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New dosimetry methods for radiological and nuclear emergency management

Thesis submitted in fulfilment of the requirement for the degree of Doctor of
Philosophy

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Declaration

The material presented in this thesis summarizes the results of independent research conducted at the Scottish Universities Environmental Research Centre (SUERC), College of Science and Engineering, university of Glasgow (Environmental Sciences). The research was supervised by Professor David Sanderson and Dr. Alan Cresswell, both from SUERC. This thesis represents my own research, and I have fully acknowledged any published or unpublished work from other researchers within the text.

Signed

Hamdan Alghamdi

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Abstract

During all phases following a nuclear or radiological incident analyses of doses received by members of the public and responders are required. Rapid and reliable dose assessment is critical for the effective management of radiological emergencies; for medical triage, understanding exposure levels, directing protective actions, and conducting subsequent analyses of the impact of the incident. Current practice has been reviewed, highlighting the potential for near real-time luminescence dosimetry to assist with such assessments, including low dose response that supports public reassurance below doses of medical significance, using common materials present at the time of the incident. A number of materials which might be found in the immediate vicinity of people have previously been investigated with regard to their potential to act as radiation dosimeters. The work in this thesis investigates the properties of common household salt and talc, using portable Optically Stimulated Luminescence (OSL) and Infra-Red Stimulated Luminescence (IRSL) instruments capable of rapid measurements in the field. The potential of these materials to measure radiation levels and provide rapid, cost-effective insights into exposure patterns using new methods is explored. This approach aims to support emergency response strategies by leveraging accessible materials to improve decision-making in radiological incidents, bridging a key gap in large-scale radiation measurements and initial triage support.

Common salt has previously been shown to have the potential for retrospective dosimetry in the mGy dose range using laboratory instrumentation. This thesis investigates the use of portable instruments, with unprepared commercially sourced salt, in dose ranges below mGy. Responses from pulsed IRSL laboratory systems and portable OSL instruments were compared. For OSL measurements, detection limits of 7 μ Gy have been demonstrated, with detection limits of 30-340 μ Gy for the other instruments investigated. Linear dose responses in the 0-500 μ Gy range were determined over this dose range. This work examines the effects of signal stability and sample storage conditions. The OSL signals initially show a brief decrease in luminescence during the first few days after irradiation, followed by a gradual increase with longer storage periods. Between days 8 and 64, the results remain relatively stable, which is crucial for dose estimation during both the early and later stages of responding to radiological emergencies, and methods for correcting for these signal variations at shorter and longer

periods have been developed and demonstrated. However, exposure to light and moisture leads to a rapid loss of OSL signals.

Three practical experiments were conducted using salt to simulate real accident scenarios, measure radiation, estimate dose, and compare the results with gamma systems (backpack). The first experiment was conducted under controlled laboratory conditions. The second mapped natural and artificial radiation fields in an outside environment. The final experiment mapped complex radiation fields within an accelerator laboratory. The results demonstrate that salt has considerable potential for use in dosimetry below mGy and that measurements can be conducted with portable OSL instruments. Furthermore, the results of the first two experiments compared well to theoretical doses and measurements with different systems. The results confirmed that this approach can provide reliable dose estimates for radiological accidents. The salt system has demonstrated its ability to map the spatial boundaries of radiation fields, serving as a low cost radiation mapping tool. Protocols must be instituted for testing and assessment during exercises, taking into account variables such as zeroing, ambient conditions, and the necessity for fading adjustments

The studies of talc focused on the optimal conditions for measuring the radiation-induced OSL signal using the SUERC Portable OSL Reader. It also addressed the inherent complexities associated with geological residual signals observed in talc sourced from Luzenac Pharma's packing line. This residual signal can be removed through thermal treatment, specifically at 400°C for 1 hour, after which the talc exhibits sufficient sensitivity to detect doses in the mGy range through to the radiologically significant range of 0.5 to 3 Gy, making it a promising candidate for field-deployable radiation assessment, such as in emergency response scenarios following radiological incidents. However, the observed fading and zeroing behaviours of talc introduce critical considerations that must be addressed to ensure reliable dose estimation. The fading data exhibit a complex decay pattern, suggesting the presence of multiple trap depths, with an initial signal loss of approximately 6% within 24 hours post-irradiation, escalating to a substantial 65% reduction of the original OSL signal within 128 days at ambient temperature. Such behaviour necessitates the incorporation of fading correction factors tailored to the time elapsed between irradiation and measurement, as an uncorrected signal loss could lead to systematic underestimation of doses, particularly in retrospective dosimetry applications. Additionally, the zeroing behaviour poses further challenges. Incomplete zeroing could leave residual signals that overlap with those induced by a recent radiation event. This overlap

complicates the ability to accurately distinguish between background dose contributions and acute doses from a specific incident, potentially compromising the method's specificity.

The work presented here has demonstrated that the novel approach of using salt or talc with portable OSL systems is capable of delivering dose estimates in the range from a few μGy to several Gy in near real-time, complementing existing techniques. To optimize this approach, comprehensive protocols should be developed for both testing exercises and evaluations, which could lead to wider acceptance of these approaches offering a robust, low-cost solution for rapid dose assessment for both emergency response and environmental dosimetry.

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Alghamdi, H., Sanderson, D., Carmichael, L., Cresswell, A., Martin, L., 2022. The use of portable OSL and IRSL measurements of NaCl in low dose assessments following a radiological or nuclear emergency. *Front. Public Health* 10, 969829. <https://doi.org/10.3389/fpubh.2022.969829>.

Alghamdi, H., Sanderson, D., Carmichael, L., Cresswell, A., Martin, L., 2024. Radiological or nuclear OSL dosimetry using commonplace salt. *Radiation Measurements* 174 (Issues 7–8):107141. doi:10.1016/j.radmeas.2024.107141

Chapter 1

Introduction

1.1. Context

Earthquakes, volcanic eruptions, tsunamis, hurricanes and floods, nuclear power plant disasters, nuclear accidents, as well as radiological terrorist attacks are a few examples of the many types of mass-casualty disasters that occur in contemporary society. Researchers and government officials are driven to explore how vulnerable, prepared and responsive communities are to such disasters, aiming to lessen their impact and boost the capacity of societies to mitigate their effects and enhance the resilience of communities and their ability to recover from them (NRC, 2006; Kohn et al., 2012). Radiological and nuclear disasters are rare, their impact on conventional response plans, health providers and first responders is substantial owing to concerns that are not present in other sorts of disasters (Coleman et al., 2015; Jaworska, 2009).

When faced with a major radiological or nuclear event, rapid and comprehensive evaluation is crucial. Key priorities include the imperative to promptly assess the nature of the incident, determine the affected areas, identify potentially affected individuals (triage). Prompt access to accurate information and the use of appropriate measurement methods are essential, enabling authorities to make decisions regarding protective measures, medical interventions, and resource allocation and manage radiation exposure and/or injuries (Coleman et al., 2009). The management of mass casualty radiation exposure caused by nuclear or radiation accidents is dependent on the type of incident and the understanding of a person's level of exposure to radiation. Radiation victims are triaged based on clinical signs and symptoms including nausea and vomiting or blood counts. Thus, information pertaining to the timing and method of exposure or contamination and doses are essential to support both medical and public health measures (Jaworska, 2009). Hence, to strengthen societal resilience, being prepared is vital (Coleman et al., 2015). Specifically, responding to radiological disasters requires the implementation of personalised preparedness measures (Knebel et al., 2011; Hick et al., 2011, additional information in Chapter 2).

Addressing possible nuclear or radiological incidents involves a multi-phase approach. The critical first step in incident management is rapid assessment of the situation and prioritising safeguarding members of the public who are at greatest risk of exposure and danger and who are situated off-site. This initial evaluation forms the foundation for subsequent response actions and decision-making processes. Prompt information is essential at this point to effectively guide decision-makers. First responders may need to address the needs of civilian populations, which can include decontamination, screening, medical intervention, accommodation, food, water, and even evacuating people from impacted regions. Nevertheless, responding to these incidents can be challenging owing to the absence of medical infrastructure, the possibility of a substantial number of affected individuals and the requirement to monitor possible contamination and the levels of radioactive exposure experienced by first responders. Effective management for successful mitigation of radiation-related harm relies heavily on access to precise and suitable methods for quantifying exposure levels and applying them in an effective way. For minor accidents involving a limited number of individuals, even those with severe injuries may be treated effectively using the available medical resources, making the situation controllable. Nonetheless, during a large-scale event, the sheer magnitude of individuals impacted might be beyond the capacity of the existing emergency medical services (Alghamdi et al., 2022; Coleman et al., 2009; Flood et al., 2011). Consequently, it is vital to assess the level of radiation exposure after a radiological accident with the aim of 1) guiding decision-makers and providing medical support even when radiation exposure symptoms are not immediately apparent, 2) establish a triage system in relation to large-scale accidents and 3) establish affected areas to support decisions of sheltering and the evacuation of people.

1.2. Problem and significance

Emergency dosimetry, dose reconstruction, calculation dosimetry, nuclear terrorism and biological dosimetry were identified as key radiation protection challenges, which have a substantial impact on emergency management throughout a major radioactive incident (McDonald, 2010) underlines the importance of accurately assessing the absorbed dose in individuals who may have been purposefully or accidentally exposed in these types of incidents. Consequently, as the risk of radiological accidents or terrorist acts involving radioactive materials increases, emergency dosimetry or retrospective dosimetry is crucial.

These methods assess radiation exposure in the aftermath of a radiological or nuclear incident, as the estimation of radiation exposure will considerably assist with separate medical assessments of the injured (Grace et al., 2011).

Responses to potential nuclear or radiological incidents involve several phases. Initially there needs to be a rapid assessment of the nature of the incident, and priority given to protecting members of the public at greatest risk off-site, the identification of people that may have been affected (triage) and estimates of radiation doses received by first responders and the general public are of the utmost importance (Alghamdi et al. 2023). At this stage, realtime or near

realtime information is very important to guide decision makers. First responders would have to deal with civilian populations that may require decontamination, screening, medical treatment, housing, food, and water, as well as potential evacuation from affected areas. Responses may be impeded by loss of medical infrastructure, potentially large numbers of affected people and requirements to monitor potential contamination and doses received by first responders. Furthermore, a nuclear event evolves over time, with increasing numbers of victims due to delayed health effects from radiation exposure (e.g., ARS, cancer), continued infrastructure loss, and the affected area's progression from fallout to deposition and redistribution leading to changing requirements for management and response (Gougelet et al., 2010). Thus, the management of radiation injuries or exposure will be critically dependent on the availability and application of appropriate measurement methods in a timely manner [e.g., (Coleman et al., 2009)]. In these situations, information from appropriate measurements would let response managers triage casualties and decide how to best use limited available resources [e.g., (Flood et al., 2011)].

Instrumental measurements are capable of providing real time information, both for response management and the protection of first responders. Retrospective assessments may be conducted within a few days of the incident, and thus be available for emergency response and recovery, or several years later when the focus might also include scientific investigation of radiation effects and consequences. Personal dosimeters and dose rate instruments are routinely provided to personnel assigned to nuclear emergency response organizations' rescue teams, provision of such devices to other first responders and members of the public is less common. During the early phases of emergency response it is highly unlikely that enough instrumental systems would be available to provide a comprehensive assessment of the extent of contamination and associated dose rates. Moreover, conventional personal dosimeters are not

commonly used in the general population, resulting in limited timely information on the doses that individuals may have received. It is therefore often necessary to retrospectively estimate absorbed dose to make assessments of radiological impacts in an emergency situation and to provide accurate information to the general public. The dose ranges of interest depend upon the assessment requirements. In the initial stages, triage for people requiring immediate medical attention would require assessment of doses in excess of a few hundred mSv, decisions on evacuation, sheltering, food and water restrictions, etc., would be based on dose rates with intervention levels typically of the order of tens of $\mu\text{Gy hr}^{-1}$ (e.g., Rea et al. 2010; Godfrey-Smith and Pass, 1997; ICRP, 2007; ICRP, 2009). Consideration of psychological effects and the mental health of potentially exposed individuals and communities may require assessments of dose at levels well below those for purely clinical requirements (Hasegawa et al. 2015). Critical decisions need to be made on short timescales, and this requires dosimetric measurements and assessments immediately following the occurrence of an accidental or malicious use of radiation (Woda et al. 2009). In later stages of response it may be necessary to reconstruct the doses that individuals and communities received (Williams et al. 2014). Determining lower radiation doses than those used for early countermeasure decisions may also be necessary for retrospective analysis to support recovery and scientific investigations (Alghamdi et al., 2024).

Several methods for dosimetric assessment in the absence of conventional personal dosimeters have been developed, following experience of nuclear weapons in Japan and nuclear accidents [e.g., (Jacob et al. 2002)]. Instrumental measurements using portable gamma spectrometry systems and sample analysis can identify current radionuclide distributions, from which initial depositions can be estimated by modelling radionuclide decay and environmental redistribution. A primary method of estimating doses received by individuals is through biodosimetry, the direct measurement of changes in human physiology associated with radiation exposure (Swartz et al., 2010; Simon et al., 2010). Advantages of biodosimetry include potential sensitivity to radiation damage, and the direct link between actual damage and clinical decision making. Disadvantages include potential lack of specificity as the same damage can be caused by other mechanisms and involve invasive procedures with sample handling and analysis requiring specialist laboratories (Swartz et al., 2010). Whole body monitoring and specific monitoring of individual body organs (e.g., the thyroid) allow measurement of internal contamination following inhalation and ingestion, which is an additional pathway for receiving radiation doses but beyond the scope of this work which focusses on external radiation exposure. Alternative methods which can complement modelled

initial deposition is to estimate the dose absorbed by common objects and biological tissues collected from areas and individuals (Simon et al., 2010). This may be performed through the identification of radio-induced defects with physical techniques such as electron paramagnetic resonance (EPR), optically stimulated luminescence (OSL), and thermoluminescence (TL). Luminescence methods have been used in retrospective dosimetry to better understand past events and to study the impact of these (Haskell, 1993; Göksu et al., 2006). It is imperative that dosimeters capable of providing rapid data collection and registering doses over orders of magnitude from μGy to Gy , be widely available, and ideally should be capable of delivering near real-time results. Passive dosimeters based on thermoluminescence (TL) and optically stimulated luminescence (OSL) techniques are potentially suitable options for this purpose if they can be gathered and measured quickly. Rapid methods of assessing external radiation using commonly held personal objects or objects from the surroundings would thus be invaluable for triage purposes. These methods play a part in emergency response, although they have not yet been incorporated in emergency response strategies. These methods also provide information on exposure levels, particularly in retrospective dosimetry scenarios. In the absence of them, rescue personnel would be unable to obtain precise information regarding radiation doses for individuals or populations. Accumulated radiation exposures in biological samples and materials can be quantified using these methods. The absence of these techniques would impede efforts to comprehend the comprehensive picture of radiation exposure over time. These methods can also quantify the effects of radiation on various materials in the environment. Without them, it would be impossible to assess the complete extent of environmental contamination. EPR, OSL and TL can contribute to the study of long-term effects of radiation. Their absence could limit our ability to track and understand long-term health impacts on affected populations. Emergency response efforts will be less comprehensive and effective in addressing the complex challenges posed by nuclear and radiological disasters if these dosimetry techniques are not incorporated in emergency response strategies (Alghamdi et al., 2022; Alghamdi et al., 2024).

A study of OSL from electronic components of mobile phones and ID cards appears to have opened up the feasibility of dosimetry and dose reconstruction using the electronic components of gadgets of everyday use in the events of unforeseen situations of radiological accidents, including the event of a dirty bomb by terrorist groups (Pradhan et al., 2008). A variety of common household materials have been investigated for their potential use in OSL dosimetry, including porcelain (Bøtter and McKeever, 1996; Thomsen et al., 2002), household salt [NaCl ;

e.g., (Thomsen et al., 2002; Bernhardsson et al., 2009)], Multiple items, including plastic cards, garments, and shoes, were investigated for radiation exposure analysis (Sholom et al., 2014), as were salted crackers, almonds, pretzels, and potato chips (Christiansson et al., 2017). Many of these techniques are suited to low to high dose regimes where identification of people who may develop medical conditions due to their exposure is required. There is, however, a requirement to confirm that individuals have not received a potentially harmful radiation dose, to provide reassurance to people, especially in situations where large numbers of people may have been affected. This needs a dosimetry system that can register ultra-low doses, and that could be widely available, or potentially deployed by pre-positioning suitable materials within areas at risk. Common table salt (NaCl) has been proposed as a retrospective dosimeter that would be widely present, it can be found in homes, workplaces, and restaurants all over the world. This means that collecting samples would be relatively simple, and sample preparation would be minimal.

Notwithstanding significant progressions in these techniques, there are persistent doubts with regards to their practicability in handling a large-scale emergency comprising a considerable number of people, which would be challenging to manage using conventional methods. Moreover, it is essential to have a variety of efficient methods and resources with the intention of supplementing the response to nuclear or radiological emergencies.

1.3 Response

To address the above concerns, the ability to make use of an OSL portable instrument that could provide rapid measurements by deploying the device at or near the incident site using readily available materials for emergency dosimetry or retrospective dosimetry has been investigated in the research presented here. If possible, under field conditions, these systems should demonstrate a reasonable performance during initial dose assessments, eliminating the need to transport samples to the laboratory for analysis. Furthermore, the sample data should be sufficient to generate substantial amounts of high-quality data within emergency timeframes. It should be readily accessible in the following a radiological accidents, be carried close to the person, have a signal that is sufficiently robust to permit the detection of a dose at the threshold necessary for triage and typically available amongst the public. Similarly, it is imperative that sample processing is both uncomplicated and expeditious to accommodate the evaluation of a significant quantity of samples within a limited timeframe.

The aim of the work presented in this thesis is to assess the performance of portable optically stimulated luminescence (OSL) systems for rapid radiation dose assessment using common materials, potentially reducing the reliance on laboratory-based sample analysis. By comparing the sensitivity and performance of these portable systems with traditional laboratory equipment, the research seeks to determine whether field-deployable OSL instruments can deliver comparable or even superior results. This approach could greatly improve emergency response capabilities by facilitating quick and accurate dose measurements at or near incident sites, utilizing readily available materials as dosimeters.

1.4 Research questions and thesis design

The work in this thesis seeks to address the problems mentioned previously and provide answers to the following questions:

- 1- Can an OSL portable instrument perform adequately and effectively measure low radiation doses after radiological or nuclear incidents, hence eliminating the need for sample analysis utilising laboratory instruments?
- 2- Is it possible for rapid on-site measurements using these systems, predominantly in radiation emergencies or in the aftermath of significant radiation accidents?
- 3- What are the luminescence properties of the materials studied? How do they perform with portable instruments?
- 4- What are the advantages and disadvantages associated with using different dosimeter materials for this purpose, and how might these findings inform broader applications in the field?
- 5- What is the precise level of dose estimations by radiometric mapping using two-dimensional arrays of optically salt dosimeters in comparison with radiological survey using backpack systems?

Following the introductory section in Chapter 1, the thesis establishes the theoretical framework in Chapter 2. This chapter presents the necessary theoretical background, detailing key principles, concepts, and existing research that support the study. This section presents a review of radiological accidents, emergency preparedness and response, and features the most important scientific aspects connected with significant radiation or nuclear incidences thus far, for instance nuclear and radiological risk categories. It contextualizes the research within the

broader field of radiation dosimetry and emergency response, preparing the reader for the experimental work and analysis that follow. This theoretical framework is essential for understanding the methodologies used and for interpreting the results discussed in the subsequent chapters. The second part of the thesis focuses on presenting the experimental outcomes. Chapter 3 will examine the use of portable instruments with unprepared commercially sourced salt in dose ranges below 100 μGy . A comparative analysis was performed to evaluate the responses of portable optically stimulated luminescence (OSL) instruments and pulsed infrared stimulated luminescence (IRSL) instruments. Dose responses in the 0-500 μGy range were determined for the most sensitive systems. Additionally, this chapter explores the optimal conditions for measuring radiation-induced OSL signals in sodium chloride (NaCl). Chapter 3 involved practical investigations of crucial OSL characteristics, with a particular emphasis on signal stability over time. Furthermore, the investigation investigated the impact of external factors, including humidity and light exposure, on the OSL response in NaCl samples. The objective of this approach is to offer a comprehensive understanding of the practical applications and constraints of utilising common salt as a radiation dosimeter in a variety of environmental conditions. The results enhance the knowledge of low-dose radiation detection methods and the potential of utilising common materials in radiation monitoring scenarios. Chapter 4 presents a case study on dosimetry using common talc with portable instrumentation, providing background information on the use of talc for dosimetry, the rationale for the investigation, and the methodologies utilised for the preparation of talc samples for dosimetry experiments. It also describes the different instruments used for measurements, how they were compared, and demonstrates the talc's potential in this application. Additionally, it describes the different instruments used for measurements, how they were compared, and shows the talc's sensitivity to radiation. Dose responses in the 0-1500 μGy range were determined for the most sensitive systems, and the chapter explores TL analysis of glow curve characteristics performed on the talc samples and details experiments on how simulated daylight affects the dosimetry properties of talc. Chapter 4 interprets the results, discusses their implications, and draws conclusions about the effectiveness of common talc for dosimetry applications. Chapter 5 focuses on the use of passive dosimeter arrays for spatial definition of radiation fields, mapping natural background radiation fields, detecting and accurately mapping the spatial distribution of dose rates from a locally controlled radiation source and mapping the spatial distribution of a complex radiation field emitted by a 5 MV tandem accelerator. For this work, I have used salt, following characterisation in Chapter 3. Chapter 5 will present the first extensive set of field trials that

practically demonstrate the effectiveness of salt dosimeters in multiple applications. These trials showcase the utility of salt dosimeters in mapping radiation fields and measuring individual doses across diverse scenarios and within three different radiation environments, demonstrating the method's potential in real-world scenarios. The overall objective of the thesis is to offer complementary methods to current instrumental measurements by examining the potential of common materials as retrospective near real time dosimeters. This method will provide dose assessments in situations where real-time monitoring is not feasible. It will improve the spatial and temporal resolution of dose mapping. The approach aims to create a radiation dosimetry method that is both cost-effective and broadly accessible. As a result, it will promote more well-informed decision-making in the areas of medical triage, evacuation, and long-term health observation. The work conducted is summarised in the conclusion of this thesis (Chapter 6), which also highlights possibilities for future research.

Chapter 2

Background of radiological or nuclear accidents, emergency preparedness and response

2.1. Introduction

In the previous chapter, the main structure objectives and research questions of the thesis were outlined, providing a pathway for the research. This chapter builds on that foundation by summarizing the key topic areas related to the biological impact of ionizing radiation on human health, exposure pathways, categories of nuclear or radiological risk, accidents and incidents, and radiological or nuclear emergency response measurement techniques. It aims to establish the broader context of emergency response, highlighting its significance and complexities. Additionally, this chapter identifies critical knowledge gaps in the field. These gaps serve as the foundation for the investigations addressed throughout the rest of this thesis in chapters 3,4, and 5, guiding the exploration of solutions to strengthen preparedness and response capabilities in emergency management through new dosimetry methods.

The increasing use of nuclear technology and radioactive materials has brought significant advancements in energy production, medicine, and industry. However, this growth also heightens the risk of large-scale radiological or nuclear accidents, underscoring the critical need for robust safety measures, emergency preparedness, and effective response protocols. Nuclear and radiological accidents can arise from various sources, including industrial applications using beta radiation and gamma radiation for radiography of material structures, cancer treatments with gamma rays, smoke detectors employing alpha sources, and medical imaging procedures involving X-rays. Public perception and policy have been significantly influenced by the numerous significant incidents that have occurred since the inception of nuclear power. The consequences of these incidents on individuals, societies and the environment are multifaceted and long-lasting. The accumulation of evidence about radiation's health impacts has served as the foundation for national and international radiation protection regulations. Notable incidents include the Chernobyl disaster in 1986, which resulted in widespread radioactive contamination and health impacts. The Fukushima Daiichi accident in 2011 further highlighted vulnerabilities in nuclear safety systems during natural disasters. These events

demonstrate the severe consequences that can arise from failures in nuclear technology management. The history of nuclear accidents emphasizes the importance of implementing stringent safety protocols and maintaining a strong safety culture within the nuclear industry. While these radiation and nuclear technologies offer substantial benefits, the potential for major radiation or nuclear accidents remains a serious concern that necessitates ongoing vigilance and improvement in safety practices (Rojavin et al., 2011; Alghamdi et al., 2022).

The International Atomic Energy Agency (IAEA) characterizes nuclear and radiological incidents as exceptional circumstances requiring prompt intervention. These situations necessitate immediate action to reduce potential harm to public health, safety, well-being, property, and environmental integrity. This definition underscores the critical nature of these incidents and the importance of swift, coordinated efforts to address them effectively (IAEA, 2012). The primary goal during these emergencies is to confirm the availability of well-prepared response plans at the site level, along with the local, regional, national and international levels, as applicable (IAEA, 2006). To mitigate the occurrence of radiation or nuclear hazards, the IAEA has established specific criteria as regards maintaining nuclear security and nuclear safety. Nuclear security and safety are distinct but interconnected areas within radiation protection. Security measures are designed to prevent illegal access, theft, or malicious acts involving radioactive materials and facilities. In contrast, safety protocols focus on maintaining optimal operational conditions and reducing accident risks to protect workers, the public, and the environment from radiation exposure. Recently, experts and global organizations have been assessing the risks associated with various radiation incidents and developing comprehensive response strategies for scenarios in which both security and safety systems are compromised. These initiatives aim not only to manage accidents effectively when they occur but also to reduce the incidence of such emergencies in the first place, mitigate their impacts if they occur, and minimize harm to emergency responders, civilians, and ecosystems during a radiological or nuclear emergency. This chapter seeks to summarise the current state of knowledge relevant to radiation and nuclear accidents, along with the cumulative knowledge related to it. This is subsequently followed by a discussion as regards the components of emergency preparedness, exposure pathways, planning and response to nuclear accidents. It will also underline a number of gaps in the existing knowledge.

2.2 The biological impact of ionizing radiation on human health

Ionizing radiation can affect the human body through two primary mechanisms: internal contamination and external exposure. Internal contamination happens when radioactive materials are ingested, inhaled, or absorbed into the body, while external exposure involves radiation from sources outside the body interacting with tissues. In many cases, individuals may experience both types simultaneously, such as when surrounded by and inhaling radioactive particles. Internal contamination generally poses a greater risk than external exposure for equivalent doses. This increased hazard arises because radioactive substances within the body deliver continuous radiation exposure over time, unimpeded by protective barriers like skin, and can accumulate in specific organs, leading to higher localized doses. The biological impact of ionizing radiation on living systems is primarily due to its ability to damage cellular structures, particularly DNA. This damage can occur through direct or indirect pathways. Direct effects involve radiation directly interacting with DNA molecules, while indirect impacts emerge when water molecules are ionised (Reisz et al. 2014), creating unstable particles (free radicals) (such as OH hydroxyl or H^+ hydrogen radicals) that later damage parts of the cell.

When ionizing radiation breaks DNA strands, cells attempt to repair the damage by using the intact strand as a template. However, severe damage may lead to mutations or cell death if the repair process is unsuccessful. Widespread cellular damage can result in various health issues for living organisms. The consequences of radiation exposure are typically categorized into two types of effects: 1. Deterministic effects: These result from extensive cell death and typically have a threshold dose below which they do not occur. 2. Stochastic effects: These are probabilistic in nature and are associated with cellular mutations, potentially leading to long-term health risks.

2.2.1 Deterministic effects

Deterministic effects are closely tied to the amount of radiation absorbed, with the intensity of the impact growing as the exposure increases. These outcomes hinge on damage to tissues. Factors like cellular composition, proliferation rate, and reaction to radiation contribute to differences between tissue types. Examples of such predictable outcomes include skin burns, cataracts (although still debated), haematological deficiencies, reduced fertility, or brain harm during pregnancy (ICRP, 2012). Deterministic effects are characterised by the presence of a threshold dose, which is typically around 0.1 Gy or higher, below which the effect does not

manifest. This threshold is subject to change based on the specific tissue and effect in question (ICRP, 2007). For example, radiation-induced malformations are generally regarded as having a dose threshold of approximately 100 mGy. Nevertheless, recent research has questioned certain long-standing assumptions regarding the thresholds for specific effects. For instance, the threshold for lens opacities was traditionally believed to be greater than 1 Gy (ICRP 2007). The strength of the impact intensifies when the exposure exceeds the threshold. Acute radiation illness (ARS) may occur if the whole body is rapidly exposed to an elevated level of radiation. There are three distinct periods in the progression of ARS, each of which is distinguished by its own set of symptoms and durations. Symptoms such as nausea, vomiting, fatigue, and diarrhoea are indicative of the initial prodromal phase, which typically lasts from hours to days. The radiation dose received is the determinant of the severity and onset of these symptoms. Sometimes, patients may experience radiological burning and reduced consciousness. Subsequent to the prodromal phase, patients undergo the latent phase, which may last for days or weeks. Throughout this time, individuals frequently experience a temporary recovery in their condition, despite the underlying damage, and feel relatively well. Manifest illness is the concluding and most critically important phase. This phase may entail severe complications, such as haemorrhage, infections, and gastrointestinal disturbances when radiation doses exceed 6-8 Gy. Moreover, patients may experience haematopoietic effects as a result of bone marrow injury, as well as cerebral and neurovascular complications as a result of central nervous system damage. These complications can potentially lead to fatality (Walker et al. 1989). It is essential to estimate the dose accurately to implement effective medical interventions, with timely whole-body dose assessment being particularly critical for expeditious treatment, especially in mass casualty situations. Although the most significant risk is generally associated with whole-body exposure, partial-body irradiation can also lead to substantial health risks, depending on the affected region.

2.2.2 Stochastic effects

In contrast to the deterministic effects, radiation risks are predominantly stochastic at lower doses, particularly somatic effects (cancer) and genetic effects. These effects are frequently linked to repeated low-dose exposures and can occur across a wide range of doses, with the probability increasing with dose. In contrast to deterministic effects, stochastic effects do not have a threshold dose below which they cannot occur. The risk of cancer increases proportionally as the radiation dose exceeds 100 mSv (ICRP, 2007). The cumulative impact of multiple minor exposures is considered equivalent to a single larger exposure of the same total

dose, which is a key characteristic of stochastic effects. This concept is essential for comprehending the long-term radiation hazards in medical and occupational environments. The hereditary effects of radiation, which are germline mutations that are induced by radiation and are transmitted to the offspring, are not taken into account in this study. This is due to the fact that they have not been detected in human populations receiving high doses, and any potential harm would be overshadowed by the far higher spontaneous mutation rate (ICRP, 2007). Understanding stochastic effects is crucial for the development of effective radiation protection measures, particularly in situations that involve low-dose, long-term exposures.

2.3 Exposure pathways

Exposure pathways consist of five fundamental components, the source of contamination, the medium and mechanism responsible for transporting the contamination in the environment, the location where exposure occurs, the specific exposure path and the population or organisms subjected to the exposure, for instance rabbits in contaminated soil or individuals consuming contaminated fish. When assessing radiation exposure, all relevant pathways must be examined, including those unrelated to atmospheric plumes, such as groundwater contamination or direct contact with radioactive materials. These pathways include: (i) external exposure to radiation present from the plume, (ii) external exposure to radioactive materials placed on surfaces, including skin and clothing, (iii) internal exposure resulting from inhaling radionuclides during and after the passage of the plume, including those originating from resuspended soil particles, and (iv) internal exposure through the consumption of contaminated food (Müller and Bleher, 1997). Deciding the radiation exposure pathways and assessing doses for the affected population is one of the most important basic requirements that must be met before the emergency ends. Characterisation of exposure status should be conducted to ascertain individuals who require long-term medical attention, adjust or remove some of the necessary preventive measures to protect first responders and emergency workers and plan for short and long-term recovery (IAEA, 2018). Following the Chernobyl disaster, the primary route of ^{131}I ingestion was via cow's milk, whereas Fukushima's prompt evacuations shifted the dominant pathway to inhalation during plume passage (Uyba et al., 2018).

2.4 Categories of nuclear or radiological risk, accidents and incidents

2.4.1 Nuclear Power Station Accidents

Nuclear science and technology have made substantial advancements in recent decades, providing countless benefits for society. Nevertheless, in addition to these advantages, there have been damaging consequences resulting from the inappropriate use of nuclear energy and radiation technology, resulting in catastrophic events and breaches of global accords. Global concerns about nuclear security are a key focus of international discussions. Although the number of nuclear warheads has decreased in recent decades, the widespread use of nuclear technologies and limited advancements in disarmament efforts continue to pose significant risks. The threats of nuclear terrorism and regional conflicts involving atomic weapons remain pressing issues. These situations endanger environmental integrity, public health, and global economic stability. The international community is challenged to balance the benefits of nuclear technology with its inherent dangers, highlighting the necessity for strong security measures and a renewed commitment to disarmament goals. While “full-scale” nuclear conflict may be doubtful, the solitary use of nuclear-based weapons (NBWs) by terrorist organisations remains a persistent threat (Knopf, 2012; Wei and Dewji, 2024). A nuclear detonation undertaken by terrorists epitomises the most extreme situation. In conjunction with the massive destruction of the physical infrastructure, a sizeable number of fatalities could be predicted, given that radiation exposures greater than 3.5 Gy are deadly within 30 days without prompt and effective medical intervention (Mettler and Voelz, 2002).

Other potential scenarios pertaining to the use of NBW include the distribution of radioactive materials, with or without explosives, as well as direct assaults against nuclear reactors.

Numerous factors can contribute to nuclear accidents, including design flaws, human error or equipment failure. Amongst the most prevailing causes of reactor damage are coolant loss or reduced coolant flow, in conjunction with unexpected fluctuations in activity levels. While the nuclear industry adheres to stringent safety protocols, the potential for unforeseen reactor malfunctions and subsequent environmental contamination remains a significant concern. Moreover, the storage and transportation of spent nuclear fuel present additional safety challenges. Although major incidents in civilian nuclear power have been infrequent and often contained, the possibility of a catastrophic nuclear event persists. This underscores the critical importance of comprehensive contingency planning to address potential large-scale civilian

nuclear accidents, whether caused by human error or factors beyond our control (Rojavin et al., 2011).

The U.S. Nuclear Regulatory Commission (US.NRC, 1975) conducted a comprehensive assessment of potential reactor incident risks, categorizing accident scenarios into four distinct groups: **Release A:** In the most dangerous nuclear accidents, containment fails when the core becomes entirely molten, resulting in extensive environmental contamination with highly radioactive materials. **Release B:** Delayed containment failure hours after core melting, leading to significant but reduced radionuclide dispersal due to decay and partial retention through aerosol settling. **Release C:** Subterranean containment failure without major above-ground leakage. **Release D:** Intact containment with minimal radioactivity release within design parameters. The most severe scenario involves core meltdown and subsequent radioactive material dispersion, posing the greatest threat in nuclear reactor incidents. This event can lead to widespread environmental contamination and potential health hazards, making it the most critical concern for nuclear safety.

The International Atomic Energy Agency (IAEA) introduced a standardized classification system for nuclear incidents in 1989 as a universal rating scale that is employed by nuclear licensees to classify incidents (Webb et al., 2006). The International Nuclear Event Scale (INES) was developed as a rapid alert system and global tool to report nuclear and radiological events to the public in a coherent manner. As illustrated in Figure 2.1, the lower three levels (1-3) are designated as "incidents," indicating less severe occurrences. The upper four levels (4-7) are classified as "accidents," representing more serious and potentially dangerous situations. The INES rankings cover an extensive range of activities comprising events at facilities and activities involving radiation sources, industrial applications, for instance industrial radiography, medical radiation applications in healthcare, operations at nuclear power facilities, and events related to the transportation of radioactive material. The scale also addresses situations where radiation sources are missing or stolen, as well as cases of radioactive materials unexpectedly found in recycled metal. This graduated scale allows for a nuanced assessment of nuclear-related events, facilitating clear communication about their potential impact and required response.

Three areas of impact are considered to evaluate nuclear and radiological accidents and incidents (IAEA, 2008):

- Human health and ecological consequences: Individuals and ecosystems nearest to the event face the highest risk of significant radiation exposure.
- Radiological containment measures: These assess the effectiveness of safety systems designed to prevent abnormal radiation levels and contain radioactive material releases within a facility, minimizing exposure risks.
- Safety in depth: This evaluates failures in safety measures designed to prevent accidents, even when there is no direct impact on individuals or the environment.

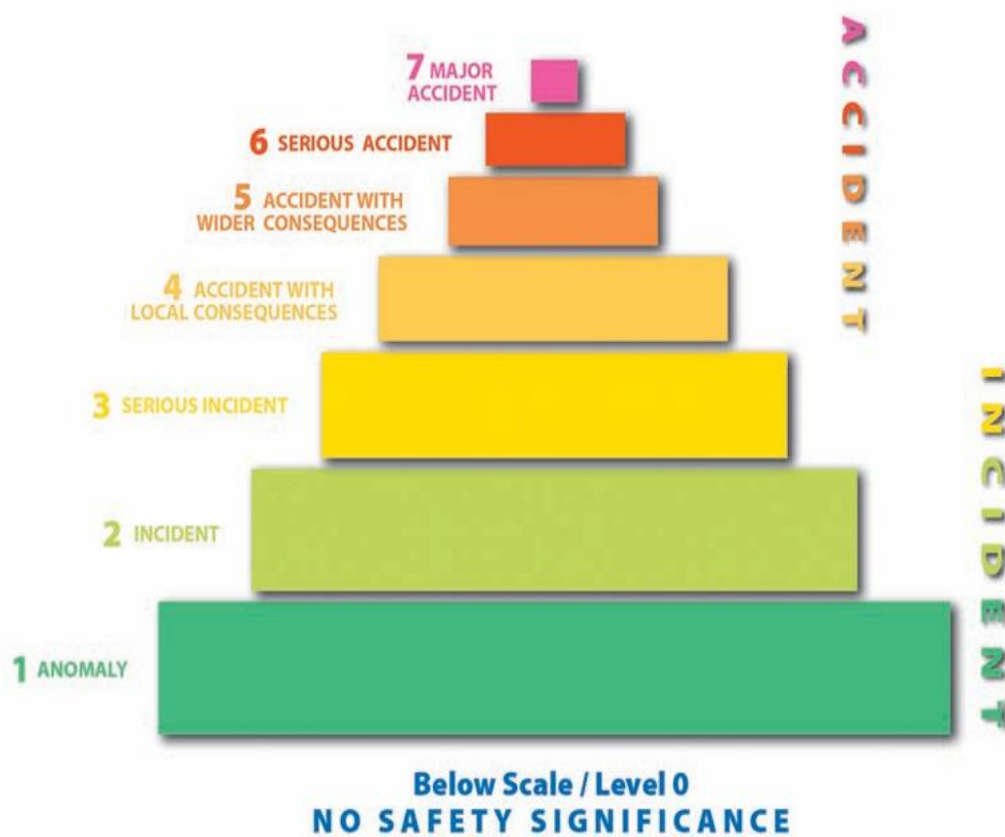


Fig. 2.1. The International Atomic Energy Agency (IAEA) created a standardized classification system for nuclear and radiological incidents, known as the International Nuclear and Radiological Event Scale (INES). Republished from the IAEA (2008)

The ranking of events based on their impact on human health and the environment takes into account the real radiological effects on workers, the public and the environment. The evaluation of events relies on the radiation exposure levels for both employees and the general populace, as well as the quantification of any radioactive materials. Table 2.1 presents a summary of the effects at each level on both the population and the environment.

Table 2.1. The International Nuclear Event Scale (INES) provides a structured framework for evaluating the impact of nuclear and radiological events. Created by the International Atomic Energy Agency (IAEA; 2008). Developed by the International Atomic Energy Agency (IAEA; 2008)

Intensity	Level	Impact on environment and people	Area of impact
			On-site Impact
Major accident	7	A major radioactive release could cause enormous health and environmental damage, requiring evacuations, monitoring, and extensive cleanup and recovery resources.	
Serious accident	6	Radioactive discharge may need the comprehensive use of established measures.	
Accident with off-site risk	5	Restricted radioactive emissions can require protection and might result in fatalities due to radiation exposure.	Significant reactor damage or fire may result in the emission of radioactive materials, posing significant risks of public radiation exposure. This can result from a major incident or fire
Accident without significant off-site risk	4	Minor radioactive release may limit food use. Nevertheless, such an incident could still lead to at least one radiation-related fatality.	Severe nuclear incidents may melt fuel, releasing hazardous radiation within the facility and risking public exposure.
Serious incident	3	Workers may face high radiation doses that exceed the legally established yearly exposure limit by more than ten times, causing tissue damage and acute symptoms, although they may not be fatal.	Some nuclear incidents may expose workers to radiation levels above 1 Sv/h and result in unexpected contamination, posing health risks and low but concerning public exposure potential Near accident—no protective layers remaining
Incident	2	In some radioactive events, public radiation exposure can exceed 10 millisieverts, significantly exceeding typical levels and prompting concerns.	In some nuclear facility incidents, radiation levels can exceed 50 millisieverts per hour, presenting significant health hazards. Unanticipated areas may potentially become significantly contaminated, leading to extensive exposure or contamination, contrary to design projections.
Anomaly	1		Exceeded public radiation limits, minor safety system deficiencies with safeguards operational, and misappropriated or lost low-level radioactive substances
Below scale	0	They fall below the threshold for formal classification on established incident scales	

Chernobyl (1986) and Fukushima (2011) were ranked seventh on the scale employed by the International Atomic Energy Agency. These accidents produced the dispersal of radioactive materials as a consequence of the meltdown of the reactor cores and damage to containment. On April 28, 1986, the Chernobyl accident happened when the No. 4 reactor exploded, destroying the building and exposing the nuclear core. The graphite in the core burned for nine

days, emitting over 10^{18} Bq of ^{131}I and more than 10^{17} Bq of ^{137}Cs , resulting in extensive radioactive pollution. This continues to be one of the most catastrophic nuclear incidents in history, which caused widespread contamination to many areas; both civilians and emergency personnel experienced significant radiation exposure. Measurements taken in the affected area around 10 days later revealed alarming ground-level radiation levels up to $200\text{ }\mu\text{Gy/h}$ at Pripjat. These intensities posed serious health risks to those present during the initial response, underscoring the severe and immediate consequences of the disaster (Kortov and Ustyantsev, 2013). On March 11, earthquakes struck the Japanese cities of the Tohoku region, including Fukushima Prefecture. The Fukushima Daiichi nuclear power station is on the coast, about 60km from Fukushima City. The Fukushima Daiichi nuclear disaster occurred when a loss of power to the coolant pumps caused four reactors to overheat. Between March 12th and 15th, 2011, hydrogen generated by zirconium-steam reactions accumulated in the containment buildings, leading to three explosions. The incident released over 10^{17} Bq of ^{131}I and more than 10^{16} Bq of ^{137}Cs , resulting in significant radioactive contamination which triggered the evacuation of sizable parts of the region, estimated to be 83,000 individuals. Likewise, considerable and massive releases of radioactive materials into the environment (Kortov and Ustyantsev, 2013). The Fukushima nuclear disaster was a devastating event, compounded by a powerful earthquake and the subsequent tsunami. The Fukushima mental health and lifestyle study stresses that this cataclysmic event triggered extensive psychological distress amongst the inhabitants of the evacuation zone. Besides mental health issues, there are enduring lifestyle-related issues; the displacement of residents after the nuclear incident raised several health concerns. Studies have indicated changes in population health metrics, including higher rates of obesity, cardiovascular, and metabolic disorders among evacuees (Hasegawa et al., 2016).

