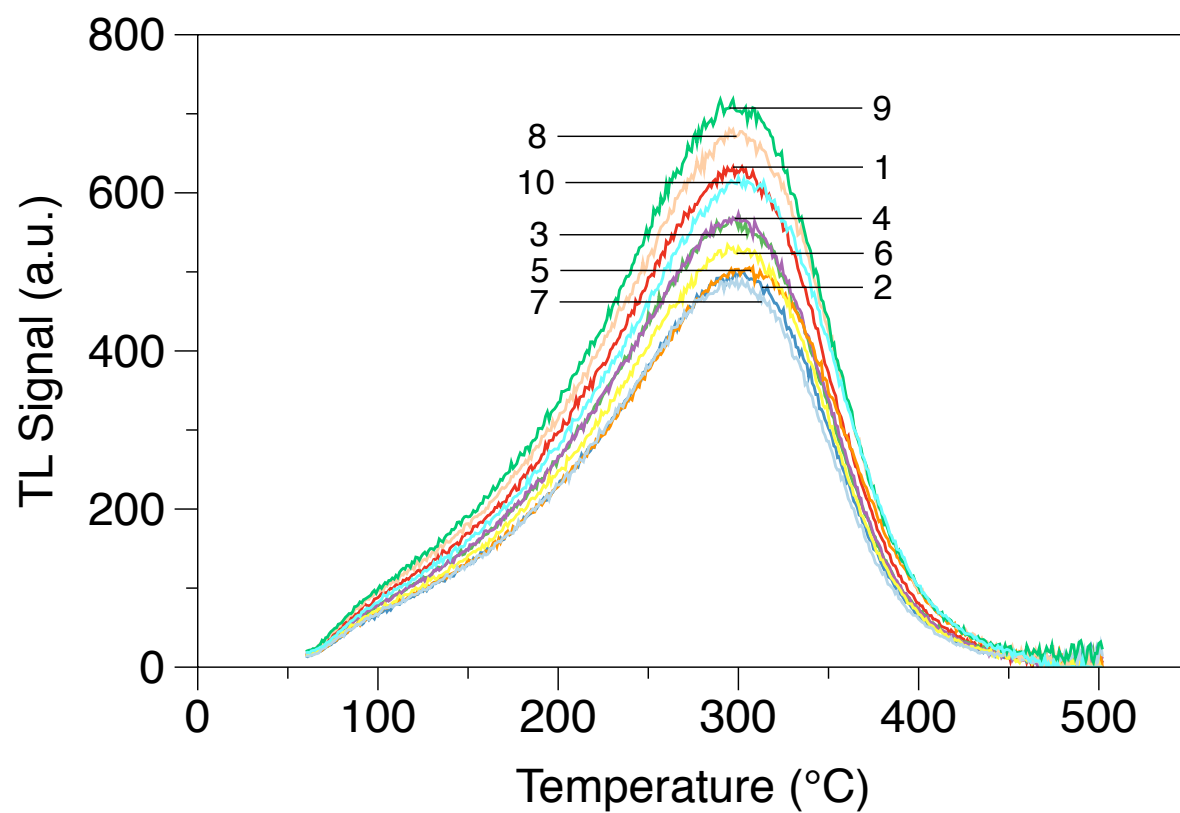


Figure 3.4: RIS TL glow curves from ten aliquots of GG from a single LG G4 device after receiving a dose of 20 Gy.

between GG and soda-lime glass, as well as between GG samples from different phone models using elemental analysis techniques (i.e., scanning electron microscopy energy-dispersive spectroscopy, laser ablation inductively coupled mass spectrometry, X-ray fluorescence, and refractive index measurements). Notably, Seyfang et al. (2015) [25] were able to distinguish between generations of the same series phone (e.g., an iPhone 3 from an iPhone 5) using the varying concentrations of potassium, tin, zirconium, and aluminum present in the GG from those devices.

An explanation for the elemental discrepancies between phones of different GG generations is that Corning modifies the abundance of the aforementioned dopants to produce their desired outcomes (e.g., stronger glass). However, for glasses of the same GG generation that are assumed to be identical, the differences could arise as a result of individual manufacturer strengthening processes. Corning is a bulk glass provider, and a finisher performs the ion-exchange process. In any case, the observed RIS sensitivities and glow curve shapes are hypothesized to be a by-product of the glasses' varying elemental abundances.

3.3.2.2 Background signal TL glow curves

GG samples regularly exhibit a TL signal prior to radiation exposure, termed the BGS, which is completely removed upon initial readout; this phenomenon was reported in display glass samples by Bassinet et al. (2010) [26] as well as in investigations of GG by Discher et al. (2016) [20] and McKeever et al. (2017) [21].

Figure 3.3 also shows the BGS from each of the Samsung Galaxy S devices. The BGSs, beginning at $\sim 150^\circ\text{C}$, have a peak that appears at glow curve temperatures which are ~ 25 – 50°C higher than the RIS. In addition, the BGS is a product of deeper traps, revealing further differences between the generations with the appearance of a high-temperature peak at $\sim 400^\circ\text{C}$ for generation 4 glass [Figs. 3.3(f) and 3.3(g)].

Attempting to group these devices by using the BGS TL glow curves is much less straightforward than when doing so with the RIS TL glow curves. This is due to not only the GG generations changing from phone to phone but also because of the addition of factors introduced between phone models to be discussed in Secs. 3.3.2.3 – 3.3.2.7. These factors specifically involve the individual manufacturer's methods for adhering the protective

glass to the device. Therefore, it may be concluded that while the RIS TL glow curves are characteristic of the GG generation, the BGS TL glow curves are a result of both the combined changes in GG and smartphone model.

3.3.2.3 Background signal origin

The origin of the BGS in display glasses was suggested to be from UV light exposure as part of the thin-film transistor structure fabrication process (Discher and Woda, 2013) [27]. For protective glass, it is presumed that the BGS results from UV light exposure during the curing of the adhesive used to affix the glass to the display. Just as protective glass has advanced with the proliferation of touchscreen devices, so have the adhesives used to attach it to the devices. The earliest smartphones used either a simple double-sided display tape or a pressure-sensitive adhesive. Current methods now utilize UV-curable optically clear adhesive films and liquid optically clear adhesives [28].

Most modern smartphone manufacturers are switching to liquid optically clear adhesives because they offer many advantages over traditional adhesives, e.g., superior optical properties, reworkability, and the ability to work on uneven surfaces. Liquid optically clear adhesives are applied to secure the protective glass (i.e., GG) to the touchscreen display. Curing the adhesive requires the use of UV light, and this is the proposed source of the BGS (the same is true for the optically clear adhesive films).

A UV-cured adhesive was used at different times on different devices, depending on the manufacturer. For instance, on Apple devices prior to the iPhone 5S, the BGS corresponded to a dose-equivalent of less than 400 mGy. However, for the 5S and the iPhone models that have followed, the corresponding dose-equivalent for the BGS is more than 10 Gy. The term dose-equivalent is used here to mean the dose to the sample that would be required in order for the TL from the RIS glow curve, integrated between the temperatures 100 °C and 250 °C, to be equal to that of the BGS glow curve, integrated over the same interval. This increase in the relative size of the BGS coincides with Apple's patent applications starting in late 2012 pertaining to the use of liquid optically clear adhesives [29, 30].

3.3.2.4 Background signal reproduction

In an attempt to reproduce the BGS in a laboratory environment, thermally annealed samples from a Samsung Galaxy S2 were exposed to varying wavelengths of UV light for 30 min (Fig. 3.5). These included a solar simulator in addition to 254, 302, and 365 nm UV sources, as well as combinations thereof. A glow curve following a beta dose of 20 Gy is included in Fig. 3.5 for comparison. Figure 3.5 illustrates that the magnitude and shapes of the glow curves for each exposure are quite different. While some of this variation can be attributed to differences in source irradiance, as listed in Sec. 3.2, the disparity in magnitude observed in Fig. 3.5(a) cannot be explained by such small differences in irradiance alone. Nor can the irradiance variations account for the differences in glow curve shape.

The normalized curves in this figure show the relative peak positions with respect to that of the BGS [Fig. 3.5(b)]. The peak temperature of the RIS is $\sim 40^\circ\text{C}$ below the BGS, and the signals for 302 nm and 254 nm are below that of the RIS. The peak temperature for the TL signal following exposure to the solar simulator is $\sim 20^\circ\text{C}$ below that of the BGS. None of these signals resembled the BGS; however, when the solar simulator and the 302 nm UV source were used together, the glow curve shapes of the BGS and UV-induced signals aligned [Fig. 3.5(c)]. Note that the low-temperature portion of the resulting curve does not appear in the BGS. This is due to thermal fading of this portion of the BGS.

These results help to confirm that the BGS is a product of exposure to UV light, specifically, from a wide-spectrum source. This conclusion became apparent after no single UV wavelength was able to match the BGS in either strength or peak position, but a combination of the solar simulator and the 302 nm UV source was able to do so. In addition, when the sample was exposed to a filtered solar simulator (which removed the short wavelength portion of the signal), the magnitude of the resulting TL signal was much lower, verifying that the short wavelengths are required to achieve the large TL signals. Therefore, to duplicate the BGS an exposure to both short and long wavelength UV sources (e.g., solar simulator + 302 nm), or perhaps a single, wide-spectrum source is required.

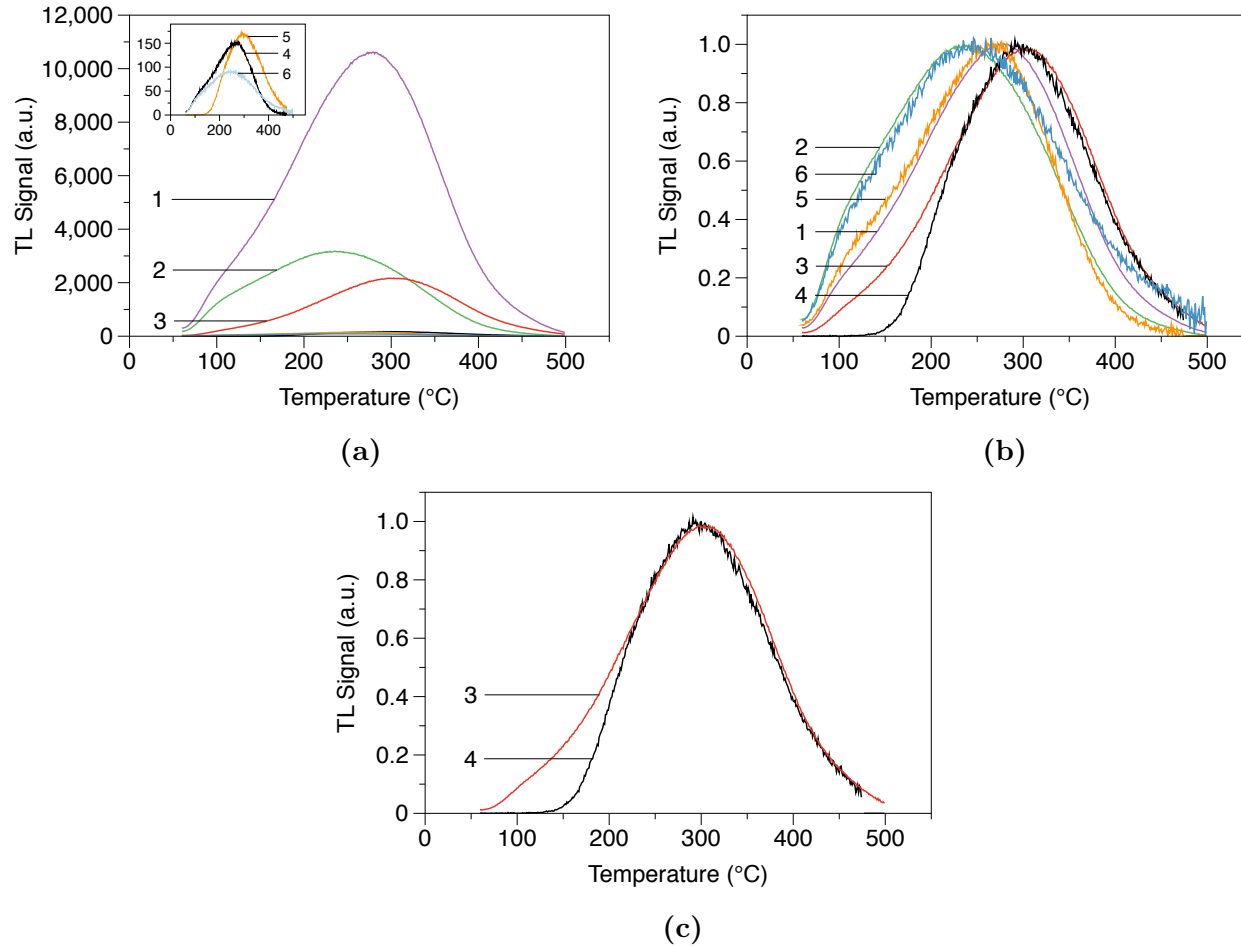


Figure 3.5: TL glow curves for samples of GG from a Samsung Galaxy S2 after various exposures. The glow curves correspond to exposures from the following: a solar simulator (1), 254 nm (2), solar simulator + 302 nm (3), the BGS (4), 20 Gy (5), and 302 nm (6). (a) The intensity relationship between these exposures. (The inset plot is an amplified view of this intensity relationship for exposures 4, 5, and 6.) (b) Normalized peak intensities of these exposures. (c) A comparison of the normalized solar simulator + 302 nm exposure (3) and the BGS (4).

3.3.2.5 Background signal uniformity

Even among UV-cured adhesive smartphones, there exists a large variability in the magnitude of the BGS. This is particularly seen between manufacturers but, in some cases, is also seen between samples from the same phone. This phenomenon is exemplified by a 2D BGS intensity map for the top half of a Microsoft Windows phone screen, seen in Fig. 3.6. There exists a clear vertical BGS gradient, as well as a lateral variability in the BGS intensity. This is a similar finding to that reported by Kim et al. (2019) [23] in which the dose distribution was found to be dependent on the location from which the sample was collected from the device.

Another instance of nonuniform UV exposure was recently reported by McKeever et al. (2018) [18], in which the authors encountered a larger signal for both BGS TL and EPR on certain models when observed from aliquots taken from the edge of the glass compared to those taken from the center. This phenomenon could be an example of a precuring step taken by these manufacturers as reported in Lu et al. (2012) [28], where precuring is the act of partially curing the screen on the sides, or at selected spots on the surface, to further check the alignment and bond effectiveness before completely curing the adhesive. This same technique could be responsible for the high BGS intensities found in the corner of the phone, illustrated in Fig. 3.6.

While it is evident that variations exist in the BGS intensity for aliquots of the same phone, it is unclear if this is caused by the sensitivity differences inherent in the glass, as discussed in Sec. 3.3.2.1, or due to an uneven exposure as suggested above. To determine the source of the BGS nonuniformity, the signal [Fig. 3.7(a)] was analyzed from the same aliquots that were used in the intragenerational sensitivity study. The BGS intensities were calculated as an integral between 250 °C and 450 °C then individually corrected for sensitivity. The sensitivity was determined by the ratio of the RIS, shown in Fig. 3.4, to the aliquot's dose (integrated over the same region). The results, compared in Fig. 3.7(b), demonstrate that BGSs differ even after individual correction; therefore, it is surmised that the nonuniformity is not a product of the sensitivity alone but is likely a result of both the aliquot sensitivity and an uneven UV exposure during the curing process. Note that the

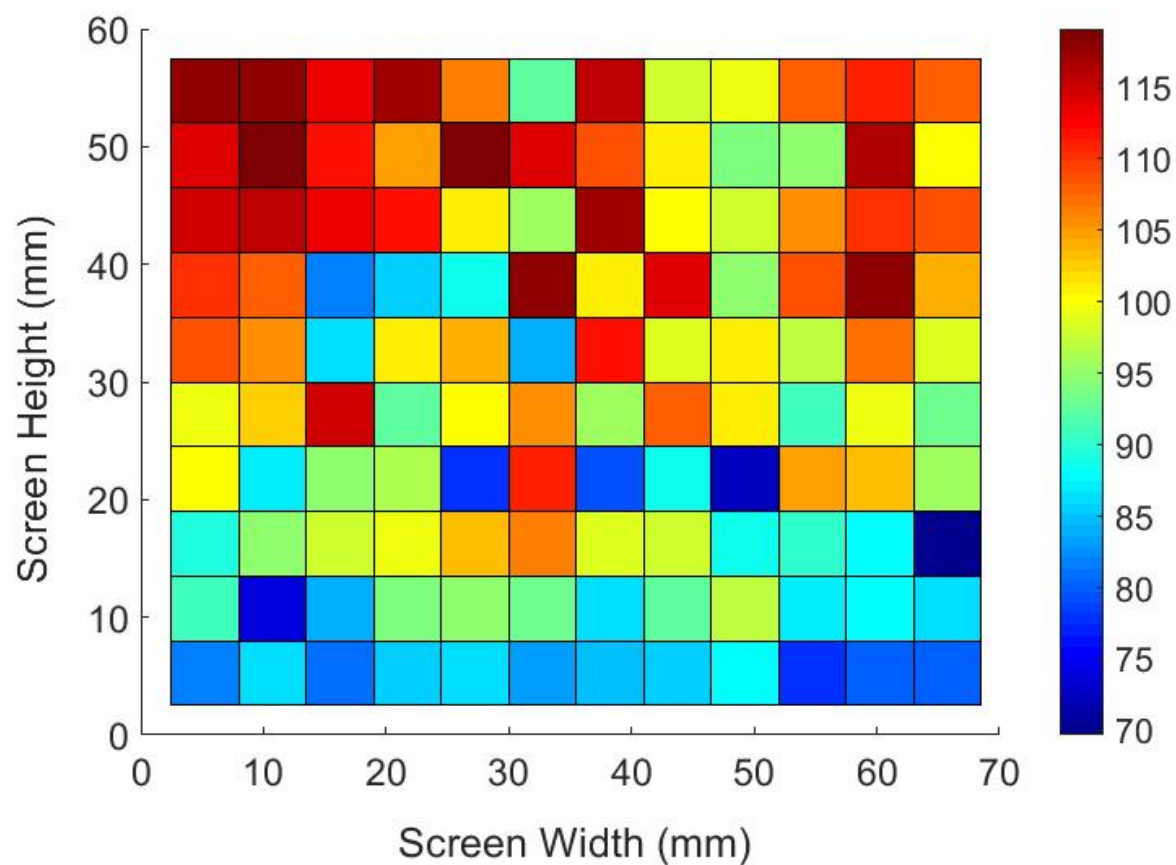
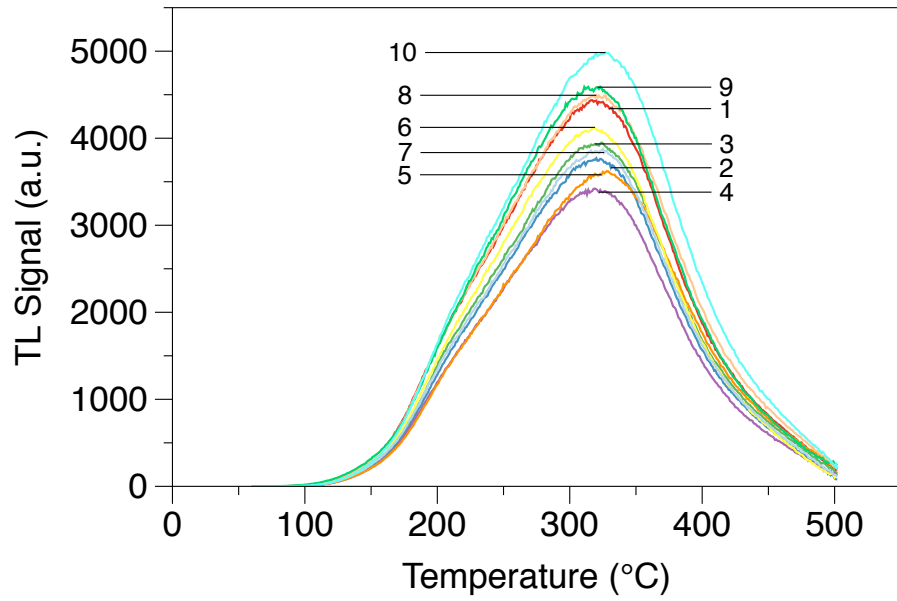
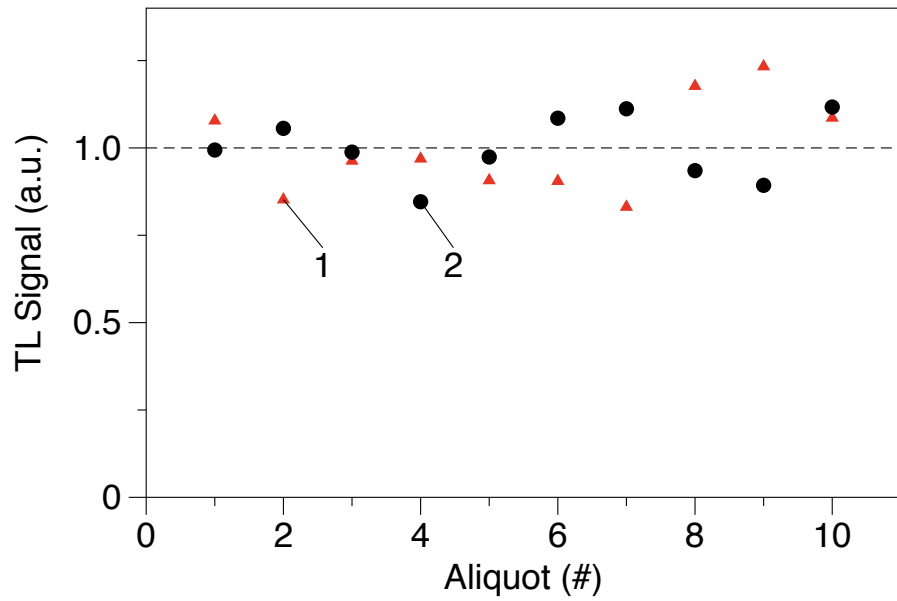


Figure 3.6: A 2D intensity map of the BGS from the top half of a Windows Lumia 640 created by cutting the glass into $5.5 \times 5.5 \text{ mm}^2$ aliquots. Each square represents one aliquot. The color bar represents the intensity of the BGS.



(a)



(b)

Figure 3.7: BGS TL for GG from an LG G4 device. (a) TL glow curves of the BGS for ten aliquots of GG from a single LG G4 device. These are the same ten aliquots used in the sensitivity study seen in Fig. 3.4. (b) Comparison of calculated sensitivities (RIS/dose) (1) and sensitivity-corrected BGS intensities (BGS/RIS/dose) (2) for each aliquot. The data were normalized to the average values of RIS/dose and BGS/RIS/dose, respectively.

reproducibility of the sensitivity measurement remained constant within 1–2% for repeated exposure and measurement of the same aliquot.

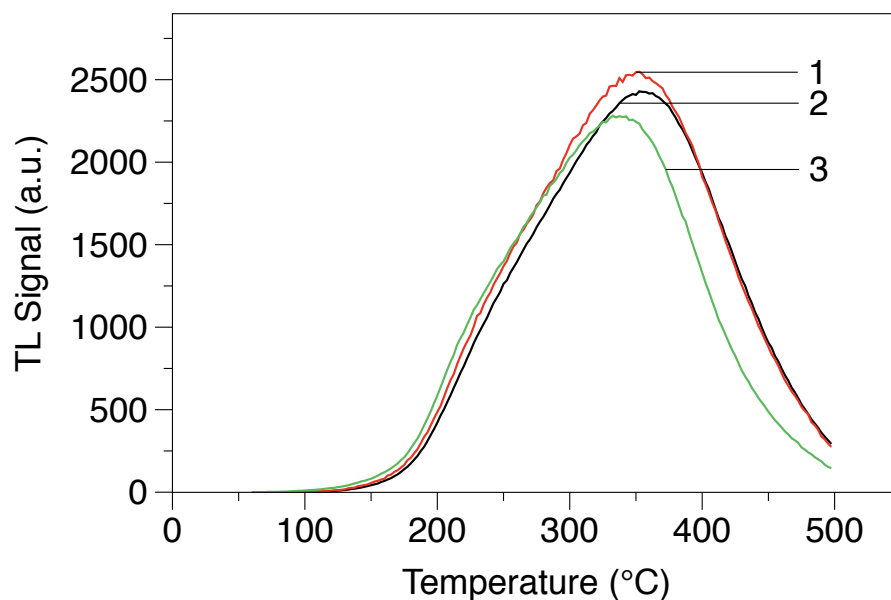
3.3.2.6 Background signal reduction

The overlap of the BGS with the RIS complicates potential dose-reconstruction techniques. The most straightforward method to account for the existence of a BGS would be to subtract its contribution from the total dose estimation. However, the large variability that can occur in the BGS magnitude, observed in many samples of GG, does not allow for this.