Nuclear incidents develop quickly, increasing in both impact and complexity. As the situation progresses, the number of victims rises, infrastructure deteriorates, and radioactive material spreads, which requires adaptive management strategies and changing requirements with respect to management and response (Gougelet et al., 2010). Early symptoms, such as nausea and changes in blood count, may suggest radiation exposure but are not conclusive. Accurate dose assessment is essential for an effective response and the safety of responders (Alghamdi et al., 2022). Emergency dosimetry primarily aims to evaluate severe radiation effects and enable rapid classification of victims. Significant external radiation exposure often signifies major incidents, generally classified as Level 5 or higher on incident scales. Although such

high-level events are uncommon, they pose the gravest consequences and necessitate thorough pre-planned safety protocols. In these critical scenarios (Levels 6 and 7), both immediate and retrospective radiation dose assessment techniques are essential for managing the response and comprehending the impact of the incident (Bossin et al., 2019; Bailiff et al., 2016).

2.4.2. Transport accidents and loss of radiological material

Accidents that occur during transportation of radioactive materials is another form of unintentional radioactive incident that has the potential to endanger a larger population. The International Atomic Energy Agency has classified the movement of nuclear and radioactive materials, along with other operations involving mobile hazardous sources, as potential causes of nuclear or radiological emergencies necessitating preventive actions. In 2018, the International Atomic Energy Agency published the Regulations for the Safe Transport of Radioactive Materials; meeting these requirements leads to a high level of security for the transportation of radioactive materials (IAEA, 2018). Therefore, advance planning and preparation are necessary to provide an effective response (IAEA, 2008; IAEA, 2002a,b). The inappropriate transportation of radioactive material can expose neighbouring passengers to contamination, especially when the sources lack adequate shielding. Additionally, there is a danger of complete loss of the radioactive source, possibly causing widespread contamination. Over the past decade, the IAEA has disclosed between 100 and 140 incidents involving unsecured radioactive sources and unauthorized transport or unlawful disposal (IAEA, 2017). Among these, a small number directly impacted the population due to mishandling or loss of radioactive substances during transportation. The International Atomic Energy Agency has categorised the main types of road accidents that should be considered for emergency planning. These categories include: (a) Collision, (b) Fire or explosion, (c) Immersion or flooding, and (d) Loss of load or spillage. While maritime accidents can be classified as follows: (a) Collision, which refers to the impact or a crash between two objects or entities, (b) Grounding, which occurs when a vessel or aircraft becomes immobilised or stuck after making contact with the ground or a solid surface (c) Combustion or detonation, (e) Structural integrity failure, (f) Inability to maintain control, (g) Damage to the vessel or equipment, (h) Crashing or listing, (i) Flooding or foundering, which occurs when a ship takes in water and sinks, (j) A missing ship, which signifies a ship that cannot be located or is lost, (k) Cargo damage caused by excessive rolling motion, and (l) Cargo damage occurring during loading or unloading. Aviation accidents can be classified into the following categories: (a) Crashes that occur upon impact with the ground, (b) Collisions or impacts that occur while the aircraft is in flight, (c)

Fires that occur on the ground during various stages of operation, such as take-off or landing, (d) Fires that arise while the aircraft is in flight, (e) Explosions that occur while the aircraft is in flight, (f) Incidents that comprise the aircraft being submerged in water, and (g) Events that occur during the loading and unloading of aircraft at airports (IAEA, 2022). In 2002, a radiological incident occurred in Bolivia involving the improper transport of a ^{192}Ir source. The radioactive material was accidentally transported on a public bus departing from Cochabamba, exposing passengers to radiation during the long journey. Investigations revealed that safety protocols were not followed, especially the critical step of ensuring the secure placement of the source. This oversight potentially resulted in significant radiation exposure for some individuals, and during the eight-hour trip, the source exposed passengers to radiation, resulting in a maximum dose of 2.77 Gy (IAEA, 2004a). This event highlights the essential need for strict adherence to safety procedures when handling radioactive materials.

An orphan source is an unregulated radioactive substance that presents a considerable radiation hazard. This term refers to radioactive materials that have forfeited regulatory supervision owing to factors such as abandonment, misplacement, theft, or unauthorised transportation. Orphan sources represent significant safety and security risks, as they may expose unwitting humans to hazardous radiation or be used for nefarious reasons (IAEA, 2004b). Orphan sources are unlikely to produce large-scale incidents, nonetheless they remain capable of injuring the general public (Ortiz et al., 1999).

In 1987, Goiania, Brazil was the location of a radiological disaster caused by the release of radioactive material. A piece of abandoned radiotherapy apparatus containing a ^{137}Cs source that was exceedingly radioactive was discovered in a scrapyard. The proprietor of the scrapyard and a few others demolished the machine without being aware of the dangers involved. Consequently, the individuals and others in the vicinity were unwittingly exposed to radioactive material. Four people died as a direct consequence of the incident, whilst an additional 249 individuals were determined to be contaminated with radioactive material (IAEA, 1988; IAEA, 1998a). This incident underlines the importance of correctly disposing of and handling radioactive materials to prevent the unintentional exposure of the general public. In late 1994, an unauthorized entry into an Estonian nuclear waste site led to a significant radiation event. Three persons extracted a container containing a ^{137}Cs source, with one individual transporting it to their residence. This activity resulted in inadvertent radiation exposure for household members. Although officials swiftly identified the source, the repercussions were severe: one individual perished, many others had injuries, and adjacent dwellings were evacuated owing to

heightened radiation levels. This event underscores the critical importance of securing radioactive materials and the potential dangers of unauthorized access to nuclear facilities (IAEA, 1998b). In early 2000, a radiological incident occurred in Samut Prakan Province, Thailand, when scrap collectors unknowingly obtained an unsecured, high-activity ^{60}Co source. The dismantling of its container at a scrapyard resulted in significant radiation exposure for the individuals involved and those nearby. In the weeks that followed, affected individuals exhibited symptoms consistent with acute radiation syndrome, prompting medical intervention. Physicians identified the signs of radiation injury in multiple patients, raising concerns about an uncontrolled radioactive source in the community. Subsequent analysis revealed the source's considerable activity, highlighting the seriousness of the exposure event and the critical need for proper radiological safety measures. The activity of the found source was assessed at 15.7 TBq (425 Ci) of ^{60}Co (IAEA, 2002c).

2.4.3 Radiological Terrorism Incidents

Radiological attacks can have a wide range of impacts. Certain occurrences may have restricted, localised impacts, but others might lead to widespread environmental contamination over extensive areas, frequently covering a few miles or more. The magnitude and extent of these events are contingent upon parameters like the kind and amount of radioactive material employed, the dispersal mechanism, and environmental circumstances (Harper et al., 2007). Radiological terrorism incidents may expose a small number of individuals, while others could potentially expose hundreds or even thousands of people to dangerous levels of radioactive contamination. Regardless of scale, these events pose serious health risks to those affected, as even little instances can lead to hazardous radiation exposure. Hence, radiological attacks can lead to significant economic consequences, often resulting in property contamination and the need for large-scale evacuations (Ferguson, 2009). This highlights the urgent necessity for emergency responders (e.g., Civil Defence, health services, police, emergency management officials and incident commanders) and decision-makers to be adequately prepared for these scenarios. Broga (2011) described five varieties of radiological or nuclear terrorism incidents, including devices aimed at dispersing radioactive materials (RDDs), exposing individuals to radiation (REDs), contaminating vital resources such as food, water, or other necessities with radioactive substances, the release of radioactive materials from established radiological or nuclear facilities or during transportation, and the use of improvised nuclear devices (INDs). Recognizing these different types of threats is essential for creating comprehensive response strategies and minimizing potential impacts on public health and the economy.

Radiological Dispersal Devices (RDDs)

Radiological dispersal devices (RDDs) are regarded as a potential terrorist tool on account of their ability to diffuse radiological material when detonated (Flynn and Goans 2006; Harper et al., 2007) and generate significant damage, fear and economic harm, despite the fact that the actual health risks are relatively low. This type of weapon is regularly referred to as a "dirty bomb". According to Barnett et al. (2006), the building of an RDD is straightforward and the materials that are necessary to produce one are readily available. Weather conditions, the physical and chemical radionuclide dispersal method and the design of the device are elements that have an impact on the plume, and hence, the area affected by the spread of radioactive contaminants (Harper et al., 2007). In the wake of the outdoor detonation of an RDD, following a radiological release, the first airborne contamination will likely dissipate from the immediate area within 15 minutes. The rapid dissipation mitigates the danger of acute radiation exposure by inhalation for both emergency responders and adjacent civilians. Nonetheless, it is crucial to acknowledge that although the immediate inhalation risk may diminish, additional dangers and long-term consequences may still endure in the impacted region. (Harper et al., 2007). In contrast, devices with ineffective dispersal mechanisms can lead to concentrated areas of intense radiation with high external exposure rates or generate radioactively contaminated projectiles as ballistic fragments (Harper et al., 2007). The frequent use of nuclear materials and the regular use of the radioactive components in medical applications (Barnett et al., 2006) both assist with an increase in the risks of illegal and potentially RDD attack. Worldwide, there are countless sources of radioactive material that are unsafe or unaccounted for. These materials could be acquired by rogue nations and/or terrorist groups to be utilised in dirty bombs. The number of people directly harmed or killed may range from none to potentially hundreds, depending on several key factors. These factors include the explosive power utilized, the design and construction of the device, its placement, and the population density in the surrounding area at the time of the incident. The interaction of these elements significantly affects the severity of the immediate consequences. (NCRP, 2001; NCRP, 2011). Their use would also result in an expensive clean-up of decontamination. Therefore, these incidents highlight the crucial need for comprehensive strategies to manage radioactive substances. Essential components of these strategies encompass the augmentation of nuclear safety regulations, the fortification of security measures, and the establishment of comprehensive emergency response frameworks. Proficient readiness and synchronised reactions to possible radiological incidents are crucial for reducing hazards and alleviating repercussions. This comprehensive strategy is

essential for safeguarding human health and maintaining environmental integrity against any radioactive hazards. Detecting the production of radiological weapons prior to the detonation of a RDD is undoubtedly the most desirable outcome. This dictates a strong level of collaboration among law enforcement, intelligence agencies, industrial and medical facilities that handle or store radionuclides, in collaboration with other regulatory authorities tasked with supervising the lawful use and delivery of these goods.

Radiological exposure Device (REDs)

A radiological exposure device (RED) uses concealed radioactive sources to irradiate unsuspecting individuals in public spaces, rather than dispersing radioactive contamination. These devices can be hidden in high-traffic areas such as public transportation or crowded venues (NCRP, 2001). The health risks associated with REDs depend on many factors, particularly the type of radioactive material used, the duration of exposure, and which body parts are irradiated. Prolonged exposure to high radiation levels can lead to acute radiation syndrome (ARS), with symptoms potentially appearing between hours to weeks post-exposure. Generally, exposure to radiation levels above 1.5-2 Gy is considered a risk for ARS. The health effects of such exposure can vary widely, ranging from minor issues to severe conditions, including cancer or even death. It is important to note that individuals can respond differently to radiation exposure; some may experience no noticeable health effects despite significant exposure (NCRP, 2011).

Deliberate Contamination of Food, Water or Consumables

A potential radiological threat involves deliberately introducing radioactive substances into essential resources. This could include contaminating food supplies, water sources, or other commonly consumed products with hazardous materials. Such an attack aims to expose unsuspecting populations to harmful radiation through ingestion or contact with contaminated items, which could lead to widespread health concerns and public panic. Rapid detection and monitoring of ionising radiation are imperative to determine the scale and severity of a nuclear incident (NCRP, 2011; NCPR, 2001). This requires the employment of both fixed and mobile radiation detection instruments to measure radiation levels and identify the types and amounts of radioactive substances. The IAEA (2015a) claims that real-time monitoring and data sharing promote effective decision-making and guide response efforts.

Dispersion of Radioactive Material from Radiological or Nuclear Facilities or in-Transit Materials.

Nuclear and radiological facilities often possess documented emergency measures for unintentional emissions. In the event of an intentional assault or sabotage at these locations, the response would likely adhere to the same techniques employed for radiological dispersion situations from a RDD (NCRP, 2011). This method employs established safety standards to address both accidental and deliberate radioactive incidents, guaranteeing a synchronised and efficient emergency response irrespective of the origin.

Improvised Nuclear Device

An improvised nuclear device (IND) refers to any nuclear explosive that is created or acquired through illegal means. This includes stolen weapons, unlawfully purchased devices, or even crude nuclear explosives made by non-state actors. Regardless of how they are obtained or constructed, INDs would have effects comparable to those of conventional nuclear weapons if detonated. The threat posed by such devices highlights the urgent need for robust nuclear security and non-proliferation efforts to avoid unauthorized access to nuclear materials and technology. Nowadays, the most probable scenario for the exploitation of nuclear weapons by terrorists involves a single, likely low-yield fission device (NCRP, 2001; NCRP, 2005). It results in catastrophic loss of life, has a considerable impact on public health and safety, destroys infrastructure and contaminates an exceptionally large area. A nuclear terrorism incident would have a catastrophic impact on the immediate area, and emergency response support capabilities would possibly be destroyed or seriously endangered. In contrast to radiological dispersion incidents, which usually allow local emergency infrastructure to function, a nuclear terrorism attack would probably need external response resources. The immediate blast zone would likely incapacitate or obliterate local emergency resources, necessitating external aid for the devastated area. The distinct variation in reaction dynamics highlights the specific problems posed by nuclear terrorism scenarios in contrast to other radiological threats (NCRP, 2001).

2.5 Radiological or Nuclear Emergency response

The consequences of a radiological or nuclear disaster might differ significantly based on the characteristics of the event and the radioactive substances implicated. The extent of environmental pollution and its health impacts on impacted people can vary from negligible to profound. This variation is dependent on criteria including the type and amount of radioactive material released, the methods of dispersal, and local conditions. Conversely, many

components of the response and the protection of individuals are similar irrespective of the scale of the incident and the types of radioactive materials concerned. To effectively handle and react to emergencies, it is crucial to have a comprehensive grasp of the risks and potential ramifications associated with radiation emergencies (WHO, 2017). Emergency preparedness refers to a series of decisions and actions undertaken before a nuclear emergency, intended to address any situation that may impact the population and environment, with the objective of minimising offsite repercussions to the greatest extent possible (de la Rosa Blul, 2021). The primary aim during a radiological or nuclear emergency is to guarantee safety and to protect those who are affected. From a radiation protection standpoint, this entails taking all necessary measures to prevent any harmful tissue reactions resulting from radiation exposure and to minimise the occurrence of potential long-term health effects in the affected population (ICRP, 2007). Additionally, there are other health effects associated with concerns pertaining to their own health and that of their relatives, which can have additional health effects. These psychological impacts may necessitate further investigation and consideration in comparison to the tangible health effects resulting from radiation exposure.

Unfortunately, previous nuclear disasters have underlined the challenge connected with striking a careful balance between the potential harms and benefits. When planning for and responding to emergencies, it is crucial to consider both the radiological and non-radiological health consequences. Chernobyl and Fukushima are examples of nuclear catastrophes that have far-reaching repercussions that surpass the immediate radiological effects. Communities and individuals are frequently profoundly affected by the long-term non-radiological effects, which are frequently more significant and persistent. In the event of a radiation calamity, authorities typically implement restricted zones, which necessitate extensive evacuations. This displacement results in the displacement of residents into transitory shelters or alternative accommodations for extended periods, which disrupts their lives and routines. A variety of health challenges may result from the conditions of these transient living arrangements. Infectious disease epidemics may result from crowded spaces and shared facilities. Mental health issues, such as anxiety and depression, can be precipitated by the stress of displacement, ambiguity about the future, and loss of community connections (e.g., Hasegawa et al., 2016; ICRP, 2009). Furthermore, cardiovascular issues may be exacerbated or precipitated by abrupt lifestyle modifications and unfamiliar environments. Many evacuees find it difficult to adjust to their new circumstances. Behavioural issues, particularly among vulnerable groups such as children and the elderly, can be the result of the precipitous shift in daily routines and the trauma

of displacement. These obstacles manifest in a variety of ways, including increased aggression, substance misuse, or social withdrawal.

The Three Mile Island incident underscored inadequate emergency planning and communication challenges. Information pandemonium, telephone network congestion, and inadequate hospital evacuation protocols were identified as critical concerns (IAEA, 2012). The Chernobyl catastrophe had significant long-term effects on economic stability, social structures, and mental health. Although acute radiation syndrome resulted in the loss of life and an increase in the incidence of thyroid cancer among children who were exposed to radioactive iodine, the psychological and socioeconomic consequences were equally significant (IAEA, 2012). The Fukushima accident, compounded by a severe earthquake and tsunami, presented unique challenges. While the direct health impacts of radiation exposure were mitigated to some extent for emergency personnel and residents through protective measures, significant health challenges arose, including the collapse of the radioactive emergency medical system, increased death rates among displaced older adults, public health concerns for Fukushima residents, and fatalities during evacuation. The Fukushima mental health and lifestyle survey revealed that the evacuation zones' residents experienced severe psychological distress as a result of the Fukushima accident. In addition to psychological and behavioural health difficulties, lifestyle-related concerns encompass a heightened incidence of hypertension, diabetes mellitus, and dyslipidaemia, along with alterations in health-related behaviours among evacuees. Both the Fukushima and Three Mile Island disasters exhibited commonalities, including the unanticipated enlargement of evacuation zones and the lack of evacuation strategies by hospitals and nursing facilities (Hasegawa et al., 2016). Furthermore, precautions must be taken to guarantee safety and evaluate whether the benefits justify the risks involved. Regrettably, recent disasters have demonstrated the daunting challenge associated with achieving this delicate balance (IAEA, 2015). In the event of a nuclear or radiological emergency, the coordination and implementation of protective measures require the cooperation of various authorities and expert organisations. The specific composition of decision-making groups responsible for formulating and executing countermeasures varies based on the characteristics of the emergency and the phase of the situation. Nuclear emergencies can encompass a vast array of scenarios with distinct consequences for both the population and the environment (de la Rosa Blul, 2021). In these emergencies, various response and protective actions are required, including the emergency and retrospective dosimetry of ionising radiation, evaluation of radiation doses, categorisation of the emergency, mobilisation

of response organisations, implementation of radiological monitoring, provision of guidance on protective measures, e.g., sheltering, together with the administration of prophylaxis when considered necessary (Shekhar et al., 2020).

2.5.1 Preparedness for radiological emergencies

Radiation incidents and radiological emergencies provide unique challenges that require specialised measures to safeguard public health and safety. Addressing these catastrophes necessitates customised strategies to alleviate possible harm to communities and people. The unique characteristics of radioactive catastrophes necessitate meticulously designed response strategies to efficiently mitigate their effects and protect public welfare. The objective of emergency preparedness is to create and maintain the capacity required within an organisation's operational framework. The capacity to manage and respond to nuclear or radioactive incidents encompasses a range of levels, from local communities to international collaborations. This comprehensive capability incorporates a range of interconnected components. It entails defining authority and responsibilities, establishing an organisational structure and allocating personnel, coordinating mechanisms, creating and implementing plans and procedures, providing the necessary tools, equipment and facilities, conducting training, drills and exercises, besides establishing a comprehensive management system (IAEA, 2015). Effective readiness for a radiological event necessitates ongoing planning, training of first responders, and the implementation of evaluations and emergency simulations. This encompasses activities such as formulating evacuation plans and instituting communication protocols by authorities, while epidemiological studies to evaluate the effects and the implementation of a dosimetry framework, which involves assessing the radiation doses received by individuals, are typically conducted or funded by universities or governmental research institutes. It should be mentioned that these considerations must be tailored to the specific circumstances of each incident, and even within a particular scenario, adjustments must be made based on the local environment. Factors such as location, time of day, weather conditions and the nature of the accident will affect the extent of the contamination, in addition to the number of casualties (Coleman et al., 2009).

Having a comprehensive understanding of the risks associated with radiological emergencies is critical. This entails evaluating the likelihood of these incidents, identifying potential sources of radiation and assessing the possible effects as regards human health and the environment. Conducting risk assessments supports the identification of vulnerable areas and populations,

aiding the development of more effective planning and response strategies. The creation of comprehensive emergency response plans is a fundamental aspect of preparedness. These plans necessitate a collaborative endeavour among governmental entities at several tiers, disaster response agencies, law enforcement and security personnel, healthcare professionals and institutions, as well as experts in radiation protection and safety. The plans should encompass protocols, define roles and responsibilities, ascertain effective communication strategies, outline evacuation procedures and allocate resources appropriately. Likewise, preparedness extends beyond the immediate aftermath of an incident, it also encompasses planning and research on the necessary measures to be taken in the aftermath of an incident and the prioritisation of those activities. Investigating radiation exposure reduction and precise dosimetry techniques is crucial for formulating viable treatment approaches. In radiological emergencies, first responders, including paramedics and firemen, are often the initial personnel to arrive at the location. Although mild catastrophes are often manageable by local hospitals, major occurrences can rapidly exceed the capacity of healthcare systems. Consequently, it is essential to evaluate and enhance the capability to handle mass casualty incidents, including constraints in facilities, personnel, and resources. Proper medical readiness is essential for tackling the distinct problems presented by radioactive accidents and guaranteeing excellent patient care, especially in potentially stressed circumstances (DiCarlo et al., 2011, Alghamdi et al., 2022).

A significant challenge in equipping healthcare systems for radiological and nuclear catastrophes is their rarity. This rarity results in medical personnel frequently lacking actual expertise in identifying and addressing radiation-related health consequences. The lack of real-world exposure to such situations may impede the development of competence and preparedness among healthcare professionals, thereby affecting their capacity to respond effectively in a crisis (Jasper et al., 2005). Developing training programmes for emergency responders, medical staff and relevant personnel is essential to provide them with the necessary knowledge and skills to cope with radiological incidents. Regular exercises, including tabletop drills and full-scale simulations, help identify gaps in preparedness, test response capabilities and improve coordination among different agencies. Informing and educating the public as regards radiological emergencies is fundamental. Public awareness campaigns should provide information pertaining to radiation risks, emergency response procedures and protective measures. Moreover, establishing clear communication channels to disseminate suitable and accurate information during emergencies can help public anxiety and panic, promote a better

understanding of the situation, encourage conformance with safety measures and facilitate the smoother implementation of emergency procedures. Having the appropriate infrastructure and equipment is essential to manage radiological emergencies effectively. This includes specialised monitoring and detection systems, decontamination and treatment equipment, besides facilities to deal with contaminated individuals or objects. Regular maintenance and testing of equipment are essential to ensure their reliability during emergencies. Radiological emergencies can transcend national boundaries, necessitating international cooperation, whilst sharing best practice, expertise and resources among countries strengthens preparedness and response capabilities. International agreements and frameworks, such as the International Atomic Energy Agency (IAEA, 2007) guidelines and conventions for early warning and aid in nuclear accidents or radiological emergencies promote such cooperation.

Essentially, preparedness for radiological emergencies demands a multidimensional approach containing risk assessment, emergency planning, training, public education, the development of infrastructure and international cooperation. By addressing these aspects, authorities can heighten their ability to respond effectively, protect public health and minimise the consequences of radiological incidents.

Emergency Planning Zones off-site EPZs

Nuclear emergency planning frequently involves defining zones surrounding a nuclear facility where preemptive actions are established and rehearsed prior to any incident. Emergency planning zones are essential elements of off-site preparedness and response systems for radiological or nuclear emergencies. In the event of a radiological emergency, pre-planned protective measures are implemented to ensure the safety and well-being of the public. Local conditions, geography, and demographics may influence the precise size and shape of these zones. Authorities within these zones implement pre-planned protective measures, including the distribution of potassium iodide tablets, sheltering-in-place, and evacuation. The precise size and shape of these zones may differ depending on local conditions, geography, and demographics. Typically, three main types of EPZs are established, as shown in Figure 2.2:

Precautionary Action Zone (PAZ): This is the area where inhabitants take immediate action, such as evacuation, in the event of a nuclear incident prior to or shortly after the onset of radioactive material release, with the intention of substantially reducing the likelihood of significant deterministic impacts (IAEA, 2007). Itaya (2013) determined it to be a radius of approximately 5 kilometres surrounding the plant.

Action Planning Zone (UPZ): A zone that

is located 5 and 30 kilometres from the plant (Itoya, 2013), where preparations are established for critical protective action to be taken, in line with either international or national standards, with the aim of averting doses off-site, such as sheltering or taking iodine pills, contingent upon the emergency action level (EAL) and operational intervention level (OIL), in conjunction with environmental monitoring data (IAEA, 2007). **Plume Protection Planning Area (PPA):** The area where residents take precautions, for instance sheltering to avoid being exposed to radioactive material (Itoya, 2013).

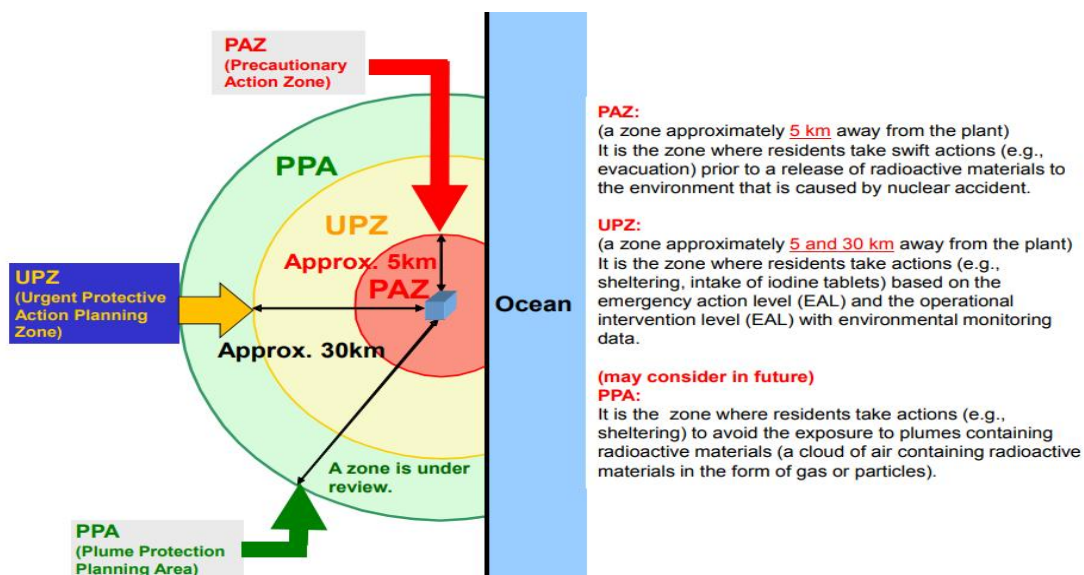


Figure 2.2 The flow diagram of Key Zones for Nuclear Disaster Measures Adapted from Itoya (2013).

The approach to Emergency Planning Zones (EPZs) for radiation or nuclear disasters has both advantages and disadvantages. Predefined circular zones facilitate the planning and execution of emergency procedures, while well-defined EPZs offer clear guidance for evacuation and protective measures. However, in the event of an accident, circular zones may not account for real-time conditions during an actual emergency, such as wind direction and plume movement. Also, simple circular zones may not reflect the effects of population distribution, local topography and prevailing weather conditions. Thus, emergency planners should contemplate the implementation of EPZs that are both flexible and scalable, capable of adapting to real-time incidents, and that incorporate advanced modelling and monitoring technologies to facilitate more precise risk assessments.

2.5.2 Response during emergency phase

In the initial phases of an emergency, response organisations concentrate on adopting preventative measures to minimise the potential consequences and to prevent the development of unsuitable conditions. This strategic approach allows the prompt implementation of protective measures at the site and, if necessary, in surrounding areas. These attempts to mitigate the situation are supplemented by additional protective measures and responses specifically designed to address the needs of individuals who are at risk of or already experiencing the effects of the emergency. The immediate response to a radiological incident involves immediately gathering essential details pertaining to the event, such as its location and a basic description, while also assessing the initial level of radiation exposure. Furthermore, communicating accurate information promptly and reliably to the public and affected individuals is crucial. Providing guidance and support as regards sheltering in place is advised, whereas the need for evacuation is evaluated by considering the balance between exposure to risks and other potential hazards. Equally, collecting basic information relating to the population affected assists in aiding follow-up measures to address their needs effectively (Oughton et al., 2017).

The responses encompass several stages, including during and after the accident, with the primary objectives of protecting human life, regaining control of the situation and mitigating the consequences, mitigating or minimising harmful deterministic effects and reducing the risk of stochastic effects. It also comprises avoiding further contamination, together with initiating recovery and rehabilitation efforts (IAEA, 2015). It is beneficial to use different time phases to describe the framework for managing a radiation emergency using three-time phases: an urgent response phase (involving immediate protective actions), an early response phase (involving early protective actions) and a transition phase (Figure 2.3) (IAEA, 2018). Public Health England (2019) uses early phases, intermediate phases and long-term phases to describe the emergency response phases. Classifying the stages of radioactive accidents aids in preparedness; nevertheless, precisely delineating these phases during a real occurrence can prove difficult. This is especially significant when attempting to distinguish the first reaction phase from the subsequent transitional step. The dynamic character of emergencies sometimes blurs the distinctions between theoretical stages, complicating the execution of pre-established plans in real time, as the actions undertaken during this period may overlap and aid the completion of specialised activities related to both phases (IAEA, 2018; Public Health England, 2019).

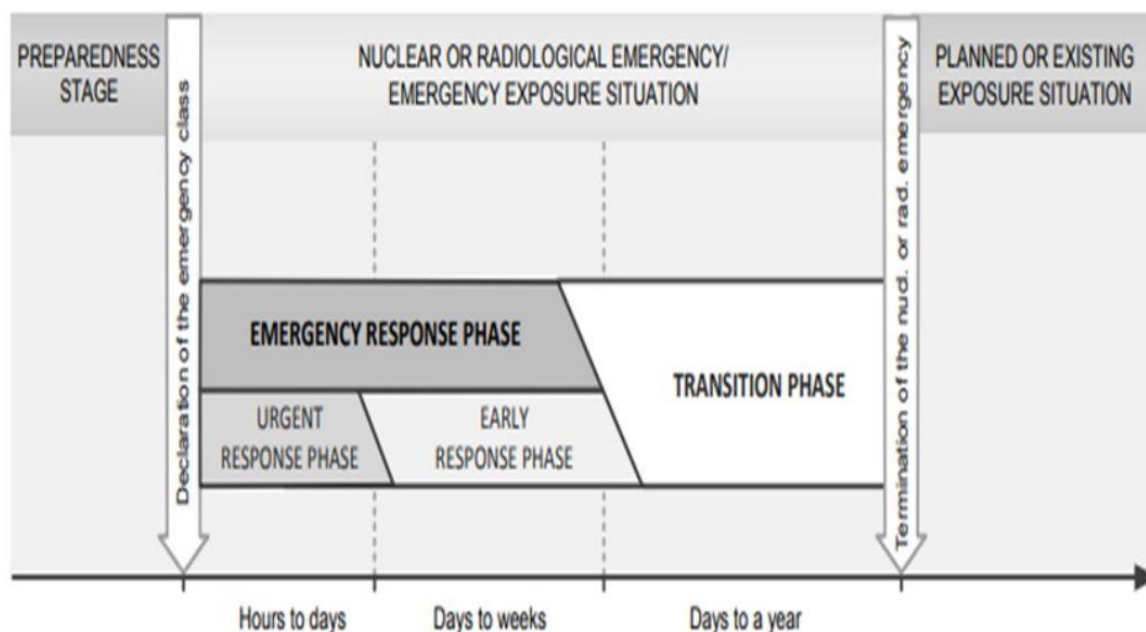


Figure 2.3. Temporal sequence of emergency response phases for nuclear or radioactive incident within a certain geographical region or a single site (Reproduced from the IAEA, 2018).

Incident characterisation:

The prompt detection of an event permits the application of protective measures. These measures may include evacuation, sheltering, administering potassium iodide for thyroid blocking, besides containing contamination. Basically, if the Goiania accident had been detected earlier, it would have been possible to prevent widespread contamination and significant exposure to certain individuals (IAEA, 1988). In the case of the London polonium incident, the hospital failed to observe the alpha radiation from ^{210}Po on admission of the victim to hospital. This delay thwarted the identification of radiation exposure for a significant amount of time. Early detection would have been beneficial in terms of handling the casualty's medical treatment and avoiding contamination of the surroundings, in addition to other individuals (IAEA, 2012). Crafting effective emergency strategies demands a thorough analysis of several key incident components. This includes pinpointing the origin and nature of the radioactive release, modelling how radioactive materials spread through air and settle on surfaces, identifying vulnerable populations in the affected areas, mapping potential routes of radiation exposure, together with the exposure pathways.

In every phase of an emergency, especially during the transition phase, it is essential to conduct the processes relating to the justification and strengthening of the protection strategy. These

procedures entail the continuous evaluation of how the protection strategy influences the radiological situation on the whole, including assessing factors such as (a) the residual doses individuals are exposed to compared to reference levels, (b) the social implications, and (c) any non-radiological consequences. This regular assessment should illustrate the advancements achieved in accomplishing the conditions necessary to terminate the emergency and should prompt modifications to the protection strategy when required. Response systems and radiological and nuclear emergency plans differ based on the assortment of agencies and systems within countries. Figure 2.4 illustrates a broadly applicable response mechanism. In this diagram, the importance of measuring doses acts as a fourth step in the system, and afterwards as a tenth step upon which physical and chemical analysis, medical screening procedures and subsequent epidemiological studies are formed.

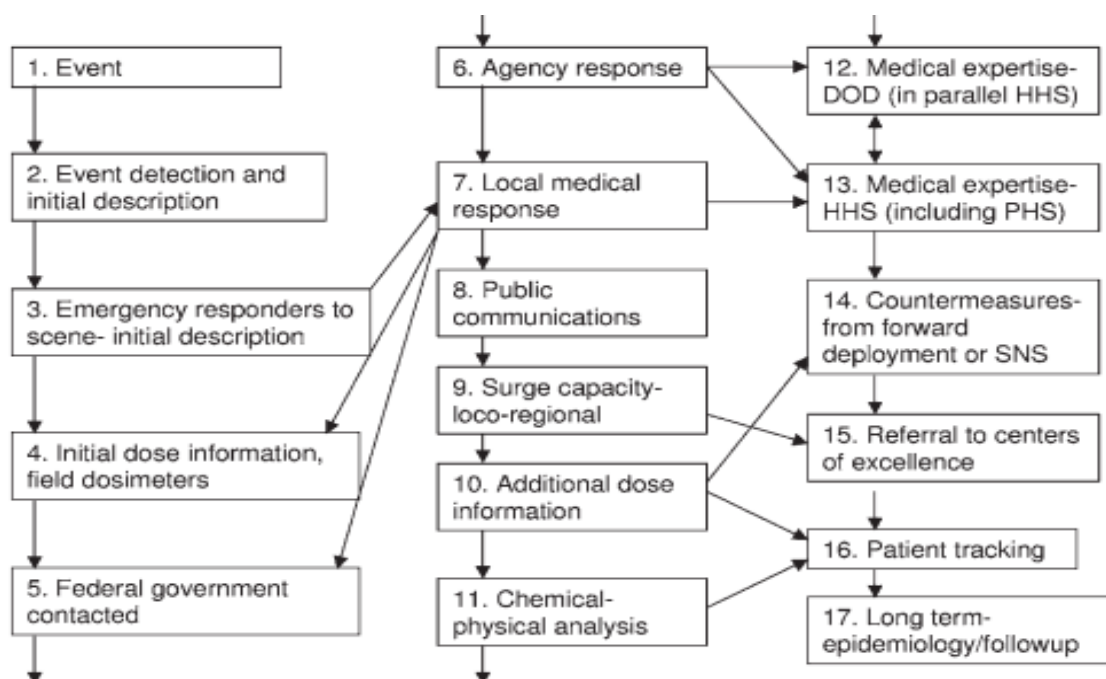


Figure 2.4. The flow diagram of the medical response chain illustrates how various components are interconnected in addressing a radiation event. Each box in the diagram corresponds to a specific period in the response plan, while the arrows denote the interactions and dependencies among these processes. The diagram functions as a visual representation of the sequential progression of the medical response process. (Adapted from Coleman et al., 2009).

The medical reaction to a radiation event is influenced by the event type and the number of casualties implicated. In the case of a large-scale event, the group of radiation casualties would comprise individuals with varying levels of severity. This includes individuals who have been directly affected by the initial blast and may have traumatic injuries, as well as those injured by the fallout. The initial wave of patients is anticipated to arrive at hospital emergency services within 12 hours, as forecasted by Hick et al. (2011). In large-scale disasters with significant casualties of hundreds of thousands, conventional medical infrastructure is rapidly inundated. This circumstance requires the establishment of triage systems to prioritise treatment and efficiently distribute few resources. The influx of patients frequently surpasses hospital capabilities, necessitating new strategies to handle casualties. The underlying obstacle of managing a substantial inflow of injured persons persists as a challenging issue for emergency responders and healthcare systems, irrespective of the precise sort of catastrophic (Coleman et al. 2009). Triage protocols are implemented to assess and prioritise patients based on the level of care required, with the intention of optimising the utilisation of limited medical resources.

Triage systems in large-scale catastrophes are tailored to the particular characteristics of the event and the resources at hand (Bostick et al., 2008). This approach employs many triage stages. Bostick et al. (2008) delineated four phases of triage pertaining to radiation incidents. The initial phase, first-order triage, transpires during community-level assessment, whereby individuals assess their need for aid based on their circumstances at the moment of the incident. The second stage entails pre-hospital assessment to determine whether individuals need additional medical treatment. The third step is hospital-based triage, which prioritises the treatment of patients arriving at medical institutions. Treatment triage distributes scarce medical resources to individuals most likely to get benefit from them. This stage may entail the application of emergency dosimetry to determine radiation exposure levels. Results of emergency dosimetry measurements are typically accessible within 24 to 96 hours, or occasionally longer, allowing individuals with no severe symptoms to wait at home for the assessment results, reducing the burden on hospitals. With respect to radiation accidents, Triage criteria are based on the estimated dose received by each individual. Typically, four categories are distinguished: 1) below 0.5 Gy, where no radiation exposure symptoms are expected and patients can return home without medical care; 2) 0.5-2 Gy, where medical care can be deferred until after the initial 4-day stage; 3) 2-6 Gy, where immediate care is desirable; and 4) above 6 Gy, where patients receive palliative care. However, concerning emergency dosimetry, the levels of triage are streamlined into two distinct categories (below and above 2 Gy) in the initial

triage phase (Bailiff et al., 2016). The crucial threshold dose of 2 Gy is derived from data pertaining to the Chernobyl cohort, in which no fatalities were recorded below this dose (Guskova et al., 1987). Although clinical symptoms related to radiation exposure which were outlined in detail in section (2.2) can aid in medical triage, an alternate approach is required due to the characteristics of radiation damage, which may not be apparent during physical examinations during the initial 12 hours. Individuals without visible injuries should nonetheless undergo evaluation for exposure to radiation (Coleman et al., 2011). Moreover, particular medical symptoms associated with radiation exposure, such as nausea and neurological manifestations, may be triggered by stress and psychological trauma, resulting in hospital admissions for the "worried well" (Hick et al., 2011). This may facilitate the proliferation of panic, underscoring the necessity for an emergency/retrospective dosimetry device to provide precise dose assessments. The recovery phase following the incident, which usually extends over several years, involves ongoing evaluations of the community and may initiate epidemiological research if deemed beneficial (Coleman et al., 2009).

Urgent response phase: This phase refers to the specific timeframe within the broader emergency response phase, beginning with the identification of immediate actions required for an effective response and concluding once all the necessary tasks have been completed. These acts encompass both mitigatory measures implemented by the operator and urgent preventative measures implemented both on-site and off-site (IAEA, 2018). The early phase of an emergency is characterised by the release of radioactive substances into the surrounding environment (Papamichail and French, 2000). The urgent phase, as defined by Crick et al. (2004), extends from the occurrence of abnormal conditions in the plant until stability is restored, any dispersed radioactive plumes (in case of a release) have dissipated, and immediate protective measures have been taken. However, obtaining reliable monitoring data during this phase is repeatedly challenging owing to their limited availability. Consequently, mathematical models are frequently employed to assess the spatial and temporal distribution of radioactive contamination, particularly when monitoring data are absent during nuclear emergencies, for example in the urgent phase (Sweeck et al., 2020). A specific period during the emergency response phase is when immediate measures, for instance evacuation, iodine thyroid blocking and sheltering are urgently undertaken to effectively tackle the emergency conditions identified. This phase typically lasts from a few hours to several days contingent upon the type and magnitude of the nuclear or radiological emergency. In minor radiological events, such as mishaps involving the transportation of radioactive materials or occurrences with confined

hazardous sources, the critical first reaction phase may be comparatively short. These minor emergencies often require concentrated yet brief interventions, generally enduring only a few hours. (IAEA,2015; IAEA, 2018). First responders should promptly conduct an initial assessment without delaying notifications. The assessment should consider the following observable criteria: (a) The location of the emergency. (b) Available information pertaining to the site, including its geography (e.g., hilly terrain, plains), local human population, facilities and any special environmental concerns. (c) The accessibility of the site. (d) The type of initial incident (e.g., collision, fire, submersion). (e) Human injuries. (f) Weather conditions. (g) Indicators, inscriptions (such as UN numbers and correct shipping names), signs or transportation records. (h) The presence of other hazardous materials or risks in close proximity to the location, such as: (i) Significant amounts of highly flammable liquids or gases. (ii) Materials that have the potential to explode. (iii) Hazardous substances that are toxic or corrosive. (i) Signs of breached containment or compromised protection of packages. (j) Evidence suggesting that the emergency may have been the result of a deliberate and harmful act (IAEA, 2022).

Early response phase: The early response phase occurs within the emergency response stage and commences once the radiological situation has been adequately assessed. During this phase, the need for early preventative actions and other response measures, such as relocation, is identified based on the available information (IAEA, 2015; IAEA, 2018). Papamichail and French (2000) assert that the response shifts into the early response phase after the source of the release has been stabilised and additional substantial releases are improbable. During this stage, radiation measurements become available. Decisions regarding protective measures increasingly rely on this data to safeguard individuals and the environment in the intermediate and long-term (Public Health England, 2019). The duration of the early response phase can range from days to weeks, contingent upon the sort and magnitude of the nuclear or radiological emergency. The radiological assessment plays a crucial role in providing critical information to emergency responders and decision-makers in connection with radiological and associated hazards. The primary goal of this assessment is to: (a) effectively manage and mitigate the emergency situation. (b) Diminish the probability and mitigate the consequences of any emission of radioactive materials. (c) Enhance the efficiency of safeguarding and ensuring safety during the response. (d) Determine and obtain any necessary further specialised assistance (e.g., consultants in chemical hazard assessment) and approve their participation. (e) Ensure the site is returned to a secure and steady state (IAEA, 2022).

Transition phase: This phase occurs following the emergency response stage and can last anywhere from a few days up to several months. This stage marks the point at which the situation has been stabilised by ascertaining a detailed description of the radiological situation and by beginning to implement activities through which the state of emergency can be ended. The end of a radiological event marks the shift from the transition phase for a specific area or site to sustained management, indicating the beginning of either a present exposure scenario or a planned exposure scenario (IAEA, 2022).

Countermeasures and Protective Actions in a radiological emergency

A number of protective actions can be executed to protect people in the event of a radiological emergency. These are a subcategory of protective acts specifically devised to limit exposure to radioactive contamination by means of external exposure, inhalation and ingestion, the efficacy of which will be substantially diminished if it is delayed. The actions to be implemented depend on the kind and magnitude of the radiation scale accident and their appropriateness (Mustonen, 2008). **Urgent precautionary protective action:** Evacuation, sheltering, distribution of stable iodine, medical management and restrictions on consuming contaminated food (IAEA, 2007). **Immediate protective action:** Evacuation, sheltering, distribution of stable iodine, medical management and restrictions on consuming contaminated food (EPA, 2017). **Long-term protective measures:** Relocation and long-term restrictions on consuming contaminated food (EPA, 2017).

Protecting the public from an airborne hazardous radiation discharge demands the prompt selection of suitable protective measures. Decision-makers must consider a combination of several factors that personify the release, weather conditions, together with the people who may be affected before choosing whether to recommend shelter-in-place or evacuation (Sorensen, 2004). Chandra et al. (2020) assert that sheltering, stable iodine prophylaxis and the evacuation of inhabitants have customarily been the principal short-term protective steps in off-site nuclear emergency planning and response plans.

Internal thyroid radioiodine exposure is the most serious radiation threat for the public pertaining to a significant radiation accident at a nuclear power plant (Uyba et al., 2018). The radioactive iodine might be discharged in a plume or cloud following a nuclear accident, contaminating the environment and giving rise to external exposure. Inhalation of polluted air and ingestion of tainted food and water may cause internal radiation exposure and the absorption of radioactive iodine, predominantly by the thyroid gland (WHO, 1999).

Consequently, off-site nuclear emergency planning and response plans have traditionally concentrated on stable iodine prophylaxis, as the foremost short-term protective action. The effectiveness of stable iodine prophylaxis has been demonstrated throughout the years by its capacity to diminish radioiodine absorption and minimise the occurrence of thyroid cancer in the treated population (Chandra et al., 2020). Thus, iodine should be dispensed in advance of any intake of radioiodine or as soon as possible. Oral administration of stable iodine within six hours of radioactive iodine inhalation effectively prevents thyroid uptake (Ohba et al., 2021). Administering stable iodine before or at the commencement of exposure to radioactive iodine totally obstructs radioiodine absorption by saturating the thyroid gland with stable iodine, hence significantly diminishing internal exposure to the thyroid. Its effectiveness decreases dramatically after exposure, attaining only 7% 24 hours after irradiation (Bazyka et al., 2016). Chandra et al. (2020) contend that providing prophylaxis to homes ahead of time, also known as predistribution, during the preparatory stage is justifiable on the basis of effective and judicious radiation protection (Chandra et al., 2020). Due to an absence of direct thyroid assessments during the Fukushima disaster, thyroid doses were estimated using radioecological models, with only marginally more than 1000 residents measured. Thyroid doses to children were estimated to be in the hundreds of mGy range. Following the Chernobyl disaster, the most common route to consume ^{131}I was by means of cow's milk (Uyba et al., 2018).

Evacuation during a nuclear emergency is critical to prevent radioactive harm from hazardous materials and to minimise the overall impact of the accident. Evacuation preceding the discharge of radioactive material is the only protective measure that can completely avoid each sort of radiation triggered by radioactive release, making it a critical component of nuclear emergency response and management (Zou et al., 2018). Nonetheless, the decision to evacuate a nuclear power plant is contingent upon four primary factors: response actions, safety standards, timing of evacuation, and the area, method, and capacity of evacuation routes. With respect to many types of emergency exposure situations, exposure rates are highest immediately after the event and thenceforth decrease over time. This denotes that specific protective measures, such as sheltering, must be taken as soon as possible in order to be effective. Fundamentally, there is insufficient time to conduct detailed exposure evaluations in real-time in order to implement these actions. Therefore, it is imperative to develop beforehand, a set of internally consistent criteria regarding taking these actions and to develop appropriate risk factors (demonstrated as easily and quickly measurable quantities or observables), to facilitate their initiation in an emergency (ICRP, 2007). The most effective initial response after

a nuclear explosion is to find shelter in the closest secure building or structure and remain there until directed by authorities.(EPA, 2017). The IAEA (2007) maintains that the effectiveness of sheltering varies considerably, depending on the characteristics of the radioactive release or the sources of the exposure.

2.5.3 Recovery process for radiological emergencies

In the recovery phases after a nuclear or radiological disaster, it is essential to evaluate the radiation exposure of both the general populace and rescuers. This evaluation is essential for guiding preventive measures and for doing further studies of the incident's effects. The long-term consequences of radiological and nuclear disasters require a comprehensive and sustainable approach that extends beyond the initial response. The need for long-term recovery strategies is paramount when planning for nuclear and radiological disasters, as the impact of these events can extend for decades and create additional challenges over time, such as Fukushima and Chernobyl. During the initial phases of an emergency, it is essential to recognise the necessity of a long-term recovery process and integrate this into the comprehensive response strategy (IAEA, 2015; WHO, 2017; Alghamdi et al., 2022).

Successful recovery plans for radiological and nuclear emergencies should include a carefully planned, effective and practically justified set of activities such as continuous environmental monitoring to track radiation levels in air, soil, water and food sources; continuous rapid testing of radiation levels for the general public and first responders using various physical and biological measurement methods; and the implementation of long-term health monitoring programs to detect changes that may occur over time, such as cancer; and psychosocial support services for those affected. In addition, recovery plans should include the restoration of damaged areas, the restoration of public services and infrastructure, and the provision of support to displaced communities. Therefore, recovery plans should include mechanisms for close cooperation and coordination between various government agencies, ministries, health care providers, first responders and public health services. The integration of these elements and the training of staff on them is essential in early recovery plans for radiological and nuclear emergencies, as authorities can better mitigate the long-term effects of radiological accidents and work to restore damaged areas to safe, stable and sustainable conditions (Chunsheng et al., 2022).

2.6 Measurement techniques

2.6.1 Instrumental Techniques

Estimating doses during response to nuclear and radiation emergencies is the basis for protecting against radiation and its deleterious effects. Therefore, the most effective assessment of doses is by way of understanding the concentration of radioactivity in the environment and measuring dose rates. Radiological monitoring and measurements are necessary to obtain accurate information that functions as the basis for measures and decisions taken during the management of radiological or nuclear emergencies. Environmental monitoring investigations encompass the establishment of initial quality standards, the identification of environmental patterns, the detection of any abnormalities and the discovery of developing environmental concerns. Accurately classifying the exact components of environmental monitoring data collected under normal conditions is essential. The principal purposes of emergency radiation monitoring in the environment are to deliver precise and rapid information regarding the levels, scope and duration of radiation and environmental pollution caused by radionuclides, present a comprehensive description of the physical and chemical characteristics of the hazard, assist in the prevention and management of the spread of contamination, and support decision-makers in implementing immediate, intermediate and long-term measures to protect the population, including agricultural measures and restrictions on food. It is also to provide information to guarantee the safety of emergency and recovery personnel, disseminate information to the public regarding the level of risk involved, deliver data for finding patients necessitating long-term medical surveillance and validate the effectiveness of protective measures. Environmental monitoring may involve evaluating dose rates and sampling radionuclides from the plume to assess compliance with operational standards related to disaster preparedness and response. (IAEA, 2023).

The Chernobyl disaster, which occurred on April 26, 1986, was the most severe nuclear disaster ever recorded, leading to extensive contamination of the surrounding area. The accident produced global repercussions, prompting widespread public concern. The Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) is crucial for global nuclear non-proliferation by enforcing a ban on nuclear test explosions. It operates the International Monitoring System (IMS), a sophisticated network of seismic, hydroacoustic, infrasound, and radionuclide stations to detect nuclear tests worldwide. The CTBTO's International Data Centre (IDC) analyzes data to ensure accurate event detection, location, and characterization, supporting treaty

compliance. By fostering international cooperation, it promotes peace and security through scientific verification of nuclear test bans. Its work enhances global stability by deterring nuclear testing and providing data for scientific research and disaster monitoring (Hasan et al., 2023). However, it also presented countries with a valuable opportunity to assess their emergency preparedness, monitoring systems, response capabilities and methods. In Pakistan, various high-speed air samplers have been installed at numerous places throughout the country to record environmental radioactivity and collect airborne particulates, which are then analysed using gamma spectrometry. The examination of the samples discloses the typical levels of different radioactive isotopes in the immediate surroundings. Additionally, a monthly analysis is conducted on food samples, which encompass various items such as meat, milk and vegetables. Hungary made the key decision to protect the public and provide updates on the situation and its developments were grounded in the findings of the environmental monitoring programme after the Chernobyl nuclear plant accident. Hungary made a more comprehensive and well-structured environmental monitoring programme that was established around a nuclear power plant. In 1986, the knowledge and expertise gained over a period of more than 25 years permitted the prompt enactment of a comprehensive environmental monitoring programme shortly after receiving data regarding the Chernobyl nuclear plant accident. The Netherlands experienced many challenges during its response to the significant radioactive contamination that spread over large areas after the Chernobyl accident, as emergency plans did not include response requirements regarding transboundary radiation. Therefore, the Netherlands began a sizeable radiation monitoring project that describes all the necessary operations that must be undertaken quickly to protect the population from any dangers involving radioactive materials in the Netherlands and abroad (Dal et al., 1990; Sztanyik et al., 1990; Hasan et al., 1990).

The incident at the Fukushima Daiichi nuclear power plant (FDNPP) occurred on March 11, 2011, because of the Great East Japan Earthquake. This resulted in the release of large amounts of radioactive substances into the surrounding area. The primary radioactive elements emitted into the atmosphere were iodine (^{131}I) and caesium (^{134}Cs and ^{137}Cs). Iodine-131 has a half-life of eight days, while ^{134}Cs has a half-life of two years and ^{137}Cs has a half-life of 30 years. These radioactive materials were distributed across a significant part of Japan's land surface. Consequently, extensive monitoring of radioactivity has been conducted over a protracted period, along with studies on related environmental radioactivity (Hashimoto et al., 2013; Cresswell et al., 2016). Airborne gamma spectrometry technology delivers a number of benefits

over traditional ground-based monitoring approaches in terms of establishing an advanced reaction.

Mapping surface radiation using gamma-ray spectrometric systems

The gamma-ray spectrometry method is extensively utilised in several spheres. The method was originally created for uranium exploration. Radiometric surveying measures the environmental spatial distribution of radiation in the environment and aims to assess the environmental radioisotope distribution including both natural and synthetic radioactive materials influencing the radiation field at any specific point. It is now also utilised for geological mapping (Anderson and Nash, 1997), soil mapping (Cook et al., 1996), and monitoring radiation levels (Sanderson et al., 1995). Following the nuclear events at the Chernobyl and Fukushima Daiichi nuclear power plants, these strategies have attracted more interest and acceptance (Sanderson and Ferguson, 1997; Sanderson et al., 2004).

Spectrometry systems can be employed on aircraft or vehicles or carried by operators using backpacks, and each strategy possesses distinct advantages and disadvantages. The systems employed for these surveys typically comprise scintillation crystal or HPGe detectors, either individually or in arrays, in conjunction with a spectrometer, a GPS receiver to record the measurement location, and a mobile computer to collect data and perform analysis (Cresswell et al., 2016). The requirement for specific authorisation for low-altitude flights restricts the use of airborne surveys, particularly in metropolitan areas where navigational obstacles are more pronounced than in rural regions. Ground vehicle systems may be exploited in open terrain with a suitable off-road vehicle, but they are primarily used on highways, where the road surface occupies a substantial part of the field of view (Korsbech et al., 1999; Mellander et al., 2002; Sanderson et al., 2003b). When creating a positional reference system, backpack systems carried by walkers have the ability to incorporate every accessible location. Backpack-based radiometric surveys are ideal for assessing dose rates by reason of their ability to cover the entire region and overcome barriers that impede the use of aerial and vehicle surveys. Radiometric backpack systems enable the creation of detailed maps that depict the spread of radioactivity in small regions. Accurate radiometric mapping may be utilised to accurately identify locations with higher levels of contamination. This data can assist in directing cleanup operations by pinpointing the locations with the highest levels of pollution. By employing accurate mapping techniques, it is possible to identify tiny areas with concentrated levels of

local activity. If these venues are extensively utilised by the public, they may receive preferential treatment in remediation projects (see Chapter 5 for further details).

Nuclear and severe radiation emergencies, as evidenced by the Chernobyl and Fukushima incidents, are characterized by a rapidly evolving radiation situation at the onset of the release and the restricted availability of data for dose assessment, including dose rates, air concentrations, deposition densities, individual doses, and body burdens of the most pertinent populations. The radioactive decay of short-lived radionuclides within the mixture of released materials and the environmental spread of deposited radionuclides result in a fast reduction in dose rates following the ending of the radioactive release, provided the source is contained. The experiences of the Chernobyl and Fukushima nuclear accidents demonstrated that dosimetry was a critical tool in emergency situations for decision-making processes, including the estimation of the health risk resulting from the exposure, the application of protective measures, the decision to administer medical treatment, the removal of external or internal contamination (decontamination), the monitoring and communication of long-term health effects, and the adaptation to accident variables. The Fukushima and Chernobyl nuclear accidents highlighted significant challenges in accurately assessing external radiation exposure during the critical urgent response and early response phase of emergency response. In Fukushima, the tsunami's impact rendered most electronic personal dosimeters (EPDs) inoperable due to water damage, creating a substantial gap in individual dose data for emergency workers throughout March. This situation severely hampered efforts to monitor and manage radiation exposure effectively during the initial response period. Similarly, the Chernobyl incident highlighted limitations in existing dosimetry equipment. The personal film badge dosimeters used by workers at the Chernobyl Nuclear Power Plant (ChNPP) proved inadequate for the extreme radiation levels encountered and unable to provide meaningful dose information for accident witnesses and early responders. This shortcoming in dosimetry capabilities persisted until June 1986 when more suitable dosimeters were deployed, finally enabling proper radiation monitoring for atomic workers involved in the response and cleanup efforts .

Gamma-ray spectrometry is a widely used and accepted method, applicable across various systems including stationary installations, vehicle-mounted systems, airborne platforms, and portable devices. In aircraft, high-sensitivity γ -ray detectors enable ambient radioactivity measurements at intervals of just seconds, offering a sample rate 100 to 1,000 times superior to conventional methods (Sanderson et al., 1989a,b, 1995), with the added advantage of

mobility across diverse terrain unaffected by ground-level obstructions or natural barriers. Vehicle-deployed systems facilitate immediate radiation monitoring and environmental evaluation over regional scales, while backpack systems allow for detailed mapping of radiation distribution in small regions. Accurate radiometric mapping can identify more polluted regions (Mellander et al. 2002; Sanderson et al., 2003b; Cresswell et al., 2011; Cresswell et al. 2013; Buchanan et al., 2016). However, in the initial stages of an accident, there may be insufficient information regarding the nature and extent of the radioactive release, which presents a challenge for accurate dose assessments. Gamma-ray spectrometry is a complex process that necessitates specialised knowledge and a significant amount of time, often spanning several days or weeks, to be applied to aircraft or vehicles. The accurate interpretation of gamma-ray spectra necessitates skilled personnel, time, and the collection of high-quality data to ensure reliable analysis. The necessity to promptly evaluate public exposure may result in incomplete or hasty measurements. Representative dose measurements for the entire affected population can be challenging to acquire due to factors such as weather conditions and terrain, which can considerably influence the distribution of radionuclides. Identifying and measuring radiation exposure from incidents can be complicated because natural ambient radiation might mask minor contamination. The precision of exposure estimates can vary due to shielding effects and the geometry of the source, potentially leading to either lower or higher calculations of the actual levels. Advanced systems, such as airborne platforms, can be costly and necessitate substantial logistical support for comprehensive surveys. In the immediate aftermath of a disaster, there may be an insufficient number of personnel or equipment to conduct comprehensive dose assessments over extensive areas. (see Chapter 5 for further details). In urgent scenarios with limited timeframes, other approaches with less complex technologies may be required to conduct a thorough examination. These strategies can be more efficient and appropriate to implement and utilise. They are also valuable to determine the doses received over a period of hours or days after significant radiological occurrences, particularly in cases where prompt dose monitoring was not implemented. Hence, retroactive dosimetry using common materials is of benefit in evaluating previous occurrences of exposure and situations where initial monitoring was lacking (see section 2.7.3 for further details). Each approach plays a role in a comprehensive strategy for responding to nuclear and radiological incidents, frequently working together to provide a complete understanding of the radiological conditions and effects (see chapters 3, 4, 5 for further details).

2.6.2 Passive Dosimetry

The main objective of dosimetry is to determine the dose that a material absorbs. Currently, the measurements and systems which are employed to evaluate the “amount” of ionising radiation dose that personnel in radiation facilities are exposed to are more advanced. Nevertheless, the scenarios that are portrayed in section 2.2, required the establishment of alternative methods to calculate radiation doses in public settings where standard dosimetry methods are not ordinarily available. Basically, the dosimetry needs to remain consistent, whether in the immediate aftermath or over an extended period in the wake of a radiological or nuclear catastrophe, given that it is essential to evaluate individuals' exposure to radiation. In the initial phase following this sort of an event, the most pressing requirement with respect to radiological assessment is triage, which aims to distinguish between individuals who are generally well but concerned and those who need more comprehensive medical care and, in theory, intervention. Over a period of time, it is essential to continuously monitor the health of the individuals in the population who were exposed to radiation, whether during or after the initial release of radiation. This monitoring addresses both individual healthcare needs and epidemiological studies aimed at understanding the long-term health effects of radiation exposure. Since it is unlikely that the public would own dosimeters or personal radiation dose monitors, novel methods must be employed to evaluate radiation exposure at the individual, population, and environmental levels. This is attainable by means of two primary methods, chiefly emergency dosimetry and retrospective dosimetry (Alghamdi et al., 2022; Alghamdi et al., 2024).

Conducting dosimetry immediately after the catastrophe would encompass a rapid assessment procedure resulting in only people whose absorbed radiation dose was determined to be greater than a set limit, such as 2 Gy, being evaluated at hospital. This is termed emergency dosimetry, as it would be required immediately after the incident, from hours to weeks after the occurrence of the original exposure. Emergency dosimetry primarily focuses on deterministic effects and rapid triage. External exposure is the main source of the dose. As a result, deterministic effects and quick triage are the main goals of emergency dosimetry (Bailiff et al., 2016). Retrospective dosimetry is also concerned with how energy from ionizing radiation is transferred to matter and then estimated and quantified. Therefore, retrospective dosimetry seeks to calculate the amount of energy that has been deposited in matter, frequently human tissue, at some point at any given time after exposure, from hours to years or decades following the exposure and can be linked to epidemiological studies (Bailiff et al., 2016). In the long-term phase, retrospective

dosimetry focuses on epidemiology and stochastic consequences and the target dose needed for retrospective dosimetry is much lower, 100 mGy (ICRU, 2002).

The triage criteria specified have been discussed in numerous publications and reports, including papers published by Alexander et al. (2007), Simon et al. (2010) and Rea et al., (2010). In 2013, the MULTIBIODOSE (MBD) project was completed. The project was funded by the European Commission and oversees high-scale radiological casualties during integration, and reports dose estimates and when they can be used in an emergency situation (Jaworska et al., 2015). In the MBD project, the dosimetric triage categorisation was divided into low (<1 Gy), medium (1–2 Gy) and high (>2 Gy). It is evident that the pivotal threshold for triage is situated at 2 Gy, beyond which it is recommended that individuals be directed toward subsequent medical evaluation and conceivably intervention. Conversely, for doses below 2 Gy, individuals may receive advice to return to their homes temporarily. This approach guarantees that critical medical facilities are not hampered, allowing them to allocate resources to patients with more severe and potentially life-threatening injuries (Jaworska et al., 2015; Bailiff et al., 2016). The selection of 2 Gy as the pivotal triage threshold is substantiated by findings from studies concerning individuals affected by the Chernobyl disaster (Bailiff et al., 2016). Guskova et al. (1987) asserted that among a group of 134 cases with acute radiation, no fatalities were observed, 31 patients with assessed doses below 2.1 Gy. Equally, as the absorbed doses surpassed 2.1 Gy, there was a progressive rise in mortality rates. Specifically, there was one death within the dose range of 2.2 to 4.1 Gy, seven deaths within the 4.2 to 6.4 Gy range and a notable increase to 20 deaths in the 6.1 to 16.0 Gy dose range.

In their work, McKeever and Sholom (2016) stressed the essential characteristics that a dosimetry system must have for the specific application of population triage. This is the means to detect a minimum dose (which will be explained later) of 0.5 Gy and the ability to establish a triage threshold at 2 Gy. Moreover, it must only be created by ionizing radiation to prevent false positives. Likewise, to remain sufficiently steady in the days to weeks following the initial exposure and should be quick and simple. Additionally, considering emergency dosimetry, the substitute material exploited for physical dosimetry should meet essential criteria: 1) be commonly available among the population, 2) be located near an individual's body, 3) possess the necessary sensitivity, and 4) exhibit a signal fading rate that enables the signal to be read days to weeks after the incident occurs. In a paper distributed in 1975 (CEC, 1975), the European Communities Commission detailed the technical published guidelines for thermoluminescence dosimetry in personal monitoring for photons and electrons from external

sources. The following are a few of the crucial characteristics that affect how effectively luminescence detectors are used:

- High sensitivity to radiation: This denotes the luminescence response per unit absorbed dose, specifying the system's ability to detect even small changes in radiation levels.
- The luminescence signal must demonstrate a linear dose-response relationship throughout an extensive dosage range, ensuring a continuous and proportionate rise with the administered dose while circumventing both superlinear and sublinear responses.
- Low limit of detection: This denotes the system's ability to distinguish the smallest dose from a zero dose reading, guaranteeing accurate detection of even minimal levels of radiation.
- Maintaining a stable and consistent signal that withstands physicochemical alterations arising from exposure procedures and repeated annealing.
- Employing uncomplicated annealing techniques to revert to its original state following irradiation.

Sullivan et al. (2013) describe the emergency dosimetry techniques that should be applied following a radiological event. These methods should be a reliable, affordable, easy to use, field-ready, high throughput, established approach (readily comparable between laboratories; non-experimental), radiation-specific (not impacted by confounding ambient influences), along with simple sample collection and preparation. Moreover, the results should be easy to obtain and delivered quickly after an incident. In the search for methods meeting these criteria, various dosimetry approaches have been recommended, encompassing both physical and biological methods. Both physical and biological methods can evaluate absorbed dose at the individual level, but they have various benefits and drawbacks, according to Swartz et al. (2011). This section aims to provide an overview of emergency dosimetry and retrospective dosimetry. The two basic types of radiation dosimeters, biological and physical, will be evaluated.

2.6.2.1 Biological dosimetry

In the field of radiation dosimetry and medical triage, biological retrospective dosimetry methods rely on the assessment of radiation-induced changes within the human body to derive dose estimations, providing valuable information for medical triage and dose reconstruction when conventional dosimetry data is unavailable or insufficient. These changes may encompass cytogenetic, genetic, haematological changes, or be rooted in the identification of

protein biomarkers. These methods administer a comprehensive whole-body dose, effectively covering the entire body as the bloodstream circulates throughout. It is important to accept that a spectrum of biological techniques has been developed, with a handful gaining wide acceptance, while others remain in the process of refinement and development, as confirmed by Blakely et al. (2009) and the International Atomic Energy Agency (2011). Possible vulnerability to radiation harm and the evident correlation between actual damage and clinical decision-making are two advantages of biodosimetry. Through the examination of biological markers, medical professionals can get valuable insights that closely mirror the true effects of radiation on an individual's health, facilitating more knowledgeable and focused treatment strategies. The disadvantages include the possibility of a lack of specificity since many other biological processes may result in the same biological changes, as well as the use of invasive sampling procedures that need specialised facilities for sample handling and analysis (Swartz et al., 2010).

Cytogenetic techniques

Cytogenetic techniques consist of the examination of chromosome damage resulting from ionizing radiation. In the context of emergency dosimetry, these techniques focus on examining the chromosomes present in peripheral blood lymphocytes (Ainsbury and Lloyd, 2010). Among biological dosimetry methods, cytogenetic approaches are accepted as the most advanced, with the dicentric chromosome assay being the most commonly employed, as reported by Simon et al., (2010). Dicentric assay is typically portrayed as the gold standard, given that it is widely acknowledged as the most precise and sensitive approach currently available (Alexander et al., 2007). It consists of chromosome structures resulting from radiation-induced damage, particularly in the form of two centromeres within a single chromosome. By calculating the dicentric chromosomes in a sample, it is possible to estimate the radiation dose to which an individual has been exposed. Dicentric chromosome assays are a valuable tool regarding the assessment of radiation doses, specifically in situations concerning accidental or intentional radiation exposure (IAEA, 2011). In full mode, the lower limit of detection is roughly 0.1 Gy, while in triage mode, it is approximately 0.5 Gy. A fundamental benefit of the dicentric assay is its ability to assess the consistency of irradiation by investigating the scale of changes per cell. It is essential to note that the presence of dicentric chromosomes lessens over time due to the turnover of lymphocytes, making this particular technique unacceptable for use long after the radiation exposure event, as indicated by Wang et al., (2010). Nonetheless, regardless of its various benefits, this method is very sluggish. It

takes around 55 hours from the time the sample is received to the dose estimate. The micronucleus test, which measures radiation exposure by analysing the development of micronuclei, small, extra-nuclear entities made of intact or fragmented chromosomes, is one of the additional cytogenetic techniques. This method is particularly valuable in cases where rapid assessment is required. It is applicable in situations where dicentric chromosome analysis may not be feasible (Fenech, 2007; Huber et al., 1983) and premature chromosome condensation (PCC), which accelerates the normal chromosome condensation process, permitting earlier visualisation and analysis of radiation-induced chromosomal damage. This approach is particularly advantageous when assessing acute exposure and has been instrumental in dose estimation following radiological incidents (Pantelias and Maillie, 1984) and fluorescence in situ hybridisation (FISH) assays, enabling the visualisation and quantification of specific chromosomal abnormalities. This procedure is beneficial as regards studying complex chromosomal rearrangements and translocations induced by radiation exposure. FISH assays present a complementary approach to dicentric chromosome assays, affording a better understanding of more complex radiation-induced genomic alterations (Finnon et al., 1995).

Genetic techniques

Genetic techniques that investigate changes in gene expression are imperative in emergency dosimetry. By means of analysing radiation-induced gene expression changes, a better understanding can be acquired of the molecular responses to radiation exposure. Recognising radiation's impact on gene expression is essential to evaluate exposure, assess risk and tailor medical responses. Numerous genes' expression levels may be simultaneously evaluated thanks to microarray technology. In radiation dosimetry, it is employed to identify genes whose expression is modified by radiation exposure. This method conveys a comprehensive view of the transcriptomic response to radiation (Ainsbury et al., 2022). Gene expression assay RNA-Seq is a powerful tool to gauge gene expression, delivering high-throughput, accuracy, besides the ability to identify novel transcripts and the principal genetic technique utilised for emergency dosimetry (Wang et al., 2010).

Haematological techniques

Haematological techniques that focus on the testing of radiation-induced changes in blood cells are integral to radiation dosimetry. These techniques are dependent on the blood cell counts post-accident (Dainiak et al., 2003). Detectable changes typically occur with doses equal to or exceeding 5 Gy, although individual susceptibility to radiation varies. Consequently, it is

crucial for a reference baseline to be established for each person, preferably shortly after exposure to radiation, although this may well introduce additional uncertainty, as noted by Ainsbury and Lloyd, (2010).

Biomarkers for proteins

Protein biomarkers are specific molecules whose levels change in response to radiation exposure, making them valuable indicators of biological responses. The use of protein biomarkers in radiation dosimetry can prepare a more wide-ranging assessment of the effects of radiation on living organisms. Many protein biomarkers are highly sensitive to radiation-induced damage and can be specific to certain kinds of radiation, such as X-rays, gamma rays or alpha particles. The γ -H2AX protein is acknowledged as the most beneficial radiation marker (Moquet et al., 2017). A considerably quicker method pertaining to biological dosimetry is the application of γ -H2AX. When ionizing radiation induces double-strand breaks in a cell's DNA, the neighbouring histone γ -H2AX is phosphorylated as part of the cellular DNA damage response, resulting in the phosphorylated form known as γ -H2AX (Rothkamm and Horn, 2009). The initial days after radiation exposure are the most effective period for employing this method as a triage tool because H2AX foci attains its highest point within an hour of exposure and subsequently decreases rapidly. It is possible to provide a dose estimation after approximately three hours, with the lower limit of detection set at 0.5 Gy, as documented by Ainsbury et al., (2011).

2.6.2.2 Physical dosimetry for emergency response

There are a number of important new potential for accident dosimetry with physically based dosimetry processes. Physical methods for evaluating dose in biologically sourced materials (dental enamel, fingernails, and toenails) or in non-biological materials (Bailiff et al., 2016). Physical effects caused by the absorbed radiation are the basis for physical dosimetry processes, which are measured in physical materials, biologically generated materials, or commonplace items that a person may wear or carry. Electron paramagnetic resonance (EPR) applied to tooth enamel or nails (Chumak et al., 1999; Sholom and McKeever, 2016) and thermoluminescence or optically stimulated luminescence (Bailiff et al., 2016; Ainsbury and Lloyd, 2010) are two common physical techniques utilised in retrospective dosimetry, enabling the quantification of energy absorbed by materials, including quartz in bricks and ceramics, alumina substrate surface mount resistors, and tooth enamel. Physical dosimetry has a few obvious advantages over biodosimetry, one of which being the ability to complete the dose reconstruction in a

matter of hours (2-4 hours) following sample receipt. Consequently, when assessing several samples—ranging from hundreds to thousands—for exposure levels associated with extensive radiological or nuclear emergencies, physical measuring approaches are expected to be beneficial and complementary to other sorting methods (Sholom et al., 2022).

Luminescence dosimetry

When an insulator or semiconductor is exposed to ionizing radiation, it produces mobile charge carriers that may become trapped at imperfections in the material's atomic structure. The same fundamental concept underlies both thermoluminescence (TL) and optically stimulated luminescence (OSL). In these procedures, ionising radiation causes electrons in an insulator or semiconductor's valence band to gain energy, which then propels them into metastable states or traps between the valence and conduction bands. In the solid, this results in the creation of electron-hole pairs, the number of which is commensurate with the radiation dose received. The system receives additional energy during a readout from either light exposure (OSL) or heating (TL). This energy excites the trapped electrons, causing them to travel via the conduction band and recombine with vacant holes, bringing about the emission of photons. This luminescence signal acts as a measure of the initial radiation exposure (Alghamdi et al., 2024). At present, numerous materials that are commonly used in radiation facilities have been produced for personal dosimetry, for example calcium sulphate, calcium fluoride, lithium fluoride, aluminium oxide or beryllium oxide (McKeever et al., 1995). Luminescence dosimetry is an effective emergency dosimetry technology on account of its many benefits, including low cost, great sensitivity to dose and immediate dose measurement. Natural minerals exposed to ionising radiation, such as quartz and feldspars, also exhibit a TL/OSL response. This phenomenon has been used in archaeological dating to determine the age of artifacts and geological materials (Aitken, 1985). Luminescence methods may be used to test the radiation sensitivity of many more materials found in the environment. As a result, luminescence methods were quickly adopted as a possible biodosimetry replacement in both emergency and retrospective dosimetry settings.

Building materials

Concerning retrospective studies, luminescence methods were among the initial approaches employed to evaluate absorbed dose following exposure to nuclear accidents. Ceramic building materials, such as fired-clay tiles and bricks, have long been the main medium used for dosimetry measurements. Additionally, natural quartz has been shown to be the ideal mineral

to determine radiation doses. Likewise, porcelain has been developed methodologically as a dosimeter (Hübner and Goksu, 1997; Oks et al., 2011), notwithstanding that it has not been used or tested more extensively (Bailiff, 1997).

These techniques for reconstructing radiation doses in building materials first appeared in the 1960s, with promising evidence demonstrating that they may be used to evaluate prior radiation exposures in the wake of nuclear or radioactive accidents (Meckbach et al., 1996; Higashimura et al., 1963; Hashizume et al., 1967). Studies have applied TL techniques to calculate the exposure of the tiles used on homes in and around Hiroshima and Nagasaki that were left standing after the atomic bombs were detonated in August 1945. Ceramic-rich building materials, including bricks and tiles, are rich in quartz grains, which have made them perfect for retroactive dosimetry employing optically stimulated luminescence (OSL) and thermoluminescence (TL) methods. Natural quartz has been extensively utilised as a dosimeter in archaeological dating by reason of the stability and sensitivity of its signal, making it a reliable dosimeter. Dose retroactive simulation that was performed by Young (2005), was consistent with the thermoluminescence calculations conducted on house tiles sourced from various locations in Hiroshima (Ichikawa et al., 1987; Nagatomo et al., 1992; Nagatomo et al., 1995). Exploiting luminescence measurements in connection with dose assessment, further research was conducted at Chernobyl, the former Soviet Union (Bailiff et al., 2004a; Sato et al., 2002), the Semipalatinsk Test Site (Sato et al., 2006; Göksu et al., 2006), and the Techa River, in the Ural Mountains (Bougrov et al., 1998; Göksu et al., 2002). These studies were conducted as a continuation of the research completed on tiles acquired from Hiroshima and Nagasaki. Cement (Göksu et al., 2003) and bricks containing calcium silicate (Bailiff and Mikhailik, 2004) are additional building materials that might be employed for dose restoration (Göksu et al., 2003; Bailiff and Mikhailik, 2004).

These studies have shown that radiation doses can be assessed years after a disaster using OSL and TL techniques on building components. It is predominantly utilised in long-term epidemiological research to support other techniques, such as biodosimetry techniques and computer modelling, nonetheless it does deliver the individual dosages concerning construction materials manufactured from ceramic. Dosimetry would be considered essential for epidemiological research and it would also be required for triage immediately after an accident, specifically for emergency dosimetry. Therefore, new materials are required for emergency dosimetry. The objective of biological and physical techniques in retrospective radiation measurement is to promptly identify and prioritise individuals with substantial

exposure levels. In this context, the DEPOt project which SUERC is a partner, began in 2023. DEPOt is specifically examining the use of quartz as an emergency dosimeter in the triage dose range. The project explores thermoluminescence (TL) of semi-stable lower temperature peaks, selected for their ability to persist long enough for post-exposure measurement while decaying rapidly to avoid geological dose residuals, with the date of fabrication ensuring a clean baseline free from prior environmental doses (Palczewski et al., 2024). Also the “BioPhyMeTRE,” project recently conducted under the NATO Science for Peace and Security (SPS) Programme, focused on validating innovative biological and physical techniques for the quick screening and triage of possible victims. This is achieved through the use of user-friendly and cost-effective analytical procedures and devices. The proposed biological method integrates the two most standardised biological dosimetry methods (Dicentric and Micronuclei assays) into a singular assay, enabling the simultaneous scoring of chromosome aberrations and micronuclei on the same slide. Moreover, the physical method emphasises the utilisation of a portable, low-cost micro photoluminescence reader to evaluate individual doses using personal objects that civilians wear or transport on a daily basis. The reliability of both methods for triage in R/N emergencies will be verified through the establishment of calibration curves and inter-laboratory comparisons. The project will improve the preparedness and response capabilities for nuclear and radiation incidents in Central Asia and Europe by fostering scientific collaboration among research institutions in Kazakhstan, Croatia, and Italy (Palczewski et al., 2024).

Personal items

An essential condition for any emergency dosimetry material is that it can be extensively distributed and easily accessed by the population. Various common materials were studied by Sholom and McKeever (2014) to determine if they could be used as emergency optically stimulated luminescence (OSL) dosimeters. These included coins and paper money (banknotes) in a range of denominations and origins, as well as other kinds of plastic cards (credit and debit cards, membership cards, driver's licenses, etc.), components of clothing and footwear, in addition to various fabric samples. These samples exhibited significant differences in their OSL properties. Native signals were observed in every sample, yet they were more prominent in specific materials (e.g., some plastic card examples and paper money) than in others (for instance, other examples of plastic cards) (Sholom et al., 2011). It was determined that each sample's natural signal form was different from the radiation-induced OSL profile, facilitating separation between the two signals. It has been demonstrated that the polymers

found in business cards, plastic cards, and paper money all display unstable OSL after irradiation (fading), just like the polymer materials found in clothing. However, these polymers demonstrated a monotonic reduction that allowed adjustments using straightforward mathematical procedures. The transmission characteristics of the polymers utilised, some of which were more transparent than others, also had an impact on the sensitivity of plastic cards. Sensitivities differed throughout the materials examined. Nonetheless, the dose response curves were linear, while the Minimum Measurable Dose (MMD) values for paper money generally ranged from 40 mGy to 240 mGy (although in some cases, values as low as 20 mGy and as high as 1.5 Gy were attained). The average range of plastic card MMDs was observed to be 8 mGy to 1.5 Gy (two 2 Gy outliers). Microscopic dust particles embedded in the surface were revealed to be the dominant source of the OSL signal observed in metal coins. Scanning electron microscopy analysis of the particles revealed that they were Al silicates, maybe feldspars. Fading similar to that observed in other feldspar cases was detected. Following adjustment, MMD values were determined to vary from 30 mGy and up to 2 Gy (Sholom and McKeever, 2014).

Glass display

Thermoluminescence (TL) measurements conducted on the glass cases of mobile phones, specifically focusing on lime-aluminosilicate glass and boron-silicate glass have yielded promising outcomes in terms of dose assessment. The blue spectrum emission in the 150-250°C temperature range of the glow curve. The dose response within this temperature range was linear for absorbed doses ranging from 10 mGy to 20 Gy and any observed fading was established to be correctable by way of universal fading correction methods. Furthermore, while both glass types exhibit similar TL emission peaks, they differ in intensity. The study concludes that both glass types could be useful for retrospective dosimetry in radiological emergencies (Discher and Woda, 2014).

Common materials

In the recovery phases after a nuclear or radiological event, it is essential to evaluate the radiation exposure of both the general public and rescuers. This evaluation is essential for guiding preventative measures and carrying out later impact studies. Numerous techniques, including evaluations based on measurements of materials present at the time of the occurrence, have been used at various stages following an incident (Sholom et al., 2011). Many common home materials, such as porcelain (Thomsen et al., 2002), household salt (NaCl; e.g., (Thomsen

et al. (2002) and Bernhardsson et al. (2009)], plastic cards, garments, shoes (Sholom et al. (2014), salted crackers, almonds, pretzels and crisps (Christiansson et al., 2017) have been investigated for their possible application in OSL dosimetry. Similarly, other researchers have investigated different materials as possible emergency OSL dosimeters. Woda et al. (2010) explored chip card modules; Pascu et al. (2013) investigated electronic parts of personal gadgets; and Ekendahl et al. (2013) studied the characteristics of glass ceramics used in dental restorations. All the materials listed were judged appropriate for emergency dosage rebuilding, given specific restrictions. According to studies by Grace et al. (2011) and Rea et al. (2010), radiation-induced OSL signals may often be used to recover doses less than 2 Gy, which is the dose level that is significant in after-exposure triage, from nails, plastic buttons, or business cards

Electron paramagnetic resonance (EPR)

Electron paramagnetic resonance (EPR) has become a vital instrument in radiation dosimetry for estimating individual received doses. Using this technique, paramagnetic centres that are particularly produced by ionising radiation exposure may be identified. These centres may show up as point defects or radicals. One of the most advanced and trustworthy techniques for assessing doses in the past is the use of EPR spectroscopy on tooth enamel. Radiation-induced paramagnetic species in tooth enamel may be found and measured using EPR, which offers a reliable way to calculate previously received doses. Because of its inherent stability and capacity to withstand environmental changes, tooth enamel is a perfect choice for these kinds of tests. It can keep records of radiation exposure over time due to its special composition and structure (Fattibene and Callens, 2010; IAEA, 2002d).