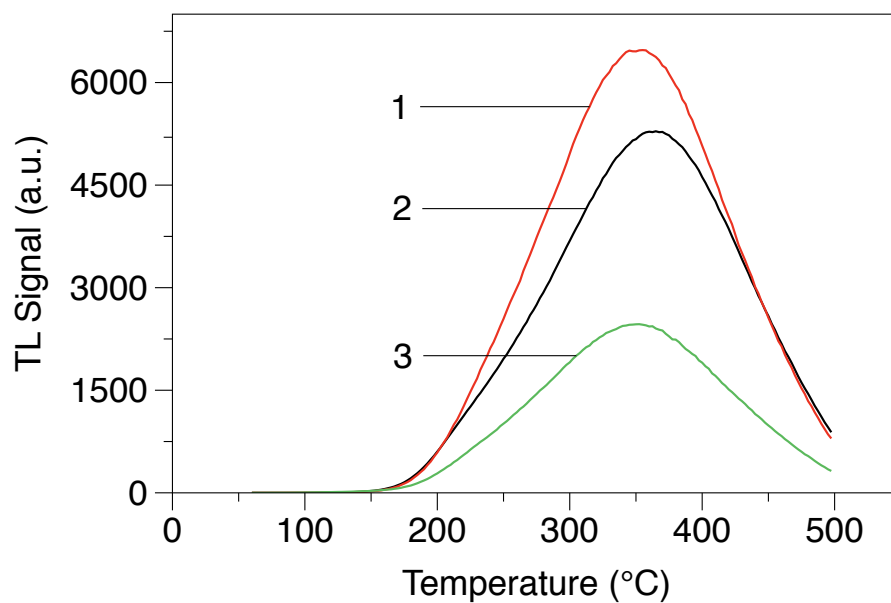
Previous authors were able to reduce the intensity of the BGS in display glass by removal of the glasses' surface layer through chemical etching or mechanical removal [31, 32]. Mechanical removal of the surface layer was tested in this work on samples of GG from two different smartphones (an LG G4 and an iPhone 6+). Nine aliquots were prepared for each phone glass: three were used to obtain the original BGS, three were used to acquire the BGS from the outer layer, and three were used for estimating the BGS from the inner layer. The glow curves, shown in Fig. 3.8, are an average of each of the three aliquots. Removal of the inner-surface glass layer causes the outer layer of glass to be the predominant TL contributor, whereas removal of the outer-surface glass layer causes the inner layer of glass to be the main TL contributor. The results in Fig. 3.8 show that the tested method was not effective in reducing the mass-normalized BGS.

It should be noted that the LG G4 glass used in the above experiment was much thinner than that from the iPhone 6+, resulting in the ability to remove only about 50–100 μm from the former surface while a 100–200 μm layer was removed from the latter. For each sample, the removal of the inner layer actually resulted in an increase in the mass-normalized BGS due to the BGS being only slightly affected by the mass of the sample being reduced. Removal of the outer layer produced a reduction in the BGS but to varying degrees for each sample (11%–51%). The differences in BGS removal effectiveness between the two samples arise from the amount of glass which can be removed; however, even a 50% decrease in a sample with a large BGS is still not satisfactory for emergency dosimetry.

The data, presented in Fig. 3.8, suggest a BGS gradient from the outer- to inner-glass surfaces. This conforms to the assumption that the glasses were in this orientation when



(a)



(b)

Figure 3.8: Mass-normalized, BGS TL glow curves for samples of GG from (a) an LG G4 and (b) an iPhone 6+ after mechanical removal of the outer-or inner-surface layers, leaving the back or front of the glass for TL analysis, respectively. The glow curves are from the front (1), original (2), and back (3). Each glow curve is an average of three separate aliquots taken from the same device.

exposed to UV. An additional consideration from these results concerns the observation that the removal of the outer-surface layer results in a significant reduction of the BGS intensity for display glasses (e.g. Discher et al., 2013 [32]) but not for GG (this work).

The explanation for this disparity lies in the optical absorption coefficient for the two glasses. As seen in Fig. 3.9, the optical absorption coefficient for a typical display glass is almost 50 times higher than that for GG in the 302 nm region. This results in a much deeper penetration of UV light into GG samples compared with display glass.

This is best illustrated by comparing the calculated UV penetration profiles for GG and display glass samples. Figures 3.10(a) and 3.10(b), using the optical absorption coefficients from Fig. 3.9, show the result of this calculation for three representative UV wavelengths (254, 302, and 365 nm). It is seen in this figure that the BGS is attenuated more slowly as a function of depth in GG compared to display glass. Therefore, using the thickness of GG found on smartphones, it is not possible to meaningfully reduce the impact of the BGS through outer-surface removal, even for the most attenuated exposure (i.e., 254 nm). In contrast, for display glass, removal of only 0.1 mm will result in more than a 95% reduction in the BGS for the same UV exposure.

3.3.2.7 A computational method for BGS removal and dose estimation

Although RIS and BGS peak at different temperatures, their glow curves still overlap substantially. This negates the possibility of using the entire glow curve for TL integration and relegates dose-reconstruction efforts to the less-stable, lower-temperature region, as was proposed by Discher et al. (2016) [20]. For their dose-reconstruction experiments, these authors integrated the TL signal over the 100–175 °C region of the glow curve.

Following the approach of Discher et al. (2016)[20], the glow curves of the eight Samsung Galaxy S phones, shown in Fig. 3.3, were analyzed to determine the BGS contribution to the overall uncertainty in dose reconstruction. After obtaining the BGS from the first glow curve, the samples were exposed to a beta dose of 20 Gy. The second glow curve was then measured, yielding the RIS for that sample. The RIS glow curves were integrated over the range 100–175 °C; these integrals were then used to calibrate the corresponding BGS in units of dose. The BGSs analyzed in this manner were found to be equivalent to doses in the range

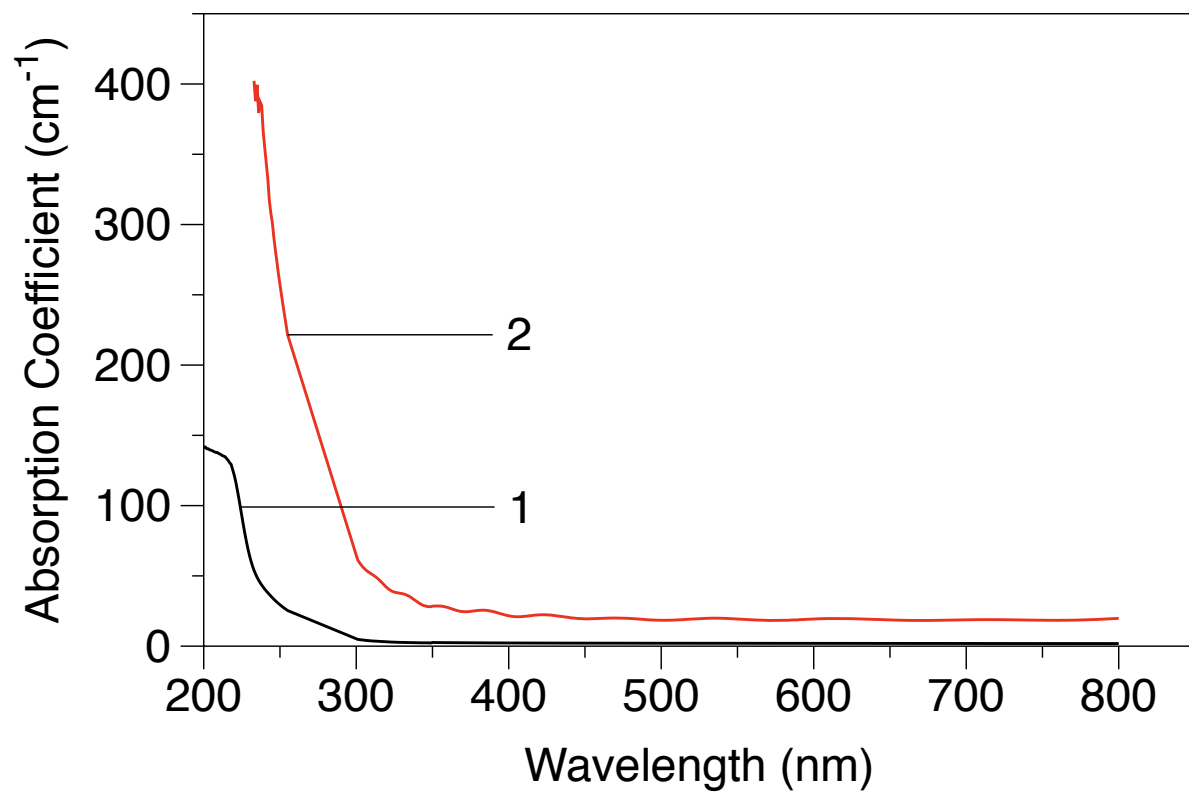
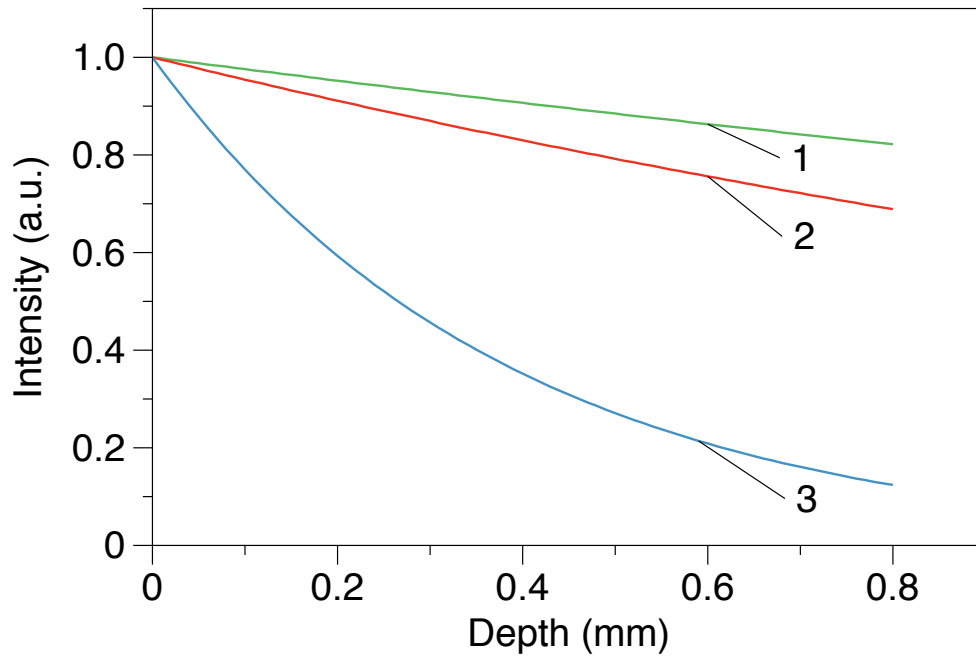
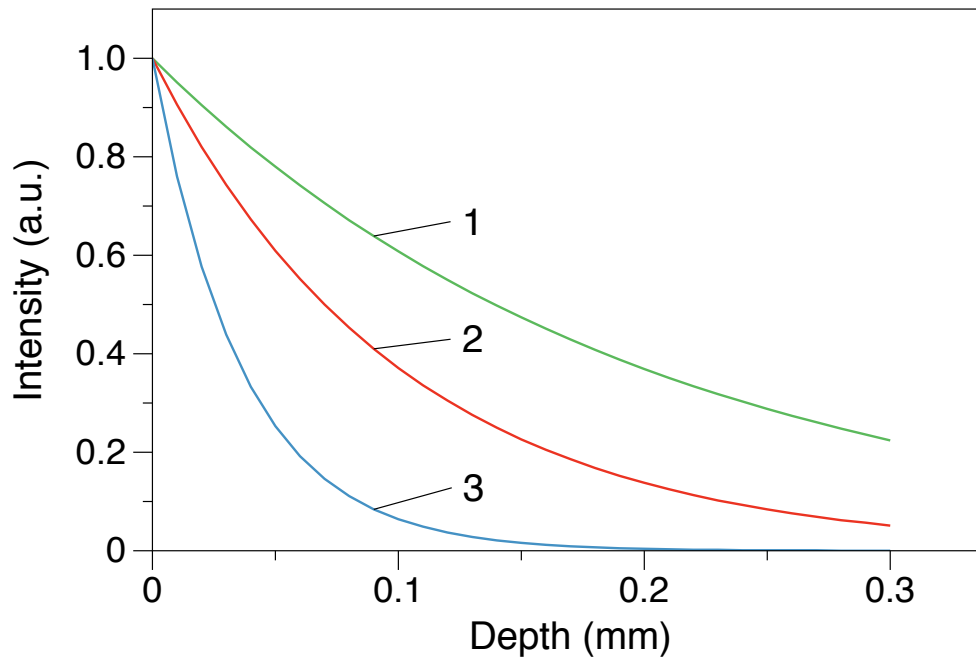


Figure 3.9: Optical absorption coefficients for a sample of GG (1) from an LG G4 device and display glass (2) sample from an Alcatel Pixi Pulsar.



(a)



(b)

Figure 3.10: Calculated UV penetration profiles for (a) display glass from an Alcatel Pixi Pulsar and for (b) GG from an LG G4 device for exposures with UV of wavelengths 365 nm (1), 302 nm (2), and 254 nm (3).

of 0.13–7.69 Gy, with an average value of 2.02 Gy and a corresponding standard deviation of ± 2.41 Gy. This extra contribution to the overall uncertainty in the dose reconstruction is due to the variability of the BGS. It is clear that the TL dosimetry approach, described in Discher et al. (2016) [20], cannot be recommended for samples of GG because the resulting uncertainties are too large for dose reconstruction.

In this work, a matrix method for TL glow curve deconvolution was tested for application in TL dosimetry with GG. This method was originally developed and used for deconvolution of EPR spectra of different materials, including tooth enamel [33] and GG [17]; however, it can also be used for deconvolution of TL glow curves consisting of several overlapping peaks. The key element for using this method in the deconvolution of TL glow curves is to obtain a set of reference TL curves specific to each GG sample. For this task, the RIS and BGS are to be used as the corresponding reference TL signals. The reference RIS is obtained by first heating the sample to a high enough temperature ($\sim 500^\circ\text{C}$) to remove the accident exposure RIS as well as the BGS. Next, the sample is irradiated to a dose large enough (10–20 Gy) that the result will be a well-formed, representative glow curve. The TL glow curve is then recorded, resulting in the reference RIS. To obtain the reference BGS, the sample is exposed to a combination of the solar simulator and a 302 nm UV light source, as described in Sec. 3.3.2.4.

With these reference spectra, the TL glow curve, TL_{accident} , from a sample containing the unknown BGS and an unknown RIS due to the accident dose, may be described by a linear combination of the reference signals; thus, $TL_{\text{accident}} = aTL_{\text{BGS}} + bTL_{\text{RIS}}$, where a and b are constants and TL_{BGS} and TL_{RIS} are the reference BGS and RIS TL curves, respectively. If each glow curve consists of n data points, then there are, thus, n equations with two unknown variables, a and b (Sholom and Chumak, 2003 [33] and Sholom et al., 2019 [17]). The method assumes that the shapes of the BGS and the RIS do not change with dose.

The method was tested on the above-mentioned Samsung Galaxy devices. Example reference TL signals, as well as the corresponding dose-response curve, can be seen in Fig. 3.11 for a Galaxy S5 sample. All TL glow curves were recorded after undergoing a preheat of 125°C for 30 s to remove their unstable, low-temperature component. Similar reference TL

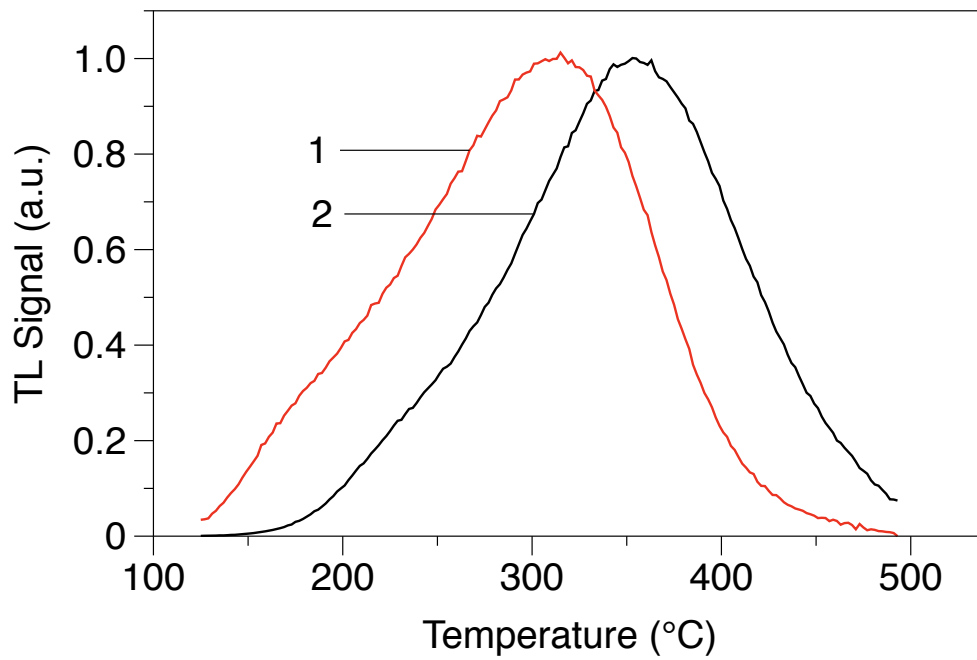
signals and dose-response curves were obtained for the other Samsung Galaxy devices, which were then used to reconstruct doses of aliquots exposed to 10 Gy (simulating an emergency exposure).

TL glow curve deconvolution results, in which the matrix method was used to separate the BGS and RIS components, for the Samsung S5 exposed to the 10 Gy simulation exposure are shown in Fig. 3.12. The fitted RIS obtained for this sample was converted to units of dose using the dose-response curve shown in Fig. 3.11(b). The dose was evaluated to be 12.2 Gy. Dose estimates for the other samples were between 10.5 and 14.3 Gy or within 5%–43% deviation from the corresponding nominal value. Further tests are required to improve the accuracy and reliability of the proposed dose-reconstruction approach and to determine potential minimum measurable dose values.

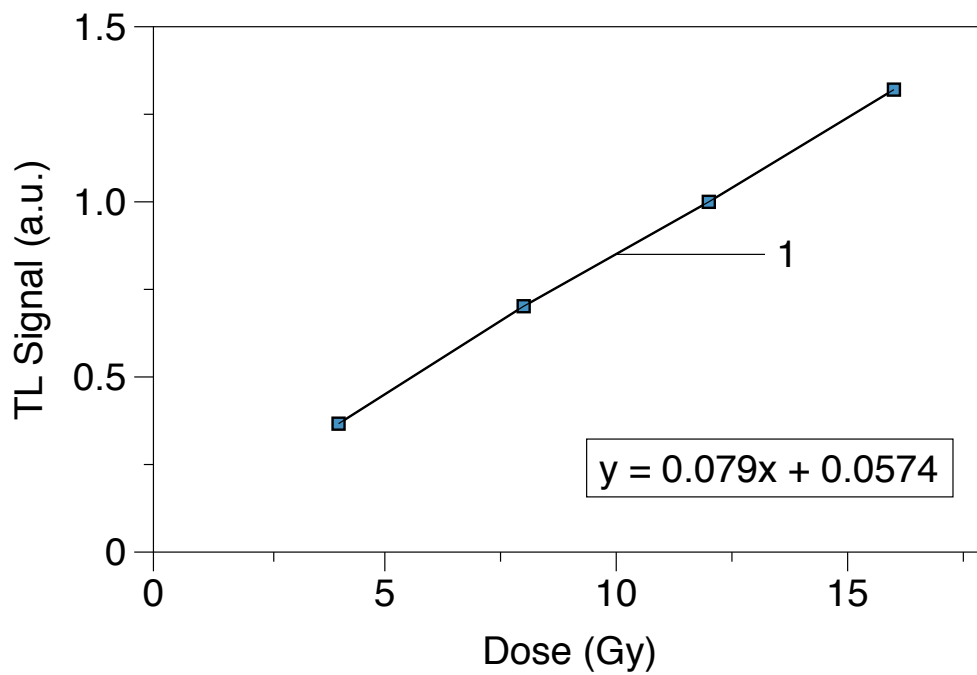
3.3.3 PTTL glow curves measurements and analysis

McKeever et al. (2017) [21] found that PTTL from GG has a higher signal stability when compared to TL. This is especially useful in emergency dosimetry when the sample cannot be immediately recorded. The method for acquiring PTTL is to first remove all TL using an initial preheat. (The appropriate temperature is sample dependent and can range from 450 to 550 °C, depending on the glow curve shape.) Next, the sample is exposed to 365 nm UV for 1 h. (254 nm and 302 nm were found to produce strong, direct, UV-induced TL signals in addition to the PTTL signal.) Lastly, the sample is reheated; the produced signal is the PTTL.

Example TL and PTTL glow curves are shown for Stemmerich GG sample in Figs. 3.13(a) and 3.13(b), respectively. This specimen has an almost nonexistent BGS and high PTTL sensitivity. The PTTL curve shapes show prominent high- and low-temperature peaks at $\sim 130^\circ\text{C}$ and $\sim 330^\circ\text{C}$, respectively. Part of this signal, however, is TL (not PTTL) that has been directly generated by the 365 nm UV exposure. Therefore, the net signal is PTTL plus UV-induced TL. Since the BGS is essentially zero in this particular sample, the signal for the unirradiated aliquot shown in Fig. 3.13(b) is almost all UV-induced TL, not PTTL, and the difference between this and the TL from the irradiated aliquot is all PTTL, caused by the 20 Gy irradiation.



(a)



(b)

Figure 3.11: Examples of (a) reference TL signals and (b) a dose-response curve for a GG sample from an S5 phone. The glow curves represent the RIS (1) and the BGS (2).

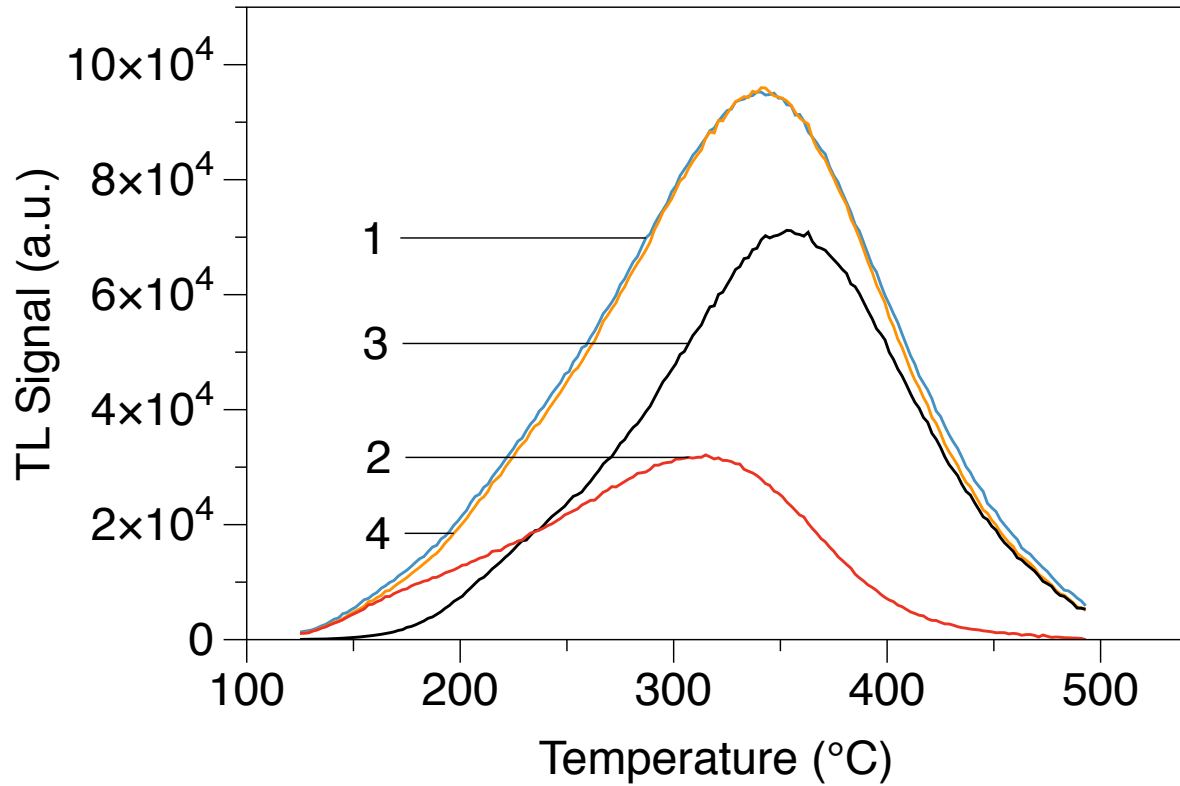
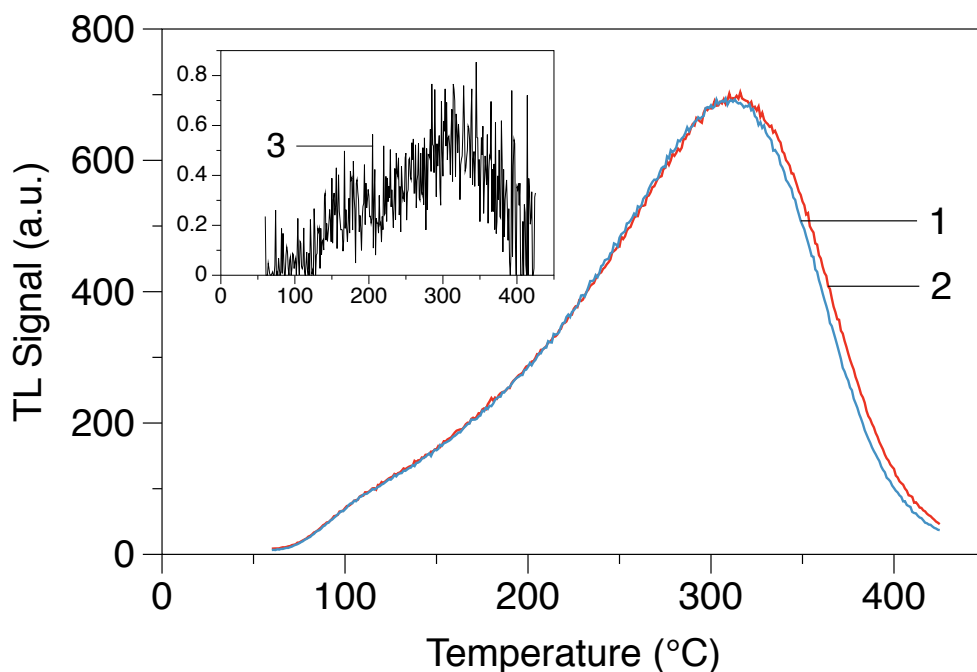
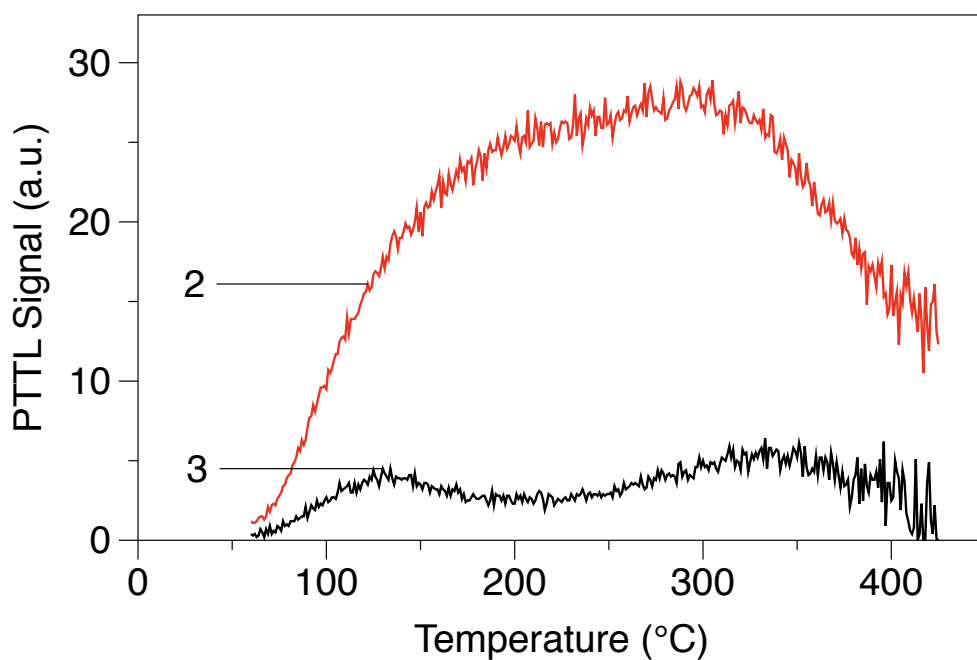


Figure 3.12: An example of the TL glow curve deconvolution using the matrix method for the GG sample from a Samsung S5 phone. The GG was exposed to 10 Gy, and the dose reconstructed for this sample was 12.2 Gy. The glowcurves represent the ARS (1), the RIS (2), the BGS (3), and the curvefit (4) using $aTL_{BGS} + bTL_{RIS}$ (see text).



(a)



(b)

Figure 3.13: (a) TL glow curves for samples of GG from Stemmerich (U.S.GG finisher). (b) PTTL glow curves from the same aliquots of GG seen in (a) (U.S. GG Finisher). The glow curves represent the ARS (1) after receiving a dose of 20 Gy, the RIS (2) after receiving a dose of 20 Gy, and the BGS (3). Each glow curve type is produced by a separate aliquot taken from the same device.

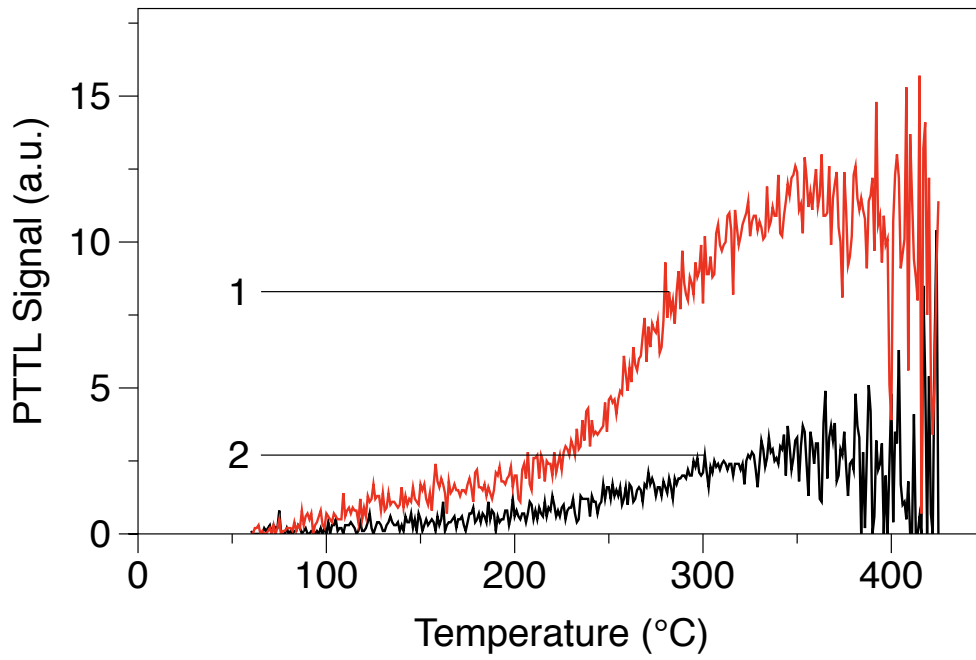
With glass from phones, the PTTL signal due to the BGS can be very strong compared to that from the RIS. PTTL curves for the Samsung S7 phone [the TL of which was shown in Fig. 3.3(g)] and the Samsung S8 phone [TL shown in Fig. 3.3(h)] are illustrated in Figs. 3.14(a) and 3.14(b). While for the S7 there is a clear difference in magnitude between the RIS and BGS PTTL curves, it should be emphasized that the RIS PTTL is obtained following a dose of 20 Gy. The RIS PTTL following a dose closer to that of interest (2 Gy) would be expected to be substantially obscured by the BGS PTTL. This is seen more clearly for the S8 sample where it can be observed that, even for a dose of 20 Gy, the RIS PTTL is comparable in magnitude to that of the BGS PTTL. Furthermore, since the RIS PTTL and the BGS PTTL are similar in shape, the matrix method of deconvolution is unlikely to be successful; thus, it was not attempted in this work.

3.4 Conclusions

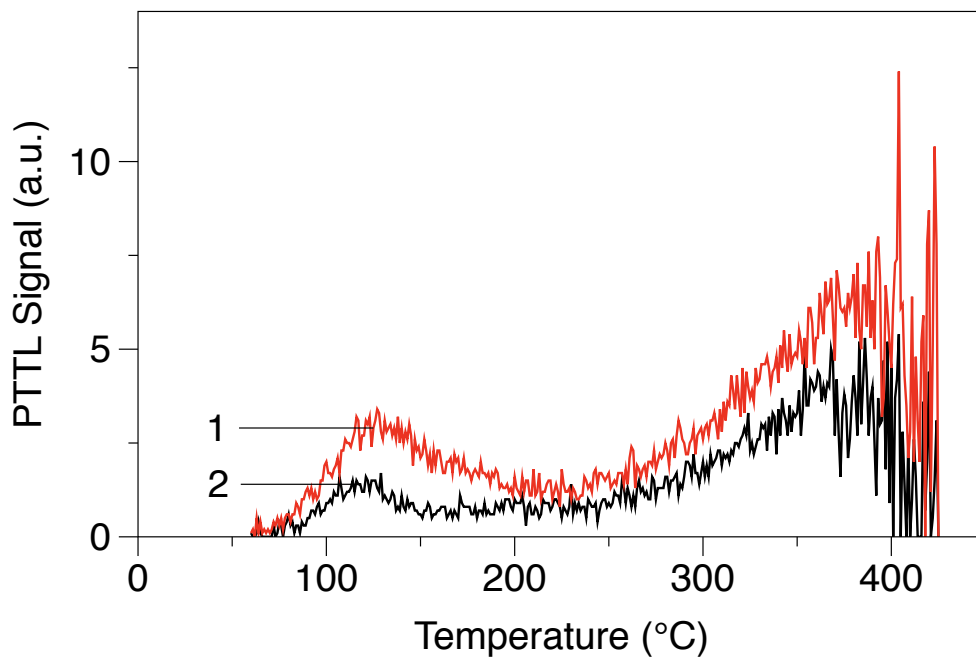
The aim of this study was to analyze the TL and PTTL properties of GG. During sample analysis, it became evident that the majority of smartphones studied in this work were encumbered by a BGS that was much larger than any previously reported (equivalent to tens of gray).

The source of the BGS was shown to be caused by UV light exposure, hypothesized to occur during the phone manufacturing process, specifically, during curing of the adhesive used to affix the GG to the device. This conclusion was supported by the reproduction of the BGS in peak shape and intensity by a combined exposure to a solar simulator and a 302 nm UV source.

In general, the BGS glow curves have a TL peak with a maximum $\sim 25\text{--}50^\circ\text{C}$ higher than that of the RIS, but nevertheless, the two signals strongly overlap. This makes dose reconstruction difficult. Additionally, the BGS intensity was found to differ by $\sim 30\%$ (even after individual sensitivity correction) for different glass samples from the same device. This also makes difficult the ability to define a standard BGS reference for use in dose reconstruction.



(a)



(b)

Figure 3.14: PTTL glow curves for samples of GG from (a) Samsung S7 and (b) Samsung S8 devices. The glow curves represent the RIS (1) after receiving a dose of 20 Gy and the BGS (2). Each glow curve is produced by a separate aliquot taken from the same device.

Mechanical removal of the GG surface layers was used in an attempt to decrease the intensity of the BGS. Unfortunately, it was found that these GG samples were too thin for removal of the surface layer to have any appreciable effects. However, it was discovered that this remains a viable method for analysis of display glasses due to their larger optical absorption coefficients for UV light exposure.

The different shapes of the BGS and RIS glow curves allow for a matrix deconvolution method to be used to separate the two signals from a glow curve containing contributions from each. The method, working under the assumption that the shapes are invariant with dose, requires that the individual RIS and BGS glow curves be obtained for each sample. Moreover, this method is unlikely to be successful for PTTL glow curves due to its RIS and BGS contributions being very similar in shape.

The results obtained are likely not limited to the models explored herein but are likely to be observed in the majority of modern phones using GG. The TL method can be used even if a BGS is present, whereas both TL and PTTL may be used with GG that has not been used in the phone manufacturing process or for the select few phones that are not hindered by a strong interference from the BGS.

For the glasses that are not encumbered by a large BGS, or for phones from which the RIS TL can be reliably separated using the matrix method, it is pertinent to perform dose-reconstruction tests to replicate real-life scenarios and to ascertain the reliability of the methods under a variety of possible conditions. This will be the focus of future studies.

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Chapter 4

OPTICALLY STIMULATED LUMINESCENCE DOSIMETRY ON MOBILE PHONE BACK PROTECTIVE GLASS

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Abstract

Protective glasses from the back of modern smartphones were tested as potential emergency dosimeters using optically stimulated luminescence (OSL). The glasses were shown to exhibit several favorable dosimetric properties including a strong sensitivity to radiation, a linear dose-response relationship from 0.1–8 Gy, a 3% reproducibility, and a minimum detectable dose in the low tens of milligray, even after significant fading. The OSL signal was observed to lose $\sim 78\%$ and $\sim 90\%$ of the original intensity over 1 hour and 1 week, respectively; however, a fading curve was developed to correct for any such signal loss. A dose-recovery test demonstrated that reconstructed doses were capable of accuracies within 20%.

4.1 Introduction

The most advantageous fortuitous, or accident, dosimeters are those that have been widely distributed throughout the general public. Smartphones currently possess over 70% market penetration in six countries (United Kingdom, Germany, United States, France, Spain, and South Korea) and retain over 3.2 billion users worldwide [1], making them one of the leading candidates on which to establish standardized retrospective dosimetry protocols. To date, the smartphone components that have been investigated for their application as fortuitous dosimeters have been predominantly those mounted to the phone's circuit board, such as resistors, inductors, and capacitors [2–11]. Additionally, a variety of glass types have also been examined. These can be found as part of the phone's display or as an element of its outer protective layer [12–18].

While the results from previous studies are promising, there is a need to continue investigations since smartphone technologies and materials continue to evolve. For example, the size and quantity of resistors that were once abundant are now becoming smaller and more scarce [19]. Glass is decreasingly used in the phone’s display as manufacturers move towards more flexible alternatives such as plastic [20]. Conversely, the glass utilized as a protective outer layer on the rear of the device, or back glass, is undergoing continued adoption by an increasing number of manufacturers. The prevalence of back glass has been closely associated with the rising popularity of inductive (wireless) charging, which requires a backing material that does not interfere with the electromagnetic charging process (i.e., non-metallic). Protective glass, specifically Gorilla Glass (GG) (an alkali-aluminosilicate glass that has been strengthened through an ion-exchange process, and whose chemical composition is proprietary), has become a popular choice over other options due to its durability and aesthetic appeal.

While GG has been previously studied using electron paramagnetic resonance (EPR) ([9, 21–25], thermoluminescence (TL) [16, 23, 26], and phototransferred thermoluminescence (PTTL) [17, 26], it was only recently investigated for its optically stimulated luminescence (OSL) properties [27]. In fact, the OSL properties of other commonly used glasses have also garnered limited attention [28–30]. This lack of research interest is due in part to the OSL signals’ known susceptibility to light. This is the main reason, prior to the study conducted by Sholom et al. (2020) [27], that only the internal smartphone components had been previously tested as potential OSL accident dosimeters.

With over 75% of smartphone users having outfitted their device with a case [31], the glass found on the back of most phones (assuming an opaque case) will be protected from light sources. Furthermore, the other 25% of phones, which were not equipped with a case, may have potentially been stored in an article of clothing (e.g., pants pocket, handbag) and would also have some protection from light exposure. Therefore, with the strong likelihood that it will be sheltered from light, glass found on the rear of the device is a candidate to serve as an OSL accident dosimeter.

There are several incentives for utilizing OSL rather than TL on back glass. The most critical is the presence of a large TL background signal (TL BGS) in GG, which was

determined by Chandler et al. (2019) [26] to be produced by exposure to ultraviolet light during the phone manufacturing process. The TL BGS, which was found incapable of being removed without severely impacting the radiation-induced signal (RIS) (the signal that is created through radiation exposure, as opposed to a signal that was present prior to such an event) results in unacceptably high uncertainties for TL-reconstructed doses due to strong overlap of the TL BGS and the TL RIS [26]. Assuming that an OSL BGS is created during the phone manufacturing process (in a similar fashion to TL BGS) the phone would only need to be exposed to an indoor or outdoor light source to be removed, which is certain to occur before case installation. This rationale is supported by the essentially non-existent OSL BGS of back glass encountered by Sholom et al. (2020) [27].

An additional argument for evaluating back glass concerns the sample preparation process. During removal of GG from the front of the device, great care must be taken to avoid damaging the display components underneath, making it a slow technique. Likewise, removal of any of the internal components is tedious as each must be individually detached under red light conditions, while rendering the phone completely inoperable. In contrast, removing the back glass can be done rapidly without fear of damaging the rest of the device. The use of a back glass could, therefore, greatly increase the possible throughput of a retrospective dosimetry service.

Lastly, since OSL requires only exposure to a light source and heating is not required, as with TL, the possibility exists to bypass the glass removal process altogether and perform the OSL measurements on the entire, intact, back side of the device. An initial foray into the use of such a non-destructive approach was performed by Sholom et al. (2020) [27] who used a pulsed-OSL (POSL) technique utilizing a custom-made OSL reader with a fiber-optic attachment. The dose-response relationship was found to be linear for doses up to 7 Gy with sample-dependent minimum detectable dose (MDD) values ranging from 0.5 Gy to 30 Gy. While more work is required to optimize this method, a non-destructive technique would offer the fastest possible dose determination, which is invaluable when performing triage measurements after an incident and would enable return of the intact device to the owner.

The focus of the current work was to further investigate the OSL properties of protective glasses employed by modern smartphones with a specific focus on those manufactured

after 2017. The effects of different preheat temperatures on the sample readout was investigated alongside an extensive analysis of samples' dosimetric properties, including the decay curve shapes and intensities, dose-response profiles, signal reproducibilities, long-term signal stabilities, and a dose-recovery test.

4.2 Materials and Methods

This study was carried out on back protective glass samples obtained from seven different smartphones (Table 4.1). It should be noted that the glass type used on Apple devices is not made public, therefore, their glasses are denoted with the letter A and a number, each symbolizing a distinctive glass type. This will be further discussed in a later section.

The samples used in the study were acquired either pre-removed or were removed from the phones in-house. For glass that was still attached to the phone, either a heat gun or heating plate (up to 90 °C) was used on the back of the phone to soften the glue used to hold it in place, allowing for easy separation with a pry tool. In both cases, the glass was cleaned with ethanol to remove any excess glue, colored film, or coating. Once cleaned, several 5.5 x 5.5 mm² aliquots were cut from each sample using a Buehler IsoMet 1000 precision section saw equipped with a diamond wafering blade and water cooling.

All TL and OSL measurements were made using a Risø DA-15 TL/OSL reader equipped with a ⁹⁰Sr/⁹⁰Y beta source, delivering 79 mGy/s. The source was calibrated to absorbed dose in water using a secondary standard ⁶⁰Co source from the National Institute of Standards and Technology (NIST). TL measurements were carried out with a BG-39 filter in a nitrogen atmosphere using a 2 °C/s heating rate to a maximum temperature of 400–500 °C. Continuous wave OSL measurements were performed with blue LED stimulation (470 nm, 30 mW/cm² power output) using a Hoya U-340 filter.

In the case of TL measurements, the RIS was calculated by subtracting a subsequent background measurement from the initial TL measurement. For OSL, the measurements were performed using an OSL stimulation time of 150 s with the dosimetric signal calculated as the difference of the signal integrated over the first and last 10 s of the OSL decay curve.

Table 4.1: Summary of GG samples obtained from online vendors or GG finishers used in this study.

Manufacturer	Model	Production Year	Glass Type	Thickness (mm)
Apple	iPhone X	2017	AI	0.8
Apple	iPhone XR	2018	A2/A3	0.82
Apple	iPhone XS	2018	A3	0.82
Apple	iPhone 11 Pro Max	2019	A4	0.82
Samsung	Galaxy S9	2018	GG 5	0.5
Samsung	Galaxy S10	2019	GG 5/6	0.48
Samsung	Note 10	2019	GG 6	0.49

All luminescence signals were mass normalized. Note that some OSL graphs are limited to 60 s to better communicate the initial curve information.

For the irradiation trial, an external ^{137}Cs source located at Los Alamos National Laboratory (LANL) was used. During irradiation, the phone was attached to the front of a 30 x 30 x 15 cm PMMA slab phantom which was positioned 168.7 cm from the source (see Fig. 4.1): the distance chosen as a compromise between exposure rate and beam size. The exposure rate to the front of the phone was 65,281.1 mR/h and was uniform over the entire phone and phantom area.

4.3 Results and Discussion

When comparing the TL glow curve shapes and peak positions along with the OSL decay curve shapes and radiation sensitivities between the glasses utilized on the devices measured in this study, it became apparent that some of the iPhones were equipped with glasses that are specific to Apple devices. Table 4.1 lists the four glass variants examined from the iPhones tested in this study (A1–A4). The A1, which was removed from an iPhone X, was observed to be consistent with samples consisting of GG5, suggesting this glass may be standard GG and not specific to this phone or other Apple devices. The iPhone XR was found to have a unique glass on the back (A2) of the device, with the glass found on the front (A3) being consistent with that found on both sides of the iPhone XS. The most current Apple device tested, the iPhone 11, was observed to have a glass (A4) specific to it on both the front and back sides. This development is consistent with reporting of custom Corning glass used in an Apple device (Tibken, 2019) [32].

In addition, no further differences were observed between the front and back glasses in both BGS and RIS measurements unless denoted by the manufacturer (e.g., the Samsung Galaxy S10 consists of GG6 on the front and GG5 on the back); therefore, while the samples analyzed in the following experiments focused on back glasses, the results may also be applicable to glass taken from the front of the device.



Figure 4.1: Irradiation of a Samsung Galaxy S9 mounted on a PMMA slab phantom using a ^{137}Cs source at LANL.

4.3.1 Background signal OSL decay curves

An important analysis for the use of GG as a potential emergency dosimeter concerns the presence and magnitude of potential BGSs that have continually hampered the successful implementation of previously tested methods (TL, PTTL, and EPR) to reliably determine accident doses.

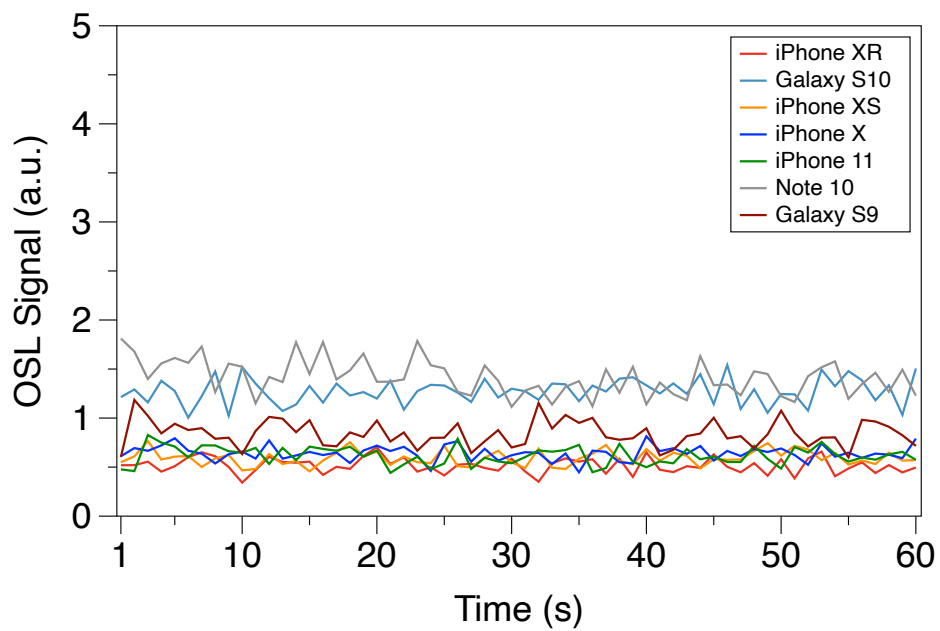
Initial results reported by Sholom et al. (2020) [27] indicated low to non-existent OSL BGS contributions from the glasses investigated by those authors. The OSL BGS measurements for the samples analyzed in this study, displayed in Fig. 4.2(a), also showed low to non-existent BGSs. The lack of a BGS from these samples is specific to the OSL analysis, however, since the TL BGS (Fig. 4.2(b)) was demonstrated to still be significant. If there was an initial OSL BGS component, it appears to have been completely erased, perhaps by exposure to light, before analysis in the laboratory.