The evaluation of past and ongoing radiation exposures has made considerable use of electron paramagnetic resonance (EPR) dosimetry (Desrosiers and Schaure, 2001; ICRU, 2002). Especially, this method has been crucial in determining radiation exposure from major incidents as atomic bombs (Nakamura et al., 1998) and the nuclear accident at Chernobyl (Skvortsov et al., 2000). However, EPR dosimetry is not limited to dental enamel and bones; it may also be used with materials that can be obtained non-invasively. These materials include, but are not limited to, glass, wool, cotton, plastics, sugar, nails, and hair. These materials have the benefit of being accessible by non-invasive techniques, which makes them perfect for accidental EPR dosimetry applications. However, considering the cases outlined in section 2.2,

when quick evaluation of dose is necessary, it becomes clear that teeth and bones would not be the best choices for the triage scheme. This is mostly because the medical treatments required to remove them would be prohibitively expensive, especially considering that in vivo technologies for radiation dose monitoring are still in the early stages of development. The effectiveness and dependability of tooth enamel in the field of retrospective dosimetry should not be overlooked, notwithstanding the practical obstacles that may arise when using it for emergency dosimetry. Because tooth enamel is stable and sensitive to radiation, it is a great dosimetric material. However, it should be mentioned that using tooth enamel for retroactive dosage evaluation requires some safety measures. In particular, teeth need to be sterilised after extraction, before dentin and enamel may be separated. The enamel must next be meticulously processed, this may involve steps like hammering and purification—in order to get it ready for the EPR measurements. According to Fattibene and Callens (2010), these crucial stages ensure the precision and dependability of the EPR dosimetry data. These varied materials' applicability for different EPR dosimetries can differ greatly. The lowest dosage levels that can be accurately quantified are known as detection limits, and they range widely, from 0.1 Gy for tooth enamel to 10 Gy for cotton. It is critical to understand that these materials' effectiveness in EPR dosimetry varies and is dependent on a number of variables, including their intrinsic radiation sensitivity and the existence of paramagnetic centres that that can be accurately quantified.

2.7 Summary

This chapter has presented a review of the radiological accidents, emergency preparedness and response and also underlined the most important scientific factors connected with the most extraordinary radiation or nuclear incidents thus far. These include nuclear and radiological risk categories, detailing how unintended exposure to elevated amounts of ionising radiation can have dire repercussions on an individual's health, necessitating medical intervention, as well as the short- and long-term management of radiation exposure victims. They also consist of the lessons learned from nuclear accidents and health effects in relation to the general public/first responders, the importance of urgent precautions, exposure pathways, contingency planning areas, besides potential scenarios.

On account of the inevitable and direct health effects on people's health, along with the long-term consequences and high cost, the effects of nuclear accidents have been identified. There are several types of incidents that could cause radioactive substances to be released into the

environment, comprising both deliberate and inadvertent occurrences. Releases of radioactive substances may result from significant incidents at nuclear plants or nuclear weapon detonations, as well as from small occurrences such as traffic accidents. The degree of contamination and the radiological effects on the environment and individuals are mostly contingent upon the nature of the event and the related radionuclides. In a radiological or nuclear emergency, people can be exposed to radiation by means of various pathways. Individuals may encounter external radiation from polluted air and internal radiation from ingested radionuclides in the early stages of an emergency. Subsequently, several surfaces in the environment and on the ground will become polluted, exposing individuals to external radiation from deposited radionuclides. Afterwards, ingested radionuclides may pollute local foods and drinking water, exposing people to internal radiation. The primary concern in a radiological or nuclear emergency is to protect the impacted individuals. From a radiation protection standpoint, this involves striving to eliminate all deterministic health consequences associated with radiation while minimising the incidence of stochastic health effects in the exposed population to a practically attainable level.

An immediate medical response to a radiological accident requires a coordinated and well-prepared approach with the aim of reducing the health risks on affected individuals. Regular monitoring of radiation levels in affected areas and monitoring the radiation dose received by individuals is fundamental. Dosimetry allows the assessment of absorbed radiation doses and guides medical decisions. Medical triage and assessment triage supports the allocation of resources and the recognition of those requiring immediate care. Furthermore, prompt medical treatment is essential to tackle radiation-related injuries. This may entail managing burns, injuries from blasts or falls, and treating symptoms of radiation sickness. During a serious radiological incident, local hospitals may lack the ability to cope with the high number of potentially exposed individuals. To deal with this, pre-hospital triage is crucial. Given the ambiguity of biological symptoms, personal dosimetry is crucial in guaranteeing accurate assessment. Long-term follow-up studies to monitor health effects of radiation are valuable, but reliable individual dose estimates are essential for their relevance.

The literature review identified one possible area for investigation: the scenario of a significant threat of widespread exposure to radiation because of a radiological or nuclear disaster impacting substantial numbers of people. In these particular situations, it would be complex to apply effective radiometric methods to provide reassurance to people. In these potential scenarios, it's possible that the vast majority of people in the area would receive little or no

radiation exposure, and hence face no adverse physical effects. However, with no knowledge about whether they have received a radiation dose there would be significant issues with stress and mental health. To alleviate such concerns, it would be useful to assure people that doses they may have received were very much less than those which might result in needing medical treatment in the near or distant future. In these particular situations, it would be complex to apply effective radiometric methods to provide reassurance to people. Consequently, a preliminary quick evaluation of the incident's nature, delineation of impacted regions, identification of potentially affected individuals (triage), and measurement of radiation exposure received by first responders and the public are essential. The provision of pertinent information and the implementation of measuring procedures are crucial for guiding decision-makers in the management of radiation damage or exposure. This necessitates a dosimeter capable of swift data collecting and recording doses throughout a range from μGy to Gy , which are widely accessible, and that can provide almost real-time findings. In the aftermath of radiation incidents, it is important to evaluate doses in μGy for many reasons. Initially, even low radiation doses can yield biological effects, especially in populations at risk or throughout extended exposure durations. Accidents can lead to extensive, low-level contamination, and accurate measurements of μGy doses is essential for evaluating exposure levels and associated health hazards. Secondly, knowing the distribution of low-dose exposure is crucial for executing successful public health actions, like evacuation, decontamination, or limitations on food and water consumption. Third, accumulated exposure to extended low-dose radiation can result in considerable long-term risks including increased cancer incidence, thus it is essential to monitor and reduce small doses. Finally, accurate dosimetry at the μGy level enables epidemiological research, helping in the improvement of radiation protection standards and enhancing preparedness for future events. Therefore, in the context of radiation incidents, μGy -level dosimetry are crucial for providing reassurance to the public, mitigating widespread panic, protecting public health and enabling decision-making.

Many of these methods described in section 2.6 are appropriate for low-to-high dose regimens when it's necessary to identify individuals who could become ill as a result of exposure. However, to provide reassurance, it is crucial to verify that no one has been exposed to radiation that may be hazardous, especially in cases when a significant number of people could have been impacted. This necessitates the use of a dosimetry device capable of detecting ultra-low doses, which may be widely accessible or maybe implemented by placing appropriate materials in places that are at danger beforehand. Given that common table salt (NaCl) is present in

homes, restaurants, and workplaces all around the world, it has been suggested as a universal retroactive dosimeter. This suggests that sample preparation would be minimal and sample collection would be rather simple. Common salt has previously been shown to have the potential for retrospective dosimetry in the mGy dose range using laboratory instrumentation. In Chapter 3, I present results of investigation of the potential of using portable instruments with unprepared commercially sourced salt in dose ranges below 100 μ Gy, which responses from pulsed IRSL and portable OSL instruments were compared (Alghamdi et al., 2022) and investigate how sample storage in both light and dark environments affects OSL signals (Alghamdi et al., 2024). Additionally, In Chapter 4, I expand the investigation to search for other common products that emergency responders may use for triage. Talc is a geological substance widely used in many different sectors. It is also readily available, sensitive, and stable (Sanderson et al., 2002). To assess its potential as a dosimetric material utilising a portable instrument, I will carry out more investigation on its luminescence characteristics in Chapter 4. Finally, Chapter 5 will explore some of the practical considerations of deploying common materials as passive dosimeters.

The aim of the research shown in this thesis is to contribute to the development of this emergency dosimetry measurement system by finding new methods for radiological or nuclear emergency dosimetry, predominantly to enhance the response. The research work is structured to achieve these goals through:

- 1) The evaluation of portable instruments through testing and validating portable dosimetry tools for field use that could be deployed at or near the incident site to provide rapid measurement capability. This rapid evaluation is essential for the timely implementation of protective measures and decision-making.
- 2) Investigating the dosimetric properties of common materials to identify the most favourable conditions for measuring OSL signals induced by radiation in these materials as alternative or complementary to other measurement methods, thus enhancing the response by using common materials that are readily available and inexpensive at the accident site and covering the time periods before other measurement methods are initiated, providing a more comprehensive picture of the affected region.
- 3) Validation studies through conducting experiments to verify the accuracy and reliability of new methods (passive dosimeters using salt) in mapping radiation fields and measuring individual doses across diverse scenarios and within three different radiation environments and

compare the results with spectrometric approaches, demonstrating the method's potential in real-world scenarios.

4) Creating guidelines for implementing these new methods and challenges, lessons learned, and future work that will develop these methods to use in emergency response scenarios.

The work presented in this thesis aims to improve the general capability and effectiveness of radiological emergency response.

Chapter 3

Case study 1: Radiological or nuclear emergency OSL dosimetry using commonplace salt

3.1 Introduction

In chapter 1, I addressed the problem that I am researching in this thesis, which is related to the requirements of dosimetric measurements and assessments immediately following the occurrence of accidental or malicious use of radiation, to enable decision-making on short timescales during responses to radiation or nuclear emergencies. Chapter 2 reviewed the main issues, needs, and current techniques for effective early management, and identified the needs for more rapid field portable dose assessments. In particular, I identified salt as a highly sensitive material that has potential for such measurements.

In later stages of response it may be necessary to reconstruct the doses that individuals and communities received. Determining lower doses than those associated with early countermeasure decision-making may also be necessary for retroactive analysis for recovery and scientific investigations (Alghamdi et al.2024). Passive dosimeters employing thermoluminescence (TL) and optically stimulated luminescence (OSL) are suitable options for this purpose. Consequently, expedient methods for detecting external radiation utilising commonplace products or environmental resources would be highly beneficial for screening purposes. Chapter 2 explores the requirements and conventional approaches, followed by the benefits of passive dosimetry. Chapter 2 has examined how luminescence techniques can be employed for absorbed dose assessment in radiological emergency situations. It has been argued that dosimetry is needed for the management of large-scale radiological accidents harming members of the general public (Chapter 2) and that luminescence techniques can be employed for dose assessment using commonly held personal objects, objects from the surroundings and material both in the household and workplace environments. In this chapter, I will be looking at salt as a commonly available, low-cost material for that role, providing a practical and accessible means of radiation detection and measurement in emergency

situations. This will involve assessments of sensitivity, detection limits and reproducibility of measurements using different portable optical luminescence readers, and signal stability. I will also explore the potential to pre-characterise dose responses for bulk produced salt, thus removing the requirement for calibration doses in field measurements.

Stoddard discovered in 1960 that light stimulation could cause luminescence in irradiated NaCl [as Reported by Geber-Bergstrand (Geber-Bergstrand, 2017)]. Observations of TL and PSL from salt in the context of detecting irradiation of food have shown that this is a sensitive of material (Sanderson et al., 1989c; Sanderson et al., 1996; Sanderson et al., 2003a). Bailey et al. (2000) conducted studies of NaCl OSL, and concluded that OSL of NaCl may be a useful dating tool Bernhardsson et al. (2009) measured linear dose responses for five different salts using 470 nm blue LEDs to stimulate signals from 5 mg samples using a Risø DA-15 TL/OSL reader, with detection limits in the 0.1–1.0 mGy Range. Ekendahl and Judas (2011) measured OSL from salt using Riso OSL/TL readers, showing that salt is a sufficiently sensitive material for retrospective and accident dosimetry with a detection limit of 0.4 mGy. Christiansson (2014) investigated the dose response for various salts also using Riso readers, demonstrating favourable dosimetric features for low-dose (mGy) applications, with a linear dose response in the range 1–100 mGy and detection limits as low as 0.2 mGy. Waldner (2021) investigated the use of NaCl pellets for occupational dosimetry using OSL, with detection limits around 20 µGy, and also reviewed data for 102 different salts purchased in 47 countries showing variation in sensitivity particularly associated with iodine content.

TL studies of different salts have demonstrated peaks at ~100 and 260°C, with emissions at 590 nm (Spooner et al., 2011; Hunter et al., 2012). The 100°C peak has been shown to have a lifetime at 20°C of 7–14 h (Spooner et al., 2012), whereas the 260°C peak has a lifetime of 4 ka (Spooner et al., 2011; Hunter et al., 2012). Pulsed annealing OSL and IRSL experiments (Spooner et al., 2012) identified OSL signals as originating from traps associated with both 100 and 260°C TL peaks, whereas the IRSL signals were identified as predominately originating from traps associated with the 100°C peak, and that there are no deeper traps in salt associated with either IRSL or OSL. Christiansson et al. (2014) reported that OSL signals stimulated with blue diodes did not fade after 140 d storage, with a preheat of 10 s at 220°C. Low rates of fading (~5% over 2–4 weeks) have also been reported (Thomsen et al., 2002; Bailey et al., 2000; Ekendahl et al., 2011). More significant fading (35% after 7 days) was reported by Timar-Gabor and Trandafir (2013) with a lower pre-heat at 150°C. Demonstrations of the use of salt as a personal dosimeter in Fukushima following the nuclear power plant accident, and in small

salt containers in a village contaminated by the Chernobyl accident with salt packages left in kitchens for 4–5 months which measured doses down to 500 μGy (Christiansson et al., 2014) have shown that radiation doses as low as 0.1–1.0 mGy region can be registered. The work reported here extends these prior investigations to lower dose regions, using portable OSL measurement systems that could be deployed at or near the incident site to provide rapid measurement capability.

This experiment in the first part, assesses whether portable instruments, which will be described in Section 3.2.1, can produce comparable or better sensitivity than laboratory-based systems. Can these systems perform adequately for initial dose assessments under field conditions, thus removing the need to transport samples for analysis on laboratory instruments, and with sample throughput sufficient to provide significant quantities of quality data on emergency timescales? Can bulk produce be pre-calibrated prior to distribution, thus allowing initial dose assessments to be made without the need for individual calibration? For these questions, system performance will be evaluated through assessments of detection limits and dose response characteristics of replicated samples of commercially packed salt sachets. Further experiments will be needed to fully assess performance under potential application scenarios, but initial questions concern sensitivity and reproducibility of measurements undertaken at ambient temperature using portable or field deployable instruments. Also, the second part of this experiment aims to determine the optimal conditions for measurements of the radiation-induced OSL signal in NaCl using the SUERC Portable OSL Reader (Sanderson and Murphy, 2010). Key OSL properties, such as, signal stability with time, the effect of light bleaching and humidity are investigated empirically. TL analyses of NaCl are conducted to determine trap parameters to better understand the observed behaviour and predict the impact of changing environmental conditions.

3.2 Materials and Methods

3.2.1 Instrumentation

This section provides an expanded explanation of the experimental apparatus used throughout this thesis. It offers a comprehensive overview of the instruments employed to investigate the physical luminescence properties of the tested samples. To measure the luminescence signals from salt, we utilized three portable instruments. Specifically, we used a portable OSL system

that is designed for luminescence measurements of sediments. This system is equipped with blue and IR diodes, as described by Sanderson and Murphy (2010). Additionally, we employed a pulsed IRSL system developed for determining whether foods have been irradiated, as described by Sanderson et al. (1996). Furthermore, we utilized an alternative system with two different IR wavelength diodes for ultra-sensitive IRSL, as outlined by Francoz (2023) and Fitzgerald et al. (2022). Finally, the TL instrument played a vital role in our study, allowing for the detailed examination of the glow curve characteristics and kinetic parameters of our samples.

3.2.1.1 Photo-stimulated luminescence food instrument

The SUERC PSL instrument (as shown in Figure 3.1) stimulates luminescence using pulsed 880 nm infrared diodes. The signal is registered in an up-down counting mode using a single photon counting photomultiplier, where the luminescence during pulses is subtracted from the dark count and any phosphorescence that occurs between pulses (Sanderson et al., 1996). The instrument can be operated in two modes: stand-alone mode, or laboratory computer mode, which allows for data storage and record keeping. For the instrument, samples are placed in disposable petri dishes, and the sample drawer is closed to prepare for measurement. The measurement process usually takes 15-60 seconds. This instrument was specifically designed to conduct screening measurements on foods that may have been exposed to high doses of radiation, using a standard method (CEN, 2009), but has also previously been used for retrospective dosimetry on bricks to 100 mGy detection limits (Niedermayer et al., 2000). For this work, net counts from 60 s measurements were recorded.



Figure 3.1 Photo-stimulated luminescence food instrument

3.2.1.2 The SUERC portable OSL reader

The Scottish Universities Environmental Research Centre (SUERC) has developed an advanced portable optically stimulated luminescence (OSL) device, building upon earlier technology designed for food analysis (Sanderson and Murphy 2010). This instrument is tailored for applications in geological and archaeological research. The device incorporates both infrared (IR) and blue light-emitting diode (LED) arrays, which can be operated in pulsed mode (up/down counting) and continuous wave stimulation. Its compact design and battery-powered operation make it highly suitable for field-based investigations, allowing on-site luminescence measurements to be conducted with ease. A variation on this using 90 mW 890 nm and 90 mW 940 nm IR diodes with a 3 mm BG 39 filter has been developed to increase efficiency for IRSL measurements by an order of magnitude specifically for studies of young sediments (Francoz, 2023) and also allowing investigation of IRSL response of feldspars to different stimulation wavelengths (Fitzgerald et al., 2022), and is also used in this work. The instruments used in this work were operated according to the sequence described in Sanderson and Murphy's (2010) study, which is suitable for rapidly measuring undifferentiated bulk polymineral samples. Figure 3.3 shows the overall process, which can be applied to many different types of samples. The process involves using a continuous wave mode with alternating measurements of 15 seconds of dark count, two 30-second measurements with longer wavelength diodes, 15 seconds of dark count, and two 30-second measurements with shorter wavelength diodes, followed by another 15 seconds of dark count for each sample. In sections 3.2.2.3, 3.2.2.5 and 3.2.2.6, the SUERC Portable OSL Reader was operated using stimulation by blue LEDs only because in section 3.2.3.1 showed higher signals and lower detection limits compared to IRSL, and blue OSL has been reported to be more stable (Bailey et al., 2000).



Figure 3.2 The SUERC portable OSL reader. Developed for luminescence measurements of sediments. Equipped with blue and IR diodes. A variation on this uses two different IR wavelength diodes for ultra-sensitive IRSL(Sanderson and Murphy, 2010) .

IRSL and OSL intensities

- $IRSL = IRSL1 + IRSL2$
- $OSL = OSL1 + OSL2$
- $IRSL = b + c - 2a - 2d \pm \sqrt{(b+c+2a+2d)}$
- $OSL = e + f - 2d - 2g \pm \sqrt{(e+f+2d+2g)}$

Proxy for age, sensitivity, dose rate

IRSL and OSL Fast front end

- $IRSL = IRSL1 - IRSL2$
- $OSL = OSL1 - OSL2$
- $IRSL = b - c \pm \sqrt{(b+c)}$
- $OSL = e - f \pm \sqrt{(e+f)}$

Fast decaying net signal

Depletion indices

- $IRdep = IRSL1/IRSL2$
- $OSLdep = OSL1/OSL2$
- $IRdep = (b-a-d)/(c-a-d) \pm IRdep * \sqrt{((b+a+d)/(b-a-d))^2 + ((c+a+d)/(c-a-d))^2}$
- $OSLdep = (e-d-g)/(f-d-g) \pm OSLdep * \sqrt{((e+d+g)/(e-d-g))^2 + ((f+d+g)/(f-d-g))^2}$

Proxy for: residuality, colour (photon fluence), diagnosis

IRSL/OSL ratio

- $IRSL/OSL = (IRSL1+IRSL2)/(OSL1+OSL2)$
- $IRSL/OSL = (b+c-2a-2d)/(e+f-2d-2g) \pm IRSL/OSL * \sqrt{((b+c+2a+2d)/(b+c-2a-2d))^2 + ((e+f+2d+2g)/(e+f-2d-2g))^2}$

May indicate mineralogical variations

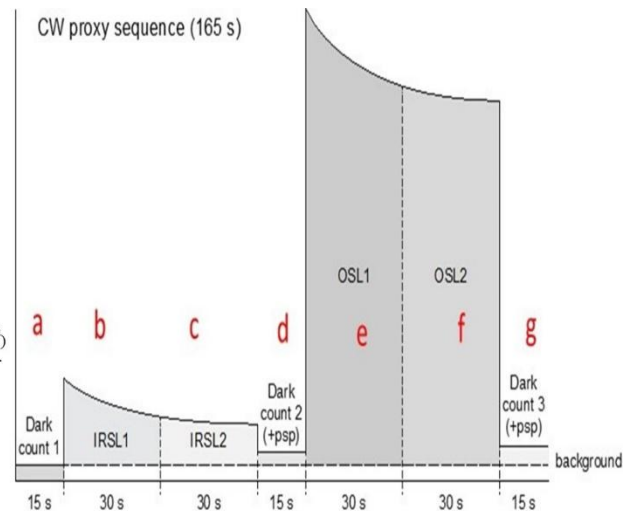


Figure 3.3 Prof. D. Sanderson's field profiling proxies sequence (Sanderson and Murphy, 2010) was developed for the SUERC portable reader, CW proxy sequence allows these to be recorded automatically.

3.2.1.3 TL instrument

TL instruments are designed to measure the thermoluminescence properties of materials, which can help determine the dose of ionizing radiation received by the material or the age of certain archaeological or geological samples. The TL reader utilized in this thesis is a specially designed SUERC device comprising of a photomultiplier tube capable of detecting individual photons, which is positioned on top of a sealed sample container (Figure 3.4). which uses an Electron Tubes 9883 QB photomultiplier filtered with 3mm Kopp 7/59 and 3 mm Schott KG1 filter glass (Sanderson et al., 2002). This filter combination transmits blue and UV light

(approximately 320 - 460 nm). Spooner et.al. (2011) report strong TL emission at 590 nm, which this filter combination will not transmit, and weaker emissions in the blue (~440 nm) and UV (370 nm) which will be detected. The fundamental parts of the TL instrument include: a) a sample holder, where the material for analysis is placed; b) a heating element, which increases the sample's temperature; c) a light detection system, typically using a photomultiplier tube (PMT) or photodiode to detect light emissions; d) a temperature control system, which regulates the heating process with precision; and e) a computer with dedicated software, connected to an Analogue to Digital Converter (ADC) and Multi-Channel Scalar (MCS) cards, to record signals and control the heating system (Spencer, 1996).

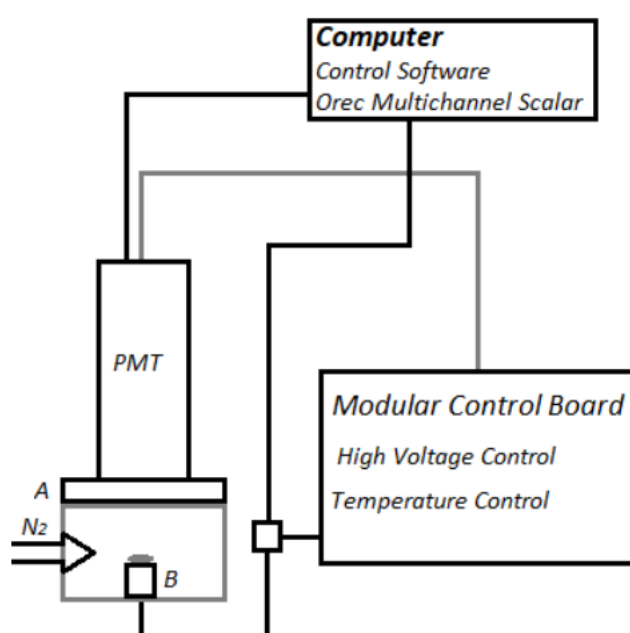


Figure 3.4 illustrates the TL reader setup. It includes a PMT with a 3mm BG39 filter positioned in a holder between the PMT and the sample chamber (A). The sample chamber is equipped with a heating unit (B), which can be manually controlled using the modular control board or automatically controlled from the computer. Reproduced from Fitzgerald, 2024.

3.2.2 Sample preparation

A box of 2,000 single serve salt sachets, all from a single batch, each of blue polyethylene containing 0.85–1.00 g >99.99% NaCl, was procured from a commercial retailer (figure 3.5) Samples were prepared from randomly selected sachets for each experiment. All sample handling and measurement was conducted under subdued lighting.



Figure 3.5 Commercially pre-packaged salt

For initial tests of response to beta irradiation, 30 samples were prepared on 30 mm diameter aluminium planchettes. These were sprayed with silicone grease as an adhesive before ~ 0.5 g of salt was spread evenly over the surface. Silicone grease is commonly used for this purpose because it does not affect the luminescence response of silicate minerals and other materials, including food stuffs (CEN, 2009). Ten of these were used to register the responses of each of the three luminescence instruments, before and after beta irradiation to a dose of 200 mGy. The initial measurements were made to determine the extent of any inherited luminescence from the as-prepared material. Samples were then exposed to beta-radiation at doses of 200 mGy at room temperature using a 0.62 GBq ^{90}Sr source of surface area 4 cm^2 mounted in a shielded irradiator with a working distance of 7.5 cm. The quartz equivalent dose rate in the sample position for this source had previously been determined (Francoz et al., 2023) relative to a series of ^{90}Sr sources in Elsec automatic irradiators and Risø readers in the luminescence dating laboratory at SUERC. These in turn had been calibrated relative to primary photon irradiations at the UK's National Physical Laboratory, and to secondary irradiations at SUERC. Following irradiation the samples were preheated for 30 min at a temperature of 50°C to remove unstable luminescence signals prior to re-measurement to establish the response to the 200 mGy dose.

3.2.3 Experimental measurements

3.2.3.1 Comparison of instruments

The experiment used beta irradiated samples on 3 cm planchettes which had received nominal 200 mGy doses. Ten samples were measured in each of the three instruments, with both portable OSL instruments using two wavelengths, giving five sets of measurements. Each measurement sequence started and ended with empty chamber backgrounds, and reference materials to confirm functionality of the instruments.

The counts for each measurement from the 200 mGy irradiated samples were used to determine a sensitivity (photon counts per Gray, c Gy^{-1}) from the 0.5 g of salt for each instrument and light source. The measurements prior to irradiation showed a residual signal that was small compared to the signals after receiving the 200 mGy dose. Measurements of salt samples that had been exposed to artificial daylight for 1 week showed luminescence signals significantly above the empty chamber, especially with 890 and 470 nm stimulation, and it is concluded that obtaining a salt sample with zero luminescence to act as a blank is impractical for this evaluation of the systems. For the purposes of estimation of minimum detectable doses in this study we consider that the empty chamber blank is satisfactory. The empty chamber background measurements produced consistent values, and minimum detection limits (MDL) were determined as the mean of these counts plus three times their standard deviation. These were then converted to dose using the sensitivity calculation, assuming a linear dose response over this range which is expected from the prior studies of luminescence from salt, giving a minimum detectable dose (MDD) in mGy.

3.2.2.2 Dose response

To determine the dose response behaviour in the microGray to sub-milliGray region 50 unopened sachets were exposed to gamma-ray doses of 20, 50, 100, 200, and 500 μGy . These were irradiated in sets of 10 using a nominal 17 MBq ^{60}Co source at a working distance of 20 cm. Ten sachets were retained as unirradiated controls. The sachets were weighed prior to use to confirm that they all contained the same mass of salt (gross weight 0.99–1.00 g). The dose rate for the ^{60}Co source had been estimated from the source activity, sample to source distance and mean gamma ray energies. This was verified in March 2021, using Fontainebleau quartz grains placed in 5 mm diameter quartz tubes within a 1 mm thick aluminium tube to develop charged particle equilibrium and gamma irradiated to estimated doses of 50 and 100 mGy (Martin et al., 2022). The powder was dispensed on disc for measurement on a Risø DA-15 OSL/TL reader, along with additional sets for control beta irradiations and a set of blanks. OSL analysis and renormalization using the ^{90}Sr source in the Risø reader was conducted and an updated ^{60}Co dose rate at this working distance was estimated. Decay corrections were applied to the ^{60}Co dose rate determined, using the half life of 5.27 y giving a dose rate of 142 $\mu\text{Gy/h}$. The total mass attenuation coefficient (in m^2/kg) for salt and air across a range of gamma-ray energies (keV) illustrates the interaction of these materials with radiation released by the ^{60}Co source at different energy levels. Figures 5.4 and 5.5 show the total mass attenuation coefficient (in m^2/kg) for salt and air throughout a range of gamma-ray energies

(keV), derived from tabulations of interaction cross sections from Storm and Israel (1970) and Hubbell (1977, 1982) produced by Tyler (1994) and Allyson (1994), focussing specifically on the primary gamma rays released by ^{60}Co at 1173 keV and 1332 keV. The total mass attenuation coefficient reflects a material's effectiveness in attenuating gamma radiation, which is crucial for evaluating its suitability for dosimetry. The mass attenuation indicates that for higher energy gamma rays (>250 keV), including the ^{60}Co lines, the response of salt (blue line) is within 2% of that of air, resulting in almost comparable dose measurements between salt and air kerma (red line) at these energies. The same attenuation qualities indicate that air's presence minimally influences gamma-ray interactions with salt, allowing for reliable measurements of radioactive doses without much interference from the ambient air. The graph also illustrates that salt and air exhibit analogous behaviour over a wide energy spectrum (100 keV to 1500 keV), therefore substantiating the assertion that their electron energy interactions are comparable. The consistent response of salt and air across the energy spectrum highlights the suitability of salt for environmental radiation evaluations, as its reactivity to gamma radiation is largely unaffected by the surrounding medium (NIST, 2025).

The full contents of each sachet were emptied into 50 mm diameter petri dishes to give an evenly distributed layer on the bottom to present to the instruments (10 sachets at each dose for each instrument). For the dose response experiments to photon irradiation in the 20–500 μGy regions samples were stored under dark conditions at room temperature for 10 days to allow any unstable signal components to decay before measurement. Prior studies, as outlined above, indicate that signals from salt do not fade significantly after a few days if pre-heating is used to remove signals associated with shallow traps. The 10d period was selected pragmatically, in order to ensure that the differences in storage time between irradiation and measurement were small compared with this post-irradiation delay. No further preheating was undertaken at this stage.

The experiment used the salt sachets which had been gamma irradiated to low dose (0–500 μGy) to develop a dose response curve over this dose range, which incorporates the range of interest for public reassurance. Ten samples at each dose, including unirradiated controls, were measured initially using the instrument with the lowest detection limit, the Portable Reader operating with 470 nm blue LEDs. The experiment was repeated later using the food instrument and the IRSL system at 890 nm.

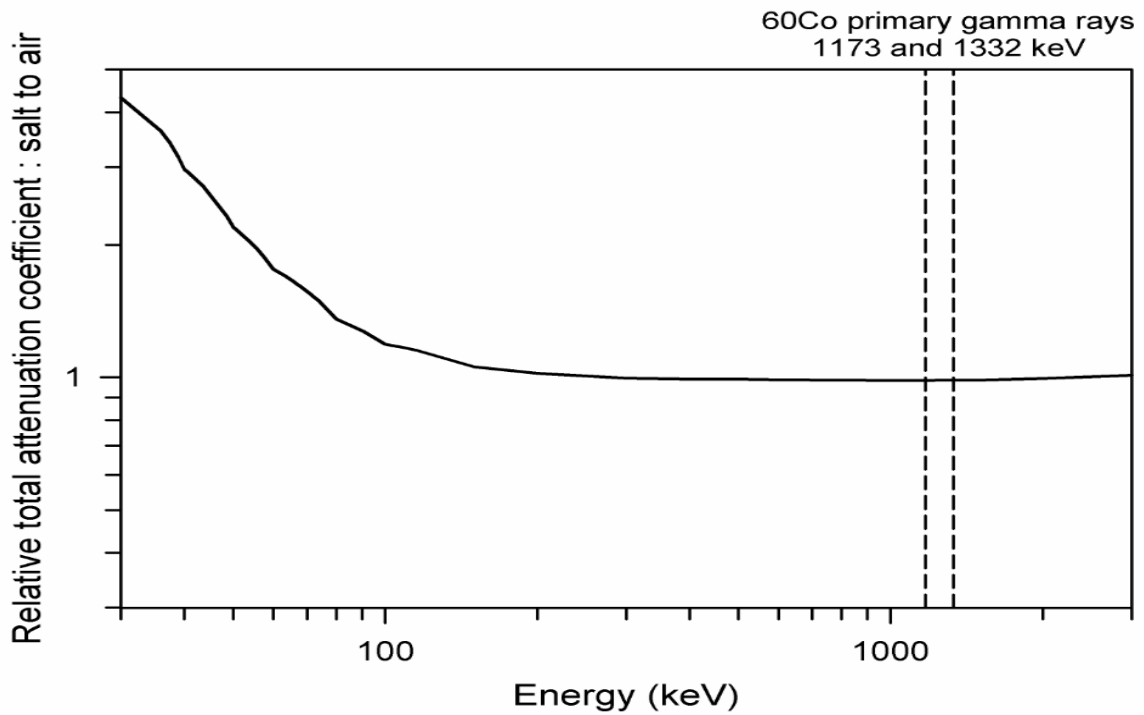


Figure 3.6 Comparison of the total mass attenuation coefficient (m^2/kg) for salt and air as a function of gamma-ray energy (keV) shown on a logarithmic scale.

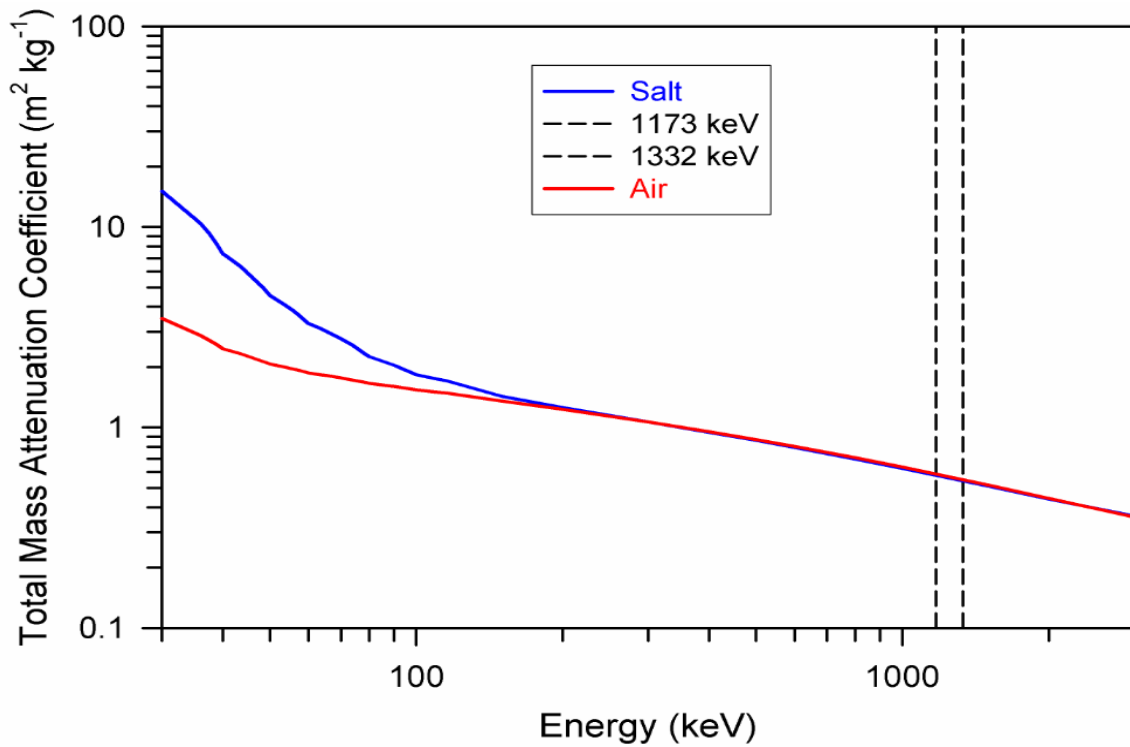


Figure 3.7 Total mass attenuation coefficient (m^2/kg) for salt (blue line) and air (red line) as a function of gamma-ray energy (keV) on a logarithmic scale, ranging from 100 keV to 1500 keV.

3.2.2.3 Signal stability tests

Signal stability can significantly impact dose reconstruction, and influences detection limits. So, the next step was to study the signal stability from salt over a period of 256 days after irradiation of the samples. Seventy unopened sachets were weighed to confirm that they all contained the same mass of salt (gross weight 0.99 –1.00 g), and irradiated to a dose of 10mGy (3days) using the ^{60}Co source. Ten sachets were retained as unirradiated controls to measure the background accumulated during storage.

The full contents of each sachet were emptied into 50 mm diameter petri dishes to deliver an evenly distributed layer on the bottom to present to the instrument (10 sachets for each storage time). The OSL readings were performed at different times post-irradiation, specifically 4, 8, 16, 32, 64, 128 and 256 days, and stored in the dark between irradiation and readout. A background reading was taken from an unirradiated sample and subtracted from the irradiated sample reading. No further preheating was undertaken at this stage. For rapid emergency measurements, it will be preferable to avoid any additional material processing. Preheating will be possible at low temperatures up to about 50 degrees using suitable ovens in the field, should this be necessary.

For emergency response, stability over shorter timescales than possible in the experiment described above would also need to be assessed. A stronger beta source was used to investigate fading over shorter intervals. Ninety samples were prepared on 30 mm diameter aluminium planchettes, sprayed with silicone grease as an adhesive before ~0.5 g of salt was spread evenly over the surface. Samples were exposed to 200 mGy at room temperature using a 0.62 GBq ^{90}Sr source of surface area 4 cm² mounted in a shielded irradiator with a working distance of 7.5 cm. The OSL readings were collected at 1, 2, 4, 8, 16, 32, 128 and 256 days to giving data with shorter timescale over-lapping the gamma radiation which allows comparison of the results of the two experiments. Calibration for the beta source using quartz has been described previously by Francoz (2023) and Alghamdi et al.,(2022).

3.2.2.4 TL Analysis of glow curve characteristics

The luminescence properties of materials principally depend on the kinetic parameters of trapping states. The trap depth (E), frequency factor (s) and order of kinetics (b) which can be estimated from TL measurements. To determine these characteristics, 10 samples of salt were prepared. Approximately 0.2 mg was placed on a Silicone sprayed 10mm disc to ensure that the salt remained attached to the disc and did not scatter during movement. No additional processing was performed on the salt samples. All subsequent procedures, such as irradiation, storage and TL measurements were performed in normal laboratory conditions (approximately at 21 ± 2 °C, relative humidity of 31%) and in darkness. All samples were given a 200 mGy dose, with TL measurements from room temperature to 500 °C at 5 °C s^{-1} with a 5 minute interval at room temperature between irradiation and readout. Kinetic parameters of the first and second peaks were determined from the Arrhenius plot of the initial rises coupled with peak maximum temperatures.

3.2.2.5 Effect of exposure to light (simulated daylight)

To explore the effects of light exposure (simulated daylight) and the possibility of removing the residual environmental signal to zero, an absorbed dose of 10 mGy was given to 40 samples of salt in their sachets. Thirty irradiated samples were stored under artificial day light in a light box with approximately 7 mWcm^{-2} total fluence (Sanderson et al., 2002) and measurements were made after delays of 2.5, 5, and 24 hours. Ten control samples were measured after storage in the dark for 24 h. Ten irradiated samples were wrapped and sealed tightly using black plastic shrink and stored under an artificial daylight box for 24 hours to investigate whether this is sufficient to protect salt from daylight bleaching.

3.2.2.6 Signal stability under different levels of relative humidity

Salt is hygroscopic, and will absorb water if stored in open air. It is essential to investigate whether crystal structure changes from water absorption influence luminescence response. To study the effects of moisture on the salt after irradiation 40 unopened sachets were given a gamma dose of 10 mGy. Ten sachets were retained unopened as unirradiated controls to measure the background signals from salt accumulated during storage. After irradiation, the full contents of each sachet were emptied into 50 mm diameter petri dishes and the gross weight recorded. Ten samples were stored at room temperature in dark storage and an air-tight aluminium chamber, with the relative humidity measured as 32 % using a Thermopro TP50 humidity instrument. Ten samples in petri dishes were also stored in a plastic box with water

in the bottom to increase relative humidity, which was measured as 53 %. The petri dishes were weighed after storage for 32 and 64 days to record changes in weight at different relative humidity levels. OSL signals were then recorded. Ten irradiated samples were wrapped and sealed tightly using heat-shrink sleeving, and stored at a relative humidity of 53% for 10 days to assess protection against hydration.

3. 3 Results

3.3.1 Backgrounds, sensitivities and detection limits

The count rates and standard deviations for measurements of the background and the salt samples irradiated to 200 mGy, for all five sets of measurements, are given in Table 3.1. The highest photon counts, from the 200 mGy dose, and lowest detection limit were given by the portable OSL instrument using blue LEDs (2303 ± 81 kc with a MDD of $6.7 \mu\text{Gy}$). All other systems gave lower counts and higher detection limits. The sensitive IR portable OSL system gave 605.9 ± 60.9 kc at 890 nm from 200 mGy (compared with 43.3 ± 1.7 kc for the same wavelength in the less sensitive system) and a MDD of $31 \mu\text{Gy}$. Note that the measurement sequence had already depleted some signal from the samples prior to the 940 nm measurements on this system, which may explain the lower sensitivity recorded. The PPSL instrument using IR stimulation in up-down counting mode gave counts of 279.2 ± 71.2 kc from 200 mGy, and a MDD of $88 \mu\text{Gy}$. All the instruments used here can have a useful role in dosimetric measurements using salt. The detection limits for the PPSL and the IR only portable system using 0.5 g samples are lower than previously reported for measurements using Risø readers which reported detection limits above $100 \mu\text{Gy}$ using aliquots with mg quantities of salt (Bernhardsson et al., 2009; Ekendahl and Judas, 2011). However, the blue OSL system is significantly more sensitive with lower detection limits.

Table 3.1 Photon counts and standard deviation for the background and 200mGy irradiated salt samples for five sets of measurements on three instruments, with calculated sensitivities and detection limits.