4.3.2 Radiation-induced OSL decay curves

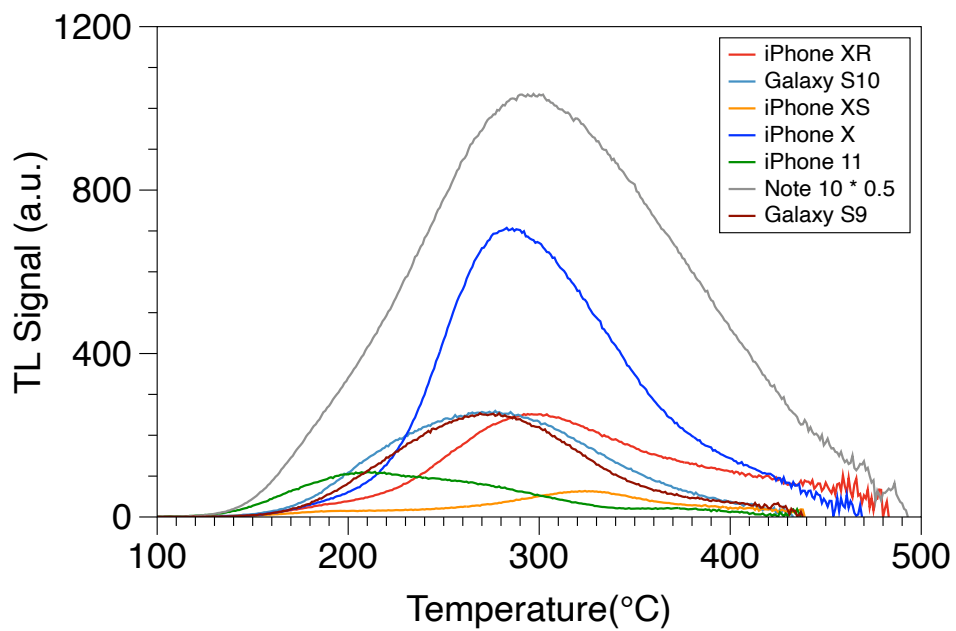
Figure 4.3(a) compares the OSL RIS decay curves produced after exposure to 0.8 Gy and illustrates that the majority of tested samples have similar radiation sensitivities. The initial (1 s) OSL signal intensities ranging from 37 counts/mg for the iPhone X to 121 counts/mg for the Note 10, with a mean of 80 counts/mg for the six samples except for iPhone XR. The latter exhibits an initial intensity at 345 counts/mg, or greater than 4 times the average of the other glasses. The aliquot-to-aliquot variability, determined using three aliquots, was found to be within 3–15% for different samples; however, it should be noted that because each aliquot is individually calibrated, this variability has no impact on any dose measurement.

The RIS decay curves exhibit quite similar decay curve shapes (Fig. 4.3(b)), except for the iPhone 11 for which a much faster OSL decay rate is observed. The exhibited shapes and decay rates are consistent with those exemplified by GG5 samples in Sholom et al. (2020) [27].

Figure 4.3(b) shows that decay curves are described by a function of the form $y = a_1 * e^{(-x/n)} + a_2 * x^{-k} + a_3$, which signifies a combination of an exponential and a power-law relationship between the OSL signal and the stimulation time. The exponential term



(a)



(b)

Figure 4.2: (a) OSL decay curves and (b) TL glow curves obtained from unirradiated samples.

is presumed to be caused by optical excitation to the conduction band, presumably from shallow traps, while the power-law component is presumed to represent stimulation to an excited state from which tunneling occurs for deeper traps [33]. It should be noted that a similar two-component function has previously been used to fit OSL decay curves from other materials, such as surface mount inductors from mobile phones [11] and chips from credit cards [9].

4.3.3 Signal Reproducibility

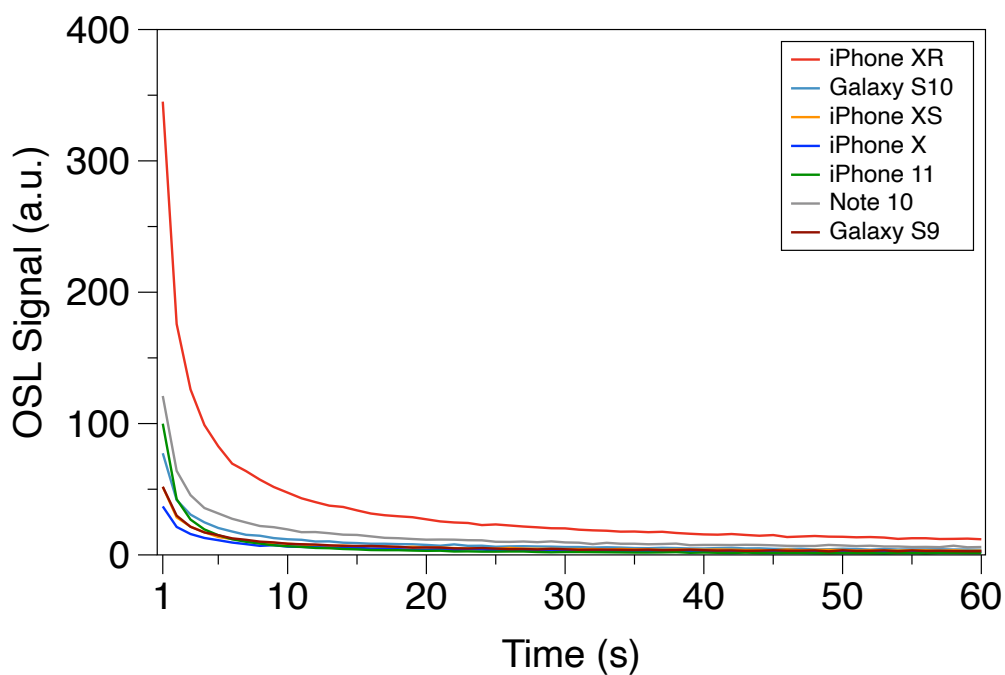
To investigate the reproducibility of the OSL signals, samples were irradiated and measured repeatedly for 10 cycles. The given dose for each cycle was 2 Gy and all responses were normalized to the value obtained from the initial response. The results, shown in Fig. 4.4, indicate that the response remains within 3% of the first measurement over the course of the experiment. This is indicative that the tested samples did not experience any significant changes in sensitivity, which allowed for measurements to continue without the need to apply any test dose corrections. Discher et al. (2016) [16] found that the TL signal reproducibility was within 6% over the same number of irradiation-readout cycles for an earlier version of the same material (GG).

4.3.4 Dose-Response Relationship

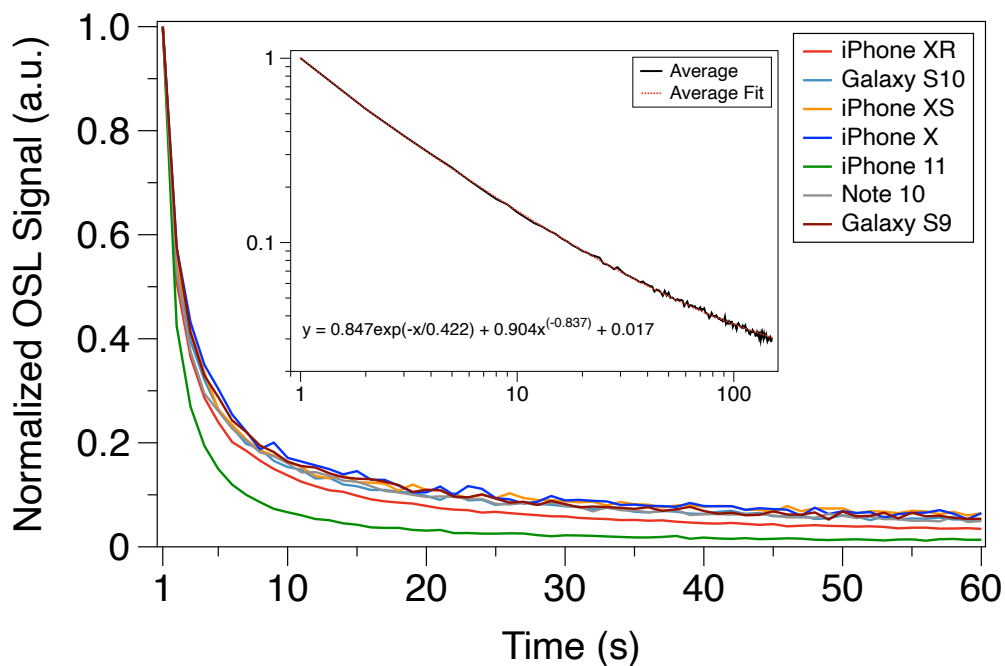
The dose dependence of the OSL signal was investigated by applying eight doses ranging from 0.1 to 8 Gy to selected samples. The same aliquot was used for each readout and subsequent irradiation with increasing dose. Representative signals obtained from a Samsung Galaxy S10 are presented in Fig. 4.5(a).

The resultant dose-response curves can be seen in Fig. 4.5(b) (each datapoint is the average of three aliquots), from which it can be observed that the signals grow linearly with dose over the tested dose range. This characteristic allows for the use of only one calibration point when assessing the accident dose.

The MDD is the dose corresponding to three standard deviations of the OSL BGS measured from unirradiated samples and was calculated to be between 0.65 mGy and



(a)



(b)

Figure 4.3: (a) OSL decay curves after exposure to 0.8 Gy. (b) Normalized OSL decay curves from the same samples. (The inset shows the average of these curves displayed on a log-log plot.)

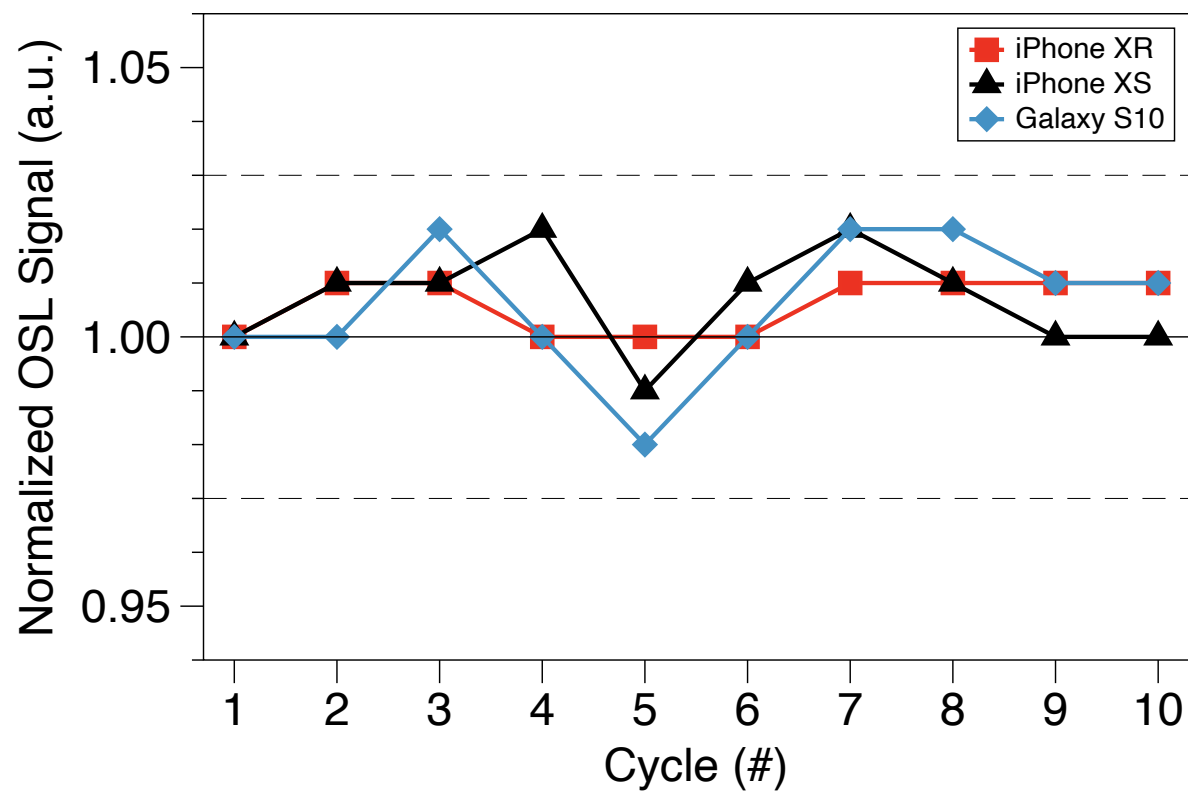
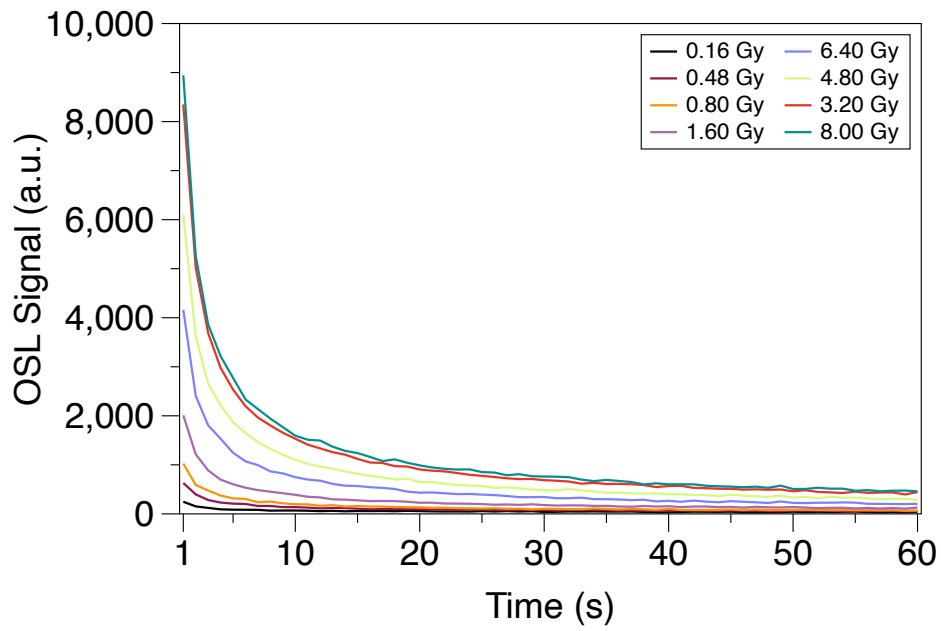
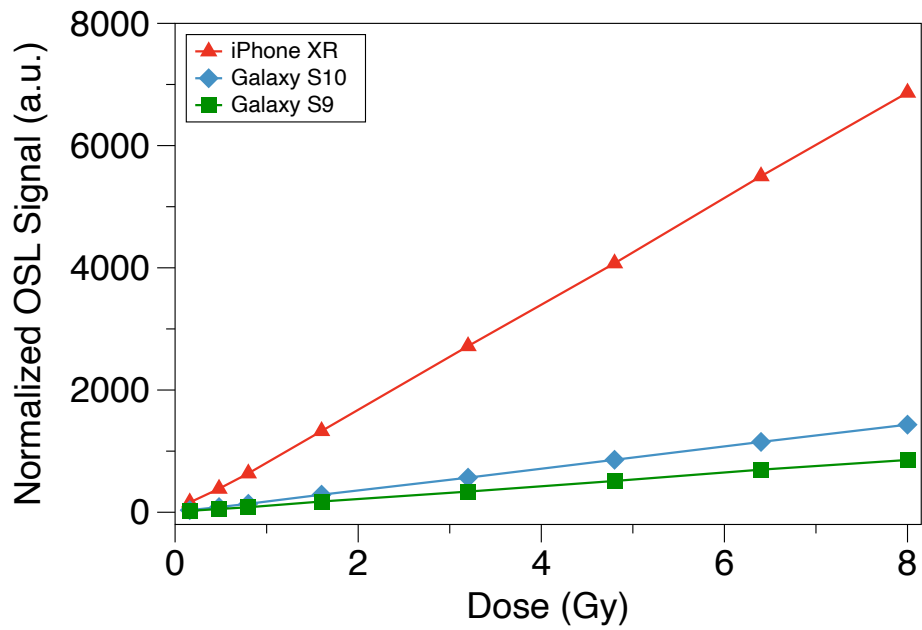


Figure 4.4: The OSL signal, normalized to the first value, for 10 cycles of repeated irradiation and readout.



(a)



(b)

Figure 4.5: (a) OSL decay curves obtained from a Samsung Galaxy S10 after irradiation with various doses. (b) Dose-response characteristics of OSL signals for three different samples.

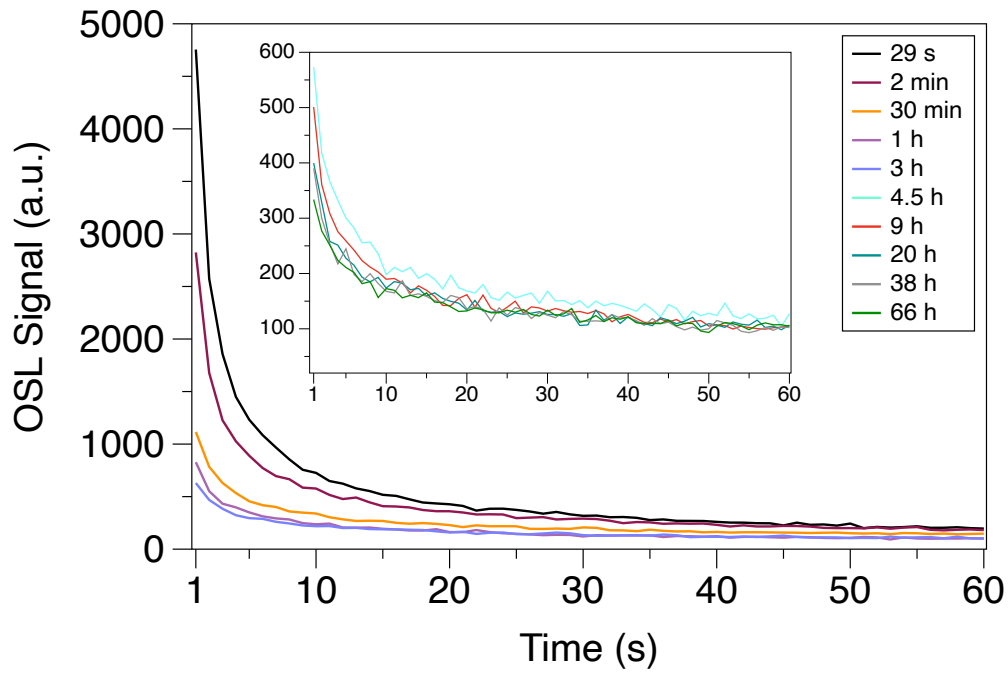
1.24 mGy for measurements taken immediately after exposure. Note that the MDD is strongly affected by signal fading, leading to an increase in MDD values with prolonged time after exposure; this will be addressed in a later section.

4.3.5 Fading

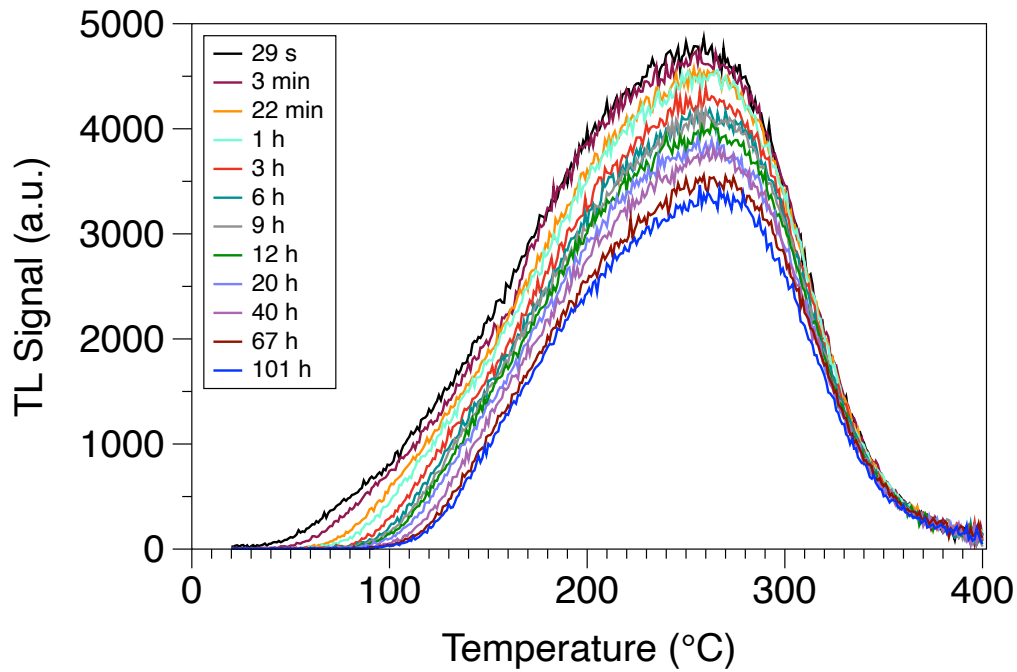
The stability of the OSL signal was investigated for selected GG samples that were stored after irradiation in the dark at ambient temperature (18–22 °C). This was accomplished by applying a dose of 2 Gy and carrying out measurements at various delay times following irradiation, up to 66 h and 118 h for the iPhone 11 and the other tested phones, respectively. The initial delay period defaults to 29 s, which corresponds to half the irradiation time (12 s), to account for fading during this period, as well as the time it takes for the instrument to transport the sample to the measurement position and begin readout (17 s). Representative OSL signals obtained for each time interval from a Samsung Galaxy S10 are presented in Fig. 4.6(a) and representative TL signals (irradiated to 5 Gy) obtained over similar time intervals for the same device are shown in Fig. 4.6(b) for comparison.

To determine the fading rate, the recorded OSL signals were normalized to the value obtained from the measurement at the effective fading time of 29 s. The results, shown in Fig. 4.7, demonstrate that the samples experience rapid signal loss over the first hour as the signal dropped to an average of 78% of their initial value. However, after this point, the fading begins to slow dramatically, becoming approximately 10% of the initial value over the remaining timespan. Additionally, the fading rates are observed to be almost equal for all tested samples barring that of the iPhone 11 for which the signal fading is more pronounced over the first hour.

The OSL signal fading that occurs for protective glass necessitates that any OSL measurement data to be used in the determination of accident doses must be corrected by the application of a fading factor. The fading factor is based on the relationship between the signal loss and time that has elapsed after exposure and is created by fitting the results, plotted on a log-log scale, to the combination of an exponential and power-law functions of the form $y = a_1 * e^{(-x/n)} + a_2 * x^{-k}$. The power-law behavior is indicative that tunneling from deeper traps is the dominant fading component at longer fading times;



(a)



(b)

Figure 4.6: (a) OSL decay curves irradiated to 2 Gy and (b) TL glow curves irradiated to 5 Gy from a Samsung Galaxy S10 after various delay periods.

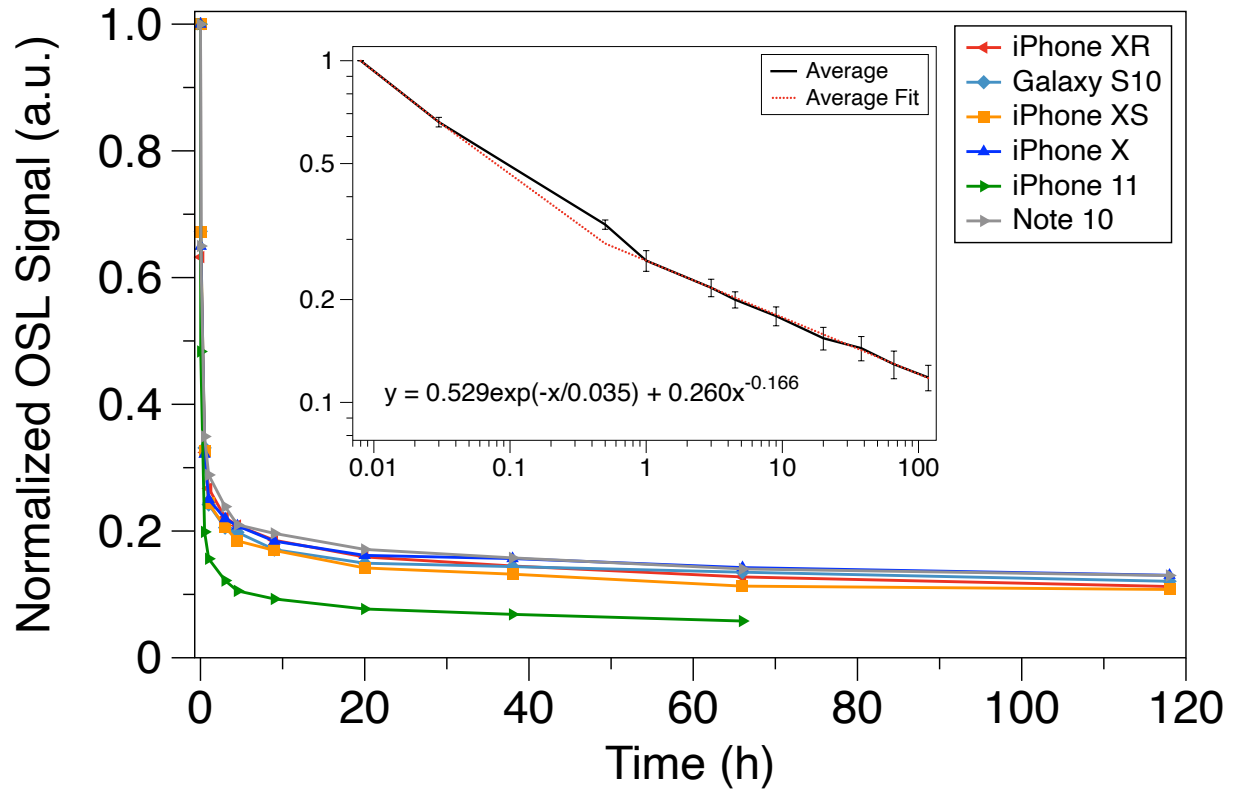


Figure 4.7: Fading of the OSL signal in samples exposed to a dose of 2 Gy. All signals were normalized to the value obtained immediately after irradiation. (The inset shows the average of the curves (excluding the iPhone 11) displayed on a log-log plot.)

however, the shallowest traps do contribute over short decay periods and are represented by the exponential term. Since the shallow traps are likely to be represented by a distribution, representing the thermal decay component by a single exponential term is only an approximation; however, the main contributor to the decay is the power-law function.