	Instrument and wavelength				
	PPSL	Portable OSL 1		Portable OSL 2	
		IR (890nm)	IR(940nm)	IR (890nm)	OSL (470nm)
Background (empty chamber)	20 ± 34	-10 ± 32	-4 ± 31	45 ± 25	-61 ± 26
MDL (counts)	123	95	94	74	78
Pre-irradiation counts	113 ± 72	-4 ± 73	-146 ± 89	-27 ± 128	673 ± 160
200mGy counts	$279,200 \pm 71,200$	$605,900 \pm 60,900$	$65,500 \pm 21,800$	$43,300 \pm 1700$	$23,03,300 \pm 80,700$
Sensitivity (counts mGy ⁻¹)	1400 ± 240	3030 ± 300	330 ± 110	220 ± 10	$11,520 \pm 400$
MDD (mGy)	0.088	0.031	0.286	0.340	0.0067

3.3.2 Dose response

The gamma irradiated materials were used to construct dose response curves for salt irradiated to low dose (0–500 μGy). The mean net photon counts and standard deviation recorded from 10 samples of salt at each dose are given in Table 3.2, with the mean counts, after subtracting the mean counts for the 0 μGy samples, plotted in Figure 3.8. For the blue OSL signals the data in Figure 3.8 are well-described by a linear regression (slope $44.5 \pm 0.9 \text{ c } \mu\text{Gy}^{-1}$). The 0 μGy signal would correspond to a residual dose of $66.1 \pm 4.4 \mu\text{Gy}$. Dose response curves for the other instruments and wavelengths (Figure 3.8) also show linear regressions with smaller slopes (6.4 ± 0.5 and $4.8 \pm 0.2 \text{ c } \mu\text{Gy}^{-1}$ for the 890 nm IRSI and pulsed PSL respectively) reflecting the different sensitivities (Table 3.2). The signals without an additional dose are simply explained as a result of prior exposure of the salt to environmental doses arising from naturally occurring radionuclides and cosmic rays. For the initial measurements using blue OSL, this corresponded to a dose of $66.1 \pm 4.4 \mu\text{Gy}$. The subsequent measurements, 105 d later, using IR (890 nm) stimulation gave a dose of $213 \pm 23 \mu\text{Gy}$, the difference corresponding to a dose rate of $0.058 \pm 0.001 \mu\text{Gy h}^{-1}$. The gamma dose rate in the cupboard where the salt was stored was measured as $0.063 \pm 0.002 \mu\text{Gy h}^{-1}$ using a $2 \times 2''$ NaI spectrometer, which is entirely consistent with the values observed.

Table 3.2 Mean and standard deviation OSL photon counts recorded using the SUERC Portable OSL reader at 470 nm, the IRSL instrument at 890 nm and the pulsed PSL instrument, from 10 sachets of salt exposed to gamma doses from 0-500 μGy .

	Portable OSL 470 nm		Portable IRSL 890 nm		Pulsed PSL 880 nm	
Dose (μGy)	Net OSL	CV (%)	Net IRSL	CV (%)	Net IRSL	CV (%)
0	3534 ± 453	12.8	1204 ± 313	26.0	1324 ± 102	7.7
20	3307 ± 689	20.8	1443 ± 300	20.8	1256 ± 150	12.0
50	5091 ± 460	9.0	1843 ± 607	32.9	1487 ± 122	8.2
100	7323 ± 444	6.1	2214 ± 202	9.1	1701 ± 143	8.4
200	$11,860 \pm 1086$	9.2	2388 ± 655	27.5	2038 ± 237	11.7
500	$25,202 \pm 2303$	9.1	4565 ± 687	15.1	3649 ± 385	10.6

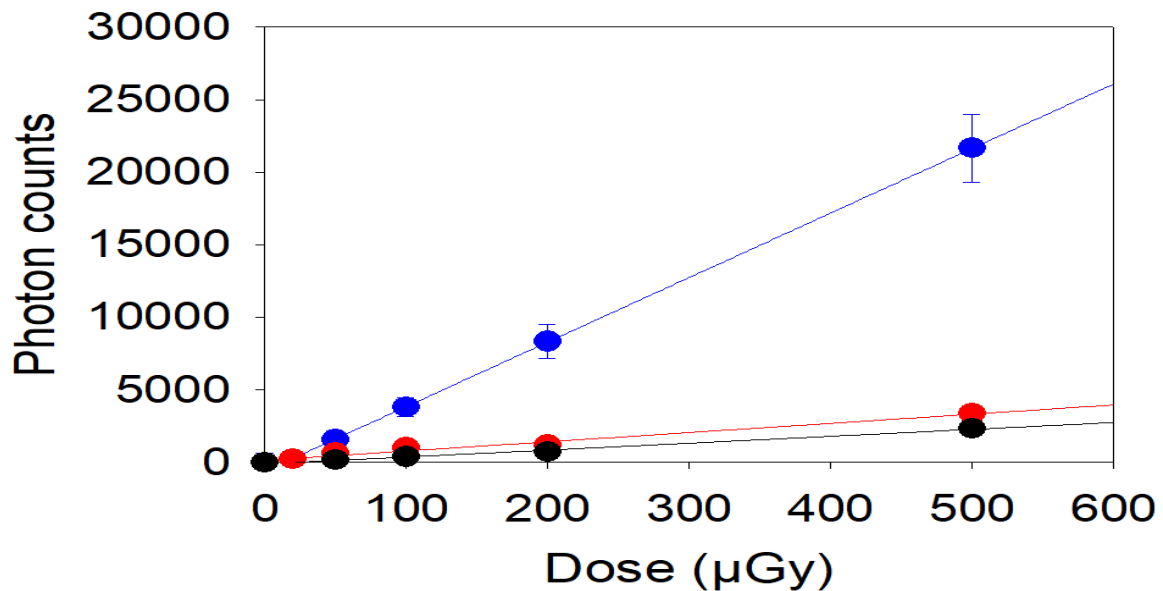


Figure 3.8. Dose response from gamma irradiated samples measured using a blue OSL portable reader (blue), 890nm IRSL (red) and the pulsed PSL (black) instruments, after subtraction of the signals from the salt which did not receive additional doses (Alghamdi et al., 2022).

3.3.3 Signal stability tests

The results of the signal stability experiments are shown in Figure 3.9, where the OSL counts have been normalized by dividing by the dose given (10 mGy with ^{60}Co and 200 mGy with ^{90}Sr) and sample mass. For the overlap region covered by both experiments (from 4 days onwards) it can be seen that the results are reproducible within uncertainties and follow the same pattern with time. There is therefore no reason, on the basis of these data, to consider that fading differs between beta irradiation using $^{90}\text{Sr}/^{90}\text{Y}$ sources and gamma irradiation with ^{60}Co .

Similarly fading results are equivalent with doses of 10 mGy and 200 mGy. For the shorter period only beta irradiated data are available. Combining both sets signals were observed to decrease over the first 4 days, and then increase over the 8-256 days period.

Reverse fading has been reported by other authors in their respective salt samples. Biernacka et al. (2016) observed reverse fading of the signal from the salt for a short time scale of seconds. Similarly, this” inverse fading” has been reported for a longer time scale of days in a comparable investigation (Christiansson et al., 2014; Singh et al., 2018). In contrast, another investigation of six aliquots of NaCl demonstrated no significant short-term fading (Bailey et al., 2000). Other authors (Ekendahl et al., 2022) reported fading over a 20-day period, yet it was deemed insignificant for accident dosimetry, in agreement with other researchers (Thomsen et al., 2002). The phenomenon of signal instability shortly after irradiation has been also reported by other researchers for different periods of time (Bernhardsson et al., 2021). These various prior studies have shown variability in stability of OSL signals from salt, potentially reflecting variability in the characteristics of salt from different origins or variations in experimental conditions.

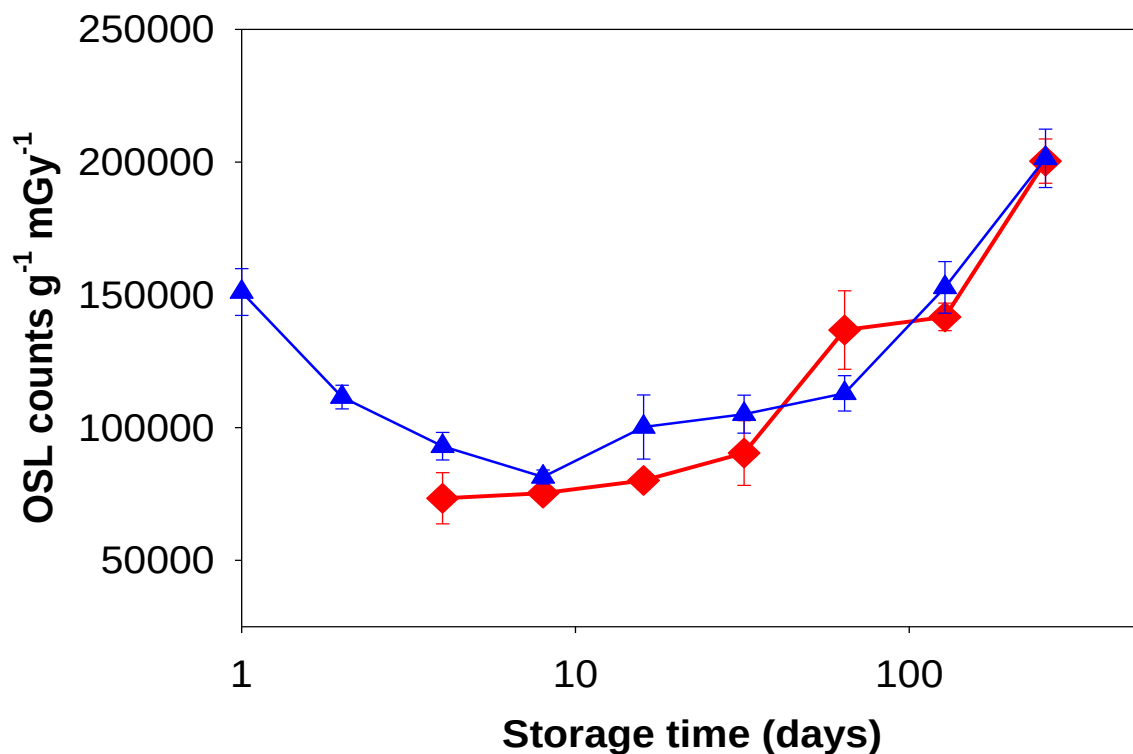


Figure 3.9. Normalized net OSL counts as a function of storage time following 10 mGy gamma (red), 200 mGy beta (blue) irradiation. Error bars indicate the standard error for 10 aliquots for each measurement (Alghamdi et al., 2024).

3.3.4 TL Analysis

Glow curve characteristics

A characteristic glow curve for table salt recorded from room temperature to 500 °C at a heating rate of 5 °C/s, after beta irradiation to 200 mGy is shown in Figure 3.10. All salt samples exhibit similar behaviour for their glow curves. The TL glow curve obtained from the reading of the samples has two glow peaks that were recorded from the samples between the temperature range 110 °C and 300 °C. This NaCl sample has two $T_{\max}$ (TL peak maximum) at average temperatures of 110 °C and 284 °C, with the peaks at 284 °C approximately an order of magnitude larger. These temperature values agree with the glow curves reported by Spooner (Spooner et al., 2011). An investigation of 10 Indian salt brands (Gartia et al., 2004) demonstrated that more than two peaks are regularly observable, but only those at ~258 °C and higher were deemed appropriate for dosimetry. The presence of a main peak at ~266 °C was also reported for an Alpine salt with iodine and two types of rock salt in Romania (Timar-Gabor and Trandafir, 2013). A different study (Polymeris et al., 2011) identified the main dosimetric peak for most of the analysed commercial Greek salt samples to be at ~220 °C, while for a natural Turkish salt, two distinct dosimetric peaks were observed at ~200 and ~300 °C. Other authors (Rodriguez-Lazcano et al., 2012) observed peaks at 180 and 220 °C for natural salt and only the 220 °C peak for synthetic NaCl. Timar-Gabor & Trandafir, (2013) and Ekendahl and Judas, (2011) reported that the 100 °C peak is not thermally stable, by exposing the sample to light these shallow unstable traps can be eliminated. This peak fades progressively during storage under room conditions (Murthy et al. 2006). Singh et al. (2018) have reported that the intensity of the higher temperature TL peaks increased with storage time while the low temperature TL peak at ~140 °C was seen to decrease, they suggested that this implies that charge gets transferred from traps associated with the lower temperature peak to traps associated with the higher temperature TL peaks.

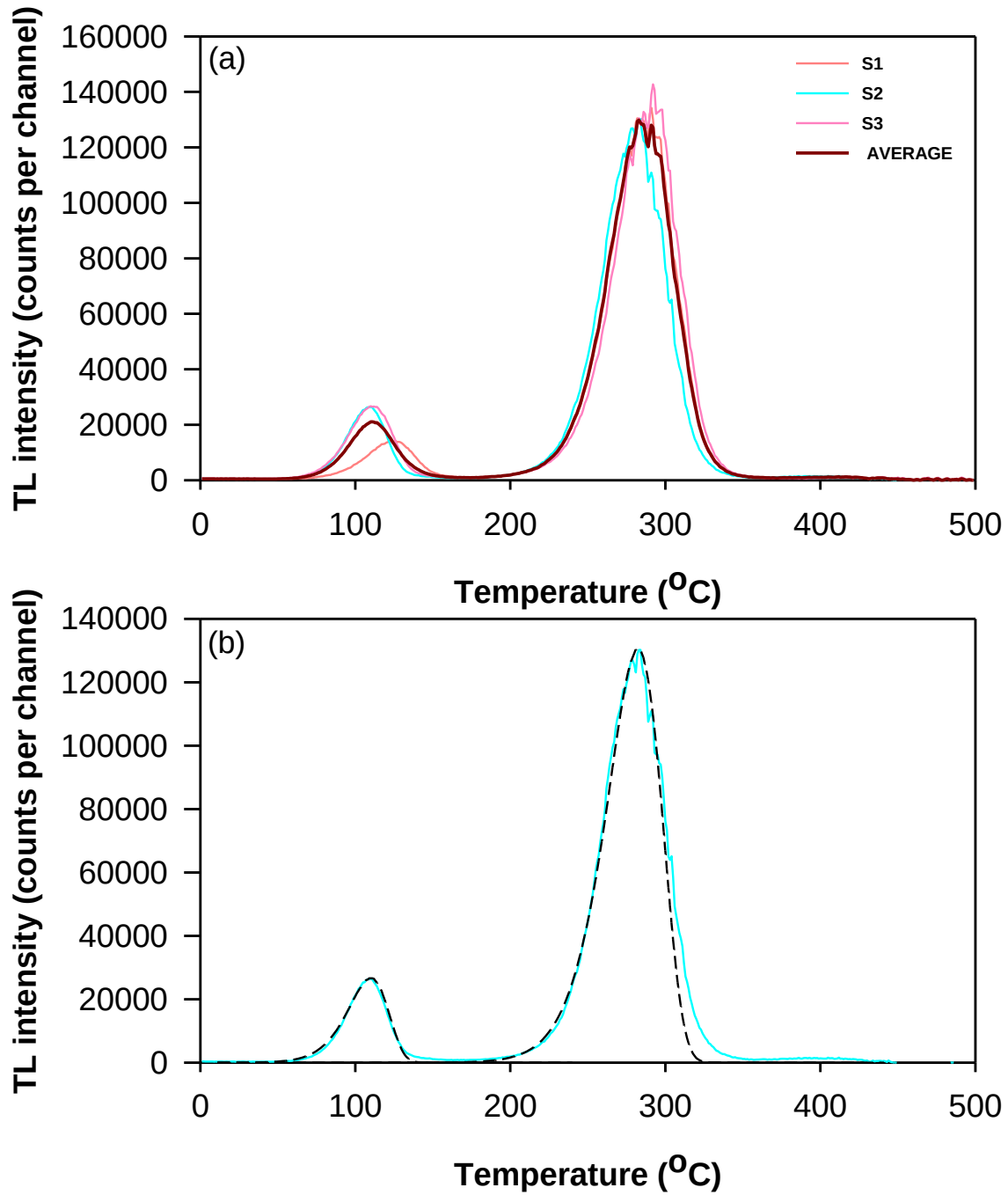


Figure 3.10. TL glow curve for salt irradiated with 200 mGy, recorded 5 min after irradiation at a heating rate of 5°C s^{-1} , (a) showing signals from three aliquots and the average glow curve, (b) showing measured S2 and simulated peak shapes (dashed lines) (Alghamdi et al., 2022).

Kinetic parameters were calculated using SUERC TL analysis software. The glow curves were transformed to Arrhenius plots, with the average of these shown in Figure 3.11. For each TL peak the kinetic parameters were determined for each measurement, with natural logarithm of counts plotted against $1/kT$ where k is Boltzmann's constant ($8.617 \times 10^{-5} \text{ eV K}^{-1}$) and T is the temperature in Kelvin. The slope of the peak rise gives the trap depth E (eV), and the frequency

factor s (s^{-1}) is then calculated from the peak temperature and heating rate assuming first order kinetics. The glow curves for the two have been simulated, again assuming first order kinetics, for these parameters. These simulated curves, normalised to the peak counts and T_{max} in the experimental measurements are shown in Figure 3.11 (b) in comparison with the S_2 measurement. The simulations assuming first order kinetics are a very close match to the measured glow curve, thus justifying this assumption. Mean lifetimes for each trap are then calculated as $s^{-1} \exp(E/kT_s)$ where T_s is the storage temperature.

Table 3.3. lists the mean activation energies, frequency factors and calculated life time at 20 °C for the traps associated with P1 and P2 obtained as described above. The values for P1 give a short lifetime at ambient temperature of 1.47 h, whereas P2 is effectively stable at room temperature. Tiwari and Pau (2011) reported TL analysis on salt with two peaks observed, the first at approximately 100 °C was observed after 2 h but not present in measurements at 2 d and 4 d, the second at 476 K (203 °C) was present in all measurements. They calculated kinetic parameters for the second peak using curve fitting and glow curve deconvolution (GCD) with E values of approximately 0.9 eV and 1.1 eV respectively, and a frequency factor from GCD of $5\text{-}7 \times 10^{12} s^{-1}$. Shahein et al. (2019) reported estimated values of the activation energies E (eV) and frequency factors for five salt samples which ranged between 0.57 -0.92 eV , 1.30×10^7 - $1.53 \times 10^{12} s^{-1}$ respectively for P1 and 0.862-1.205 eV, 8.98×10^8 - $4.64 \times 10^{12} s^{-1}$ respectively for P2. For P1, the trap energy calculated here agrees with Tiwari and Pau (2011) and the top of the range of values from Shahein et.al. (2019), with the energy of P2 calculated here higher than both of these prior studies. The frequency factors calculated here are an order of magnitude smaller than those reported by Tiwari and Pau (2011), but within the ranges reported by Shahein et.al. (2019). These prior studies, along with the results of this study, show variability in the kinetic parameters of salt, potentially reflecting variations in experimental conditions or variability in the characteristics of salt from different origins.

Table 3.3. The determined kinetic parameters and life time at 20 °C for the first and second peaks, for measurements following a 5 minute interval after irradiation.

T_{max} (°C)	E (eV)	s (s^{-1})	τ_{20} (hours)
110.0 ± 0.4	0.89 ± 0.01	$(3.8 \pm 1.5) \times 10^{11}$	1.47 ± 0.17
283.7 ± 0.5	1.38 ± 0.03	$(2.0 \pm 0.4) \times 10^{12}$	$(7.7 \pm 0.9) \times 10^7$

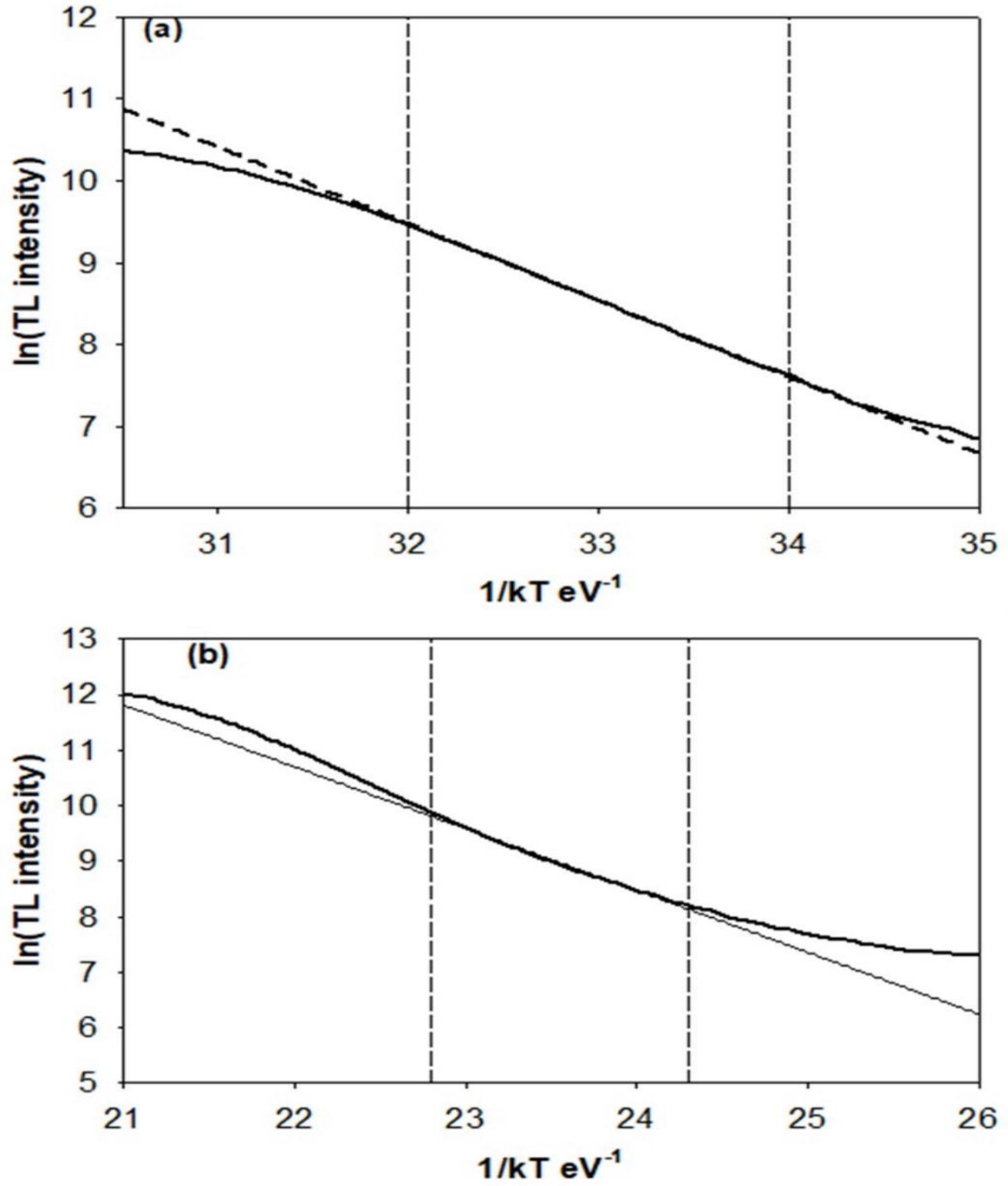


Fig. 3.11: (a) plot of initial rise with linear fit with fitting parameters for the selected range $32\text{-}34 \text{ eV}^{-1}$ ($68 - 84^\circ\text{C}$) for the $T_{\text{max}} 110^\circ\text{C}$ peak. (b) plot of initial rise with linear fit with fitting parameters for the selected range $22.8\text{-}24.5 \text{ eV}^{-1}$ ($206\text{-}235^\circ\text{C}$) for the $T_{\text{max}} 284^\circ\text{C}$ peak. The plots are an average of 7 measurements (Alghamdi et al., 2024).

3.3.5 Impact of light exposure

The results of the experiments exposing samples to simulated daylight using an artificial daylight box with approximately 7 mW cm^{-2} are given in Table 3.4, which shows a reduction of OSL counts by $> 99\%$ after 2.5 h light exposure and reduction to empty chamber counts within 24 h. Previous studies (Ekendahl and Judas, 2011) have shown that light exposure using ordinary laboratory light (fluorescent tubes providing 0.05 mW cm^{-2}), the OSL signal in NaCl decreases to approximately 37% after 5 min. Furthermore, after 4 hours, the signal is approximately 9% of its original value. Christiansson et al., (2014) reported that after 1 min, the signal is 30% of the original value and $<1\%$ of the signal remained after 90 min using fluorescent lamp light, with an illuminance of 1,100 lux (0.16 mW cm^{-2}). Hunter et al. (2012) also reported rapid bleaching of salt using TL by 90% following 10 min exposure to daylight. The data here are consistent with these prior observations, with more rapid signal loss in this work under more intense light, demonstrating the need to protect salt from light exposure while signals develop, and the need for handling samples with minimal light exposure during measurement. This also provides a mechanism to remove prior naturally induced signals before deployment. Given the requirement for light proof covering for dosimeters in the field, ten sachets of salt were enclosed in black plastic heat shrink wrap, with a hot wire used to seal the ends, and stored in the light box for 24 h. The OSL measurements for these are also given in Table 3.4, and confirm that the black heat shrink is sufficient to protect salt against light exposure.

Table 3.4. Mean and standard Err. of photon counts recorded in 30s using the SUERC Portable OSL Reader after storage in darkroom and under artificial daylight. The salt samples were irradiated with 10 mGy and 10 sachets are measured for each time.

Time (hours)	Storage	Counts in 30 s	CV (%)
24	Darkroom	$(176.1 \pm 2.9) \times 10^3$	5
2.5	Daylight	$1,036 \pm 54$	15
5	Daylight	893 ± 12	4
24	Daylight	677 ± 24	10
24 using black heat-shrink	Daylight	$(188.8 \pm 7.4) \times 10^3$	11

3.3.6 Relative humidity effect during storage

The results of the experiments investigating the impact of a relative humidity are shown in Table 3.5. No significant influence of the relative humidity on the OSL signal was observed with the samples at a relative humidity level of 32% after 32 days and 64 days, with the average mass change during this period was (0.86 ± 0.09) mg and (0.93 ± 0.70) mg, respectively. At a relative humidity level of 53% there was a large variation in mass increase, between 2.5 and 139 mg, with a mean value of 33 mg, and a complete signal loss after 32 days from all ten aliquots. The characteristics of salt were significantly changed for those samples with partial dissolution, suggesting the possible destruction or alteration of their crystal structure that denotes a need to protect against very high humidity.

The results of the experiment to protect the salt against relative humidity (at 53%) are also given in Table 3.5. As can be seen the heat shrink protected samples retained a signal of some 124k counts after 10 days, and showed no measurable weight change. Note that these samples were stored for 32 and 64 d, and the previous stability analysis (Fig.3.7) suggests that between 10 and 32 d the signal should increase by approximately a factor of 20–30%, and this would explain some of the observed signal increase relative to the heat shrink protected samples. Taking account of the fading result in Fig. 3.7 these results suggest that the black heat-shrink is sufficient to protect against both relative hydration and loss of signal through bleaching.

Table 3.5. Changing sample mass and OSL counts in 30s following storage under different relative humidity levels. The salt samples were irradiated with 10 mGy prior to storage and 10 sachets are measured for each time. Uncertainties are the standard error on 10 measurements.

Relative humidity (%)	Time (Days)	Change of weight (mg)	Net OSL (counts per 30 second)	CV (%)
32	32	0.86 ± 0.09	$(216 \pm 10) \times 10^3$	4
32	64	0.93 ± 0.70	$(256 \pm 3) \times 10^3$	22
53	32	33 ± 46	541.0 ± 9.5	5
53 using black shrink	10	0.05 ± 0.08	$(124 \pm 5) \times 10^3$	3

3.4 Discussion and conclusions

NaCl is a widely available material both in the household and workplace environments, which, in line with previous work has demonstrated has a strong radiation-induced OSL signal, and exhibits very promising dosimetric properties for use in accidental and retrospective dosimetry (e.g., Ekendahl and Judas, 2011, Thomsen et al. 2002; Bernhardsson et al. 2009; Christiansson et al. 2012, Alghamdi et al.2022, Alghamdi et al.2024).

In section 3.3.1 and 3.3.2 in line with previous work, I have demonstrated that salt shows highly promising dosimetric properties for retrospective dosimetry and rapid dose assessment in an emergency situation. Furthermore, the work reported here has shown that portable instruments can make low dose determinations, significantly below 100 μGy , more quickly and conveniently than using laboratory based instruments. Using bulk prepacked materials the results from sets of 10 sachets are reproduced to high precision across a series of doses, suggesting that initial dose assessments can be made for such material without individual re-calibration of each dosimeter. For readout using the blue LEDs in the SUERC Portable OSL Reader minimum detection limits of 7 μGy have been determined from single ~ 1 g salt sachets. A linear dose-response relationship was observed in the 0–500 μGy range. A non-zero intercept corresponding to an initial dose of 60–70 μGy was noted, and is attributed to the environmental dose experienced by the salt sachets in the period since manufacture. The other instruments investigated would also be suitable for such applications, though with slightly higher detection limits for the PPSL instrument developed for food analyses and the higher sensitivity IRSL version of the portable reader.

Thus, such instruments would be capable of measurements of doses <100 μGy , and can be used under battery operation in the field or nearby location. This would allow the deployment of multiple systems, and measurement of samples without the need to transport them to remote laboratories. Common reference materials are already supplied with the instruments, these would be able to account for variations in stimulation power or photomultiplier response between different instruments. Precalibration of salt samples from single batches, or across multiple batches should they be sufficiently similar in luminescence characteristics, would allow measurements without requiring additional calibration doses in the field. This would be a significant advance, reducing the time required for measurements compared to laboratory calibration approaches.

The measurement protocol used here involved 60 s measurements per aliquot, allowing measurements of 30–40 aliquots per hour on a single instrument. For these OSL measurements, 90% of the signal was generated within 15 s so shorter measurement times per sample, and more aliquots per hour, would be possible without significant loss of sensitivity. For this work, 10 aliquots were used per sample, however the coefficients of variation at <10% would permit lower levels of replication, and hence more samples per hour. Further investigation of the interplay between measurement sequence, sample throughput, sensitivity and the influence of post irradiation delays on signal response would be useful.

Prior studies have indicated that the OSL signal, after allowing for decay of the less stable components, has a long lifetime at 20 °C (Spooner et al., 2011; Hunter et al., 2012) suitable for retrospective dosimetry. Further studies would be needed to assess stability of this signal at elevated environmental temperatures, and to develop measurement protocols to either allow less stable components to decay prior to measurement (which could include pre-heating) or to account for these signals.

The observation of an initial signal prior to artificial irradiation indicates that salt is sensitive enough for dosimetry at natural environmental dose rates. For low-dose retrospective dosimetry methods to either remove or account for this initial signal would need to be investigated.

The samples analyzed here showed very small dispersion in the response to radiation doses, thus a dose response curve and initial signal can be determined from a small subsample of the batch prior to deployment, and applied to all of the sachets. If other salt samples show the same responses to known doses then a universal calibration may be possible. As noted by Waldner (2021), investigations of the properties of each specific salt is warranted prior to use in dosimetric applications, this would identify whether a general response curve is applicable or whether a curve specific to that salt would be needed. Further work is needed to evaluate the responses of different sources of salt, and to consider possible modes of deployment of bulk material of this sort, and the potential for initial rapid estimates of dose to be made under emergency conditions using precalibrated materials.

The practicality of using salt as a retrospective dosimeter in response to nuclear or radiological emergencies would also need to manage deployment and collection of salt samples without light exposure or hydration. Christiansson et al. (2014) have demonstrated that white plastic containers or paper sachets do not sufficiently protect the sample from light exposure, whereas

cardboard boxes and black plastic containers do, and the work presented here confirms that black plastic protects the salt from light.

This work in Sections 3.3.4, 3.3.5 and 3.3.6 seeks to identify the most favourable conditions for measuring OSL signals induced by radiation in NaCl. It involves empirical investigations into important OSL characteristics, including the signal's stability over time and its response to factors like light exposure and humidity.

The signal stability was evaluated using the blue LEDs in the SUERC Portable OSL Reader with salt sachets irradiated using a 10 mGy gamma dose over a range of storage periods from 4 to 256 days. To evaluate stability over a 1-4 d period, which is a critical timescale for emergency response, salt samples dispensed to planchettes were irradiated with 200 mGy beta doses. The results show short-term initial fading over the first 4-8 days following irradiation, followed by a slight increase in luminescence intensity after prolonged storage (>60 d). The period from 8-60d is more stable, which covers much of the period of interest for dose reconstruction in the early stages of radiological emergency response. However, for initial responses within the first week of an emergency, the observed signal loss is significant and would need to be accounted for. For longer periods, there is an unexplained gradual increase in OSL signals with time.

Characterisation of the TL from irradiated salt samples was used to determine kinetic parameters with the aim of understanding how the observed signal stability relates to different traps in the system. The TL glow curves show two peaks at 110 °C (P 1) and 284 °C (P 2). The lifetime of P 1 is calculated as 1.47 h at 20 °C, which is consistent with prior studies showing rapid fading over 24 h (Tiwari and Pau, 2011; Spooner et al., 2012) which is too short a lifetime to explain the initial decay of OSL signals over the first 4–8 d. P 2 has been previously identified as considered suitable for dosimetry since such peaks have lifetimes of the order of a few hundred years (Gartia et al., 2004), the lifetime determined here is effectively stable so this also does not explain the initial decay observed.

Ekendahl and Judas (2011) and Zhang et al. (2005) report experiments measuring OSL from salt held at different temperatures. Between temperatures of 80 °C and 120 °C the OSL signal remains constant, suggesting that it does not stem from shallower traps. However, the OSL signal increases between 120 °C and 210 °C, which was attributed to the transfer of charge from shallow traps to deeper traps associated with OSL. When the sample is heated to 300 °C the OSL signal is completely extinguished. These experiments suggest that the primary origin of

the OSL signal arises from the deeper traps. In our study, the increase in OSL signal with storage time after 8 days as described above Fig. 1 which means a mechanism for temporary charge storage in a metastable site, which can later feed the population in deeper traps that it would have implications for readout protocols.

The experiments on light and humidity effects on OSL reported here confirm that salt is highly sensitive to light exposure and higher levels of humidity, both of which result in almost complete loss of OSL signal. This leads to a requirement to protect salt from both light exposure and elevated humidity while signals accumulate, and for sample handling to minimise light exposure and excess humidity. Experiments with enclosing salt sachets in black plastic shrink wrap have shown that this material can be adequately sealed to prevent light exposure and protect against elevated humidity, thus providing a practical means for deployment of salt as a field dosimeter.

The results have conclusively demonstrated that using bulk prepacked common salt with a portable OSL reader is a rapid and effective means of determining doses below 100 μGy and can be used under battery operation in the field or nearby locations removing the need to transport samples to remote laboratories which is a suitable material for emergency and retrospective dosimetry (Alghamdi et al.2022). OSL signals demonstrate complex stability behaviour, with both rapid initial signal loss over 4–8 d, and a signal recovery from about 60 d after irradiation. Further work is required to better understand this behaviour, and to identify protocols to account for this. A practical approach to protecting salt from light and moisture has been identified using the black plastic shrink. Field trials will be needed to practically demonstrate the utility of salt dosimeters in mapping radiation fields and measuring doses received by individuals (Alghamdi et al.2024). This will be explored further in Chapter 5.

While NaCl is very highly sensitive, its hygroscopic nature may lead to physical instability in addition to the luminescence signal fading behaviour described here. Therefore, a short investigation will also follow of a more physically stable material, also available in bulk at low cost, an example of which includes talc. The following chapter will explore whether talc produces both IRSL and OSL signals which can be read with portable equipment and examines the sensitivity, zeroing properties and signal stability with a view to appraising its potential for future development.

Chapter 4

Case study 2: Dosimetry using common talc

4.1. Introduction

The previous chapters (1 and 2) have underscored the critical need for diverse and swift dose assessment methods in radiological emergencies. These techniques are essential for several key purposes: rapid triage of potentially exposed individuals, providing accurate information to alleviate public concerns and guiding decision-making processes for implementing protective measures as shown in sections (2.5.1, 2.6.1, 2.6.2). Chapter 3 explored the viability of table salt for radiation dose measurements using portable instruments Alghamdi et al. (2022). The study purposely examined dose levels below 100 μGy and demonstrated that portable OSL instruments are a promising method for emergency dosimetry within this range. In addition, we observed linear dose responses for OSL/IRSL in the range of 0-500 μGy . Additionally, detection limits down to 7 μGy (blue OSL) were proven. This chapter expands the investigation to another common material (talc). While salt is highly sensitive (as shown in Chapter 3), it is important to recognise that salt dosimeters must be protected from light exposure and moisture and to take account of the signal evolution and fading with time. While these features of salt dosimeters are further explored in Chapter 5, it is also relevant to this research to consider whether there are more physically stable natural materials which could also be used for emergency dosimetry. By examining talc's dosimetric properties, I aim to broaden the spectrum of readily available materials that could potentially serve as radiation dosimeters within the critical dose range for early medical triage (0.5-3 Gy).

Talc has a wide range of industrial and commercial applications due to its unique properties. Its primary uses include serving as a common ingredient in ceramics, paints, and roofing materials, as well as in cosmetic products and baby powders. In the pharmaceutical industry, talc functions as a lubricant and diluent in tablet formulations, a glidant in capsule formulations, and a filler or coating agent (Virta, 2005; Sanderson et al., 2002; Ekendahl and Judas, 2011).. Talc is a naturally occurring mineral predominantly consisting of hydrated magnesium silicate,

denoted by the chemical formula $\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$. It is among the softest known minerals, rated as 1 on the Mohs scale of mineral hardness. Talc generally manifests as foliated or fibrous aggregates and possesses a distinctive greasy or soapy texture. The hue may vary from light to dark green, brown, white, or grey, and it can sometimes be colourless (Virta, 2005; Sanderson et al., 2002, Bray, 1994).

A significant study by Sanderson et al. (2002), undertaken with the support of the Food Standards Agency, provides critical knowledge into the thermoluminescence (TL) properties of talc, establishing a foundation for its potential use as dosimetry in the dose range of interest for food processing with ranges from a few hundred Gy to 10 kGy. This report, available in the University of Glasgow's Enlighten repository, examined the luminescence properties of talc to evaluate its influence on the detection of irradiated foods according to the EN1788 standard, while its conclusions suggest wider ramifications for radiation measurement. This study investigated the thermoluminescence (TL) signals of talc samples sourced from several origins, including pharmaceutical-grade materials. The research evaluated a wide range of genuine talc samples obtained from quarries and mines in France, Italy, Sardinia, China, Mexico, and Australia, in addition to irradiated pharmaceutical-grade talc from a supplier in the UK. The main aim was to evaluate the potential influence of talc on the EN1788 methodology for detection of irradiated foods, and hence investigated high dose responses. Following preliminary preparation and exposure to a 200 Gy irradiation dose, every sample was evaluated through thermoluminescence analysis.

The dose response and behaviour of two samples were examined in a light box, at ambient and elevated temperatures, and during storage. Initial observations revealed that the thermoluminescence (TL) signals from the samples had considerable sensitivity to light exposure. This observation prompted further investigation into whether these samples also display optically stimulated luminescence (OSL) and infrared stimulated luminescence (IRSL) properties. In order to generate initial estimates of trap parameters, exploratory kinetic analysis was implemented. All talc samples exhibited a significant thermoluminescence (TL) response. The glow curves were recorded on the SUERC TL readers as well as on Risø DA15 readers, and the data were recorded at room temperature to 400, 450 or 500 °C. The radiation-induced thermoluminescence (TL) response in most talc samples was characterized by four main glow peaks—Peaks I, II, III, and IV. The apparent temperatures of peaks I to IV respectively are: Peak I 140-160°C (SUERC instrument); 160-180°C (Risø); 190-210°C (SUERC); 220-240 °C (Risø); 260-280 °C (SUERC); 280-300 °C (Risø); Peak IV 320-340 °C (SUERC); 360-380°C.

Thus, peak temperatures recorded by the Risø instrument are some 15-20 °C degrees higher than the SUERC PC reader. So, the observed peak temperatures for Peaks I, II, III, and IV were different for the two readers. The different optical filters on the instruments also affect absolute sensitivity. TL intensity increased linearly from 100 to 6400 Gy, followed by non-linear saturation in the kGy range, indicating the ability to record significant radiation doses. Stability evaluations further emphasised talc's viability as a dosimeter. The radiation-induced TL signals across all four peaks exhibited stability at ambient temperatures throughout the research period, with only little thermal degradation observed in the lower-temperature peaks (e.g., Peak I) at 50 °C. During the fading test, samples kept in the light box exhibited a significant decrease in signal. This observation prompts the question of whether exposure to light could also induce stimulated luminescence, such as IRSL (infrared stimulated luminescence) or OSL (optically stimulated luminescence). Kinetic research verified that many traps contribute to the principal TL peaks, offering more evidence of the spontaneous occurrence of TL. The TL response after high-dose irradiation may be differentiated from geological signals by a magnitude difference of one to two orders in the low-temperature peaks. The report assessed the apparent doses from the natural residual signals, utilising the dose response curves and sensitivities relative to a 200 Gy standard dose. The data indicated that the high temperature TL peaks had residual doses of several hundred Gy or more, but the lower peaks had lower geological residual doses, with many samples in the 1-10 Gy range for peaks 1 and 2. This finding indicates possible uses in radiation detection and dose assessment, although no work was conducted to investigate responses to lower doses relevant to nuclear emergency response. The TL signals created by radiation in talc are persistent at ambient temperatures for brief durations, specifically up to 34 days as seen in the study. Nevertheless, storage at high temperatures (50 °C) results in the thermal degradation of low-temperature peaks (Peak I and II). The thermal processing of talc (e.g., at 140 °C for 20 minutes) diminishes residual TL signals in the lower temperature peaks, hence rendering thermally treated talc less likely to disrupt dosimetry applications.

The report primarily examines the thermoluminescence (TL) characteristics of talc, although the findings clearly suggest that talc possesses significant potential for dosimetry applications. However, it raised unresolved questions, which are investigated here, regarding the low dose behaviour, whether the material is sensitive to optically stimulated luminescence (OSL) within the 0.5-3 Gy range and the extent to which optically stimulated luminescence exhibits geological residual signals, and the degree to which geological residuals could affect optical

readouts, which have the potential to be conducted in field settings. Although the prior research provides a foundation, it does not comprehensively delineate the behaviour at low doses, and especially for optically stimulated luminescence (OSL) sensitivity within the 0.5-3 Gy range. The material's proven sensitivity to radiation, along with its ability to preserve luminescence signals in particular environmental circumstances. As a geological material common across many industries, is readily accessible and possesses key features such as sensitivity and stability for dosimetry applications. These attributes indicate that talc might potentially function as an efficient emergency dosimeter. Its extensive availability and economic efficiency further augment its appropriateness for such applications. This unresolved question presents a significant opportunity for additional exploration, which we intend to examine thoroughly in this chapter. Therefore, in this chapter, additional research will be conducted on its luminescence properties using portable instruments to evaluate their potential as dosimetry materials. Initial questions concern sensitivity, reproducibility, detection limits and dose responses. I also intend to use the SUERC Portable OSL Reader (Sanderson and Murphy, 2010) to assess radiation-induced OSL signals in talc. Having established that the samples studied show OSL, the thermal stability of geological OSL signals was investigated. The sensitivity of thermally zeroed material in the triage dose range was evaluated, and the stability of OSL signals was examined across various time intervals extending to 128 days post-radiation for dark storage and under light bleaching.