The resultant average fading curve for the tested glasses (excluding the iPhone 11) is shown in the Fig. 4.7 inset and is characterized by the equation $y = 0.529e^{(-x/0.035)} + (0.260x - 0.166)$; this equation will be used to correct for signal fading when performing dose-reconstruction tests. The OSL signal loss results are in agreement with those presented by Sholom et al. (2020) [27]. Figure 4.8 compares TL fading curves integrated over different temperature regions and illustrates that the OSL fading rate is similar to that of the low-temperature (80–120 °C) TL region.

As previously mentioned, the signal fading has a large effect on the MDD. The value of the MDD after a 118-h delay period increases by a factor of 8 to 5.52–10.51 mGy. An additional experiment was conducted to determine if the signal loss was affected by the magnitude of the dose applied to the sample; no such dependency was observed.

4.3.6 OSL after preheating

To investigate the influence of different trapping centers on the OSL process, the samples were preheated, after irradiation to 2 Gy and before OSL measurement, to temperatures in the range 25–325 °C in increments of 25 °C. After each OSL readout, the samples were annealed to 450 °C to avoid potential complications due to any dose accumulation and then re-irradiated with the same dose. The obtained OSL curves are presented in Fig. 4.9(a) for a Samsung Galaxy S10, in which it can be seen that the decay curve intensity decreases with preheat temperature.

To compare the OSL signal as a function of preheat temperature, the signals were normalized to the value recorded at 25 °C. The results, displayed in Fig. 4.9(b), show that the majority of the OSL signal intensity is contributed by the lower-temperature traps, signified by the greater than 50% intensity loss by all samples following a preheat to 100 °C. In addition, it is observed that all OSL intensity has been erased following a preheat to 325 °C.

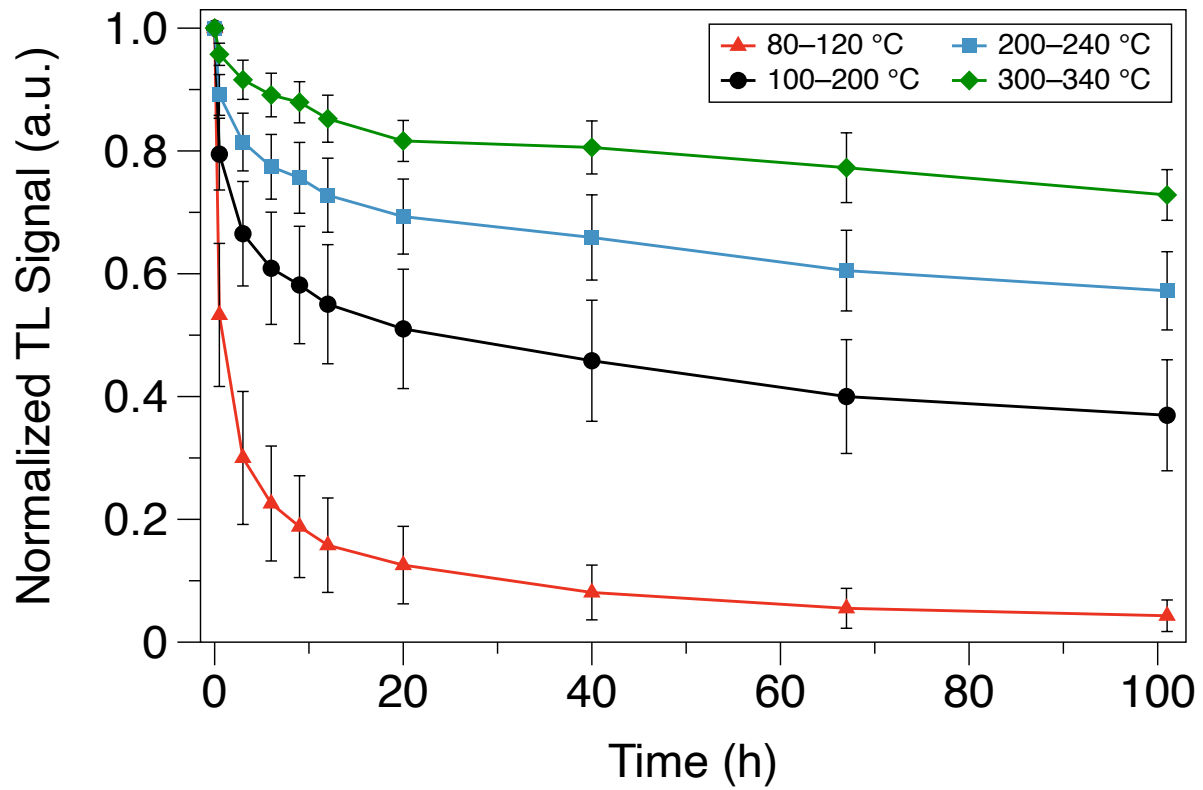
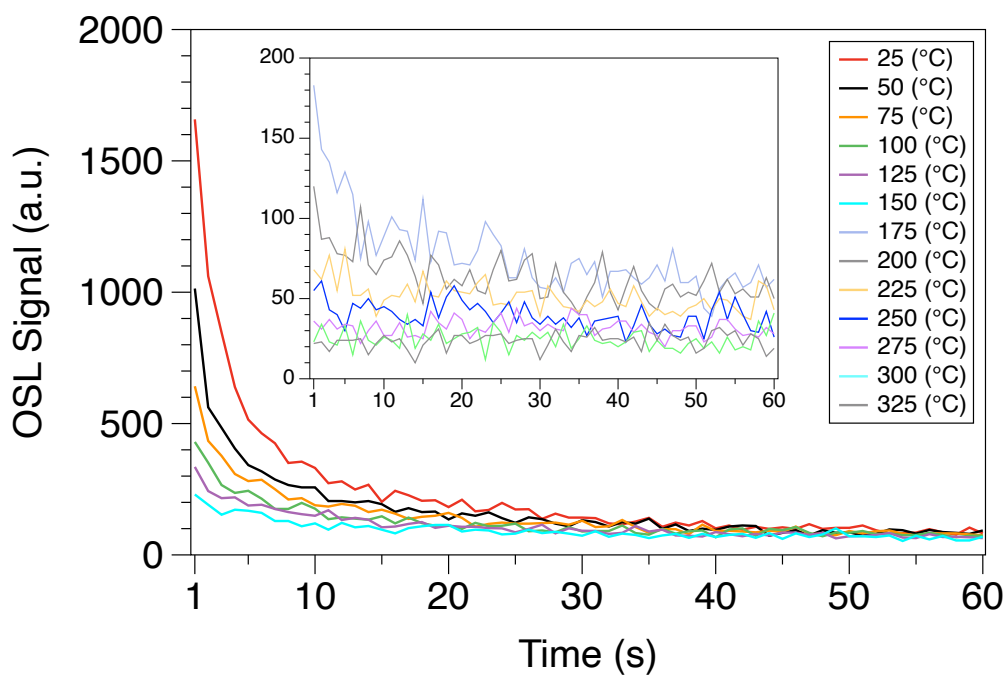
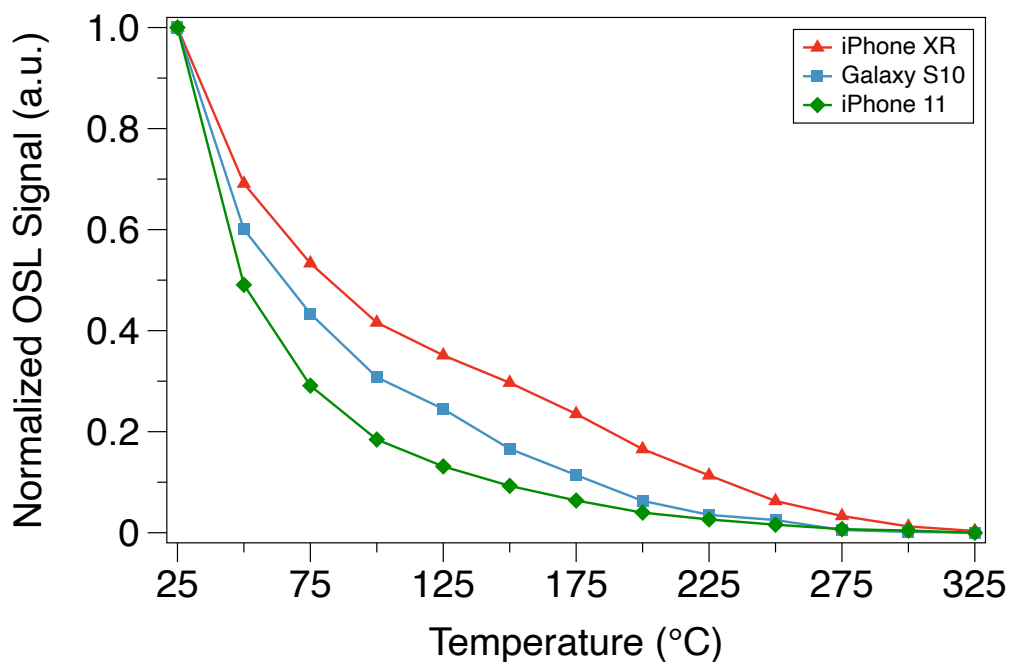


Figure 4.8: TL fading curves for various temperature regions. Each curve is the average of the same six devices utilized in the OSL fading determination.



(a)



(b)

Figure 4.9: (a) OSL decay curves from a Samsung Galaxy S10 after various preheat temperatures. (b) OSL signal as a function of preheat temperature, for three different phones, normalized to the value obtained at 25 °C.

Figure 4.9(b) also reveals that each sample’s OSL signal originates from a different distribution of trapping centers, evidenced by their varying responses to the preheat temperatures. When contrasting the results from each sample, it is apparent that the preheats have a much larger impact on the OSL signal intensity of the iPhone 11, which lost over 50% of its original signal following the preheat temperature of 50 °C, compared to a 40% or less signal degradation in the other phones. This indicates that a more significant portion of the OSL signal arising from the iPhone 11 is associated with lower-temperature trapping centers compared to that from the other tested samples. This is consistent with the greater magnitude of lower-temperature TL exhibited by the iPhone 11, shown in Fig. 4.10, in relation to the other samples. The increased lower-temperature TL is also consistent with the increased fading rate observed in the iPhone 11 glass, since fading most commonly originates from lower-temperature traps.

To compare the effects of sample preheating and measurement delay on the OSL signal, a dose of 2 Gy was applied to two sets of samples that were measured at various fading periods after irradiation. One set was preheated to 90 °C before measurement while no additional treatment was applied to the second set of samples. Note that 90 °C is the maximum temperature used in this study to remove the back glass from its corresponding phone. Figure 4.11 illustrates that both sample sets experience the same amount of signal loss 3 h after irradiation. This is significant since it indicates that, for fading times greater than 3 h, applying heat in the glass removal process does not affect the “accident” OSL signal. The component of the OSL signal that is affected by a pre-heat to 90 °C will have already faded prior to glass removal.

4.3.7 Dose-Recovery Test

A dose-recovery test is the most critical aspect to consider when examining potential accident dosimeters. To replicate an accident scenario, an intact Samsung Galaxy S9, outfitted with an opaque case, was irradiated with a dose of 2 Gy from ^{137}Cs gamma rays at LANL in the anterior-posterior geometry under ambient illumination conditions. Following irradiation, the device was shipped to Oklahoma State University for measurement, arriving 5 days later.

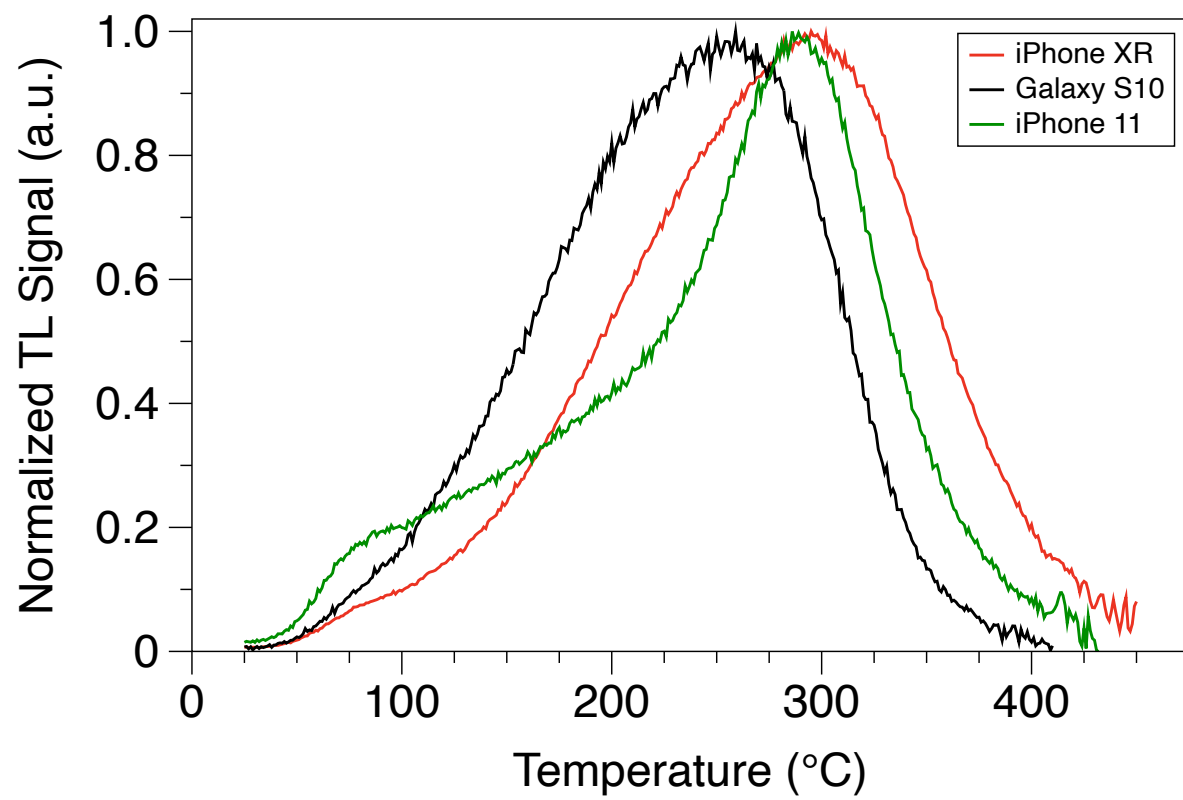


Figure 4.10: Normalized RIS TL glow curves following exposure to 0.8 Gy.

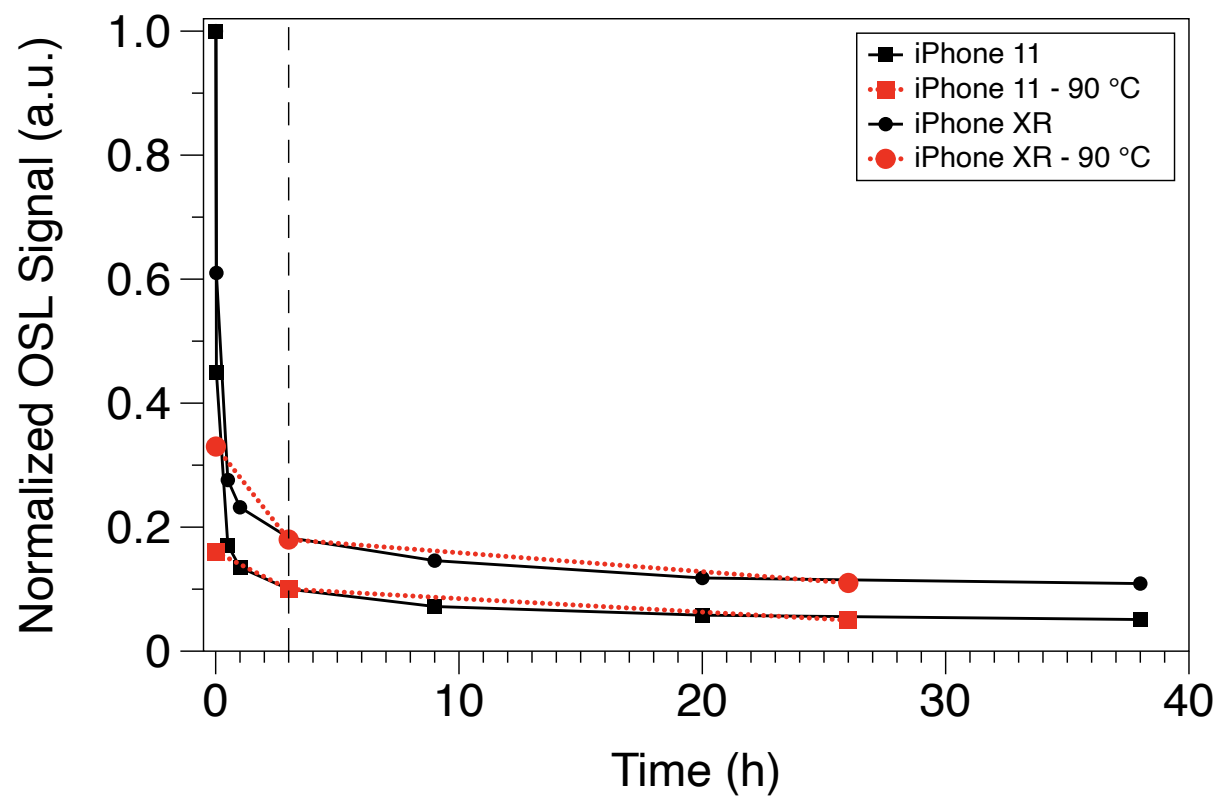


Figure 4.11: OSL signal as a function of preheat temperature and time, normalized to the value obtained at 25 °C.

Sample preparation was conducted under red light conditions, which consisted of removing the back glass from the device, with the assistance of a heating plate operating at 90 °C, from which six aliquots were cut. The obtained dosimetric signal was converted to units of dose using a calibration of 2 Gy via the Risø internal beta source.

As noted in Section 4.3.5, the OSL signal from GG exhibits fading; therefore, the obtained OSL signal was corrected by applying the previously presented fading curve. The results of the dose reconstruction test are reported in Table 4.2, from where it can be seen that the deviation of the estimated and nominal dose values is below 20% (280 mGy). These results are quite promising for the purposes of accident dosimetry and demonstrate that back protective glasses could function as a potential tool in the determination of accident doses.

4.4 Conclusions

The aim of this study was to examine the OSL properties of protective glasses utilized on the back of modern smartphones. One of the primary reasons for evaluating back glass with an OSL method was the potential lack of any interfering BGSs; this was confirmed when no such signals were observed from the samples measured in this study.

Additional assessed dosimetric properties included a linear dose response over the tested range of 0.1–8 Gy, signal reproducibility within 3% over 10 cycles of repeated irradiation and readout, and MDD values between 0.65 mGy and 1.24 mGy immediately after irradiation. The signal stability over increased storage times was also examined and was observed to experience rapid signal loss over the first hour following irradiation, losing about 78% of the original signal intensity. After which, the signal loss slowed drastically, declining an additional ~12% over the subsequent 117 h.

Another important aspect for utilizing back glass is the suggestion that those equipped with an opaque case will not experience any signal degradation from light exposure. This was demonstrated with the successful completion of a dose-recovery test that resulted in a fading-corrected, estimated dose within 20% of the nominal dose.

Table 4.2: Results from the dose recovery test.

Phone Model	Nominal dose, Gy	t_{delay}	OSL dose, Gy	Fading coefficient	Fading- corrected dose $\pm$ std, Gy	Deviation, Gy
Galaxy S9	2.0	5	0.20	0.11	1.72 $\pm$ 0.24	-0.28

The results presented herein support the continued investigation into OSL methods on protective back glasses for use as possible emergency dosimeters. It also represents an essential step toward establishing an in situ OSL dosimetry method on intact smartphones, which will prove to be a quick and cheap route to providing personal dosimetry to large numbers of the population.

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Chapter 5

CONVERSION FACTORS FOR ABSORBED DOSE IN A MOBILE PHONE TO ABSORBED DOSE IN AN ANTHROPOMORPHIC PHANTOM FOR EMERGENCY DOSIMETRY APPLICATIONS: OSL AND TL EXPERIMENTAL RESULTS

A version of this manuscript is in preparation for publication by J. R. Chandler et al.:

Chandler, J.R., Sholom, S., McKeever, S.W.S., Velásquez, D., and Hall, H. L. "Conversion factors for absorbed dose in a mobile phone to absorbed dose in an anthropomorphic phantom for emergency dosimetry applications: OSL and TL experimental result". (In Preparation).

Abstract

An anthropomorphic phantom was equipped with three smartphones and irradiated in five separate exposure geometries. The phantom was outfitted with TLD-700 chips to measure the absorbed dose in the individual organs, while the absorbed dose in the phone was calculated by utilizing the phone's surface mount resistors and back protective glasses. The results indicate a strong dependence on the phone location with respect to the source due to shielding from the body. Based on this data, conversion factors were calculated for the separate exposure scenarios that, assuming the exposure details are known, can be used to correlate the absorbed dose measured in the phones to the average body dose received by the person carrying them. Additional experiments were conducted to assess how the phone orientation and angle impacts the dose received by the phone components, with results indicating that adjusting these factors can produce absorbed doses upwards of 22% higher than when the front of the phone is facing the source.

5.1 Introduction

After an unforeseen radiological exposure event, non-conventional approaches must be utilized to accurately assess the dose received by affected individuals. For this reason, extensive effort has been devoted to determining the suitability of various materials as stand-in radiation dosimeters [1–3]. Although not designed for use in this capacity, several materials, smartphone components in particular (e.g., resistors and glass), have been shown to exhibit the necessary attributes, such as signal stability and linear dose-response characteristics. These characteristics, along with their widespread popularity and the fact

that they are carried by the owner on or near their person, allows them to be potentially used as fortuitous, personal dosimeters for the general public.

The majority of research has, thus far, been performed to assess the dose to the phone components themselves; however, it is the dose to the individual that is the ultimate goal. To date, there have been two experimental studies using anthropomorphic phantoms that have utilized smartphones as fortuitous dosimeters in various exposure scenarios. In addition, there have been two studies using Monte Carlo simulations to calculate conversion factors to convert the dose absorbed by the phone to that absorbed by the individual phantom organs based on the location of the phone on the phantom and the position and orientation of the phantom during the exposure.

The first experimental study was a field project, code-named CATO, which recreated a radiological incident that occurred in Cochabamba, Bolivia in 2002, where members of the public, while traveling on a bus, were exposed to an ^{192}Ir source that was located in the luggage storage area beneath the passenger seating [4, 5]. To recreate the exposure event, anthropomorphic phantoms and water canisters, outfitted with mobile phones, dental ceramics, salt, chip cards, as well as reference dosimetry materials [optically stimulated luminescent dosimeters (OSLDs), thermoluminescent dosimeters (TLDs), and electronic personal dosimeters (EPDs)], were positioned throughout the bus. The results from the mobile phone resistors, inductors and display glass, along with the other materials were compared to those from the conventional dosimeters and Monte Carlo simulations by Discher et al. (2021) [6] where, for the particular circumstances of this accident, and using only a selection of organs to define an “average organ dose”, a conversion factor of 0.22 ± 0.1 was found between the computed phone dose and the average organ dose.

An interesting observation from this study showed that the doses measured inside of the phone by reference OSLDs were on-average 20% lower than those recorded by the display glasses due to suspected dose-gradients within the phone. The overall reported results were promising with 43 out of 61 fortuitous dosimeter measurements being in agreement with those determined by the reference dosimeters. There were 13 outliers that showed a significant dose overestimation; however, 10 of these were able to be identified by combining the analysis from the various dosimeter materials. This multiple-method technique may also prove useful in

the future for reconstructing the dose as well as the exposure conditions (e.g., heterogeneous or homogenous exposure), if the items were located at different positions on the exposed individual.

Another experiment that simulated a small-scale exposure scenario was recently conducted by the EURADOS WG10 Working Group and the Running the European Network of Biological Dosimetry and Retrospective Physical Dosimetry (RENEB) network in which anthropomorphic phantoms, set up under various exposure conditions (e.g., partial shielding, inhomogeneous exposure) and exposure geometries (e.g., anterior posterior (AP)], were irradiated with an ^{192}Ir source [7]. The outside of each phantom was outfitted with blood tubes contained in thermos flasks, mobile phones, standard reference dosimeters, and bags filled with other fortuitous materials, such as sweeteners, candies, and salted items. The interior of each phantom was filled with various reference dosimeters in order to estimate the absorbed dose to the organs.

The goals of this experiment were to calculate the doses to the fortuitous dosimeter materials and compare them to one another and to the reference materials; to calculate the absorbed dose to the organs and compare to Monte Carlo simulations; and, lastly, to combine all of the obtained information from the various biological and physical techniques and attempt to reconstruct the various exposure conditions. The only reported data thus far are from the reference materials placed on the inside and outside of the phantom. As expected, the results show clear differences between areas that were shielded compared to those that were unshielded. Further analysis is forthcoming.

The first simulation study to address the relationship between the absorbed doses in smartphones and the absorbed doses in humans was performed by Eakins and Kouroukla (2015) [8]. The authors used the MCNP5 Monte Carlo radiation transport code and a voxel phantom to assess the dose to the resistor component located inside a simulated phone. The phone was placed on the phantom in positions that corresponded to common placement points upon a person: the chest pocket, back and front pocket of a pair of pants, and on the hip. The phantom was exposed in the anterior posterior (AP), posterior anterior (PA), left lateral (LLAT), right lateral (RLAT), rotational (ROT), isotropic (ISO), and floor (FLR)

configurations to photons with energies that corresponded to those from ^{192}Ir , ^{137}Cs , and ^{60}Co sources.

Of note, the results showed no differences in the absorbed doses from resistors located behind the battery or not, as well as no difference in the phone's orientation in relation to the source (i.e., front or back facing); this demonstrates that the attenuation from the battery had no influence on the outcome, at least for this particular setup. The results were found to be highly dependent on the location of the phone on the phantom, with the resulting dose estimates differing by up to an order of magnitude. Nonetheless, if the details of the exposure are known, the applicable conversion factors can be applied to the measured dose from the phone's resistors to produce best estimates of the dose absorbed by the individual carrying them. However, if the intricacies of the exposure are unknown the authors determined that conservative estimates could be made to establish an upper and lower bound on the individual's absorbed dose by selecting the conversion factors that were associated with dose estimates for phone positions furthest from the average over all positions.

Kim et al. (2019) [9] also performed Monte Carlo simulations to associate the absorbed dose in phones to the absorbed dose in humans. These authors utilized the Geant4 radiation transport software and a mesh phantom and focused their efforts on the display glass component of the simulated phone. The simulated scenarios were similar to those performed by Eakins et al. (2015) [8] in the selection of phone position, photon energies, and exposure geometries (lacking only the FLR exposure). However, this study also incorporated a kneeling and squatting posture as well as the standing posture.

The results showed that doses were significantly affected by the shielding from the body and, depending on the posture and phone position, exhibited a 13–90% variation in the calculated doses among the various exposure conditions. Furthermore, it was shown that if a calibration factor was applied for a standing exposure and the real exposure occurred in a squatting posture, estimates could range 0.2–2.5 times the actual dose value, demonstrating that establishing the maximum shielding effects is essential to conservatively evaluate the dose received by the individual carrying the mobile device.

The purpose of the current study was to consider experiments using an anthropomorphic phantom to examine the effects that varying the position and exposure arrangements have on the dose to the smartphone and how to then relate this to the dose absorbed by the individual organ locations in the phantom. In addition, experiments were conducted to assess the attenuation effect that a phone has on the radiation that passes through it as well as the effect of exposure at different angles on the dose to the internal components of the phone.

5.2 Materials and methods

5.2.1 Retrospective dosimetry materials

The two smartphone components selected for investigation in this study were surface mount resistors (SMRs) and protective back glasses composed of Corning’s Gorilla glass (Generation 4). The SMRs and back glasses were either extracted from the 15 Samsung Galaxy S6 smartphones utilized in this study or, in the case of the SMRs, purchased separately from an online retailer (CTS resistor products, Type 0402). The phones were purchased in various working conditions from online retailers.

These components were chosen either for their proven record as retrospective dosimeters (e.g., Bassinet et al., 2014 [10], in the case of SMRs), or for their future potential as fortuitous dosimeters (e.g., Chandler et al., 2021 [11], in the case of protective back glasses). There have been several studies (e.g., [12–14]) of SMRs using OSL which have demonstrated a high sensitivity to radiation, a lack of any interfering background signal, and a manageable fading rate. Similarly, recent studies have shown that an OSL technique employed on protective back glasses also exhibits the same favorable properties, in addition to avoiding the need for irreparable damage to the phone itself [11, 15].

5.2.2 Irradiation facility and experimental setups

All irradiations were performed using a collimated, approximately 700 Ci ^{137}Cs source at Los Alamos National Laboratory (LANL). The source’s exposure rate was calibrated with

an Exradin A3 ionization chamber that was certified by an accredited secondary standards laboratory.

5.2.2.1 Anthropomorphic phantom study setup

5.2.2.1.1 Phantom description

The anthropomorphic phantom used in this study was an Alderson Radiation Therapy (ART) (Radiology Support devices, Inc., Long Beach, CA) male phantom, which consists of the torso and head region of a 175 cm tall, 73.5 kg representative human male (Fig. 5.1). It is comprised of 35 cross-sectional slices that are made of tissue-equivalent materials that follow ICRU 44 specifications; the top 34 slices are 2.5 cm thick, and the bottom slice is 9 cm thick. Each slice has a 3 x 3 cm grid of holes in which TLD holder pins may be placed. The holder pins are made of the same tissue-equivalent materials but have an added recess at one end that allows for the insertion of TLD chips.

5.2.2.1.2 Anthropomorphic Phantom Positioning

At the irradiation facility, the maximum distance in which the anthropomorphic phantom could be placed away from the source was 328.5 cm, but this corresponded to a beam size that was insufficiently uniform over the entire phantom. Therefore, the exposures were completed in two stages for each geometry, one concentrating on the upper portion of the phantom while the other focused on the lower portion. This approach allowed for the use of a smaller, more uniform beam size (60 cm within 2%) with an exposure rate of 0.15 Gy/hr.

To accommodate the smaller beam size, the phantom height off the floor was adjusted so that the phantom slices of interest were centered within the beam for each setup; this corresponded to slices 1–19 and 19–35 for the top- and bottom-focused irradiations, respectively.

For all setups, the phantom was secured to a metal turntable, which itself was situated on an aluminum table. For the bottom-focused setups, the phantom height was increased by the addition of two PMMA blocks between the turntable and aluminum table. Additionally,

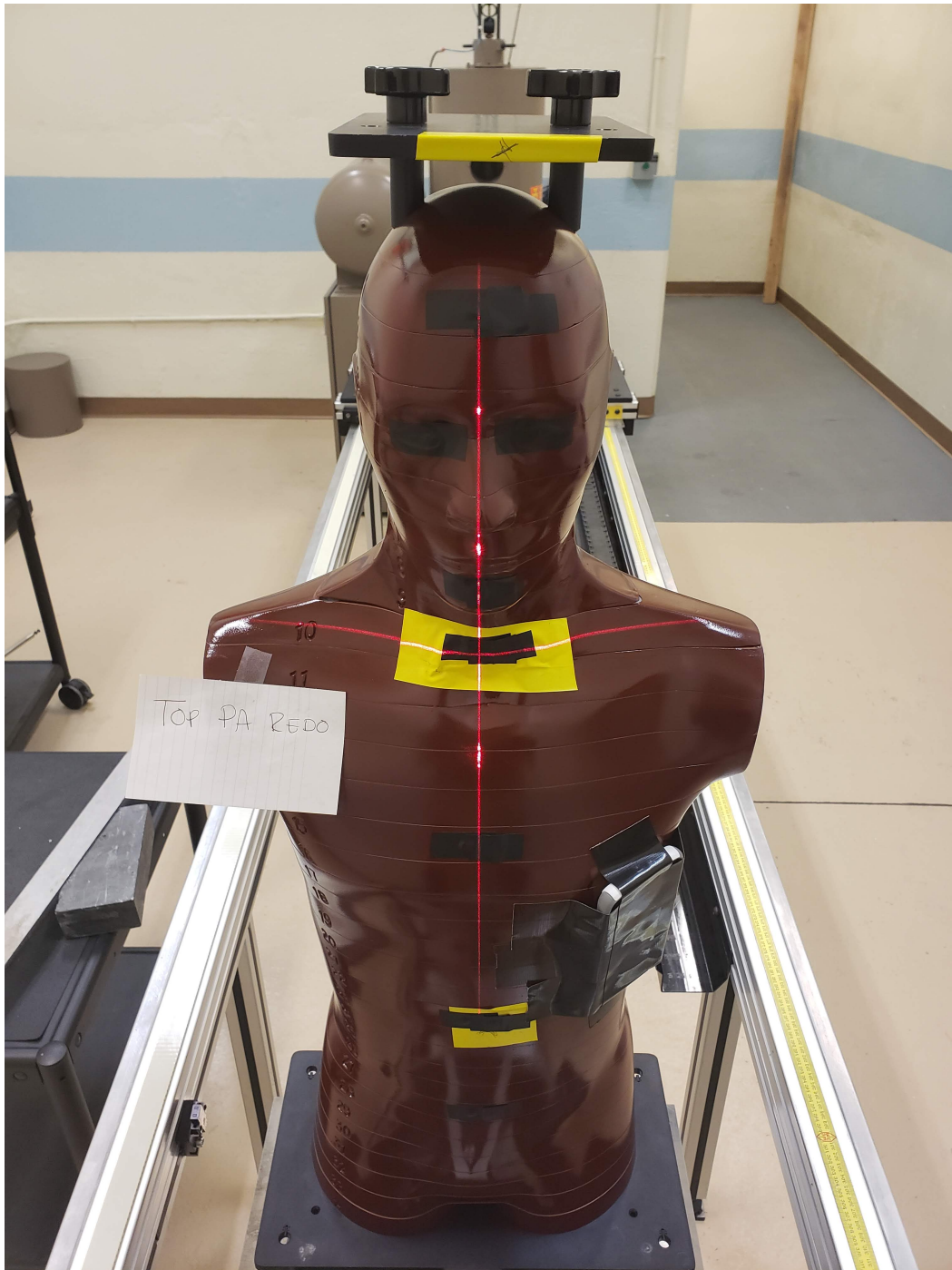


Figure 5.1: The ART phantom being positioned for irradiation at LANL.

the thick, bottom slice of the phantom was not used in the top-oriented setups but was added to the bottom-oriented setups for the additional height. For time considerations, the head and neck portions of the phantom were not attached when utilizing the bottom-oriented phantom setups, limiting the irradiated portion of the phantom to slices 14–35 (Fig. 5.2). As stated, the slices used for dose determination were 19–35; however, the irradiation was performed with the additional slices to better simulate realistic scattering affects.

It should be noted that extensive testing was done to ensure no discrepancies were introduced between the bottom and top irradiations. This included testing for any additional scattering effects between the stacking material and ensuring that slices that overlapped between configurations produced consistent results. Guide lasers were also utilized to assist with consistent positioning between each setup.

5.2.2.1.3 Phone Placement and Exposure Geometries

In the anthropomorphic phantom exposures, one Samsung Galaxy S6 was incorporated into each top-oriented exposure, while two were used for each bottom-oriented exposure. The phones used in the top-oriented exposures were placed on the chest and are representative of a phone being placed in a coat pocket. The phones in the bottom-oriented exposures were placed in positions that correspond to being placed in the front and back pocket of a pair of pants. Each position was chosen to reflect locations in which a phone may be carried by an individual in real life. All phones were arranged with the front of the phone facing away from the phantom. The three phone positions are illustrated in Fig. 5.3.

The phantom was exposed in five separate geometry arrangements including: AP, PA, LLAT, RLAT, and ROT; the first four are depicted in Fig. 5.3. The fifth geometry, ROT, was conducted using a turntable spinning at 2 rpm. The other geometries were arranged to be consistent with the ROT geometry, i.e., the average of the AP, PA, RLAT, and LLAT should give a good approximation of the ROT exposure. Therefore, with the center of the chest as the rotation point in the ROT geometry, the resultant PA setup is approximately 21 cm (corresponding to the depth of the chest) closer to the source than the AP setup. However, the front of the chest remained the same distance from the source in all geometries. With that said, for every setup the phantom was exposed to 2 Gy, as measured at the front of the

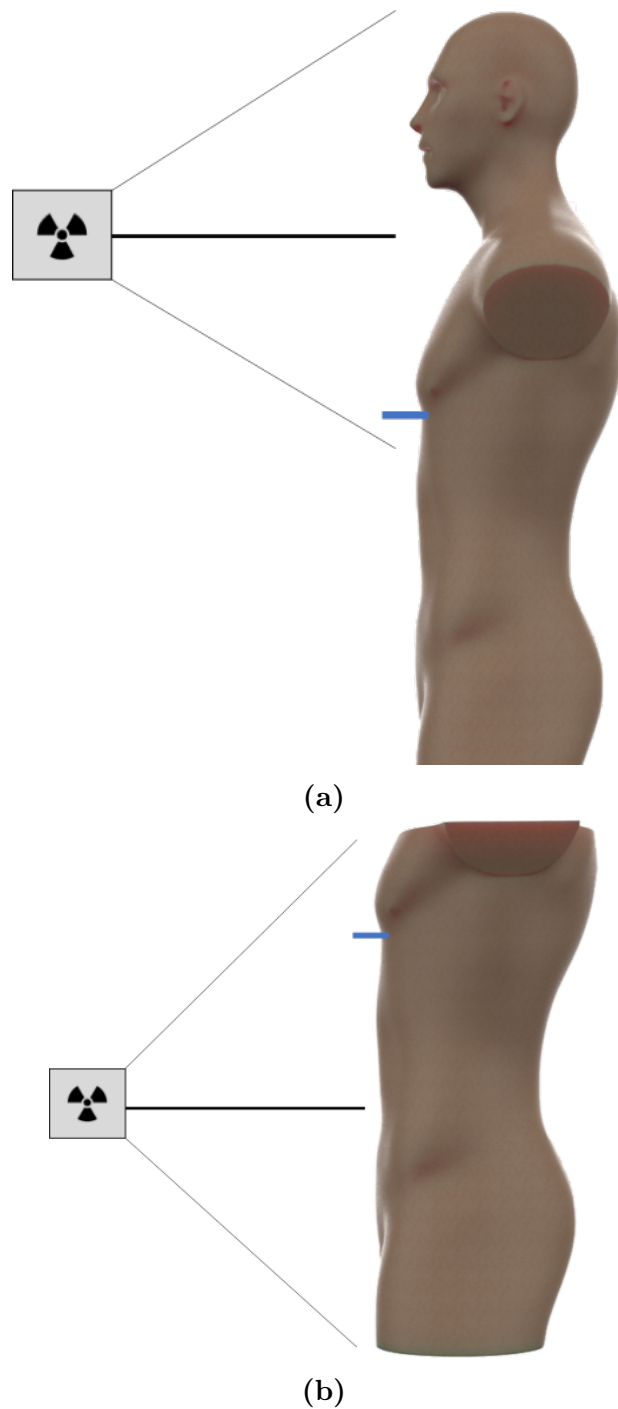


Figure 5.2: Illustration of a) the top-oriented (slices 1–34) and b) bottom-oriented (slices 14–35) setups with the corresponding position of the source. The blue line in each figure represents the location of slice 19, demarcating the portion of the phantom used for dosimetry in each setup.

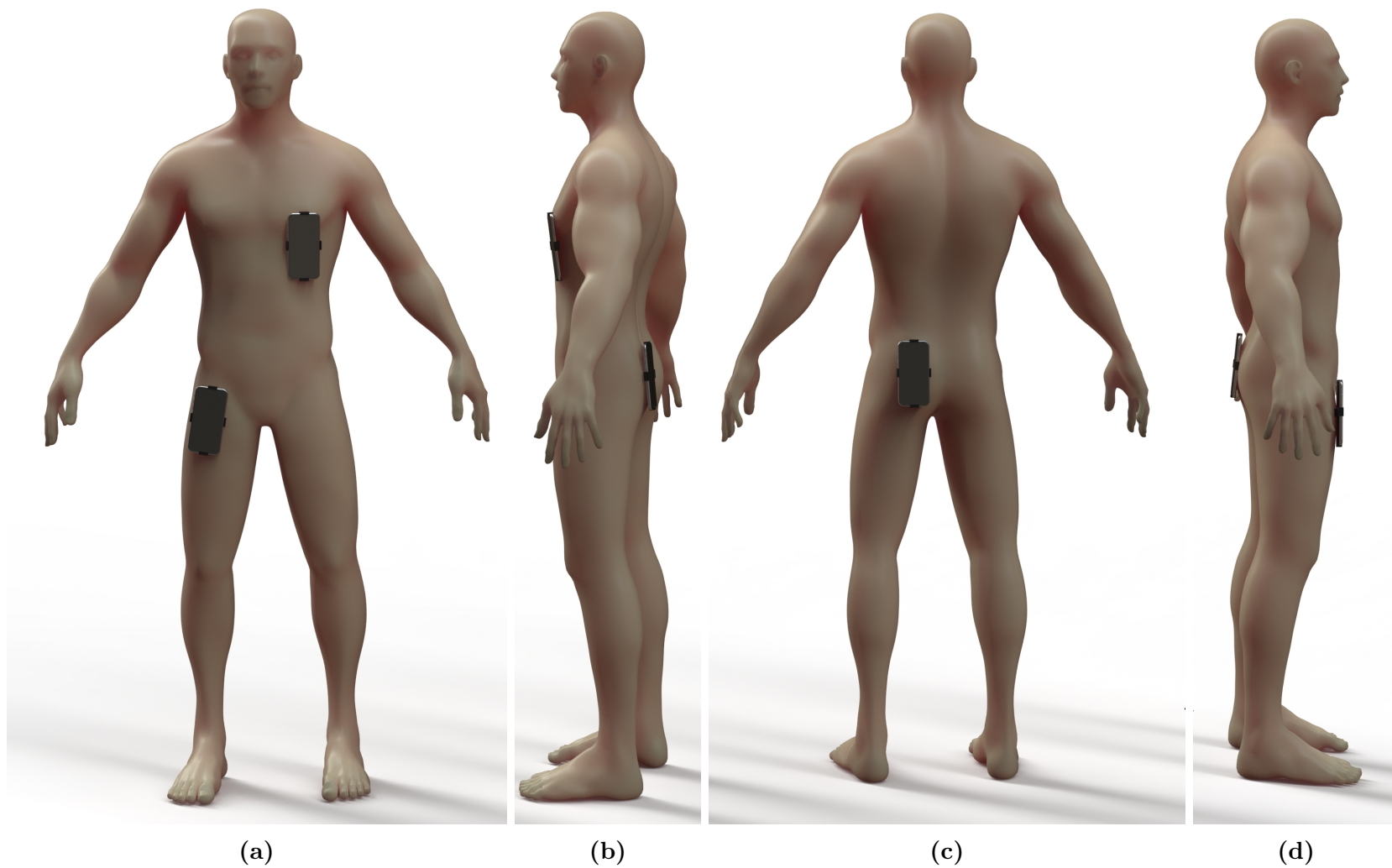


Figure 5.3: Illustration of the phones positioned on four of the geometries of interest. (a) AP, (b) LLAT, (c) PA, (d) RLAT.

chest in the AP geometry. In addition, the phone and phantom surfaces were equipped with standard OSL and TL reference dosimeters, i.e., Luxel films and TLD-700 chips, with each wrapped in light-tight black tape, lined with standard computer paper to prevent sticking. In total, because each geometry was utilized in both the top- and bottom-oriented setups, ten separate irradiations were performed.

5.2.2.1.4 Organ TLD Positions

As previously mentioned, the ART phantom has holes throughout, each of which can be equipped with TLD holder pins that allow for the precise placement of TLD chips inside of the phantom. In this study, the TLDs were placed in positions that correlated to major organs of interest.

Taking into consideration the time necessary to place, remove, readout, and anneal the TLDs for 10 separate irradiations, the number of TLDs used within each organ was kept to the minimum possible to accurately assess the dose while also maintaining the unique organ symmetries. This strategy is supported by Pederson et al. (2020) [16] who demonstrated the ability to accurately estimate the organ dose values using only a subset of the TLD organ positions, when they are selected in a logical, symmetrical fashion. The organs and the number of TLDs contained within the phantom to represent them are shown in Table 5.1. In addition, 30 Luxel dosimeters were placed about the surface of the phantom to measure the dose to the skin, breasts, and testes, totaling 17 organ locations in all.

5.2.2.2 Phone Attenuation

A Samsung Galaxy S7, outfitted with an $\text{Al}_2\text{O}_3\text{:C,Mg}$ film (manufactured by Landauer Inc.) adhered to each side, was positioned, facing forwards, on a $30 \times 30 \times 15 \text{ cm}^3$ PMMA slab phantom that was located 200 cm from the source (see Fig. 5.4). The film consists of a $47 \text{ }\mu\text{m}$ active layer deposited on a $75 \text{ }\mu\text{m}$ thick polyester substrate, for a total film thickness of $\sim 125 \text{ }\mu\text{m}$. The film was cut into $68 \times 120 \text{ mm}^2$ segments to match the dimensions of the phone. The entire arrangement was covered in black tape to protect the OSL films from extraneous light and a 2-Gy dose was delivered to the assembly. A reference irradiation was also performed with only the film in place (i.e., no phone) using the same setup. The

Table 5.1: The number of TLDs used inside of the phantom to measure each organ dose.

Organ	# of TLDs
Bladder	4
Brain	6
Trans. Colon	7
Eyes	2
Esophagus	6
Gall Bladder	1
Heart	6
Kidneys	6
Liver	8
Lungs	14
Prostate	2
Spleen	4
Stomach	10
Thyroid	2

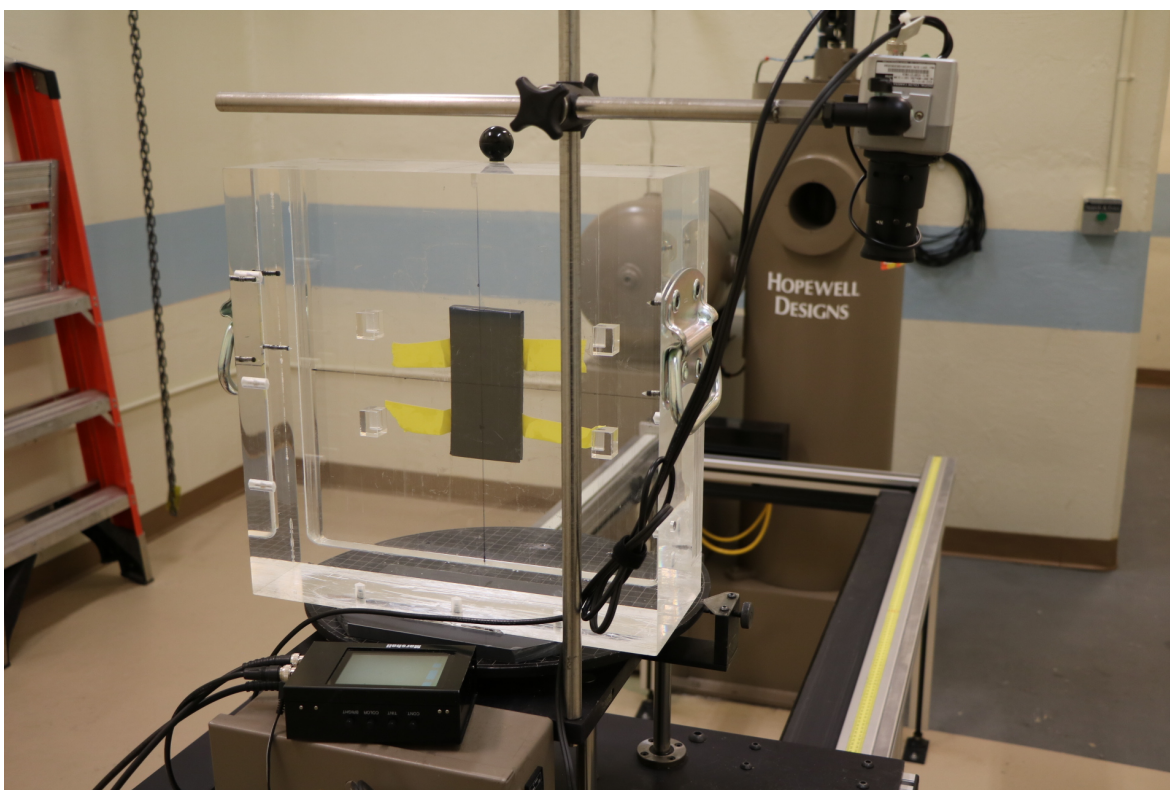


Figure 5.4: Irradiation of a Samsung Galaxy S7, equipped with $\text{Al}_2\text{O}_3:\text{C}$, Mg films, using a ^{137}Cs source at LANL.

exposure rate to the front of the phone at this position was 0.42 Gy/hr and was uniform over the entire phone and phantom area.