4.2 Sample preparation

The samples used in this experiment, a fine white powder of natural talc, were samples of Luzenac Pharma from the packing line. The white powders were acquired from Carrière Luzenac Quarry (Latitude N= 42°48.507, Longitude E=1°48.067). The samples had been packaged and stored in lightproof containers at the Scottish Universities Environmental Research Centre since 2002, when they had been used as part of a short investigation of the luminescence properties of talc conducted for the Food Standards Agency (Sanderson et al., 2002). It is numbered D9. SP5756 (Packed sample of Luzenac Pharma from the packing line).

Talc has shown measurable responses using thermal bleaching and has shown very promising dosimetric properties (Sanderson et al., 2002; Ekendahl and Reimtz, 2022). However, the application of talc for use in accidental and retrospective dosimetry may face a major challenge if there are large accumulated geological signals which affect IRSL or OSL by being associated

with the more stable traps already identified in the earlier TL studies. If this is the case such residuals would need to be removed by thermal treatment or optical bleaching or otherwise accounted for. Therefore, initially, samples were prepared to measure the radiation background of talc prior to investigating the possibility of using it as a dosimetric material. Ten samples were prepared on 30 mm diameter aluminium planchettes. Luzenac talcs without prior treatment were dispensed in sets and irradiated in the triage range



Figure 4.1. Prepared talc samples on aluminium planchettes

For the initial beta irradiation response tests, 30 samples were prepared on aluminium planchettes measuring 30 mm in diameter. These were sprayed with silicone grease as an adhesive prior to spreading ~ 0.85 –1 g of talc uniformly over the surface (see Figure 4.1). Silicone grease is commonly used for this purpose for the reason that it does not affect the luminescence response of silicate minerals and other materials, including food stuffs (CEN, 2009). Ten samples were utilised to record the readings of two luminescence instruments. These readings were taken both before and after the samples were exposed to a beta irradiation dose of 200 mGy at room temperature using the 0.62 GBq ^{90}Sr source previously described.

To determine the dose response behaviour, 50 samples of talc were prepared on 30 mm diameter aluminium planchettes and were exposed to beta doses of 200, 500, 1000 and 1500 mGy using the 0.62 GBq ^{90}Sr source. Ten planchettes were retained as unirradiated controls. The planchettes were weighed prior to use to verify that each one comprised the same mass of talc (gross weight 0.85–1.00 g). For the dose response experiments to photon irradiation in the 200–1500 mGy regions, samples were stored under dark conditions at room temperature for 10 days to permit any unstable signal components to decay ahead of measurement. The 10 days period was selected with the aim of making certain that the slight differences in storage time between irradiation and measurement were small in comparison with the post-irradiation delay.

No further preheating was conducted at this stage. The OSL signals were measured using 10 planchettes at each dose for each instrument.

4.3. Experimental measurements

4.3.1 Measurement of background radiation of talc

The radiation background of the talc sample was investigated utilising Portable OSL equipment. The results were also compared to talc samples irradiated with a dose of 200 mGy under controlled conditions, allowing the investigation of differences in radiation characteristics between the natural and irradiated states. Ten samples were prepared on 30 mm diameter aluminium planchettes. Luzenac talc samples without prior treatment were dispensed in sets and irradiated in the triage range. The signal accumulated in the talc was large, so the powdered sample was preheated at a controlled rate from 250 up to about 400 °C for 60 minutes in a standard programmed laboratory and industrial-scale Carbolite furnace (CSF-12/3, UK). The purpose of this thermal treatment was to systematically remove any pre-existing residual signals. After this treatment using thermal bleaching, the radiation dose can be correlated with the scintillation signal, which can be used for dose estimation at the triage level.

4.3.2. Comparison of the instruments (Dosimetric properties)

For a comparison of the instruments, the experiment used beta-irradiated samples on 3 cm planchettes subjected to a notional dose of 200 mGy. Ten samples were analysed with each of the two devices. Each measurement series started and finished with background measurements from an empty chamber. The sensitivity (photon counts per Gray, $c\text{ Gy}^{-1}$) of each instrument and light source was determined using the counts for each measurement from the 200 mGy irradiated samples. To estimate the minimum detectable doses in this study, we considered the empty chamber measurements, which produced consistent values, to be acceptable. The minimum detection limits (MDL) were calculated as the mean of these background counts plus three times their standard deviation (Currie, 1968; Alghamdi et al., 2022). These MDL values were subsequently converted to dose using the sensitivity calculation, assuming a linear dose response within the range. This assumption is based on prior studies pertaining to luminescence associated with talc (Sanderson et al., 2002; Ekendahl and Reimitz, 2022). The resulting minimum detectable dose (MDD) is expressed in mGy. It specifies the dose at which a signal is robust enough to be distinguished from the background.

4.3.3 Dose response

The experiment utilised talc planchettes with a diameter of 30 mm to construct a dose-response curve within the range of interest for triage in emergency situations. The planchettes were irradiated to beta irradiation at dosages varying from 0 to 1500 mGy. Ten samples were measured at each dose, including unirradiated controls. The measurements were originally conducted using the Portable Reader, equipped with 470 nm blue LEDs, which had the lowest detection limit. The net photon counts were recorded. The experiment was later repeated using the IRSL system at 890 nm.

4.3.4 Signal stability tests

The stability of the signal significantly impacts the precision of dose reconstruction and affects detection thresholds. The subsequent phase involved examining the signal stability of talc samples over a period of 128 days post-irradiation.

Following the removal of the geological signal by thermal treatment at 400 °C, 40 samples were produced on 30 mm diameter aluminium planchettes, which were coated with silicone grease as an adhesive prior to the even distribution of about 0.85-1 g of talc throughout the surface. Samples were subjected to 1500 mGy at ambient temperature utilising a 0.62 GBq ⁹⁰Sr source. Ten talc samples on aluminium planchettes were preserved as unirradiated controls to assess the background accumulation throughout storage. They were weighed before use to confirm that each contained an identical quantity of talc (gross weight 0.85–1.00 g). Samples were preserved in darkness at ambient temperature for 256 days. The OSL measurements were obtained at 1, 2, 4, 8, 16, 32 and 128 days. A background reading was obtained from a unirradiated sample and subsequently subtracted from the reading of the irradiated sample.

4.3.5 TL analysis of glow curve characteristics

Four talc samples were pre-heated to 400 °C for 1 h, which completely removed the accumulated geological signal. To determine glow curve characteristics a silicone sprayed 10 mm disc was utilised to hold approximately 0.5 mg of talc in place and prevent scattering during movement. Each subsequent procedures, including irradiation, storage and TL measurements, were conducted under normal laboratory conditions (around 21 ± 2 °C and 31% relative humidity), in the darkness to prevent any optical effects (photo-transferred thermoluminescence, optical bleaching, etc.), the ground powder was kept in darkness after pre-heating, during the irradiation procedure, and until the final readout. Each sample received

a dose of 1500 mGy. TL measurements were taken at room temperature to 500 °C at a rate of 5 °C s⁻¹, with a 5-minute interval at room temperature between irradiation and readout.

4.3.6 Impact of Light Exposure (Simulated Daylight)

To investigate the impact of light exposure (simulated daylight) and the possibility of signal reduction to zero, 40 talc samples which had been thermally treated to remove geological signals dispensed onto 30 mm diameter aluminium planchettes were exposed to an absorbed dose of 1500 mGy using a beta source. Thirty samples were positioned in a lightbox that emitted about 7 mWcm⁻² total fluence, approximating daylight (Sanderson et al., 2002). OSL measurements were conducted at 2.5, 5, 24, and 48 hour intervals post-exposure. The remaining ten samples were preserved in darkness for 24 hours and served as control samples for comparison

4.4. Results and discussion

4.4.1 Backgrounds, sensitivities and detection limits

The measurements displayed a significant geological signal (see Table 4.1). This showed that the inherited signals from unprepared geological samples were close to the signals recorded after giving the samples a 200 mGy. While this confirmed that the samples all showed IRSL and OSL it emphasised the need to remove residual geological signals prior to exploring the low dose behaviour. Hence, it was necessary to explore the temperatures needed to remove the entirely residual geological signals prior to exploring the detection limits in talc using IRSL and OSL. The results of the experiments exposing samples to heating temperatures up to 400 °C are given in Table 4.2, which demonstrates that heating at 250 °C removes all of the IRSL signals. But at 300 °C, OSL signal intensities have come down by roughly one order of magnitude (thus approximately 10% left), and the treatment at 350 °C reduces OSL by approximately 30 times (so it leaves just a few percent of the original signal). These results suggest that (i) IRSL is less thermally stable than OSL (ii) that to remove all the OSL will take prolonged thermal treatment at approximately 400 degrees, and (iii) that there may be OSL contributions associated with - not only the TL peaks 3 and 4 already identified in the earlier high dose studies - but potentially also with deeper traps which have yet to be identified. These results signify that heating talc to 400 °C for 1 hour is sufficient to remove the large residual geological signal completely.

Table 4.1. The photon counts and standard error for the background and 200 mGy irradiated talc samples. The dose recorded from background radiation and geology was considerable and close to the dose given to the 200 mGy samples.

Talc	IRSL	OSL
Background	87,532 $\pm$ 7819	4,870,083 $\pm$ 280,447
After 200 mGy	94,268 $\pm$ 3221	4,972,070 $\pm$ 273,064
After heating to 400 °C for one hour	30. $\pm$ 31	608 $\pm$ 30

Table 4.2. Shows the remaining signals after a range of heating temperatures and times.

T. heating oC	Time min	IRSL		IRSL_dep		PSP	OSL		OSL_dep	PSP	IRSL/OSL
250	30	149	36.73	0.28	0.23	64	277,660	529.61	2.40	407	0.001
250	30	67	36.65	0.08	0.41	61	48,555	224.61	1.79	155	0.001
250	30	-45	38.56	1.25	2.18	75	108,387	333.53	2.10	330	0.000
250	30	170	36.19	0.45	0.24	17	233,084	486.73	1.61	671	0.001
250	30	33	37.05	-0.48	-0.45	65	182,261	431.03	1.49	546	0.000
300	30	63	36.59	-0.21	-0.32	73	14,088	125.90	1.37	122	0.004
300	30	79	37.93	0.72	0.72	60	23,765	160.27	1.01	140	0.003
300	30	126	38.44	2.23	1.69	8	13,331	120.86	1.22	-19	0.009
300	30	109	36.89	0.08	0.25	-43	14,956	127.25	1.38	-4	0.007
350	30	-70	35.24	0.08	0.39	-44	4823	78.91	1.10	23	-0.015
350	30	-93	35.48	0.63	0.52	-8	9526	104.41	0.92	6	-0.010
350	30	46	38.39	0.07	0.62	-69	10,707	109.12	0.98	-57	0.004
350	30	-128	38.99	3.00	2.77	30	9244	104.73	0.95	19	-0.014
400	60	-29	34.51	-0.60	-0.40	13	212	37.68	1.02	-3	-0.137
400	60	53	32.88	2.53	4.19	-15	364	37.79	0.60	9	0.146
400	60	50	33.79	-9.33	-36.38	-39	393	38.22	0.82	-6	0.127
400	60	-36	30.98	-2.13	-1.66	-25	374	38.55	1.38	29	-0.096

After completely removing the geological signal, the experiment was repeated to explore the detection limits in talc using IRSL and OSL using material which had been thermally zeroed. Table 4.3 provides the count rates and standard deviations for the background and talc samples, which were exposed to a dose of 200 mGy. These measurements were conducted in ten different sets. The portable OSL instrument with blue LEDs yielded the highest photon counts

(9107 ± 472) and the lowest detection limit (2 mGy) at the 200 mGy dose. In comparison, the other instruments recorded lower counts and higher detection limits. The sensitive IR portable OSL system gave 1606 ± 594 at 890 nm from 200 mGy (compared with 179 ± 36 for the same wavelength in the less sensitive system) and a MDD of 9 mGy. It is worth noting that the measurement sequence had already reduced some signals from the samples before the 940 nm measurements were taken, which may explain the lower sensitivity observed.

Table 4.3. The photon counts and standard error for the background and 200 mGy irradiated talc samples for ten sets of measurements on two instruments with calculated sensitivities and detection limits.

	Portable OSL 1		Portable OSL 2	
	IR (890 nm)	IR(940 nm)	IR (890 nm)	OSL (470 nm)
Background (empty chamber)	45 ± 25	13 ± 26	31 ± 23	199 ± 24
MDL (counts)	76	79	69	73
Pre-irradiation counts	-80 ± 39	16 ± 38	18.5 ± 37	493 ± 46
200 mGy counts	1606 ± 594	136 ± 110	179 ± 36	9107 ± 472
Sensitivity (counts mGy ⁻¹)	8 ± 3	0.69 ± 0.5	0.90 ± 0.18	45 ± 0.23
MDD (mGy)	9	115	77	2

4.4.2 Dose response

The beta irradiated materials were used to construct dose response curves for talc irradiated to 0–1500 mGy using material which had been thermally zeroed. The mean net photon counts and standard deviation recorded from 10 talc samples at each dose are presented in Table 4.4, with the mean counts, after subtracting the mean counts for the 0 μ Gy samples, plotted in Figure 4.2. In terms of the blue OSL signals, the data in Figure 4.2 are well-defined by the linear regression (slope 59.5 ± 0.79 c mGy⁻¹). Dose-response curves for the other wavelength (Figure 4.2), also depict linear regressions with smaller slopes (3.49 ± 0.39 for the 890 nm IRSL), reflecting the different sensitivities.

Table 4.4. Mean and standard Err OSL photon counts recorded using the SUERC Portable OSL reader at 470 nm and IRSL instrument at 890 nm and from ten sachets of talc exposed to beta doses from 0-1500 mGy.

	Portable OSL 470 nm		Portable IRSL 890 nm	
Dose (mGy)	Net OSL	CV (%)	Net IRSL	CV (%)
0	591 $\pm$ 14	7	- 46 $\pm$ 7	-16
200	12,096 $\pm$ 145	4	1606 $\pm$ 198	12
500	28,816 $\pm$ 207	2	2609 $\pm$ 91	3
1000	60,833 $\pm$ 368	1	4436 $\pm$ 116	3
1500	89,203 $\pm$ 510	2	5484 $\pm$ 38	1

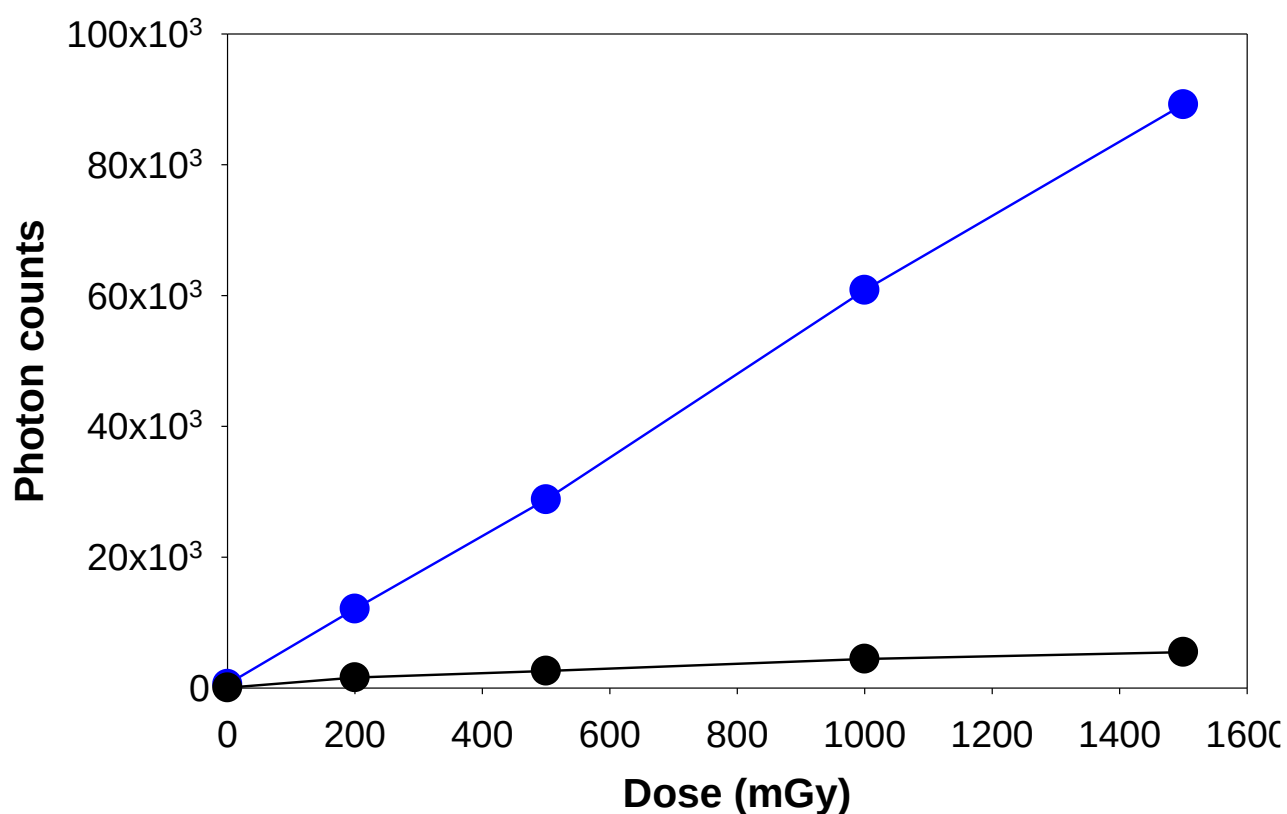


Figure 4.2. Dose response from beta irradiated samples measured using a blue OSL portable reader (blue) and 890 nm IRSL (black).

4.4.3 Signal stability tests

Fading is a critical factor that can significantly impact the ability of dose reconstruction for triage purposes. The results of the signal stability experiments are given in Table 4.5 and illustrated in Figure 4.3, where the OSL counts have been normalised by dividing by the dose

given 1500 mGy (with ^{90}Sr) and sample mass. Talc exhibits significant fading over the first few days losing approximately 35% of the original signal, and 49% over the first 2 weeks. The observed fading can greatly hinder the feasibility of dose reconstruction.

The fading rates here differ from the sharp fading rates reported by Ekendahl and Reimit (2022), who used pharmaceuticals and food supplements that were assumed to contain talc as part of their ingredients for retrospective dosimetry. In the study they conducted, the OSL signals fade to 43–50% of their original value after one day. Regarding Birgi Mefar Group (BMG) pharmaceuticals, the signals faded to approximately 70% after one day and 62% after one week. Concerning the food supplements, their OSL signals experiments confirm a substantial drop. After one day, the signals fade to approximately 25% of their initial value. Likewise, after one week, the signals drop below 20% of the original value. This previous study has revealed variability in the stability of OSL signals from talc compared with our results, possibly due to preheating the talc in my experiment. Also, the previous has utilized materials containing talc, which may have included additional components capable of contributing to the luminescence signal. In contrast, our experiments were conducted exclusively with pure talc, ensuring that the observed luminescence properties could be attributed solely to the talc itself, without interference from potential impurities or secondary materials. This distinction in material purity may account for differences in the observed results and highlights the importance of controlled experimental conditions in achieving reliable and reproducible data.

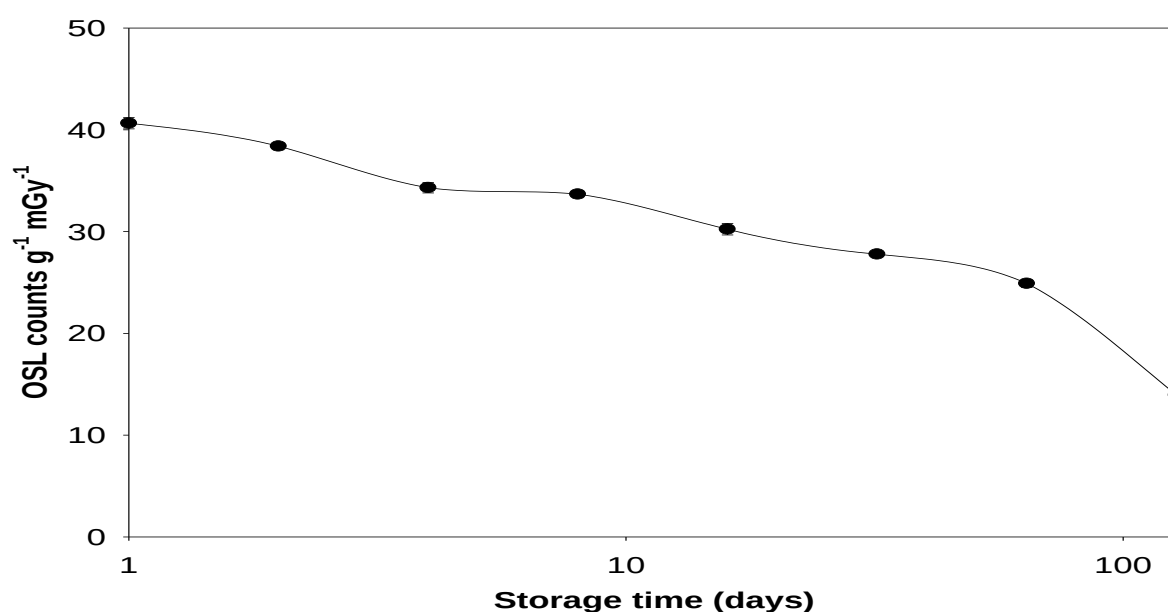


Figure 4.3. Net OSL counts in $30 \text{ s g}^{-1} \text{ mGy}^{-1}$ as a function of storage time following 1500 mGy of beta irradiation. Error bars indicate the standard error for 10 aliquots for each measurement.

Table 4.5. Mean and standard Err. of photon counts for irradiated talc which recorded 30s using the SUERC Portable OSL Reader after storage in the darkroom. The talc samples were irradiated with 1500 mGy after removing the signals. 10 planchets were measured for each time.

Days	Net. Count	CV (%)	Count/mg	Diff. %
0	$89,203.4 \pm 510.31$	2	59.469 ± 0.34	0
1	$60,969.42 \pm 828.05$	1.36	40.65 ± 0.55	0.32
2	$57,592.93 \pm 529.01$	0.92	38.39 ± 0.35	0.35
4	$51,469.57 \pm 773.43$	1.5	34.31 ± 0.51	0.42
8	$50,513.2 \pm 524.91$	1.13	33.67 ± 0.35	0.43
16	$45,355.3 \pm 853.72$	1.88	30.24 ± 0.57	0.49
32	$41,674.25 \pm 315.16$	0.76	27.78 ± 0.21	0.53
64	$37,364.22 \pm 576.63$	1.54	24.91 ± 0.38	0.58
128	$20,920.04 \pm 668.57$	3.19	13.95 ± 0.44	0.76

4.4.4 Glow curve characteristics

The TL glow curve obtained from the reading of the samples has five glow peaks recorded from the samples between temperature ranges of 100 to 200 °C as a double peak with one component around Peak I (120-140 °C) and the other at about Peak II at 160 °C. Peak III at 225–235 °C, and Peak IV at 285–295 °C, along with an additional Peak V at 460–475 °C that was not previously seen. The previous study reported by Sanderson et al. (2002), indicated Peak I at 140–160 °C, Peak II at 190–210 °C, Peak III at 260–280 °C, and Peak IV at 320–340 °C. In comparison to the initial four peaks, peak temperatures in my experiment are consistently lower by 12% to 20%. The observed changes, ascribed to varying experimental variables like irradiation dosage, sample preparation, or minor instrumental discrepancies, indicate an effect on signal resolution. The 470 °C peak in the thermoluminescence (TL) glow curve was not addressed in previous studies. This peak is especially significant because it relates directly to the optically stimulated luminescence (OSL) process in the material. When performing OSL measurements, the talc typically needs to be heated to 400 °C to completely remove OSL

signals and as the material needs to be heated to 400 °C to remove OSL signals the implication is the trap associated with the 470 °C TL peak plays a crucial role in the OSL mechanism.

An investigation of the kinetic parameters (Sanderson et.al. 2002), including activation energies (E/eV), frequency factors (s^{-1}), and mean life estimates at 0 °C and 5 °C for TL peaks I and II, demonstrated that Peak I is exhibiting thermal stability on the order of approximately 10^2 years under typical ground temperature conditions. In contrast, Peak II demonstrates significantly greater stability, with an estimated lifespan of around 10^3 years under the same conditions. The results highlight the potential of Peak II for applications requiring extended thermal stability, while Peak I may be more suitable for medium-term applications (Sanderson et al., 2002). The kinetic parameters for peaks I and II previously determined give lifetimes for these peaks at 20 °C of 7.8 y and 44 y, respectively. These are clearly inconsistent with the observed fading over several days. For this preliminary assessment of the suitability of talc for emergency dosimetry, the nature of the traps and associated TL peaks that produce the signals observed to fade with at least three components of the order of days has not been pursued further at this stage. Future investigations, including more precise TL and pulsed annealing experiments, would be recommended to understand the processes involved more fully.

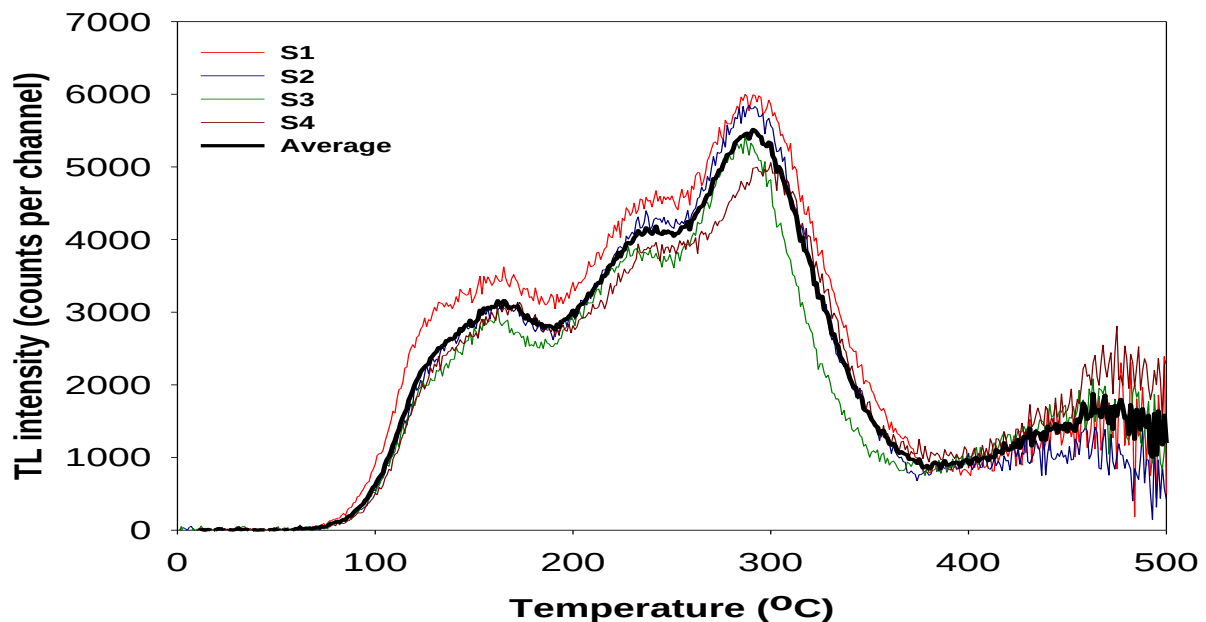


Figure 4.4. TL glow curve for talc irradiated with 1500 mGy, recorded 5 min after irradiation at a heating rate of $5\text{ }^{\circ}\text{C s}^{-1}$, exhibiting signals from four aliquots and the average glow curve.

4.4.5 Impact of light exposure

The results of the experiments exposing samples to simulated daylight after eliminating signals using an artificial daylight box with approximately 7 mWcm^{-2} are presented in Table 4.6. It indicates a reduction in OSL counts by >98% after 2.5 h light exposure and a reduction to empty chamber counts within 48 h. Sanderson et al. (2002) also reported that the rapid bleaching of talc significantly reduces the magnitude of the TL signals. Extended exposure to light also reduces the levels of the luminescence signals in the samples that were not exposed to radiation. Importantly, these experiments were conducted on samples that had been pre-treated using heating to remove geological residues, followed by irradiation. Consequently, the results reflect the light sensitivity of the radiation-induced signals in the absence of geological remnants.

Table 4.6. Mean and standard Err. of photon counts recorded using the SUERC Portable OSL Reader after storage in a darkroom and under artificial daylight. The talc samples were irradiated with 1500 mGy and diameter aluminium planchettes measured for each time.

Time(hours)	Storage	Counts in 30 s	CV (%)
2.5	Daylight	1795.33 ± 22	1
5	Daylight	1389.55 ± 34	2
24	Daylight	799.28 ± 17	2
48	Daylight	409.75 ± 14	3
24	Dark room	$60,969.41 \pm 28$	1
48	Dark room	$57,592.9 \pm 529$	3

4.5 Discussion and Conclusion

The initial part of this study demonstrated that talc demonstrates extremely promising dosimetric properties in terms of retrospective dosimetry and rapid dose assessment in an emergency situation. Similarly, the results reported here have specified that portable instruments can make dose determinations using talc in the significant range of 0.5-3 Gy (critical to medical triage in emergencies) more rapidly and conveniently than laboratory-based instruments.

Using white powders packed from Luzenac Pharma's packing line, the results from the sets of 10 planchettes are reproduced to high precision throughout a series of doses. Experimental talc

results have explained the presence of a significant geological residual signal in talc from primary quarry sources, which need to be removed before you could use OSL to register doses in the lower dose (triage) region. This can be removed thermally but only by means of high-temperature treatment.

For readouts utilising the blue LEDs in the SUERC Portable OSL Reader minimum detection limits of 2 mGy have been determined from single ~1 g talc planchettes. A linear absorbed dose-response relationship was observed in the 0–1500 mGy range. The other instruments considered would also be suitable for these applications, although with slightly higher detection limits. Thus, these instruments would be capable of measurements in doses 0.5–3 Gy region, and can also be used under battery operation in the field or nearby location. This would permit the employment of various systems with respect to radiological and nuclear emergencies and the measurement of samples without the need to transport them to remote laboratories. Pre-calibration of talc samples from single batches or across multiple batches should they be sufficiently similar in luminescence characteristics, would permit measurements without requiring additional calibration doses in the field. The measurement protocol used here comprised 60 s measurements per aliquot, allowing measurements of 30–40 aliquots per hour on a single instrument. Regarding these OSL measurements, 90% of the signal was generated within 15 s, so shorter measurement times per sample would be possible allowing more aliquots to be measured per hour without significant loss of sensitivity.

The second part of the experiments conducted in this study aimed to identify the most beneficial conditions in relation to measuring OSL signals induced by radiation in talc. It involved empirical investigations into effective OSL characteristics, including signal stability over time and its reaction to light exposure. The signal stability was evaluated using the blue LEDs in the SUERC Portable OSL Reader with talc planchets irradiated using 1500 mGy beta doses over a range of storage periods from 1 to 128 days, which is a critical timescale for emergency response. Talc exhibits fading rates, beginning at 6% after 24 hours and significantly increasing as time elapses after irradiation, losing 65% of its original value within 128 days. The period from 8 to 16 days covers much of the period of interest for dose reconstruction in the early stages of radiological emergency response. The observed signal loss is substantial and should be accounted for in the clarification of immediate results during measurement protocols in response to large-scale radiation events.

The material characterisation revealed that they are significantly similar in their TL response. The TL glow curves exhibit five glow peaks recorded from the samples between temperature ranges of 120–140 °C, 160 °C, 225–235 °C, 285–295 °C, 460–475 °C, respectively.

Compared to the initial four peaks recorded by Sanderson et al. (2002), peak temperatures in my experiment are consistently lower by 12% to 20%. The observed changes caused by differing experimental factors such as irradiation dose, sample preparation, or slight instrumental errors suggest an impact on signal resolution. The 470 °C peak in the thermoluminescence (TL) glow curve was not observed in previous studies, and may explain the observed need to hold samples at 400 °C to remove all OSL signals. The current study used a dose of 1500mGy, which is significantly lower than the doses used in previous work. But the TL glow curve maximizing temperature used here was 500 °C, compared with 450 °C in the earlier work. This extended dose range may have allowed for the observation of high-temperature peaks that were not visible temperature ranges. The detection of this 470 °C peak offers novel insights into the luminescent characteristics of talc and its prospective uses in dosimetry. Further examination of this peak may yield an expanded comprehension of charge trapping and recombination mechanisms in talc, refined OSL dosimetry methodologies using talc, and superior differentiation between geological and artificially created radiation signals. Subsequent research should concentrate on thoroughly characterising the 470 °C peak, encompassing its dose response, fading characteristics, and correlation with OSL signals across diverse talc samples from distinct geological origins.

The experiments on light effects using heated Luzenac talc recounted here corroborate that talc is exceedingly sensitive to light exposure. The results demonstrated the potential for optically resetting signals induced by laboratory radiation which results in an almost complete loss of OSL signal during two days. Accordingly, there is a need to protect talc from light exposure while signals accumulate and for sample handling to lessen light exposure. A practical approach to protecting luminescent materials from light exposure is crucial for maintaining the integrity of their signals, especially in dosimetry applications. Alghamdi et al. (2024) have demonstrated an effective method for protecting salt samples using black heat shrink material. This same mechanism can be readily adapted to protect talc samples from light exposure.

Ultimately, this study has illustrated that using talc with a portable OSL reader for dosimetry is a quick, economical and sensitive. Once residual signals are eliminated the material has sufficient sensitivity to detect doses within the radiologically significant range of 0.5–3 Gy.

This dose range is a key target for medical triage in radiological emergencies. However, improving the ability to distinguish between residual background signals and signals caused by recent radiation exposure would significantly increase its effectiveness. These results emphasise the viability of talc as an OSL dosimeter and the necessity for meticulous calibration and time-dependent correction factors in actual implementations. However, it is important to acknowledge that the need for pre-positioning and zeroing the material may limit its broader applicability. While the positive conclusions underscore the potential of talc as a dosimeter, they are qualified by the practical challenges associated with managing residual signals and ensuring accurate zeroing. Additionally, the demonstration here of fading of OSL observed in this study appears to show multiple components from a material that exhibits multiple TL peaks, raising questions as to whether the fading behaviour can be further simplified by using combined thermal treatment and optical readout. Notwithstanding these qualifications, the work presented here has confirmed that talc, which is a more physically stable geological material than salt, has OSL signals with dosimetric properties that could be exploited for emergency dosimetry under favourable conditions. The next chapter explores potential way of using arrays of passive dosimeters to map radiation fields.

Chapter 5

The use of Passive dosimeter arrays for spatial definition of radiation fields

5.1. Introduction

Chapter 3 demonstrates that using bulk prepacked materials, specifically common salt with a portable optically stimulated luminescence (OSL) reader, is an effective method for dosimetry. This approach is rapid and suitable for both emergency and retrospective dosimetry. It can operate on battery power in the field or nearby locations, eliminating the need to transport samples to remote laboratories (Alghamdi et al., 2022). Additionally, a practical method for protecting salt from light and moisture has been identified (Alghamdi et al., 2024). This characteristic, along with the widespread availability and low cost of salt, presents a unique opportunity for broad application in radiation detection and measurement. Chapter 2 described scenarios requiring the development of new approaches for evaluating radiation doses when traditional dosimetry methods are not widely available and take time to measure. After a radiological incident, two critical actions are necessary. First, there must be rapid identification of individuals who need treatment, and second, it is essential to provide reassurance to those who have not been exposed to radiation. Additionally, quickly identifying and mapping contaminated areas is vital for effective containment and cleanup efforts. These requirements highlight the importance of developing reliable, accessible, and fast methods for detecting and measuring radiation. In this chapter, we will explore the potential use of sodium chloride (NaCl) as a dosimeter for mapping radiation in affected areas. We will compare this approach to conventional techniques, such as a portable gamma spectrometry system (backpack system). By utilizing the passive dosimetry capabilities of salt, we aim to demonstrate a novel method that could complement or enhance current practices in radiation monitoring and mapping. This investigation seeks to contribute to the development of more accessible, widespread and complementary tools for radiation monitoring, ultimately improving our ability to respond to and manage radiological incidents effectively as mentioned in the first chapter.

Among the various methods employed for environmental radiation assessment, airborne gamma spectrometry (AGS) has emerged as a particularly valuable tool. Airborne gamma spectrometry (AGS) represents one of the most useful approaches for environmental radiation monitoring. Its high mobility and rapid data acquisition capabilities make it indispensable in responding to radiation release incidents (Sanderson et al. 1990a). AGS enables swift, wide-area surveys that can provide a comprehensive picture of radionuclide distribution in the environment, offering insights that ground-based measurements alone might miss. Radiological surveys serve multiple purposes in the context of emergency response and environmental monitoring. Beyond assessing contamination levels in emergency scenarios, these surveys are instrumental in monitoring for potential security breaches and tracing environmental pathways of radionuclides (Sanderson et al. 1994a, 1994b; IAEA, 2004b). This versatility makes radiological survey techniques, including AGS and mobile radiometry, an essential part of environmental surveillance for daily routine, as well as in emergency preparedness. The aerial gamma survey approach excels in comprehensively covering large regions, though its restrictions on low-altitude flights in urban areas are notable limitations. The sensitivity is adequate to detect fluctuations in natural radioactivity and to identify gamma ray sources that may pose a considerable risk. Nonetheless, the sensitivity to diminutive geographical sources is constrained; hence, enhancing the survey with a brief vehicle and backpack system is urgent, as it will provide a clear image of the radiation level in the studied area (Sanderson et al. 1997).

The Airborne Gamma Spectrometry (AGS) technique leverages the significant penetrating capabilities of gamma (γ) radiation, allowing detection and mapping of the distribution of γ -ray emitting radionuclides at ground level, conducted efficiently using high volume sodium iodide (NaI (Tl)) scintillators or alternatively, germanium (Ge) semiconductors mounted on low-flying aircraft, using appropriate spectrometers. This technique offers several advantages over conventional methods. There is an obvious acknowledgement at the European level of the necessity and significance of AGS systems as an integral part of national emergency response and the critical function they serve to making decisions during nuclear and radiological disaster management.

The high-sensitivity γ -ray detectors mounted in the aircraft can perform ambient radioactivity measurements at intervals of just seconds. This yields a sample rate that is around 100 to 1000 times superior to ground-based systems, such as road or pedestrian surveys (Sanderson et al., 1989a, 1989b, 1990b, 1994b). The remote sensing characteristics of the measures reduce the

exposure of survey crews to contamination or radiation risks. This provides an efficient method for performing surveys with comprehensive coverage, suitable for the swift identification of point sources or regions of radioactive contamination. This holds significant implications for investigations on ambient radioactivity, particularly under time limits, and is very effective in emergency response scenarios, but the necessity for specific clearances for low-altitude flights restricts the utilisation of aerial surveys, especially in urban regions where navigational challenges are greater than in rural areas.

Vehicle-deployed radiometric systems using gamma-ray spectrometry have also become effective instruments for radiation monitoring and environmental evaluation. Radiometric systems deployed in vehicles facilitate immediate measurements over regional scales in which vehicle systems' fields of vision, often ranging from 5 to 10 meters, including substantial portions of the road surface that are not anticipated to accurately reflect local deposition owing to self-remediation processes. These automotive platforms fulfil many functions in radiological protection and nuclear security. A principal use is the identification and localisation of misplaced or uncontrolled radioactive sources. Through methodical scanning of pertinent areas, these mobile devices may effectively scan extensive territories to detect possible radiation concerns or verify their absence. Vehicle-mounted spectrometers also aid in geological mapping initiatives. These devices yield useful data for comprehending geological formations and mineral distributions by monitoring naturally occurring radioactive elements in surface rocks and soils. In the aftermath of nuclear catastrophes or accidents, vehicle-mounted gamma spectrometry is essential for delineating radioactive fallout distributions. This information is crucial for evaluating environmental effects, directing remediation initiatives, and establishing public safety protocols. Automobile-based systems have begun marketing for applications in the prevention of nuclear theft and emergency preparedness for malicious actions, including nuclear or radioactive materials (Dowdall et al. 2012; Sanderson et al. 2003b, Korsbech et al. 1999; Mellander et al. 2002).

The backpack system can identify minute components measuring under one metre in diameter, with accuracy dictated by the sampling frequency. It clearly delineates the perimeters of more extensive features as well. This technology is especially useful for accurate geographic documenting of natural and anthropogenic radioactive events in limited regions and constrained places (Buchanan et al., 2016). Radiometric backpack systems enable the creation of detailed maps of radiation distribution across small regions. Accurate radiometric mapping can identify more polluted regions. This data may assist in concentrating remediation efforts

by pinpointing the locations with the highest levels of pollution. Thorough mapping enables the identification of tiny areas with elevated local activity concentrations. If these sites are in places commonly utilised by the public, they may receive preferential treatment in remediation programs (Sanderson et al., 2013). Also, backpack radiometric surveys can generate maps illustrating the distribution of dose rates and radionuclide deposition, encompassing locations within buildings, such as the cartography of potentially contaminated beaches (Cresswell and Sanderson, 2012), the mapping of urban environments (Cresswell et al., 2013), and the delineation of deposited activity from the Fukushima Daiichi incident (Sanderson et al., 2013). In Sweden, data from airborne and terrestrial measurements have recently been juxtaposed via a backpack system (Kock and Samuelsson, 2011). Radiation levels around nuclear installations in Ghana have been assessed via a backpack system (Amekudzie et al. 2011). Repeated surveys can track alterations in the geographic distribution of dose rates (Cresswell et al. 2011). The accuracy provided by these backpack systems enables the detection of localised hotspots, regions where radiation levels are markedly elevated compared to surrounding areas. This information is crucial for developing improved remediation procedures since it enables the focus of efforts on the most impactful locations (Sanderson et al., 2013). In urban areas or similar environments where individuals reside in proximity, this degree of accuracy is crucial, as little areas of elevated radioactivity may pose significant risks if overlooked. The data obtained from backpack radiometric surveys can inform risk assessments and facilitate decision-making over public access and land utilization. Public areas exhibiting heightened radiation levels, regardless of their localised nature, may be prioritised for remediation or access limitations to reduce possible exposure. Moreover, such backpack systems are simple and user-friendly, capable of conducting surveys as often as necessary over the years. This dynamic radiological surveying offers an increasingly useful instrument for managing radioactive pollution and response to nuclear or radiation emergencies. In 2012, the SUERC system was employed to gather data from two urbanised locations: the campus of Fukushima University and a section of Fukushima City. In July 2012, the bulk of Fukushima University's campus was surveyed, while measurements of the sports grounds and adjacent areas of some buildings were conducted in March and November. The assessments indicated that the majority of the campus exhibited contamination levels below 50 kBq m⁻² for ¹³⁴Cs and dose rates under 0.30 µGy h⁻¹ (Sanderson et al. 2013).