5.2.2.3 Angle Dependence

A Motorola Moto E5 smartphone, chosen for its easily removable battery and back cover, was fitted with two SMR packets and attached to the front of a 30 x 30 x 15 cm³ PMMA slab phantom that was located on a turntable, 100 cm from the source. The exposure rate to the front of the phone was 1.69 Gy/hr at this position and was uniform over the entire phone and phantom area.

The lens and battery positions, selected to evaluate any variation in the results due to the battery, were each fitted with a packet of 30 SMRs (Fig. 5.5). The lens position SMR packet was positioned horizontally, directly below the lens and above the battery, whereas the battery position SMR packet was arranged vertically behind the battery. When viewed from the front, the battery position SMR packet is in front of the battery; the opposite is true when viewed from the back. The lens position is never directly in front of or behind the battery.

The experiment was conducted by first positioning the two SMR packets inside of the phone and then delivering a dose of 2 Gy. Next, the SMR packets were replaced, and the phone was rotated about its center face to the next position. This was repeated in 30° steps from -90° to 90° with both the front and back of the phone facing the source for a total of 14 separate irradiations. The experimental setup, including the SMR packet positions, is depicted in Fig. 5.6.

5.2.3 Instrumentation and Measurement Procedures

All TL and OSL measurements were performed at Oklahoma State University (OSU) after transport from LANL via the United States Postal Service. The samples were mailed immediately after irradiation; however, due to variability in the delivery speed, the period between irradiation and measurement varied between 3 and 7 d, which is a critical factor



(a)



(b)

Figure 5.5: a) The SMR packets used in this study. b) The Motorola Moto E5, with the back cover removed, illustrating the two SMR packet positions utilized in this study.

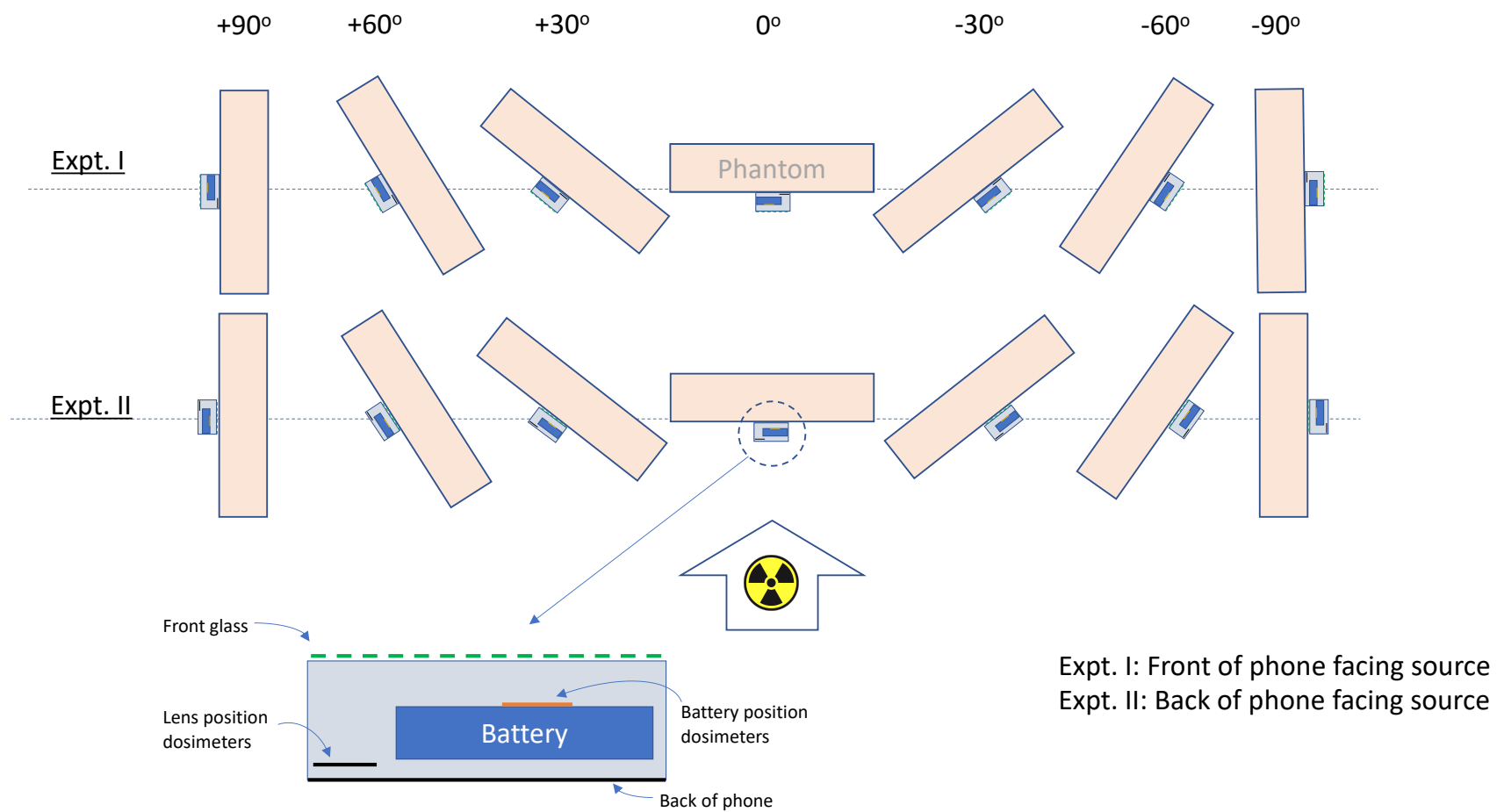


Figure 5.6: Depiction of the angle dependence experimental setup.

to consider during sample analysis. Several reference Luxel and TLD-700 dosimeters were included in each shipment to assess any dose received during transport.

Two Risø DA-15 TL/OSL readers were utilized separately for the OSL and TL measurements. Both readers were equipped with a $^{90}\text{Sr}/^{90}\text{Y}$ beta source that was calibrated to the individual dosimeter materials using the LANL ^{137}Cs irradiator. The delivered dose rates were 69 mGy/s, 70.7 mGy/s, and 64.4 mGy/s to the SMRs, glasses, and Luxels, respectively, in the OSL-dedicated reader and 40.9 mGy/s to the TLD-700 chips in the TL-dedicated reader. All OSL measurements were conducted in continuous wave mode and stimulated with a blue LED (470 nm, 30 mW/cm² power) with detection occurring through a Hoya U-340 filter, whereas the TL measurements, operating with a 5 °C/s heating rate, utilized a BG-39 detection filter and a nitrogen atmosphere.

5.2.3.1 Experimental Dosimetry Material Procedures

As noted previously, the phones were equipped with opaque cases; these were not removed until sample extraction began. In addition, all portions of the sample preparation process were conducted under red light to prevent sample bleaching due to light exposure. For the SMRs this consisted of separating the screen module from the device to access and extract the individual SMRs from the circuit board using a pry tool. The quantity of SMRs in each device was enough to prepare two aliquots consisting of approximately 20 resistors each. The back-glass procedure included separation from the device and preparing six aliquots, 5.5 x 5.5 mm² in size, using a Buehler IsoMet 1000 precision sectioning saw equipped with a diamond wafering blade and water cooling. The back glass was removed using a heating plate operating at 90 °C.

5.2.3.1.1 Glass

The back-glass measurements were performed using an OSL stimulation time of 150 s with the dosimetric signal (DS) calculated as the difference of the signal integrated over the first- and last-10 s of the OSL decay curve. The DS signal was converted to units of dose via a 2 Gy reference dose from the Risø internal beta source. The dose was then corrected for fading using an appropriate fading factor and averaged over the six aliquots. The fading

curve was developed specifically for the glass used in this study and was generated using fading evaluations up to seven days post-irradiation.

5.2.3.1.2 Resistors

The SMR measurements followed the “full mode” OSL protocol outlined in Bassinet et al. (2014) [10]. The resultant fading-corrected dose was the average of the two prepared aliquots.

5.2.3.2 Reference Dosimetry Material Procedures

5.2.3.2.1 Luxel

Luxel films were initially readout for 100 s and again after a small test dose (about 0.3 Gy) in order to normalize the DS, which was calculated as the difference of the OSL for the first and last 10 s of stimulation time. The DS was then converted to units of dose using a corresponding dose response curve that was previously obtained. The result for the phone was the average of that obtained from each of the three films. The doses from each the 30 Luxel dosimeters placed on the phantom surface were averaged to obtain the skin dose, with the dose to the breast and testes areas represented with single dosimeters.

5.2.3.2.2 TLD

TLD-700 measurements were heated to a maximum temperature of 325 °C following a preheat at 160 °C for 30 s. The TL signal was integrated over the entire glow curve and converted to units of dose using a calibration dose of ~ 0.2 Gy.

It should be noted that prior to use, each TLD-700 chip was annealed at 400 °C for 1 h to remove any remaining TL signal. This ensured a TL signal reproducibility within 2% for repeated exposure and readout. For those placed on the front of the phones, the resultant dose was the dose obtained from a single TLD, while those positioned inside the phantom was the average of the doses from the TLDs used to represent each organ.

5.2.3.2.3 2D OSL Film

OSL films were read for approximately 20 min using a custom-made OSL reader described in Ahmed et al. (2016) [17]. The obtained images were then converted to a 2D dose distribution according to Ahmed et al. (2016) [18].

5.3 Results and Discussion

5.3.1 Phantom Experiment Results

The results of the anthropomorphic phantom study, described in Section 5.2.2.1, are detailed in this section. All doses have been converted from absorbed dose in air to the absorbed dose in the medium of interest (i.e., tissue, SMR, glass, TLD, and Luxel) using the following conversion factor $(\mu_{en}/\rho)_{\text{medium}}/(\mu_{en}/\rho)_{\text{air}}$, with mass-energy absorption coefficients obtained from Hubbell and Seltzer (2004) [19].

5.3.1.1 Organ Doses

The dose measured in each organ is displayed in Table 5.2. The associated standard deviation is also presented for the organ doses determined with more than one TLD (or Luxel). As expected, the organs that experienced the highest dose variation between geometries are those that are located near the surface, such as the breast and testes, and those located asymmetrically within the body, such as the spleen and liver.

The average body dose (male), also shown in Table 5.2, was calculated for each exposure geometry. Of note, the average body dose for the ROT geometry is within 4% of that averaged over the other four geometries, which is indicative of a satisfactory phantom setup and reproducible results.

5.3.1.2 Phone Doses

This section focuses on the reference dosimeters adhered to the mobile phones as well as the mobile phone components utilized for dosimetry. The absorbed doses measured by the reference and fortuitous dosimeters, acquired from the various configurations, are compared

Table 5.2: Absorbed dose in the individual organs and average body dose received in various exposure geometries.

Organ	Absorbed Dose (Gy)				
	AP	PA	ROT	LLAT	RLAT
Bladder	2.06 (0.04)	1.04 (0.23)	1.37 (0.03)	1.22 (0.16)	1.22 (0.15)
Brain	1.18 (0.12)	1.66 (0.13)	1.56 (0.04)	1.68 (0.17)	1.68 (0.14)
Breasts	2.17	0.88	1.44	2.05	2.17
Trans. Colon	1.91 (0.17)	1.28 (0.37)	1.50 (0.04)	1.30 (0.49)	1.49 (0.50)
Eyes	1.98 (0.05)	0.91 (0.05)	1.61 (0.02)	1.79 (0.18)	1.72 (0.22)
Esophagus	1.55 (0.13)	1.79 (0.11)	1.48 (0.14)	1.01 (0.10)	0.99 (0.08)
Gall Bladder	1.77	1.47	1.40	0.96	1.69
Heart	1.80 (0.09)	1.24 (0.18)	1.43 (0.04)	1.50 (0.15)	1.12 (0.15)
Kidneys	1.31 (0.04)	2.21 (0.43)	1.45 (0.05)	1.27 (0.43)	1.23 (0.38)
Liver	1.74 (0.17)	1.60 (0.27)	1.41 (0.04)	0.89 (0.13)	1.67 (0.18)
Lungs	1.51 (0.09)	1.77 (0.07)	1.41 (0.06)	1.15 (0.38)	1.15 (0.39)
Prostate	1.83 (0.02)	1.71 (0.19)	1.29 (0.04)	1.10 (0.10)	1.09 (0.11)
Spleen	1.41 (0.15)	2.07 (0.21)	1.42 (0.05)	1.82 (0.07)	0.75 (0.03)
Skin	1.70 (0.06)	1.76 (0.12)	1.46 (0.02)	1.48 (0.12)	1.47 (0.15)
Stomach	1.68 (0.17)	1.70 (0.39)	1.42 (0.04)	1.49 (0.15)	1.06 (0.09)
Testes	1.77	0.93	1.09	0.95	0.90
Thyroid	2.14 (0.00)	1.32 (0.02)	1.84 (0.04)	2.08 (0.23)	2.03 (0.23)
Average Dose	1.60 (0.13)	1.69 (0.43)	1.46 (0.15)	1.36 (0.37)	1.49 (0.39)

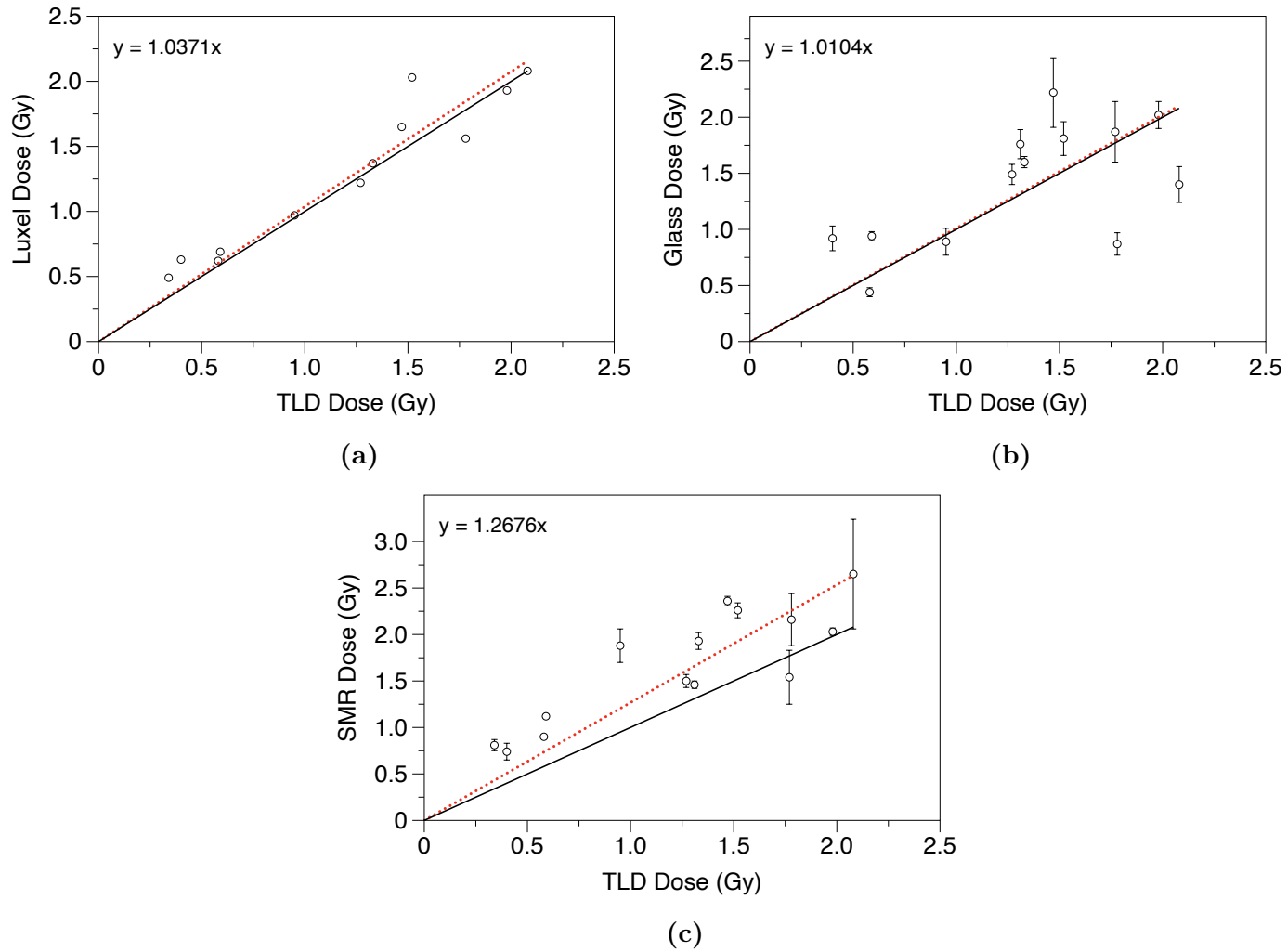


Figure 5.7: Comparison of the absorbed doses in a) Luxels, b) glasses, and c) SMRs to that absorbed in the TLDs. In each figure, the dotted line represents the linear fit of the data, and the solid line represents the 1:1 dose correspondence.

in Fig. 5.7. In each figure, the dotted lines represent the linear fits through the origin for the specific dosimeter data and the solid lines represent the 1:1 dose correspondence.

The first observation of note, which provides confidence in the calibration and readout procedures utilized in this study, is the near unity (within 5%) correlation between the two reference dosimeters (TLDs and Luxels), shown in Figs. 5.7(a). Furthermore, the absorbed dose in glass is also very similar, being only slightly higher ($\sim 1\%$) than unity in comparison with the TLD results, albeit with more scatter. The SMR component produced the only significantly different results, overestimating in relation with the TLD results by $> 15\%$. These results serve to compare the fortuitous dosimeter response to that of the reference dosimeters; however, moving forward the analysis will focus only on the absorbed doses measured in glasses and SMRs.

Figure 5.8 compares the average body dose in each exposure geometry to that received by the SMRs and glasses from the three locations on the phantom. From these data, it can be seen that the average body dose remained consistent (within approximately 10%) around 1.55 Gy for the various exposure geometries, whereas the component doses are more dispersed, ranging from 0.74–2.65 Gy and 0.41–2.22 Gy for the SMR and glass doses, respectively.

The doses are as expected in the sense that the phone locations that were less shielded produced a higher dose, while those that were more heavily shielded produced lower doses. The results affected by the distance from the source were also consistent, e.g., the results reflect the chest and side pocket positions altering their proximity to the source in the LLAT and RLAT exposures. Additionally, it is observed that the ROT exposures experience the least amount of dose divergence with the component doses ranging from 1.46 to 1.93 Gy, which is due to phantom rotation compensating for any differences (e.g., shielding and incident angle) between the various phone locations.

To further examine the effect of phone position on the doses received in each exposure geometry, Table 5.3 presents the measured SMR and glass data from each phone position and exposure geometry and compares each to that obtained from the front and chest pocket positions in the AP exposure geometry. The purpose of this is to further contrast the measured values and illustrate the potential misestimation in the received dose if either of these two standard positions were assumed in their place.

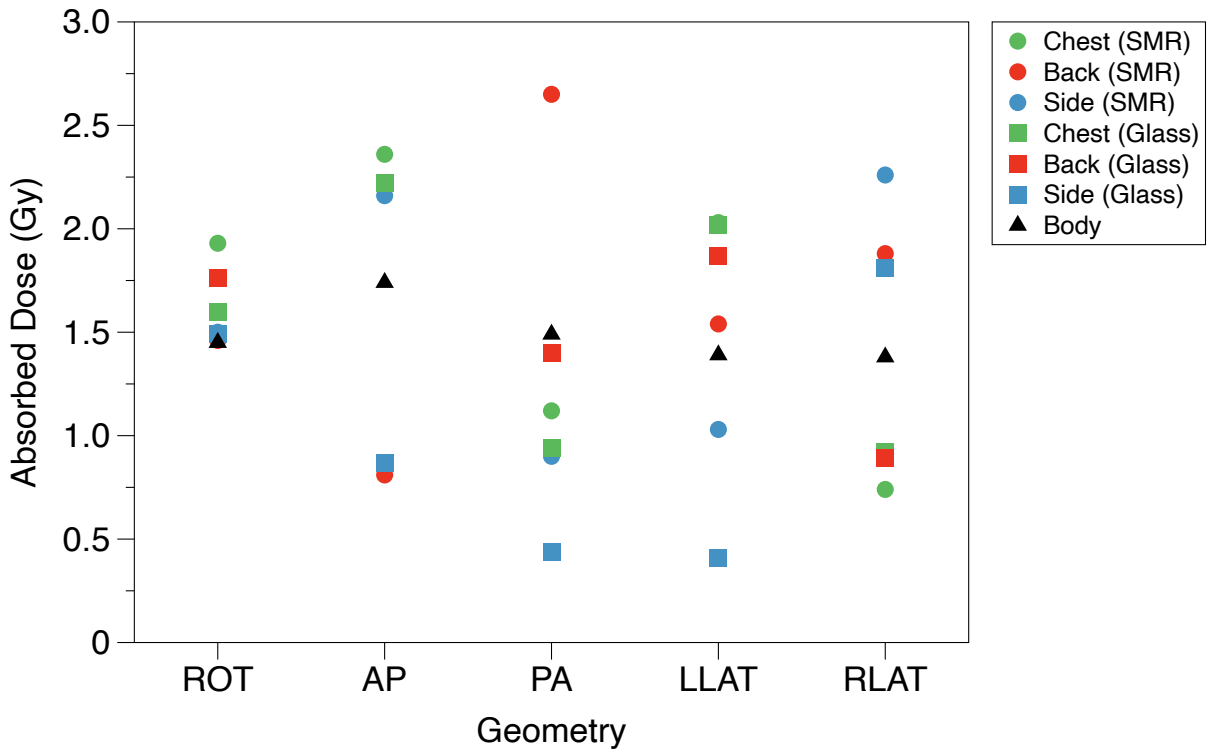


Figure 5.8: Absorbed dose measured in SMRs (circles) and glasses (squares) in comparison with the average body dose (triangles) irradiated in various setups.

Table 5.3: Absorbed dose in SMRs and glasses at different positions in various exposure geometries and their relationship with selected setups.

Exposure	Phone	SMR			Glass		
Geometry	Position	Dose (Gy)	$R_{AP,C}^{(a)}$	$R_{AP,FP}^{(b)}$	Dose (Gy)	$R_{AP,C}^{(a)}$	$R_{AP,FP}^{(b)}$
AP	Chest Pocket	2.36 (0.05)	1.00	1.09	2.22 (0.31)	1.00	2.56
	Back Pocket (Left)	0.81 (0.06)	0.34	0.38	-	-	-
	Front Pocket (Right)	2.16 (0.28)	0.91	1.00	0.87 (0.10)	0.39	1.00
PA	Chest Pocket	1.12 (0.02)	0.47	0.52	0.94 (0.04)	0.42	1.08
	Back Pocket (Left)	2.65 (0.59)	1.12	1.23	1.40 (0.16)	0.63	1.61
	Front Pocket (Right)	0.90 (0.00)	0.38	0.42	0.44 (0.04)	0.20	0.50
ROT	Chest Pocket	1.93 (0.09)	0.82	0.90	1.60 (0.05)	0.72	1.84
	Back Pocket (Left)	1.46 (0.04)	0.62	0.68	1.76 (0.13)	0.79	2.03
	Front Pocket (Right)	1.50 (0.07)	0.64	0.70	1.49 (0.09)	0.67	1.71
LLAT	Chest Pocket	2.03 (0.04)	0.86	0.94	2.02 (0.12)	0.91	2.33
	Back Pocket (Left)	1.54 (0.29)	0.65	0.72	1.87 (0.27)	0.84	2.15
	Front Pocket (Right)	1.03 (0.04)	0.44	0.48	0.41 (0.05)	0.19	0.48
RLAT	Chest Pocket	0.74 (0.09)	0.31	0.34	0.92 (0.11)	0.41	1.06
	Back Pocket (Left)	1.88 (0.18)	0.80	0.87	0.89 (0.12)	0.40	1.02
	Front Pocket (Right)	2.26 (0.08)	0.96	1.05	1.81 (0.15)	0.82	2.09

^(a) $R_{AP,C}$ defined as the dose relative to that from the AP exposure in the chest pocket location.