Instrumental measurements, such as backpacks, can deliver immediate and precise information, aiding in response management and safeguarding first responders. However,

backpack systems and traditional personal dosimeters are not widely utilised among the general populace and take time to measure, leading to a scarcity of timely data regarding the doses individuals may have received. Consequently, exploring alternative or supplementary methods to these systems is deemed crucial for evaluating doses to first responders, safeguarding the public, and facilitating evacuation, medical triage, and support for affected groups in decision-making during radiological or nuclear emergencies. Complementary techniques to estimate initial deposition include estimating the dosage received by prevalent items and biological tissues obtained from specific locations and individuals. This can be accomplished by identifying radio-induced defects using physical methods such as electron paramagnetic resonance (EPR), optically stimulated luminescence (OSL), and thermoluminescence (TL) (Alghamdi et al., 2022; Alghamdi et al., 2024). See Chapter 2 for more details.

NaCl has a strong radiation-induced OSL signal that can be measured using the optically stimulated luminescence (OSL) technique after stimulating it with blue diodes (Alghamdi et al., 2022; Alghamdi et al., 2024). NaCl is one of the most sensitive materials used in retrospective dosimetry which exhibits very promising dosimetric properties for use in accidental and retrospective dosimetry. As shown in Chapter 3, for photon energies above c.150 keV salt is good air equivalent dosimetry material and collecting samples and sample preparation would be relatively simple (e.g., Ekendahl and Judas, 2011, Thomsen et al. 2002; Bernhardsson et al. 2009; Christiansson et al. 2012; Alghamdi et al. 2022; Ekendahl et al. 2017). The use of bulk already packaged materials in sections (3.3.1, 3.3.2) has conclusively shown that dosimetry with common salt and a portable OSL reader is a quick and efficient way to determine dose below 100 μGy . It can be used in the field or nearby locations on a battery, removing the need to transport samples to distant laboratories (Alghamdi et al., 2022). Also, section 3.3.3 presented additional investigation substantiating the suitability of salt as a material for emergency and retrospective dosimetry. OSL signals have complex stability behaviour, showing a quick loss of signal over the first 4–8 days and a rebound of signal starting about 60 days following irradiation. The NaCl OSL signal is highly susceptible to optical bleaching and higher levels of humidity, both of which result in almost complete loss of OSL signal. This leads to a requirement to protect salt from both light exposure and elevated humidity while signals accumulate, and for sample handling to minimise light exposure and excess humidity. Experiments in section (3.3.5, 3.3.6) have demonstrated a practical approach

to protecting salt from light and moisture has been identified which enclosing salt sachets in black plastic shrink wrap effectively seals the material, preventing light exposure and protecting against high humidity. This makes it a practical option for using salt as a field dosimeter (Alghamdi et al. 2024).

The development and refinement of radiation measurement techniques and searching for or complementary methods to the Airborne Gamma Spectrometry (AGS) method, particularly those applicable in emergency scenarios, represent a critical area of research in radiation protection and emergency response. For the first time, this chapter reports a pilot investigation by investigating the potential of common materials as retrospective dosimeters. This investigation aims to expand the toolkit available to emergency responders and enhance our capacity to assess radiation exposure rapidly and accurately in diverse scenarios.

This investigation represents the first comprehensive field trials to practically demonstrate the utility of salt dosimeters in mapping radiation fields and measuring doses received by individuals across various scenarios and in different radiation fields from three sections: 1- A controlled, small-scale experiment within a laboratory setting .2- An outdoor exploration utilizing salt dosimeters to map natural background radiation and artificially introduced radiation fields, demonstrating the technique's applicability in environmental monitoring, which will be compared to measurements with a backpack system. 3- A complex radiation field assessment within a busy laboratory housing an accelerator at the Scottish Universities Environmental Research Centre, showcasing the method's potential in real-world scenarios. By investigating the potential of common materials as retrospective dosimeters, I aim to complement mobile radiometry by using salt dosimeters for retrospective dose assessments when real-time monitoring is unavailable, enhancing dose mapping resolution and accessibility. Enhance the spatial and temporal resolution of dose mapping. Supporting more informed decision-making in evacuation, medical triage, and long-term health monitoring.

5.2 Instrumentation

5.2.1 The SUERC portable OSL reader

The SUERC portable OSL Reader was used, as described in section 3.2.2.2. for this work, as previously described using the same readout sequence in sections (3.2.2.3, 3.2.2.5, and 3.2.2.6), the instrument was operated using stimulation by blue LEDs only, with an interleaved series of

15 s dark count measurements, two 15 s measurements with the diodes on, and 15 s dark count for each sample, because the previous study (Alghamdi et al., 2022) showed higher signals and lower detection limits compared to IRSL, and blue OSL has been reported to be more stable (Bailey et al., 2000; Alghamdi et al., 2024).

5.2.2 A portable gamma spectrometry system

A portable gamma spectrometry system, Figure 5.1, was developed at the Scottish Universities Environmental Research Centre (SUERC). This system has been used for a variety of radiometric survey tasks, such as mapping urban regions (Cresswell et al. 2013), mapping beaches that may be contaminated with radioactive particles (Cresswell and Sanderson, 2012), and mapping the Fukushima Daiichi accident deposited activity (Sanderson et al. 2013). A 3 × 3" NaI(Tl) detector with weather-proof container, a digital spectrometer, automatic gain correction, a GPS receiver, an integrated HV supply and a computer make up the SUERC Portable Gamma Spectrometry system. The whole system weighs about 4 kg, which is less than similar systems. While walking at moderate speeds of 0.5-1.0 m s⁻¹, the operator can record spectra in 512 channels covering an energy range of 30 keV to 3 MeV, with integration durations of 5-10 seconds. During the survey, the recorded spectra are analyzed and the data is used to create distribution maps of naturally occurring radionuclides such as ⁴⁰K, ²¹⁴Bi in the ²³⁸U decay series and ²⁰⁸Tl in the ²³²Th decay series, activity per unit area (kBq m⁻²) for ¹³⁷Cs and other fallout nuclides, and gamma dose rate (mGy/year or µGy/h) (Cresswell et al. 2013).

This experiment utilized a backpack-mounted system with a 10-second measurement time per spectrum, covering approximately 2 meters per reading. The survey pattern consisted of parallel lines spaced 0.5 meters apart. Placement was determined for mapping purposes using the BU-353S4 GPS receiver. This device is renowned for its low power consumption and high-sensitivity chipset, which enables rapid signal acquisition and tracking. The GPS unit offers positioning accuracy within a range of 5 to 10 meters. A portable computer powered the system and ran custom software for continuous spectrum logging with positional data, performing real-time analysis using pre-calibrated parameters. The analysis employed a spectral window with stripping algorithm to calculate activity per unit area and total terrestrial gamma dose rate, using a scaled count rate above 450 keV. The analysis includes background subtraction, accounting for internal detector activity and cosmic dose rate, which was performed using measurements from a plastic boat over open water in Loch Lomond, Scotland (56°8'N, 4°38'W). This approach was utilized for airborne measurements and was adapted for ground-

based surveys in potentially contaminated environments. Calibration parameters, considering operator shielding effects, were validated using reference sites in Scotland and Japan (Sanderson et al. 1994, Cresswell et al. 2006; 2016) also includes the derivation of uncertainties on measurements. The detector's field of view in open conditions spans approximately a 10-15 meters radius, depending on the source depth profile (Tyler et al., 1996). Dose rates were mapped using a modified inverse distance weighting method.

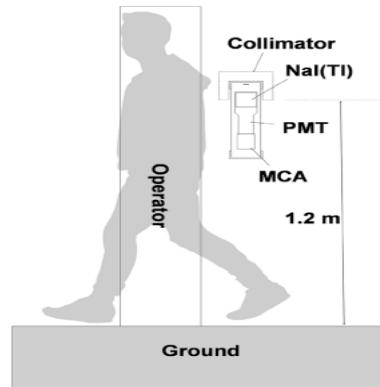


Figure. 5.1 Schematic of the SUERC Portable Gamma Spectrometry system with an optional collimator (dashed line), a weatherproof NaI(Tl) crystal with a photomultiplier (PMT) and a digital multi-channel analyzer (MCA) (Adapted from Cresswell et al., 2018).

5.3 Methods

5.3.1 Preparation of samples

This work used salt samples from the same batch described in Section (3.2.2) (Alghamdi et al., 2022; 2024). Also, the preparation process involved several critical steps to ensure the accuracy and reliability of the measurements to use in sections (5.4.1, 5.4.2 and 5.4.2):

1. Removing the residual environmental signal to zero: Each salt sample underwent a thorough signal removal process using an artificial daylight box with approximately 7 mWcm^{-2} (Alghamdi et al., 2024). This step was crucial for eliminating any pre-existing luminescence signals that could interfere with the measurement of radiation-induced effects.
2. Protective Packaging: Following the signal reset, the samples were carefully wrapped and sealed in heat-shrink sleeving. This protective measure shielded samples from light exposure,

prevented relative humidity-related effects on dosimetric properties due to relative humidity, and ensured physical integrity throughout the experiment.

All sample preparation and analysis were performed under darkness in normal laboratory conditions (approximately at 21 ± 2 °C, relative humidity of 31%). No additional processing was performed on any of the salt samples, ensuring that the results reflected the true response of the salt to the gamma irradiation under the specified conditions.

5.3.2. Dose response

To construct a dose-response curve within a dose range of 25-100 mGy, to be utilised to compute the dose rate after the analysis of the OSL signal, 20 samples were created on 30 mm diameter aluminum planchettes. Silicone oil was used as an adhesive prior to the uniform distribution of about 0.5 g of salt across the surface. Samples were subsequently subjected to beta-radiation at doses ranging from 25 to 100 mGy at ambient temperature, utilising a 0.62 GBq ^{90}Sr source with a surface area of 4 cm², positioned within a shielded irradiator at a working distance of 7.5 cm. Five samples at each dosage, including unirradiated controls, were assessed using stimulation solely by blue LEDs using the same readout sequence as previously described in sections 3.2.2.3, 3.2.2.5, and 3.2.2.6 . Samples were maintained in darkness at ambient temperature for 24 hours to facilitate the decay of any unstable signal components prior to measurement. The 24-hour duration was chosen pragmatically so that the minor discrepancies in storage time between irradiation and measurement were negligible in relation to this post-irradiation delay.

5.3.2.1 Dose response results

The beta irradiated materials were used to construct dose response curves for salt irradiated to (0 –100 mGy). The mean net photon counts and standard deviation recorded from 10 samples of salt at each dose are given in Table 5.2 with the mean counts, after subtracting the mean counts for the 0 mGy samples, plotted in Figure 5.6. For the blue OSL signals the data in Figure 5.2 are well described by a linear regression (slope $39,600.76 \pm 2750.11 \text{ c mGy}^{-1}$).

Table 5.1 Mean and standard Err OSL photon counts recorded using the SUERC Portable OSL reader at 470 nm of salt exposed to beta doses from 0-100 mGy

Dose (mGy)	Portable OSL 470nm	
	Net OSL	CV (%)
0.00	1120 ±272	7
25.00	780,418 ± 29922	11
50.00	1,626,257 ± 160590	29
100.00	3,930,584 ± 378891	28

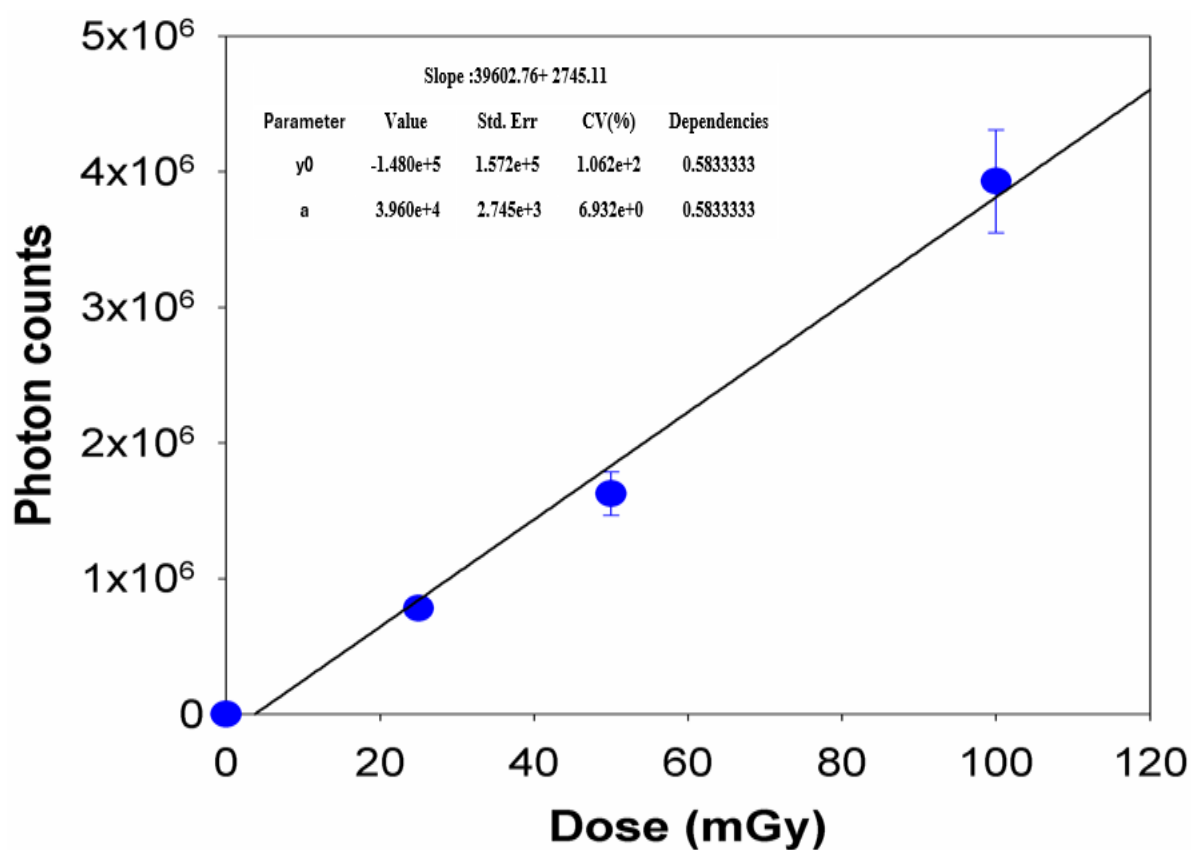


Figure 5.2. Dose response from beta irradiated samples measured using a blue OSL portable reader (blue), from sets of five individual planchettes of salt exposed to beta doses from 0–100 mGy.

5.3.3 Calibration

The calibration process involves using a reference dose of 200 mGy beta radiation source, with measurements taken 24 hours post-exposure to ensure consistency and accuracy across all experimental results.

5.3.4 Fading correction

The fading correction experiment is a crucial step in ensuring the accuracy and reliability of the measurements after irradiation of the dosimeters. To address this effect in this experiment, the results of the signal stability test, which have been presented in Chapter 3, section 3.3.3, where the OSL counts have been normalized by dividing by the dose given 200 mGy with ^{90}Sr and sample mass over a period of 256 days after irradiation of the samples Figure 3.7, where used for fading correction. By plotting the number of photons detected against time, a clear relationship between the luminescence signal and the elapsed time post-irradiation was established. This relationship was used to create a calibration curve, which was then applied to correct the fading effect in the experimental results.

5.3.4.1 Fading correction results

Since the OSL signal in salt was shown to fade over the first few days following irradiation (Alghamdi et al., 2024), a fading correction was developed to account for the signal loss that occurred during the period between irradiation and measurement. Applying a correction factor to the respective equations for each section, the adjusted doses will more accurately reflect the true dose, compensating for the fade effect. The fading correction factor (F) was determined from the previous experiment in Chapter 3, Figure 3.7, where the decay of the OSL signal was measured over a period of 256 days after irradiation of the samples with a beta source. Data were integrated over different time periods for both fading and constant signals. It was necessary to fit different functions to the first and last time periods of experimental data, as indicated in Figures 5.3 and 5.4.

The fading correction ratio is calculated as the constant integral signal divided by the integrated fading curve. The total fading constant, derived as the mean of these ratios over $T=1$ to 130 days, which related to the experiments in this chapter. The fading data was fitted to an exponential decay plus constant form with the assistance of Dr. Cresswell, which was used to estimate a fading correction factor. Fading correction calculated by comparing the signal expected without fading to that with the fading shown in Figure 5.3. Because the dose is added

continuously, the integrated area under the curve between 1 and 6 days was determined. The correction factor as a function of time was then determined as the ratio of the constant value integral to that time to the integral under the fading curve, and the average over the experimental time was used. The fading correction factor for 6 days was found to be $F=1.34$. The fading correction factor ($F= 1.34$) was applied to adjust the corrected dose ($D_{\text{corrected}}$) in section 5.4.1.1 by multiplying the initial dose (D) by the fading correction factor: $D_{\text{corrected}} (\text{mGy})= D(\text{mGy}) \times F$. Also, the fading correction factor for the time interval spanning 74 to 130 days was determined using a polynomial fit from time above 12 days as shown in Figure 5.4. Again the assistance of Dr. Cresswell is acknowledged. The calculated fading correction factor was found to be 1.08 for 74 days, which was applied to the measured dose to account for signal loss over time in section (5.4.2.1.2). It is important to note that beyond 100 days, the correction factor was less than 8%. Consequently, fading corrections were deemed unnecessary for the dose in sections 5.4.2.1.4 and 5.4.3.

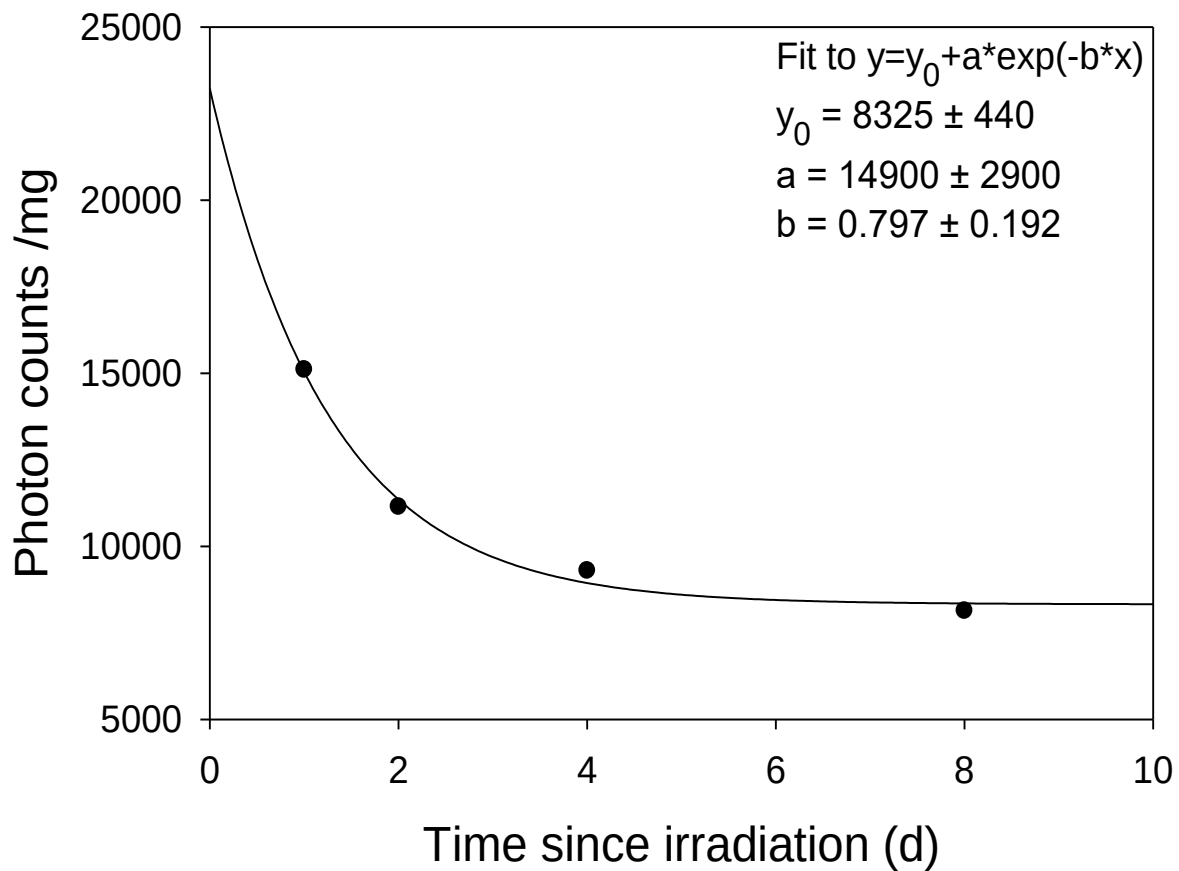


Figure 5.3. Net OSL counts in $30 \text{ s g}^{-1} \text{ mGy}^{-1}$ as a function of storage time. An exponential decay plus constant form, which was used to estimate a fading correction factor for 6 days

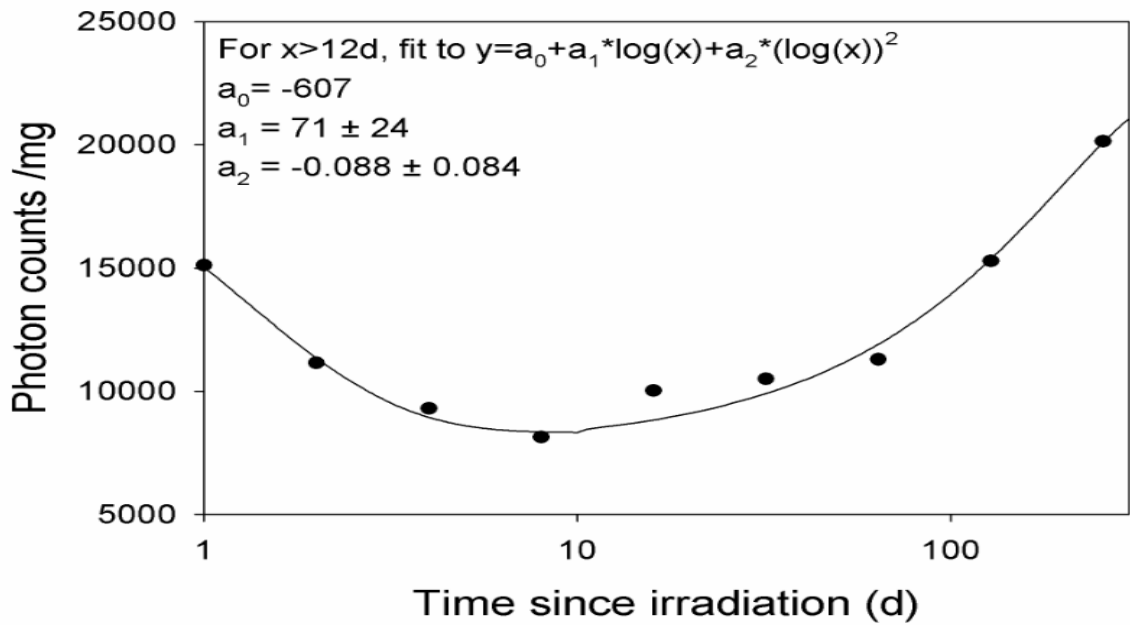


Figure 5.4. Net OSL counts in $30 \text{ s g}^{-1} \text{ mGy}^{-1}$ as a function of storage time. An exponential decay plus constant form, which was used to estimate a fading correction factor for 74, 120 and 130 days.

5.4 Experimental measurements and results

5.4.1 A controlled experiment on a small scale inside the laboratory at the Scottish Universities Environmental Research Centre.

A controlled laboratory experiment was devised to assess the feasibility of utilising salt as a large-scale passive dosimeter, simulating a real-world scenario of environmental radiation mapping using passive dosimeters. This experiment evaluates the viability of employing salt as a passive dosimeter array for detecting and mapping low-level gamma radiation exposure. The experiment aimed to simulate a scenario in which many passive dosimeters are utilised to assess radiation distribution, for example, following a radioactive event or for environmental monitoring.

A total of 78 salt samples were prepared as individual dosimeters. Initially, the signal from each sample was removed using artificial daylight and wrapped and sealed tightly using heat-shrink sleeving (Alghamdi et al., 2024). Subsequently, these prepared samples were systematically

arranged on a wooden table in a grid formation, which had been prepped as the experimental platform for this purpose within the laboratory. The table's surface area measured 100 cm by 100 cm, and the samples were positioned with a uniform spacing of 10 cm between each, forming a homogeneous grid that encompassed the whole table surface, as illustrated in Figure 5.5. To produce a spatially variable radiation field, a ^{60}Co gamma source was deployed to irradiate the salt samples, which were positioned 85 cm below the table at the centre of the array. The samples were subjected to this controlled radiation continuously for six days (144 hours), enabling the buildup of quantifiable doses. After irradiation, the full contents of each sachet were emptied into 50 mm diameter Petri dishes, and OSL signals were then recorded. No additional processing was performed on the salt samples. All procedures, such as irradiation, storage and OSL measurements, were performed in normal laboratory conditions (approximately at 21 ± 2 °C, relative humidity of 31%) and in darkness.

This method of investigation provides an extensive evaluation of salt's efficacy as a passive dosimeter in controlled radiation. The results from this experiment pave the way for significant insights into the prospective application of salt for radiation mapping in additional work (sections 5.4.2 and 5.4.3), which allow for application in real-world scenarios of environmental radiation monitoring and emergency response situation.



Figure 5.5: Salt after wrapping it on the table.

5.4.1.1 Results

The results of the experiments to assess the feasibility of utilising salt as a small scale passive dosimeter, simulating a real-world scenario of environmental radiation mapping using passive dosimeters are given in Table 5.2.

The experiment results began by measuring the OSL signals produced by salt following exposure to a ^{60}Co gamma source for 144 hours (6 days). These counts were then converted into dose values using a pre-established calibration curve. The calibration curve, derived from previous experiments had a slope $39600.76 \pm 2750.11 \text{ c mGy}^{-1}$. The absorbed dose (D) for each sample was calculated using the following formula: $D(\text{mGy}) = \text{OSL Signal (counts)} / \text{Slope (counts/mGy)}$. After that, a fade correction factor was applied to correct the dose using $D_{\text{corrected}}(\text{mGy}) = D(\text{mGy}) \times F$ (1.34).

Table 5.2 presents the average initial doses and the doses after applying a fading correction $0.393 \pm 0.027 \text{ mGy}$ and $0.527 \pm 0.037 \text{ mGy}$, respectively, while the average calculated dose mGy was $0.515 \pm 0.007 \text{ mGy}$, respectively. The results shown in Table 2 confirm that the corrected dose almost corresponds with theoretical calculations within an error of under 3%. This agreement signifies a dependable measuring method and the fading factor used mirrors the actual dose in relation to the measured dose. The spatial distribution of dose (mGy) from the salt dosimeters are shown in Figure.5.6, where dosimeters that were situated in close proximity to the centrally located source recorded higher doses, whereas those that were located at a greater distance exhibited a significant decrease in the measured radiation levels. This change in dose illustrates the salt's capacity to distinguish between radiation levels in the experimental areas. The dose is clearly correlated with the radiation source's proximity, as demonstrated in Figure 5.7, which shows the correlation between dosage and distance. The graph has three essential components: (red dots (laboratory dose corrected with a fade correction factor), black dots (laboratory dose before fade correction) and a blue line (theoretical calculations)). The graph shows that the dose decreases with increasing distance R, as expected in radiation attenuation, consistent with the inverse square law. The blue line serves as a baseline or expected behavior for comparison with the experimental data (red and black dots). The blue line is often below or close to the red dots, suggesting that the corrected experimental data (red dots) aligns reasonably well with the theoretical prediction. In contrast, the uncorrected data, represented by black dots in the graphical analysis, may not accurately reflect the actual radiation dose absorbed by dosimetry. The fact that the red dots are closer to the blue line than the black dots indicates that the fade correction improves the agreement between experimental data and theoretical predictions. The slight difference observed between the theoretical calculations and the experimental results of the dose could be due to several potential factors :1. Ideal conditions in the theoretical model versus real-world conditions, this is perhaps the most critical element. Theoretical models frequently presume ideal conditions,

but empirical tests are affected by several environmental factors, such as Inconsistent sample preparation or measurement techniques as well as scattering or absorptions from surfaces, including walls, floors, or equipment .2. The response of salt in the air may be another factor that has a slight effect as the mass attenuation shows that for higher energy ($>250\text{keV}$) gamma rays, including the ^{60}Co lines, the response of salt is within 2% of the air section 3.2.2.2. 3. Inaccuracies in distance measurement: This element, although listed, is likely to be less relevant than others if normal laboratory measuring procedures are employed.

The investigation into the viability of salt as a passive dosimeter for radiation mapping applications yielded promising results. This controlled experiment, which was conducted on a limited scale within the laboratory setting, offered valuable insights into the dosimetry properties of salt and its potential for greater-scale applications. This experiment emphasises the reliability of salt as a dosimetry material for radiation mapping purposes. It also further demonstrates salt's efficacy in generating radiation maps, albeit on a limited scale within the laboratory environment. The potential utility of salt in larger-scale, real-world applications and scenarios is indicated by its capacity to accurately map radiation distributions in this controlled environment. The minimal deviation of 3% suggests that the dosimeter accurately captured the radiation exposure, and the correction factors applied were appropriately determined, providing strong evidence that the experimental results are both reproducible and trustworthy. The success of this small-scale mapping experiment establishes the foundation for more comprehensive investigations. The results are encouraging and serve as a compelling justification for the expansion of the research beyond the controlled laboratory setting to more intricate radiation fields, the expansion of the experiment to encompass broader areas, the testing of the experiment in a variety of environmental conditions, the evaluation of the response to various types of radiation sources, and the assessment of long-term stability, as will be examined in sections 5.4.1 and 5.4.2 .

Table 5.2 Mean and standard deviation of Initial dose estimate, fading corrected dose e and calculated dose

X cm	Y cm	N. dosimeters	OSL Counts in 30 s	Initial dose estimate/ mGy	Fading corrected dose mGy	Calculated dose mGy
90	10	1	11869 ± 112	0.3 ± 0.021	0.402 ± 0.028	0.441 ± 0.005
70	10	3	14188 ± 122	0.358 ± 0.025	0.48 ± 0.034	0.499 ± 0.006
60	10	4	11806 ± 111	0.298 ± 0.021	0.399 ± 0.028	0.515 ± 0.007
50	10	5	13118 ± 117	0.331 ± 0.023	0.444 ± 0.031	0.521 ± 0.007
40	10	6	14131 ± 122	0.357 ± 0.025	0.478 ± 0.033	0.515 ± 0.007
30	10	7	13222 ± 119	0.334 ± 0.023	0.447 ± 0.031	0.499 ± 0.006
20	10	8	11695 ± 110	0.295 ± 0.021	0.396 ± 0.028	0.473 ± 0.006
90	20	9	13322 ± 119	0.336 ± 0.024	0.451 ± 0.032	0.473 ± 0.006
80	20	10	12671 ± 115	0.32 ± 0.022	0.429 ± 0.03	0.51 ± 0.007
70	20	11	15409 ± 127	0.389 ± 0.027	0.521 ± 0.036	0.54 ± 0.007
60	20	12	17313 ± 133	0.437 ± 0.03	0.586 ± 0.041	0.559 ± 0.008
50	20	13	16980 ± 133	0.429 ± 0.03	0.575 ± 0.04	0.566 ± 0.008
40	20	14	15804 ± 127	0.399 ± 0.028	0.535 ± 0.037	0.559 ± 0.008
30	20	15	12792 ± 115	0.323 ± 0.023	0.433 ± 0.03	0.54 ± 0.007
20	20	16	12232 ± 113	0.309 ± 0.022	0.414 ± 0.029	0.51 ± 0.007
10	20	17	15053 ± 125	0.38 ± 0.027	0.509 ± 0.036	0.473 ± 0.006
90	30	18	16034 ± 129	0.405 ± 0.028	0.543 ± 0.038	0.499 ± 0.006
80	30	19	15151 ± 125	0.383 ± 0.027	0.513 ± 0.036	0.54 ± 0.007
70	30	20	16078 ± 129	0.406 ± 0.028	0.544 ± 0.038	0.573 ± 0.008
60	30	21	19553 ± 142	0.494 ± 0.034	0.662 ± 0.046	0.596 ± 0.008
50	30	22	18220 ± 137	0.46 ± 0.032	0.617 ± 0.043	0.603 ± 0.008
40	30	23	15371 ± 126	0.388 ± 0.027	0.52 ± 0.036	0.596 ± 0.008
30	30	24	13593 ± 119	0.343 ± 0.024	0.46 ± 0.032	0.573 ± 0.008
20	30	25	14664 ± 124	0.37 ± 0.026	0.496 ± 0.035	0.54 ± 0.007
10	30	26	12414 ± 114	0.313 ± 0.022	0.42 ± 0.029	0.499 ± 0.006
90	40	27	14672 ± 124	0.371 ± 0.026	0.496 ± 0.035	0.515 ± 0.007
80	40	28	16557 ± 131	0.418 ± 0.029	0.56 ± 0.039	0.559 ± 0.008
70	40	29	20166 ± 144	0.509 ± 0.035	0.682 ± 0.048	0.596 ± 0.008
60	40	30	18266 ± 139	0.461 ± 0.032	0.618 ± 0.043	0.62 ± 0.009
50	40	31	18928 ± 140	0.478 ± 0.033	0.64 ± 0.045	0.628 ± 0.009
40	40	32	19872 ± 144	0.502 ± 0.035	0.672 ± 0.047	0.62 ± 0.009
30	40	33	16042 ± 129	0.405 ± 0.028	0.543 ± 0.038	0.596 ± 0.008
20	40	34	12897 ± 116	0.326 ± 0.023	0.436 ± 0.031	0.559 ± 0.008

10	40	35	15361 ± 126	0.388 ± 0.027	0.52 ± 0.036	0.515 ± 0.007
90	50	36	12802 ± 115	0.323 ± 0.023	0.433 ± 0.03	0.521 ± 0.007
80	50	37	16814 ± 133	0.425 ± 0.03	0.569 ± 0.04	0.566 ± 0.008
70	50	38	19873 ± 143	0.502 ± 0.035	0.672 ± 0.047	0.603 ± 0.008
60	50	39	21820 ± 150	0.551 ± 0.038	0.738 ± 0.051	0.628 ± 0.009
50	50	40	19621 ± 142	0.495 ± 0.035	0.664 ± 0.046	0.637 ± 0.009
40	50	40	20824 ± 147	0.526 ± 0.037	0.705 ± 0.049	0.628 ± 0.009
30	50	43	20040 ± 144	0.506 ± 0.035	0.678 ± 0.047	0.603 ± 0.008
20	50	43	15292 ± 126	0.386 ± 0.027	0.517 ± 0.036	0.566 ± 0.008
10	50	44	13007 ± 116	0.328 ± 0.023	0.44 ± 0.031	0.521 ± 0.007
90	60	45	13680 ± 119	0.345 ± 0.024	0.463 ± 0.032	0.515 ± 0.007
80	60	46	14841 ± 125	0.375 ± 0.026	0.502 ± 0.035	0.559 ± 0.008
70	60	47	17828 ± 136	0.45 ± 0.031	0.603 ± 0.042	0.596 ± 0.008
60	60	48	18463 ± 140	0.466 ± 0.033	0.625 ± 0.044	0.62 ± 0.009
50	60	49	24482 ± 159	0.618 ± 0.043	0.828 ± 0.058	0.628 ± 0.009
40	60	50	19526 ± 142	0.493 ± 0.034	0.661 ± 0.046	0.62 ± 0.009
30	60	51	18064 ± 137	0.456 ± 0.032	0.611 ± 0.043	0.596 ± 0.008
20	60	52	14883 ± 124	0.376 ± 0.026	0.504 ± 0.035	0.559 ± 0.008
10	60	53	13434 ± 118	0.339 ± 0.024	0.455 ± 0.032	0.515 ± 0.007
90	70	54	12919 ± 116	0.326 ± 0.023	0.437 ± 0.031	0.499 ± 0.006
80	70	55	16476 ± 130	0.416 ± 0.029	0.558 ± 0.039	0.54 ± 0.007
70	70	56	17989 ± 136	0.454 ± 0.032	0.609 ± 0.042	0.573 ± 0.008
60	70	57	18180 ± 138	0.459 ± 0.032	0.615 ± 0.043	0.596 ± 0.008
50	70	58	15889 ± 128	0.401 ± 0.028	0.538 ± 0.038	0.603 ± 0.008
40	70	59	17694 ± 135	0.447 ± 0.031	0.599 ± 0.042	0.596 ± 0.008
30	70	60	18221 ± 137	0.46 ± 0.032	0.617 ± 0.043	0.573 ± 0.008
20	70	61	12071 ± 113	0.305 ± 0.021	0.408 ± 0.029	0.54 ± 0.007
10	70	62	11922 ± 112	0.301 ± 0.021	0.403 ± 0.028	0.499 ± 0.006
90	80	63	14533 ± 124	0.367 ± 0.026	0.492 ± 0.034	0.473 ± 0.006
80	80	64	14090 ± 121	0.356 ± 0.025	0.477 ± 0.033	0.51 ± 0.007
70	80	65	17037 ± 133	0.43 ± 0.03	0.577 ± 0.04	0.54 ± 0.007
60	80	66	17354 ± 135	0.438 ± 0.031	0.587 ± 0.041	0.559 ± 0.008
50	80	67	17323 ± 134	0.437 ± 0.031	0.586 ± 0.041	0.566 ± 0.008
40	80	68	16390 ± 130	0.414 ± 0.029	0.555 ± 0.039	0.559 ± 0.008
30	80	69	13492 ± 119	0.341 ± 0.024	0.457 ± 0.032	0.54 ± 0.007
20	80	70	11934 ± 112	0.301 ± 0.021	0.404 ± 0.028	0.51 ± 0.007
10	80	71	11322 ± 109	0.286 ± 0.02	0.383 ± 0.027	0.473 ± 0.006
80	90	72	10653 ± 107	0.269 ± 0.019	0.36 ± 0.025	0.473 ± 0.006
70	90	73	11968 ± 112	0.302 ± 0.021	0.405 ± 0.028	0.499 ± 0.006

60	90	74	16333 $\pm$ 130	0.412 $\pm$ 0.029	0.553 $\pm$ 0.039	0.515 $\pm$ 0.007
50	90	75	13843 $\pm$ 120	0.35 $\pm$ 0.024	0.468 $\pm$ 0.033	0.521 $\pm$ 0.007
40	90	76	14616 $\pm$ 123	0.369 $\pm$ 0.026	0.495 $\pm$ 0.035	0.515 $\pm$ 0.007
30	90	77	12974 $\pm$ 116	0.328 $\pm$ 0.023	0.439 $\pm$ 0.031	0.499 $\pm$ 0.006
20	90	78	12633 $\pm$ 116	0.319 $\pm$ 0.022	0.427 $\pm$ 0.03	0.473 $\pm$ 0.006
Average			15566 $\pm$ 127	0.393 $\pm$ 0.027	0.527 $\pm$ 0.037	0.547 $\pm$ 0.007

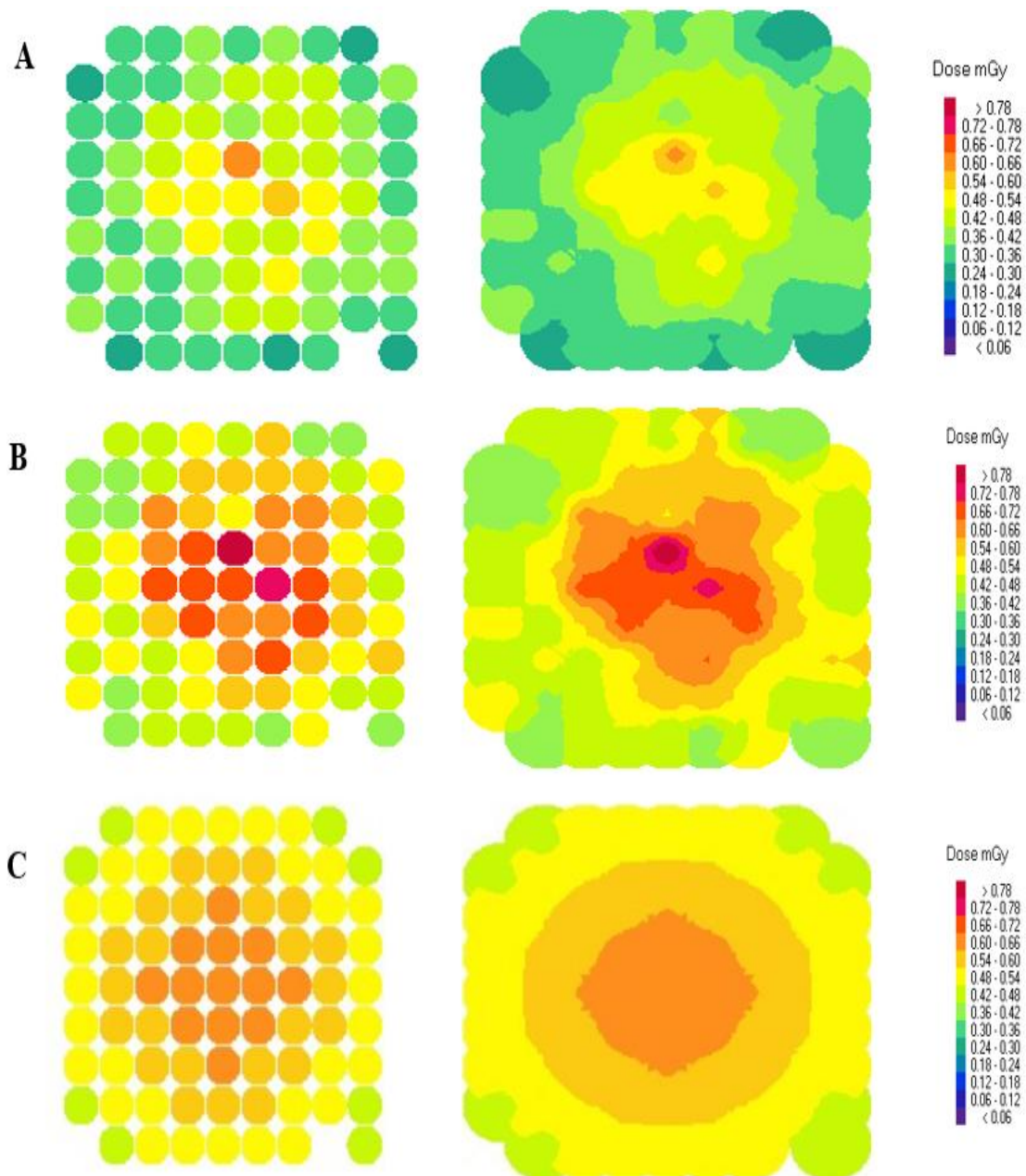


Figure 5.6 Initial mapping demonstration of concept for delimiting extents of dose rate fields inside the laboratory, (a) showing dose mGy before correction, (b) showing correction dose dose mGy and (c) showing dose mGy which was calculated.