^(b) $R_{AP,FP}$ defined as the dose relative to that from the AP exposure in the front pocket (right) location.

For each component, the phone irradiated at the chest pocket position in the AP geometry received the highest dose when compared to the other exposure setups (barring only the back pocket, PA exposure for the SMRs), overestimating the actual dose value by, on average, 47% and having a maximum overestimation of 140%. Likewise, substituting for the front pocket, AP exposure also led to discrepancies in the received dose, but to varying degrees for the glass and SMR estimations. While the average SMR dose continued to be overestimated by the substitution, with a 29% overestimation, the glass setup actually underestimated the received doses by an average of 42%, with a maximum underestimation of over 2.5 times the actual value. These data further illustrate the differences in the received dose produced by the various positions between the two components and highlight the impact that incorrectly assuming a particular exposure setup can have on the final results.

5.3.1.3 Conversion Factors

A conversion factor can be applied to convert the dose measured in the phone components to the average body dose received by the individual carrying them. These factors have been calculated by taking the ratio of the average body dose and component dose for each exposure scenario and are displayed in Fig. 5.9. All conversion factors are between 0.56 and 3.41, with an average value of 1.26. It should be noted that, while all the results could be true values, the most likely scenario is that the glass samples with values furthest from the mean were either prematurely exposed to light, slightly bleaching the signals or they experienced different fading rates, causing the fading rate correction to be inadequate, possibly due to being a replacement glass. For now, these values will be utilized, and future studies will determine their validity.

If the exact phone location and exposure geometry are known, theoretically, the corresponding conversion could be applied; however, in the large majority of scenarios this information would not be known and even if it were, the resultant data could not be expected to be precise. While overestimating the dose isn't ideal, it is much preferred to underestimating a person's absorbed dose during triage; therefore, the real benefit of this study is in utilizing the results from the most limiting setups, i.e., most shielded, to assist with establishing conservative conversion factors.

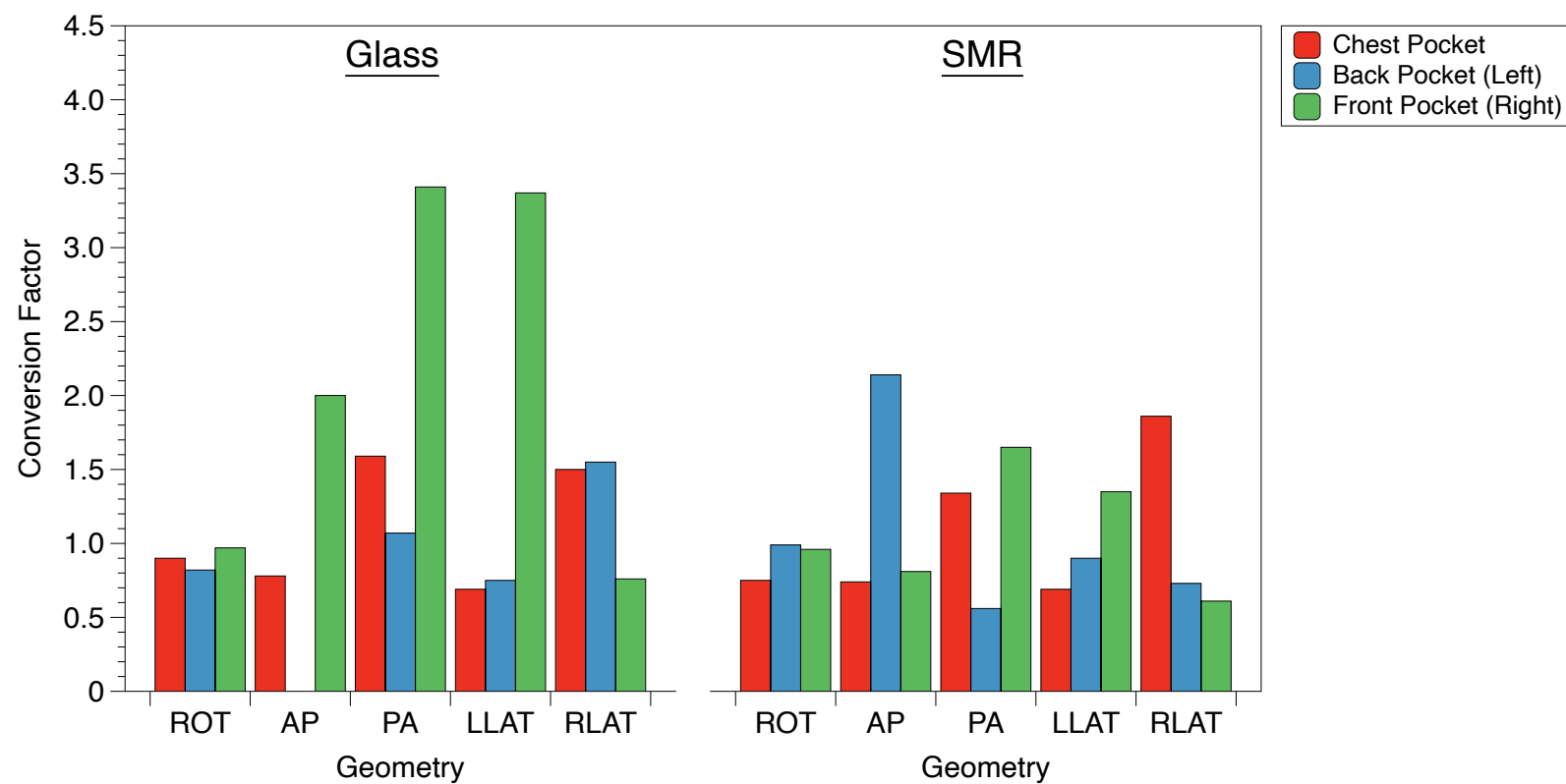


Figure 5.9: Phone dose-to-average body dose conversion factors calculated for both glasses and SMRs irradiated at different positions in various exposure geometries.

The results presented in this section suggest that, in addition to the differences in shielding, the disparity between the SMR and glass doses is most likely exacerbated by the varying response to the angle at which they are irradiated. Therefore, the following sections will take a closer look at the phone's contribution (i.e., attenuation and angle dependence) to the fluctuation in the absorbed doses.

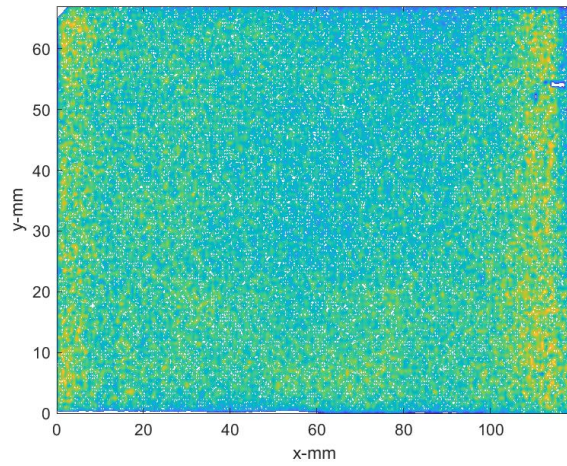
5.3.2 Attenuation Results

The 2D reconstructed results of the attenuation experiment, described in Section 5.2.2.3, are displayed in Fig. 5.10, where Figs. 5.10(a) and 5.10(b) correspond to the front and back films, respectively and Fig. 5.10(c) is the ratio of the measured doses between the two films. The figures are orientated as if the phone is placed on its left side when viewed from the front; this is further illustrated in Fig. 5.10(a) by the identified components.

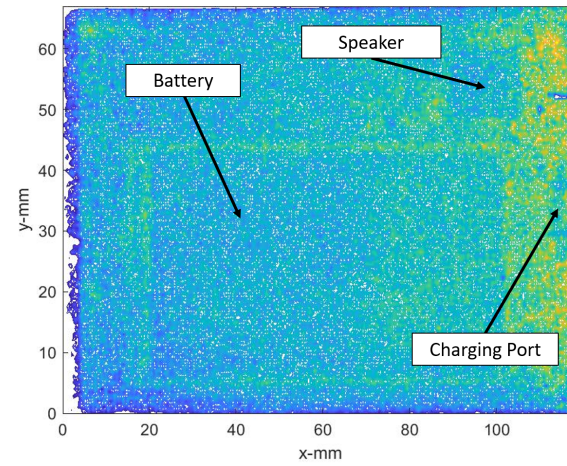
The average dose to the front film was within 1% of that from the reference film that was irradiated without a phone, demonstrating that there is no significant backscatter contribution from the phone itself. As displayed in Fig. 5.10(b), the components within a smartphone can provide varying degrees of attenuation to the source photons as they pass through the device. However, the dose averaged over the back film is still within 2% of that from the front film; this is indicative that the attenuation that the phone provides overall is small (at least for ^{137}Cs photons). In fact, in some positions, the measured dose is higher in the back film than in its front film counterpart (Fig. 5.10(c)). The greatest variation between the front and back film was approximately 10%; therefore, there should still be some consideration of the sample position during collection to avoid any underestimations. A possible illustration of these results can be seen in the similarity between the doses measured by the TLDs and the glasses, which were located on opposite sides of the phone, during the anthropomorphic phantom irradiations.

5.3.3 Angle Dependence Results

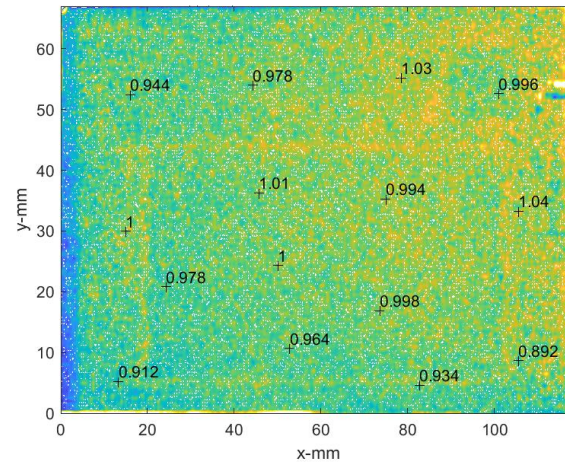
The results of the angle dependence experiment, described in Section 5.2.2.3, are depicted in Fig. 5.11. The doses measured in both positions (i.e., the battery and the lens positions;



(a)



(b)



(c)

Figure 5.10: 2D reconstructed Luxel films that were irradiated to 2 Gy while attached to a) the front of the device and b) the back of the device, with c) presenting the ratio of the doses measured from each. Concerning the figure colors, the warmer the color the higher the dose.

see Fig. 5.6) follow a similar pattern, with the largest dose variation occurring when the phone is parallel to the beam direction. When irradiated in the frontwards orientation, the lens position receives the higher average dose, whereas the battery position receives the higher average dose in the backwards orientation. For both positions (lens and battery), the average dose for all angles was approximately 7% higher in the backwards orientation. Furthermore, when considering only the angles between -60° and 60° , the average dose disparity between the two orientations rises to 13%.

The results may appear unexpected when considering only the attenuation experiment, which revealed essentially no difference in the dose measured entering and exiting the phone. However, it becomes more evident when the additional scattering produced by the battery is taken into consideration along with the known overresponse to low energy photons, which can be greater than 2x for energies below 200 keV [20].

To examine how the phone angle impacts the measurement, each dose was normalized to that measured at 0° from the same orientation. The results, shown in Fig. 5.12(a), indicate that there is, on average, a 7% higher dose absorbed by the SMRs irradiated in the -30° to -90° range compared to those measured in the 30° to 90° range for both orientations. This is likely due to additional scatter within the device produced by a dense component when oriented in this way and may not be reproducible between different phone models as the components are not located in the same positions. Therefore, the purpose of this analysis is to aid in establishing the most conservative dose estimate strategy instead of correction factors to be applied to every angle.

To assess how the phone angle in conjunction with its orientation can affect the dose estimate, the value from each backwards oriented angle was normalized to that measured at 0° in the frontward orientation (Fig. 5.12(b)). The results demonstrate that the SMRs maximize their received dose when both factors, angle and orientation, are considered, with the largest dose totals occurring at -30° for the battery position and -60° for the lens position. To consider this another way, if the phone orientation was incorrectly assumed to be irradiated at 0° with the front of the phone facing the source the maximum dose underestimation is 11% for the lens position and 22% for the battery position.

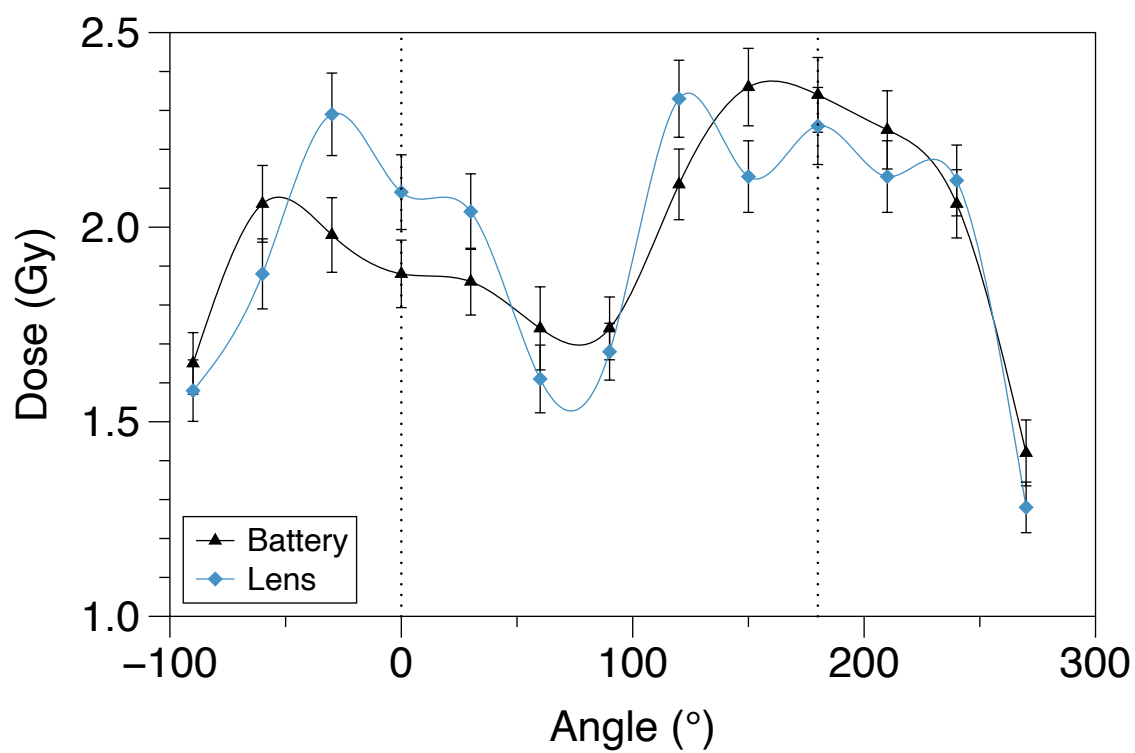
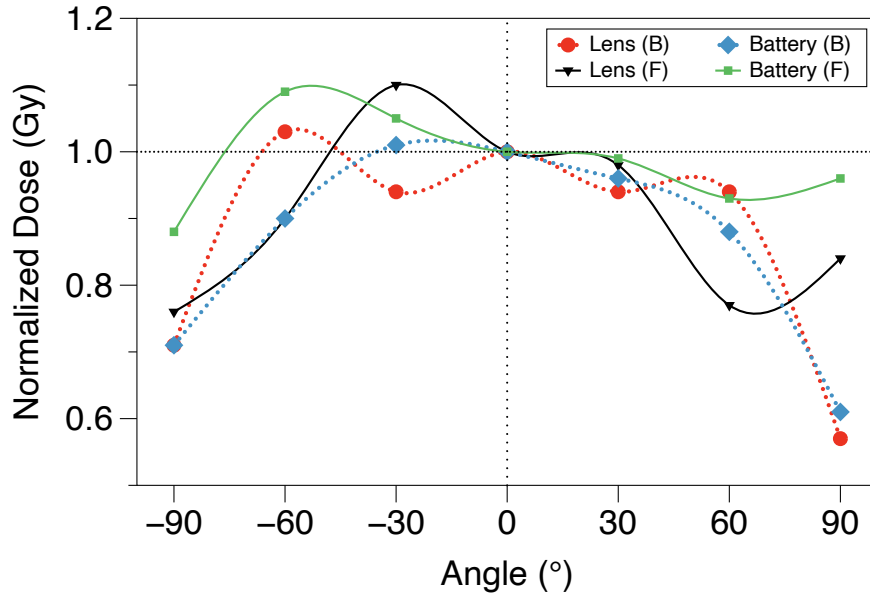
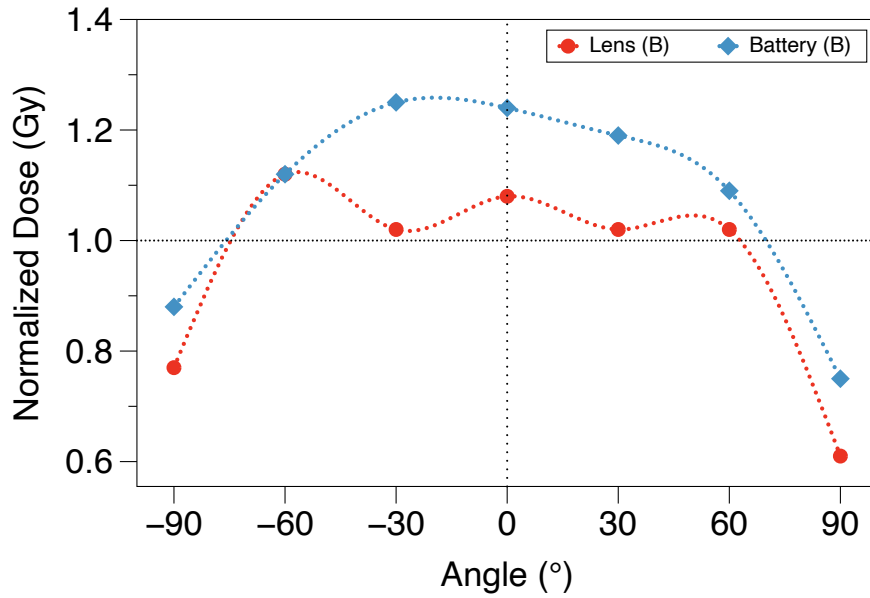


Figure 5.11: The dose measured at different angles for both the battery and lens positions after exposure to 2 Gy. The vertical lines indicate when the front and back sides of the phone are perpendicular to the beam direction, respectively.



(a)



(b)

Figure 5.12: The ratio of the doses shown in Fig. 5.11 to a) the dose at 0° from the corresponding side and b) the dose at 0° from the front side. The positions that were oriented with the front of the phone facing the source during irradiation are denoted with an ‘F’ and those oriented with the back of the phone facing the source during irradiation are denoted with a ‘B’.

The results from both the battery and lens positions indicate that to conservatively assess the SMR dose when the orientation of the phone is unknown it should be assumed to have been irradiated with the back of the phone facing the source. While the phone orientation has the largest impact on the dose measurements, the angle that generates the highest absorbed dose should also be assumed. Because the lens position is the most analogous to the position an SMR and the battery position is the worst-case demonstration, the lens position results should be more heavily weighted. Accordingly, the recommended factor when nothing is known about the phone position during irradiation is between 11 and 22%.

5.4 Conclusions

The aim of this study was to relate the dose received by smartphones, after exposure to radiation, to that of the individuals carrying them. This was accomplished by calculating the average absorbed body dose in an anthropomorphic phantom and then relating that to the dose received by the phones attached to it. Fifteen separate conversion factors, based on separate combinations of phone placement and exposure geometry, were determined for both the phone's SMR and back glass components. Evaluation of the results identified a clear variation in the estimated doses that was dependent on the phone position in relation to the geometry in which it was exposed due to shielding from the body. Additionally, the phone doses were observed to be affected by the angle at which they were positioned on the phantom. These combined factors resulted in conversion factors that ranged from 0.56–2.14 and 0.69–3.41 for the SMRs and glasses, respectively.

To further investigate how the angle at which the phone is irradiated impacts the SMR dose assessment, a separate study was performed in which the phone was irradiated from -90° to 90° with both the front and back of the phone facing the source. The results indicated that the absorbed dose was higher, to varying degrees depending on the location of the SMRs, when the back of the phone was facing the source. In addition, the dose was observed to increase or decrease depending on the angle. The combined effects produced results that were upwards of 22% higher than if the front of the phone was irradiated facing the source.

This type of work is essential in advancing the utility of fortuitous dosimeters for use in triaging radiation exposure incidents and this study represents a critical step towards their further adoption. While more effort is required to more accurately estimate the doses received by the individual based on the phone location and exposure scenario, the results presented here can be utilized to conservatively estimate the absorbed dose received by individuals when exposed in a standing posture.

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Chapter 6

CONCLUSIONS

The objectives of this research were to analyze the TL, PTTL, and OSL properties of the protective glasses commonly located on the front and back of modern smartphones and to correlate, through the creation of dose conversion factors, the absorbed dose measured in smartphone components to that of an individual carrying them.

Chapter 2 of this dissertation focused on the TL and PTTL investigation of protective glasses. The degree of BGS associated with these samples was observed to be significantly higher than had previously been reported (tens of gray versus hundreds of milligray). It was concluded that the incorporation of a new adhesive, LOCA, and its associated UV curing process on newer model smartphones is believed to be responsible for the rise in the BGSs. This was demonstrated by reproducing the distinct glow curve response in the laboratory using a solar simulator + 302 nm UV exposures, representing a wide-spectrum source. Because the BGS and RIS glow curves greatly overlap and the BGS magnitude was observed to be inconsistent, even between models of the same phone, it was deemed necessary to remove the BGS. The same mechanical removal technique utilized on the surface layers of display glasses in previous studies proved to be inadequate on samples of protective glass. Comparison of the optical absorption coefficients between the display glasses and protective glasses illustrated that while the BGS is primarily a surface effect in display glass, it has penetrated much deeper into the bulk sample of the protective glass; thus, rendering any BGS removal technique impractical. A matrix deconvolution method has been evaluated to assess each component's contributions to the measured dose, but more work is required to improve its accuracy and reliability before it can be suggested as a reliable technique. Lastly, because the PTTL processes are closely associated with that of TL, the same conclusion was reached concerning its usability on protective glasses, i.e., impractical, at least for the current supply of smartphones. Nevertheless, for protective glasses that have not been encumbered by a strong BGS, TL and PTTL still represent viable dose reconstruction techniques.

Chapter 3 of this dissertation concentrated on the OSL investigation of protective glasses, specifically on those located on the back of the device. The primary finding being the low to non-existent BGS, which was the major obstacle associated with application of both the TL and PTTL dose reconstruction methods for evaluating protective glasses located on the front of smartphones. The additional OSL properties investigated in this study included

the dose response, observed to be linear over the tested dose range of 0.1 Gy to 8 Gy, and the signal reproducibility, which remained within 3% over 10 cycles of repeated irradiation and readout. In addition, a significant signal loss was observed over the first hour following irradiation, but was relatively stable afterwards, losing an additional $\sim 12\%$ over the next 117 h. Fortunately, the signal fading was successfully accounted for by the application of a fading factor, calculated by fitting the relationship between the signal loss in the samples and time elapsed after exposure. Lastly, a dose recovery test, in which a smartphone was outfitted with an opaque case, was conducted. The dose reconstruction successfully estimated the nominal dose within 20%; thus, exemplifying the case's ability to prevent light exposure. Therefore, from this work, it is evident that smartphones glasses provide a strong opportunity on which to build a viable OSL emergency dosimetry procedure.

Chapter 4 of this dissertation focused on deriving the absorbed dose associated with an individual based on the dose reconstructed from smartphone components carried by said individual. Anthropomorphic phantom irradiations were performed for various exposure geometries (e.g., AP and PA), with each exposure containing three smartphones attached at different locations on the phantom. The absorbed dose in each organ was measured by strategically placed TLD-700 chips; these values were then averaged according to organ mass to obtain the average body dose. The smartphone doses were obtained through OSL dose reconstruction techniques performed on the SMRs and back protective glasses. Conversion factors were then calculated as the ratio of the average body dose to the absorbed dose in the phone components, for each phone location and exposure geometry. The resultant conversion factors were observed to be heavily influenced by the phone's position in relation to the source, especially when shielded by the body. An additional experiment was performed to assess the influence of the phone angle with respect to the source, in which successive irradiations of a smartphone, equipped with SMR packets, were performed at various angles. The results showed that, at least for the phone tested in this study, the largest dose occurs when the phone is irradiated with the back facing the source. In addition, doses were observed that, depending on the angle, were both higher and lower than when the phone was positioned parallel to the source, with the combination of these two effects being upwards of 22% larger.

Vita

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