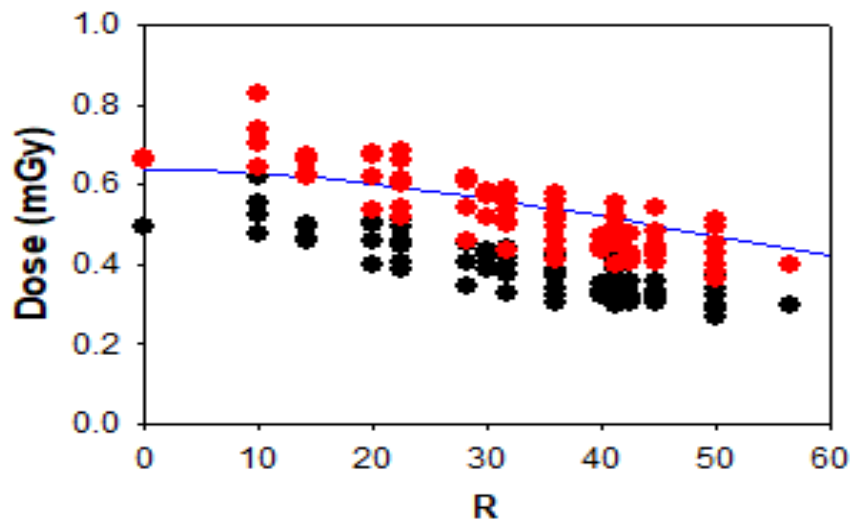


Figure 5.7. Measured dose rates for the initial mapping exercise as a function of distance from the central point, with the theoretical dose rates from the r^{-2} relationship with distance from the source.

5.4.2 A small field scheme outside using passive dosimeters

This experiment aims to assess the viability of employing ordinary table salt as a passive dosimeter for delineating natural background radiation and artificial sources in an outdoor setting, which could have important implications to use it for environmental monitoring and emergency response scenarios in future. This experiment was conducted at the Scottish Universities Environmental Research Centre (SUERC), located at the Scottish Enterprise Technology Park in East Kilbride on a secure part of the site that includes a variety of land use, including grassy areas, stone-covered surfaces, and zones with varying levels of natural and artificial radioactivity including doped concrete calibration pads, therefore serving as an optimal environment for assessing the efficacy of salt-based passive dosimeters in real-world scenarios. The definition of the spatial extent of radiation fields is crucial for making early decisions in managing radiological events and conducting environmental monitoring after radioactive events. Understanding the geographic distribution of radiation is important for developing effective protective strategies, improving resilience during nuclear or radiation emergencies, and protecting the public and first responders. So, the last part of this investigation also included an experiment conducted to see how well new methods of mapping radiation fields with passive dosimeters worked after deployments of a ^{60}Co source to create an artificial radiation field. The experiment was designed to simulate real world scenarios in which quick evaluation of radiation distribution is essential for making emergency response

plans. The area is within the site fence, so minimising the possibility of the dosimeters being disturbed and allowing the safe deployment of a ^{60}Co source to create an artificial radiation field. To facilitate comparisons between surveys and measurements, the site was divided into a series of areas (shown in figure 5.8). The grass area in the middle of the site (A). A gravel area between the grass and the SUERC buildings (B) and a concrete area just inside the fence (C), which includes calibration pads doped with enhanced concentrations of natural radionuclides.

Prior to deploying the passive dosimeters, a preliminary survey was conducted utilising SUERC's Portable Gamma Spectrometry System described in section 5.2.1, to confirm the range of dose rates measured in earlier surveys and monitor environmental change since then. A closely spaced survey pattern was followed, with parallel lines that were 0.5 to 1 meter apart. The instrument was driven by a netbook or tablet computer and utilized customized software to collect spectra continuously, along with associated positional data. Additionally, it conducted instantaneous analysis by utilising pre-established calibration parameters and a measured count rate above 450 keV was used to calculate the overall terrestrial gamma dose rate. Surveys were conducted prior to the deployment of salt dosimeters on the field and after three months following collected salt dosimeters to account for environmental change due to changing water content over the period of the natural exposure compare the dose rate, and with the ^{60}Co source deployed. Each survey included areas A, B, and C.

One hundred forty salt samples were prepared as passive dosimeters after removing the signal using a light box to zero any pre-existing luminescence. The samples were then wrapped and sealed in black plastic shrink sleeving to protect them from light exposure and environmental contaminants (Alghamdi et al., 2024) and placed in an additional black plastic zip-loc bag for additional protection. Samples were placed on hardwood stakes at a height of 75cm above ground and deployed in areas A, B, and C figure 5.9 at 2 m spacing between stakes and two dosimeters attached to each stake. The coordinates of each dosimeter were determined by measurements relative to the SUERC buildings, and verified by comparisons with the GPS positions from the backpack during static measurements over the dosimeters. The experiment ran for three months, from December 11, 2023, to February 23, 2024, enabling the dosimeters to record the cumulative natural background radiation over an extended duration, during which it was exposed to extremely cold weather, heavy snowfall, heavy rainfall, strong winds, and many sunny days. This diverse array of environmental elements offered a perfect chance to evaluate the durability and dependability of salt within the protective plastic envelopes as a

passive dosimeter material in different and frequently severe outdoor circumstances. After three months, one sachet from each stake, 100 samples, were collected and the full contents of each sachet were emptied on two 30 mm diameter aluminium planchettes and OSL signals recorded.

The second part of the experiment focused on mapping the spatial distribution of dose rates in a designated area (Area A) after the introduction of the radiation source to simulate an anthropogenic radiation field within a site where public access was controlled. After 1776 hours deployed in the field, 40 samples in area A were exposed to gamma-ray doses from a nominal 17 MBq ^{60}Co source placed on a hardwood stake at a height of 85 cm from the ground for 135 hours. During this period the dose rate was also mapped using the backpack system. Samples were collected and the full contents of each sachet were emptied on two 30 mm diameter aluminium planchettes and OSL signals were then recorded. Drone images of the test sites have been taken, which will help to extend the experiment's base maps.

The findings of this experiment may provide significant insights into the feasibility of salt-based passive dosimetry for extensive environmental radiation monitoring, especially in contexts requiring economical, easily deployable solutions for prolonged background assessments or rapid reactions to radiological events.





Figure 5.8: Shows pictures of the rear area, A, B, C, A is the grass area in the middle of the site. B includes small stones. C is the concrete area just inside the fence, which includes calibration pads doped with enhanced concentrations of natural radionuclides. (Dr Millie Bompard took the drone image).

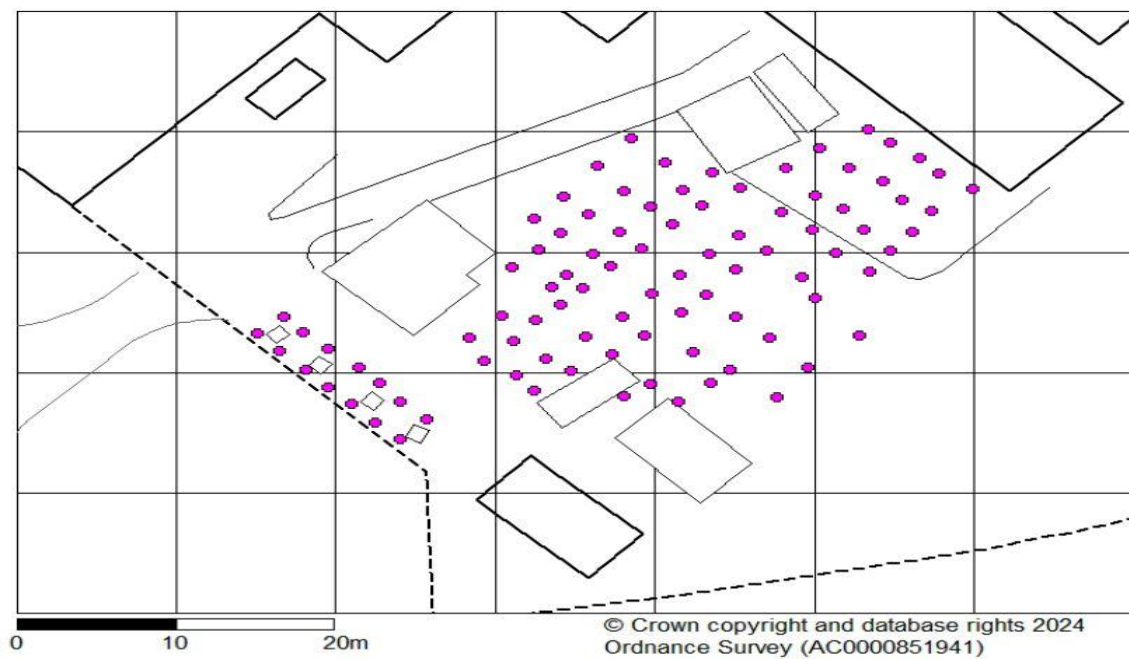


Figure 5.9: Illustration showing the distribution of dosimeters at the rear area at A, B, and C .

5.4.2.1 Results

5.4.2.1.1 Site surveys using backpack system

Maps of the distribution of dose rate for the rear area of the Scottish Universities Environmental Research Centre surveys are shown in Figure 5.10. Approximately 4800 spectra were collected over 4 days, with 7 h survey time. The results show consistent values across the surveyed areas, with natural activity primarily reflecting the underlying geology and materials in areas A, B, and C. To the right of the surveyed region, area C contains concrete calibration blocks exhibiting elevated dose rates ranging from 0.04 to 0.065 $\mu\text{Gy/h}$. This notable increase in dose rate within area C, compared to areas A and B, is attributed to radionuclides inside these blocks. Area B features granite stones that display an enhanced dose rate between 0.030 and 0.040 $\mu\text{Gy/h}$, higher than that observed in area A. In contrast, area A predominantly consists of grass areas with lower dose rates, ranging from 0.020 to 0.035 $\mu\text{Gy/h}$.

Invaluable baseline data is obtained by conducting backpack surveys to measure background radiation levels in various locations, which is essential for establishing normal radiation levels in different areas, identifying any pre-existing radiation anomalies, and enabling quick comparison during an emergency to detect abnormal radiation levels. Responders can efficiently cover large areas and access hard-to-reach locations by utilising backpack radiation detection systems, which provide high mobility and rapid deployment capabilities. In the event of a nuclear accident or calamity, backpack surveys can be swiftly deployed to evaluate the extent of contamination, identify and locate radiation sources, and direct evacuation and containment efforts. To detect changes in radiation levels over time, evaluate the effectiveness of decontamination efforts, and monitor the potential spread of radioactive materials, backpack surveys are a valuable tool for ongoing environmental monitoring. These surveys contribute to public safety by identifying secure zones and contaminated areas, guiding decisions on protective actions (e.g., shelter-in-place, evacuation), and providing data for risk communication to the public. Nuclear emergency responders require rucksack radiation surveys as an indispensable basic or complementary instrument. In the event of a nuclear incident, they substantially contribute to public safety, enhance response capabilities, and provide critical data for decision-making.

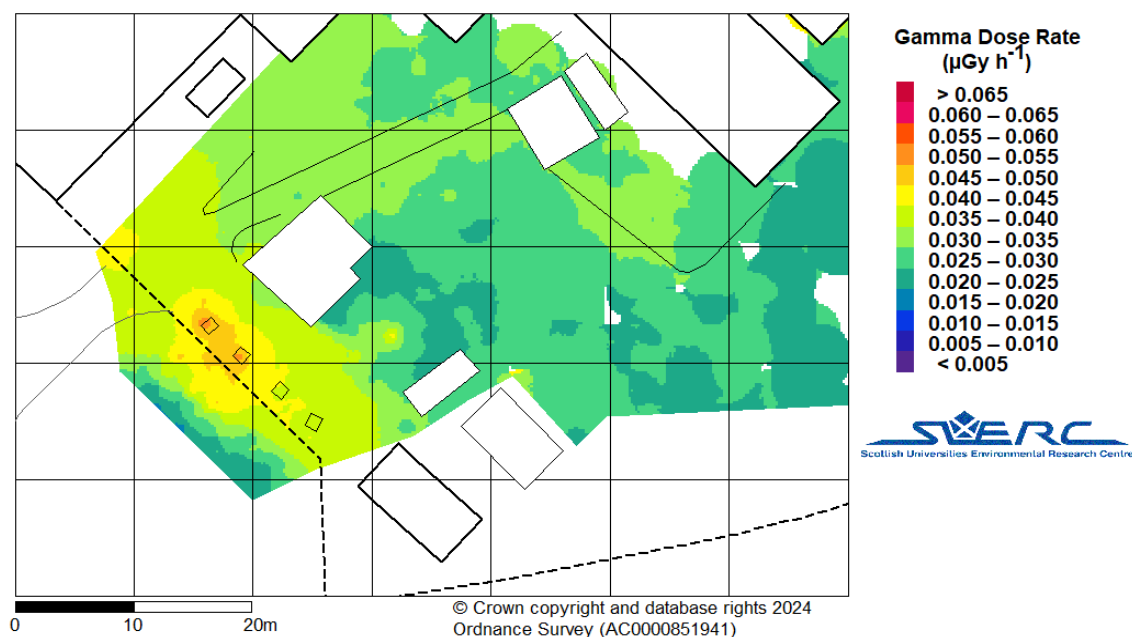


Figure 5.10. Dose rate distributions on rear area to Scottish Universities Environmental Research Centre using a backpack system.

5.4.2.1.2 Salt as passive dosimeter arrays outdoors

The results of the experiments investigating the viability of employing ordinary table salt as a passive dosimeter for delineating natural background radiation in an outdoor setting in the rear area (A, B, C) are shown in Tables 5.3, 5.4 and 5.5. The study encompassed a total of 98 dosimeters integrated over a period of 74 days (1776 hours). Following the completion of this exposure period, the dosimeters were retrieved for analysis. Each sachet is dispensed onto two aluminium planchettes. The optically stimulated luminescence (OSL) signal was then measured for each sample. These counts were then converted into dose values using a pre-established calibration curve (slope $39600.76 \pm 2750.11 \text{ c mGy}^{-1}$). The absorbed dose (D) for each sample was calculated using the following formula: $D(\text{mGy}) = \text{OSL Signal (counts)} / \text{Slope (counts/mGy)}$. After that, a fade correction factor was applied to correct the dose using $D_{\text{corrected}} (\text{mGy}) = D(\text{mGy}) \times F (1.08)$. The dose rates were determined by dividing these by the exposure period (1776h).

Figure 5.11 shows gamma dose distributions in mGy over the study areas. Both maps represent the same area but show different gamma dose distributions in (mGy). The doses range from low values (around 0.032 mGy) in some areas to higher values (up to 0.083 mGy in others). This figure provides a comparative analysis of dose levels before and after the application of

fade correction. Map A depicts the original dose distribution without fading correction, while map B demonstrates the dose distribution after fade correction has been applied. Analysis of the data revealed spatial variations in radiation levels across the study area, shown in Figure 5.11, reflecting the nature of these different areas. Dosimeters 173 and 40, located in areas C and B, respectively, recorded the highest photon counts and dose. In contrast, all dosimeters in area A consistently exhibited lower counts and dose rates. Tables 5.3, 5.4, and 5.5 present the average initial doses and the doses after applying a fading correction for these areas. Specifically, area A recorded an average initial dose and a fading-corrected dose of 0.049 ± 0.004 and 0.053 ± 0.004 , respectively. while area B also recorded average doses before and after the correction 0.051 ± 0.004 and 0.055 ± 0.004 , respectively. The average Initial dose estimate and fading corrected dose was 0.051 ± 0.004 and 0.055 ± 0.004 in area C, respectively.

The fading correction addresses the gradual loss of signal over time, which can lead to an underestimation of the true dose. After applying the fading correction, the study found that the average dose across the areas changed by only 8%. The 8% change in dose after applying the fading correction in areas A, B, and C is extremely small and does not significantly affect the overall dose estimates. These results suggest fading was far less significant than anticipated. However, several environmental and experimental factors may have influenced the accuracy of the fading correction. 1-The fading correction curve was derived from laboratory conditions at a constant temperature of approximately 21 ± 2 °C, while the outdoor experiment was conducted at significantly lower temperatures (5–10 °C). So, that difference in temperature will change the way the fading works. Future studies should calibrate fading curves at temperatures matching the field conditions to improve accuracy. 2-The outdoor experiment experienced varying water levels in the measurement areas throughout the 76-day period, while the fading correction curve was derived from laboratory conditions at a relative humidity of 31 %. Changes in humidity and water content can affect the dosimeter's response, but the exact impact remains unquantified in this experiment. 3- The electron equilibrium with the plastic shrink wrap was not considered. Variations in electron equilibrium, influenced by environmental conditions and material properties, could result in deviations in the measured dose. The fading correction applied was derived from laboratory conditions, which may not fully reflect the outdoor environment. The fading correction produced a slight change to the recorded dose, and both of the maps in Figure 5.11 are very similar. Therefore, these additional details may not make too much of a difference in practice. Nonetheless, the effects of temperature, humidity,

water variation, and electron equilibrium on the dosimeter's response are still unclear in this experiment.

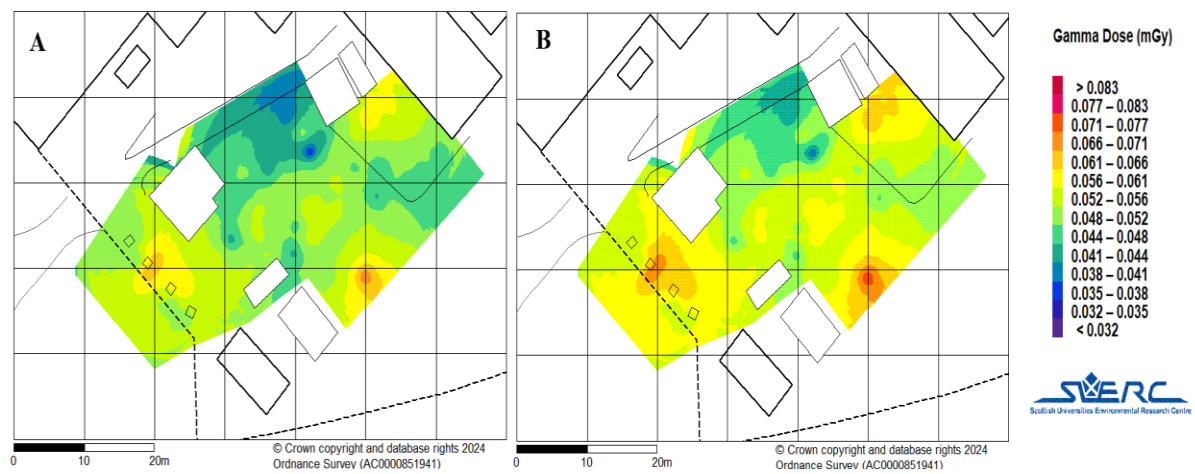


Figure 5.11. A map of the gamma dose distribution across the study areas, comparing two maps: one representing the uncorrected dose measurements (map A) and another reflecting the doses after applying a fading correction factor of 1.08 (map B).

Table 5.3 Mean and standard deviation of photon counts, Initial dose estimate, fading corrected dose and dose rate recorded using the SUERC portable OSL reader at 470 nm, from NaCl, A area (Grass areas).

X m	Y m	N. dosimeters	OSL Counts Average of two aliquots	Initial dose estimate/ mGy	Fading corrected dose mGy	Dose rate $\mu\text{Gy/h}$
264419	653229	1	1376 $\pm$ 31	0.035 $\pm$ 0.003	0.038 $\pm$ 0.003	0.02 $\pm$ 0.001
264417	653226	3	1757 $\pm$ 33	0.044 $\pm$ 0.003	0.048 $\pm$ 0.003	0.025 $\pm$ 0.002
264415	653224	5	1688 $\pm$ 33	0.043 $\pm$ 0.003	0.046 $\pm$ 0.003	0.024 $\pm$ 0.002
264413	653222	7	2076 $\pm$ 36	0.052 $\pm$ 0.004	0.057 $\pm$ 0.004	0.03 $\pm$ 0.002
264419	653224	10	1464 $\pm$ 31	0.037 $\pm$ 0.003	0.04 $\pm$ 0.003	0.021 $\pm$ 0.002
264417	653222	12	1352 $\pm$ 30	0.034 $\pm$ 0.002	0.037 $\pm$ 0.003	0.019 $\pm$ 0.001
264414	653219	14	1656 $\pm$ 33	0.042 $\pm$ 0.003	0.045 $\pm$ 0.003	0.024 $\pm$ 0.002
264412	653218	15	1718 $\pm$ 34	0.043 $\pm$ 0.003	0.047 $\pm$ 0.003	0.024 $\pm$ 0.002
264422	653227	17	2239 $\pm$ 37	0.057 $\pm$ 0.004	0.061 $\pm$ 0.004	0.032 $\pm$ 0.002
264425	653226	19	1493 $\pm$ 32	0.038 $\pm$ 0.003	0.041 $\pm$ 0.003	0.021 $\pm$ 0.002
264423	653224	21	595 $\pm$ 24	0.015 $\pm$ 0.001	0.016 $\pm$ 0.001	0.008 $\pm$ 0.001
264419	653221	25	2104 $\pm$ 37	0.053 $\pm$ 0.004	0.057 $\pm$ 0.004	0.03 $\pm$ 0.002
264417	653219	28	1910 $\pm$ 36	0.048 $\pm$ 0.003	0.052 $\pm$ 0.004	0.027 $\pm$ 0.002
264415	653217	29	2567 $\pm$ 39	0.065 $\pm$ 0.005	0.07 $\pm$ 0.005	0.036 $\pm$ 0.003
264415	653216	31	2037 $\pm$ 35	0.051 $\pm$ 0.004	0.056 $\pm$ 0.004	0.029 $\pm$ 0.002
264411	653214	33	1254 $\pm$ 33	0.032 $\pm$ 0.002	0.034 $\pm$ 0.003	0.018 $\pm$ 0.001
264424	653223	46	2004 $\pm$ 36	0.051 $\pm$ 0.004	0.055 $\pm$ 0.004	0.028 $\pm$ 0.002
264422	653221	48	2129 $\pm$ 37	0.054 $\pm$ 0.004	0.058 $\pm$ 0.004	0.03 $\pm$ 0.002
264420	6532119	50	2133 $\pm$ 36	0.054 $\pm$ 0.004	0.058 $\pm$ 0.004	0.03 $\pm$ 0.002
264418	653218	51	2076 $\pm$ 36	0.052 $\pm$ 0.004	0.057 $\pm$ 0.004	0.03 $\pm$ 0.002
264416	6532116	52	1826 $\pm$ 35	0.046 $\pm$ 0.003	0.05 $\pm$ 0.004	0.026 $\pm$ 0.002
264415	653215	54	2527 $\pm$ 39	0.064 $\pm$ 0.005	0.069 $\pm$ 0.005	0.036 $\pm$ 0.003
264413	653213	56	1798 $\pm$ 34	0.045 $\pm$ 0.003	0.049 $\pm$ 0.004	0.026 $\pm$ 0.002
264412	653212	58	1973 $\pm$ 36	0.05 $\pm$ 0.004	0.054 $\pm$ 0.004	0.028 $\pm$ 0.002
264426	653221	69	2571 $\pm$ 39	0.065 $\pm$ 0.005	0.07 $\pm$ 0.005	0.037 $\pm$ 0.003
264424	653219	71	2347 $\pm$ 38	0.059 $\pm$ 0.004	0.064 $\pm$ 0.005	0.033 $\pm$ 0.002
264422	653217	74	2630 $\pm$ 40	0.066 $\pm$ 0.005	0.072 $\pm$ 0.005	0.037 $\pm$ 0.003
264421	653216	75	1539 $\pm$ 32	0.039 $\pm$ 0.003	0.042 $\pm$ 0.003	0.022 $\pm$ 0.002
264419	653214	77	1843 $\pm$ 35	0.047 $\pm$ 0.003	0.05 $\pm$ 0.004	0.026 $\pm$ 0.002
264417	653212	79	2260 $\pm$ 37	0.057 $\pm$ 0.004	0.062 $\pm$ 0.004	0.032 $\pm$ 0.002
264414	653210	81	2214 $\pm$ 37	0.056 $\pm$ 0.004	0.06 $\pm$ 0.004	0.031 $\pm$ 0.002
264412	653209	83	2424 $\pm$ 39	0.061 $\pm$ 0.004	0.066 $\pm$ 0.005	0.034 $\pm$ 0.002

264425	653219	93	1472 ± 31	0.037 ± 0.003	0.04 ± 0.003	0.021 ± 0.002
264426	653218	95	2316 ± 38	0.058 ± 0.004	0.063 ± 0.004	0.033 ± 0.002
264424	653216	97	2435 ± 39	0.061 ± 0.004	0.066 ± 0.005	0.035 ± 0.002
264423	653214	99	2343 ± 38	0.059 ± 0.004	0.064 ± 0.005	0.033 ± 0.002
264420	653212	101	1235 ± 29	0.031 ± 0.002	0.034 ± 0.002	0.018 ± 0.001
264418	653211	103	1792 ± 35	0.045 ± 0.003	0.049 ± 0.004	0.025 ± 0.002
264416	653209	105	1933 ± 36	0.049 ± 0.004	0.053 ± 0.004	0.027 ± 0.002
264432	653219	118	1387 ± 31	0.035 ± 0.003	0.038 ± 0.003	0.02 ± 0.001
264430	653217	120	1802 ± 38	0.045 ± 0.003	0.049 ± 0.004	0.026 ± 0.002
264426	653214	122	1628 ± 33	0.041 ± 0.003	0.044 ± 0.003	0.023 ± 0.002
264423	653211	124	1877 ± 35	0.047 ± 0.003	0.051 ± 0.004	0.027 ± 0.002
264421	65208	126	1604 ± 33	0.04 ± 0.003	0.044 ± 0.003	0.023 ± 0.002
264419	653207	128	1624 ± 33	0.041 ± 0.003	0.044 ± 0.003	0.023 ± 0.002
264434	653218	139	1997 ± 33	0.05 ± 0.004	0.054 ± 0.004	0.028 ± 0.002
264431	653215	140	2223 ± 37	0.056 ± 0.004	0.061 ± 0.004	0.032 ± 0.002
264428	653212	143	2200 ± 37	0.056 ± 0.004	0.06 ± 0.004	0.031 ± 0.002
264426	653209	145	1963 ± 35	0.05 ± 0.004	0.054 ± 0.004	0.028 ± 0.002
264424	653208	147	2007 ± 36	0.051 ± 0.004	0.055 ± 0.004	0.029 ± 0.002
264422	653207	149	2601 ± 40	0.066 ± 0.005	0.071 ± 0.005	0.037 ± 0.003
264430	653210	150	3089 ± 42	0.078 ± 0.006	0.084 ± 0.006	0.044 ± 0.003
264434	653212	153	2213 ± 38	0.056 ± 0.004	0.06 ± 0.004	0.031 ± 0.002
264429	653207	154	2311 ± 37	0.058 ± 0.004	0.063 ± 0.004	0.033 ± 0.002
Average			1956 ± 35.27	0.049 ± 0.004	0.053 ± 0.004	0.028 ± 0.004

Table 5.4 Mean and standard deviation of photon counts, Initial dose estimate, fading corrected dose and recorded using the SUERC portable OSL reader at 470 nm, from NaCl, B area (Granite stones).

X m	Y m	N. dosimeters	OSL Counts Average of two aliquots	Initial dose estimate/ mGy	Fading corrected dose mGy	Dose rate μ Gy/h
264409	653212	36	2197 $\pm$ 37	0.055 $\pm$ 0.004	0.06 $\pm$ 0.004	0.031 $\pm$ 0.002
264434	653229	37	2370 $\pm$ 38	0.06 $\pm$ 0.004	0.065 $\pm$ 0.005	0.034 $\pm$ 0.002
264431	653228	40	2826 $\pm$ 41	0.071 $\pm$ 0.005	0.077 $\pm$ 0.005	0.04 $\pm$ 0.003
264429	653226	41	2162 $\pm$ 43	0.055 $\pm$ 0.004	0.059 $\pm$ 0.004	0.031 $\pm$ 0.002
264426	653225	44	2220 $\pm$ 37	0.056 $\pm$ 0.004	0.061 $\pm$ 0.004	0.032 $\pm$ 0.002
264410	653210	60	2094 $\pm$ 37	0.053 $\pm$ 0.004	0.057 $\pm$ 0.004	0.03 $\pm$ 0.002
264436	653228	62	2215 $\pm$ 38	0.056 $\pm$ 0.004	0.06 $\pm$ 0.004	0.031 $\pm$ 0.002
264431	653224	65	1922 $\pm$ 35	0.049 $\pm$ 0.003	0.052 $\pm$ 0.004	0.027 $\pm$ 0.002
264433	653226	66	2071 $\pm$ 37	0.052 $\pm$ 0.004	0.056 $\pm$ 0.004	0.029 $\pm$ 0.002
264429	653222	67	1710 $\pm$ 33	0.043 $\pm$ 0.003	0.047 $\pm$ 0.003	0.024 $\pm$ 0.002
264437	653227	86	2219 $\pm$ 37	0.056 $\pm$ 0.004	0.061 $\pm$ 0.004	0.032 $\pm$ 0.002
264435	653225	87	2099 $\pm$ 36	0.053 $\pm$ 0.004	0.057 $\pm$ 0.004	0.03 $\pm$ 0.002
264433	653223	90	1544 $\pm$ 32	0.039 $\pm$ 0.003	0.042 $\pm$ 0.003	0.022 $\pm$ 0.002
264431	653221	92	1923 $\pm$ 35	0.049 $\pm$ 0.003	0.052 $\pm$ 0.004	0.027 $\pm$ 0.002
264413	653208	108	1997 $\pm$ 35	0.05 $\pm$ 0.004	0.054 $\pm$ 0.004	0.028 $\pm$ 0.002
264439	653226	111	1889 $\pm$ 35	0.048 $\pm$ 0.003	0.052 $\pm$ 0.004	0.027 $\pm$ 0.002
264436	653224	113	2087 $\pm$ 36	0.053 $\pm$ 0.004	0.057 $\pm$ 0.004	0.03 $\pm$ 0.002
264434	653221	116	1915 $\pm$ 35	0.048 $\pm$ 0.003	0.052 $\pm$ 0.004	0.027 $\pm$ 0.002
26441	653224	130	1803 $\pm$ 34	0.046 $\pm$ 0.003	0.049 $\pm$ 0.004	0.026 $\pm$ 0.002
264438	653223	131	1818 $\pm$ 34	0.046 $\pm$ 0.003	0.05 $\pm$ 0.004	0.026 $\pm$ 0.002
264437	653221	134	1717 $\pm$ 33	0.043 $\pm$ 0.003	0.047 $\pm$ 0.003	0.024 $\pm$ 0.002
264436	653219	137	1876 $\pm$ 35	0.047 $\pm$ 0.003	0.047 $\pm$ 0.003	0.027 $\pm$ 0.002
Average			2030 $\pm$ 36	0.051 $\pm$ 0.004	0.055 $\pm$ 0.004	0.029 $\pm$ 0.002

Table 5.5 Mean and standard deviation of photon counts, Initial dose estimate, fading corrected dose and recorded using the SUERC portable OSL reader at 470 nm, from NaCl, C area (white badge boxes).

X m	Y m	N. dosimeters	OSL Counts Average of two aliquots	Initial dose estimate/ mGy	Fading corrected dose mGy	Dose rate $\mu\text{Gy/h}$
264395	653214	158	1834 ± 35	0.046 ± 0.003	0.05 ± 0.004	0.026 ± 0.002
264398	653214	161	1757 ± 33	0.044 ± 0.003	0.048 ± 0.003	0.025 ± 0.002
264396	653213	163	1944 ± 34	0.049 ± 0.004	0.053 ± 0.004	0.028 ± 0.002
264399	653213	164	2388 ± 38	0.06 ± 0.004	0.065 ± 0.005	0.034 ± 0.002
264398	653211	166	1472 ± 31	0.037 ± 0.003	0.04 ± 0.003	0.021 ± 0.002
26400	653211	167	2764 ± 41	0.07 ± 0.005	0.075 ± 0.005	0.039 ± 0.003
264399	653210	168	2984 ± 43	0.075 ± 0.005	0.081 ± 0.006	0.042 ± 0.003
264402	653210	169	2397 ± 38	0.061 ± 0.004	0.065 ± 0.005	0.034 ± 0.002
26401	653206	171	1967 ± 36	0.05 ± 0.004	0.054 ± 0.004	0.028 ± 0.002
264404	653208	173	2802 ± 41	0.071 ± 0.005	0.076 ± 0.005	0.04 ± 0.003
264403	653206	176	1698 ± 34	0.043 ± 0.003	0.046 ± 0.003	0.024 ± 0.002
264406	653206	178	2168 ± 37	0.055 ± 0.004	0.059 ± 0.004	0.031 ± 0.002
264405	653205	180	1763 ± 34	0.045 ± 0.003	0.048 ± 0.003	0.025 ± 0.002
264408	653204	182	2038 ± 40	0.051 ± 0.004	0.056 ± 0.004	0.029 ± 0.002
264406	653203	185	2166 ± 33	0.055 ± 0.004	0.059 ± 0.004	0.031 ± 0.002
264409	653203	184	2029 ± 37	0.051 ± 0.004	0.055 ± 0.004	0.029 ± 0.002
Average			2135.47 ± 36.58	0.054 ± 0.004	0.058 ± 0.004	0.03 ± 0.002

The results of a comparative analysis between the results of an experiment measuring radiation dose rates using passive dosimeters (salt), including both dose measurements before and after applying a fading correction and comparing them with measurements taken using a Backpack system are shown in Table 5.6, which shows that the passive dosimeter results compare well with spectrometric approaches between areas (A, B, and C). The fading correction slightly increases the dose rate estimates across all areas. The dose rate increases from $0.0285 \pm 0.0020 \mu\text{Gy/h}$ to $0.0308 \pm 0.0022 \mu\text{Gy/h}$ after correction at the whole area. Similar trends are observed in the stone area (A), the stone area (B) and the white box area (C), where NaCl measurements are consistently higher after applying fading correction. The fading correction is relatively consistent across all areas. This suggests that the fading effect is uniform across the different measurement locations. Across all areas, the fading correction increases the dose rate by approximately 7–8%. This consistent shift suggests a slightly fading effect in the passive

dosimeter. The uncertainties in dose rates after fading correction remain comparable to those before correction (0.019 vs. 0.022), confirming that the fading correction (7–8%, with ~1% uncertainty) does not significantly impact precision. Backpack systems measure dose rates in real time and are not subject to fading. In the whole area, the passive (fading-corrected) and Backpack system measurements agree within ~3%, well within the passive system's uncertainty ($\pm 0.0022 \mu\text{Gy/h}$), suggesting good calibration and reliability for overall site assessment. In designated regions (Grass A and White Box C), the Backpack systems indicate significantly elevated dose rates (14–15% higher) compared to the fading-corrected passive dosimeter. Conversely, in Stone Area B, the passive dosimeter registers approximately 7% higher readings. This variation may arise from the fact that passive dosimeters accumulate dose over time, thereby mitigating short-term variations, whereas active dosimeters record instantaneous rates, potentially identifying precise peaks.

The passive dosimeter (NaCl) with fading correction aligns reasonably with the active dosimeter (Backpack) for overall site assessment but shows discrepancies in specific areas due to temporal and spatial differences. The findings demonstrate that NaCl, with suitable adjustments, functions as a dependable technique for quantifying radiation dose rates, but the Backpack system offers excellent accuracy and immediate reaction. Collectively, they provide a thorough evaluation of radiation levels at the incident location.

Table 5.6 Mean and standard deviation of dose rate recorded using the SUERC portable OSL reader at 470 nm, from NaCl and backpack system to compare between areas A,B,C.

Aea	NaCl		
	NaCl Dose rate $\mu\text{Gy/h}$	NaCl Dose rate $\mu\text{Gy/h}$ after correction	Backpack Dose rate $\mu\text{Gy/h}$
Whole area	0.0285 ± 0.0020	0.0308 ± 0.0022	0.0300 ± 0.0002
Grass area A	0.0278 ± 0.0019	0.0300 ± 0.0022	0.0341 ± 0.0004
stone area B	0.0288 ± 0.0020	0.0312 ± 0.002	0.0292 ± 0.0003
white box area C	0.0307 ± 0.0021	0.0328 ± 0.002	0.0385 ± 0.0003

Figure 5.12 shows the dose rate data obtained by passive dosimeters across the research areas (A, B, and C). However, Figure 5.10 illustrates dose rates recorded by the Backpack system for the same locations. The passive dosimeters (Figure 5.12) indicate a time-integrated dose rate, representing cumulative exposure throughout the location, whereas the backpack system

(Figure 5.10) records real-time dose rate distributions. Concordance between the charts may manifest in regions characterised by steady, uniform radiation levels, where both systems register comparable averages (e.g., around 0.0300–0.0308 $\mu\text{Gy/h}$ for the whole area, as shown by Table 5.6). Variations arise due to the fading over time of the passive system (about 8%) and its time averaging, which may miss hotspots that the backpack system detects directly.

The comparative analysis of these datasets reveals several critical insights into the performance and reliability of passive versus Backpack systems in environmental radiation monitoring. The salt dosimetry effectively recorded natural radiation dose rates throughout the measurement period, accurately reflecting the characteristics of each area. The consistency in measurements across different locations validates the reliability of the salt dosimetry method. This experiment demonstrates that an array of salt dosimeters can effectively map natural background radiation. The results underscore the potential utility of salt-based dosimetry for field measurements, offering a promising alternative or complementary method to traditional radiation monitoring techniques.

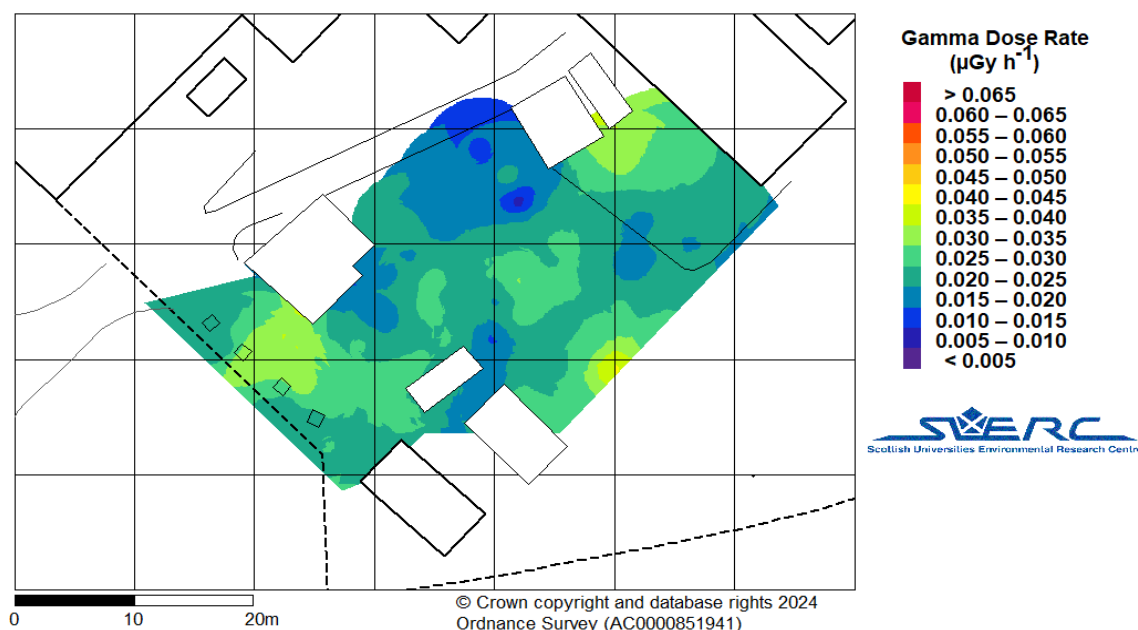


Figure 5.12. Fading corrected dose rate distributions on rear area to Scottish Universities Environmental Research Centre using passive dosimeters.

5.4.2.1.3 Site surveys using backpack system after deployed gamma source

The map of the distribution of dose rate for the rear area (A) during the exposure of 40 salt samples for 135 hours using the gamma source is shown in Figure 5.13. Approximately 110

spectra were collected during the 1 h survey time. The dose rate distribution in area A reflects levels between 0.020 and 6.11 uGy/h. The results reflect the radiation field of the source inside area A, in which the dose rate increases near the source and decreases with distance from the source. The dose rates represent the average radiation levels in the area after deploying the gamma source. The survey effectively pinpointed areas of elevated radiation, which is crucial for contamination mapping and source localization during response to nuclear and radiation emergencies. Sections 5.3.3.2 and 5.4.2.1.3 present detailed radiation measurements for the rear area (A), showing radiation levels prior to and following to the introduction of a radiation source. These measurements serve two functions: they establish a baseline radiation level before the source's introduction and quantify the radiation levels after its deployment. By comparing these two datasets, it becomes possible to calculate the net radiation dose attributable to the source. This comparative analysis not only highlights the impact of the radioactive source but also provides a clear framework for evaluating changes in radiation exposure, offering critical insights for radiation safety assessments and environmental monitoring. Sections 5.4.2.1.1 and 5.4.2.1.3 present radiation measurements to measure radiation levels for the rear area (A) before and after radioactive source deployment.

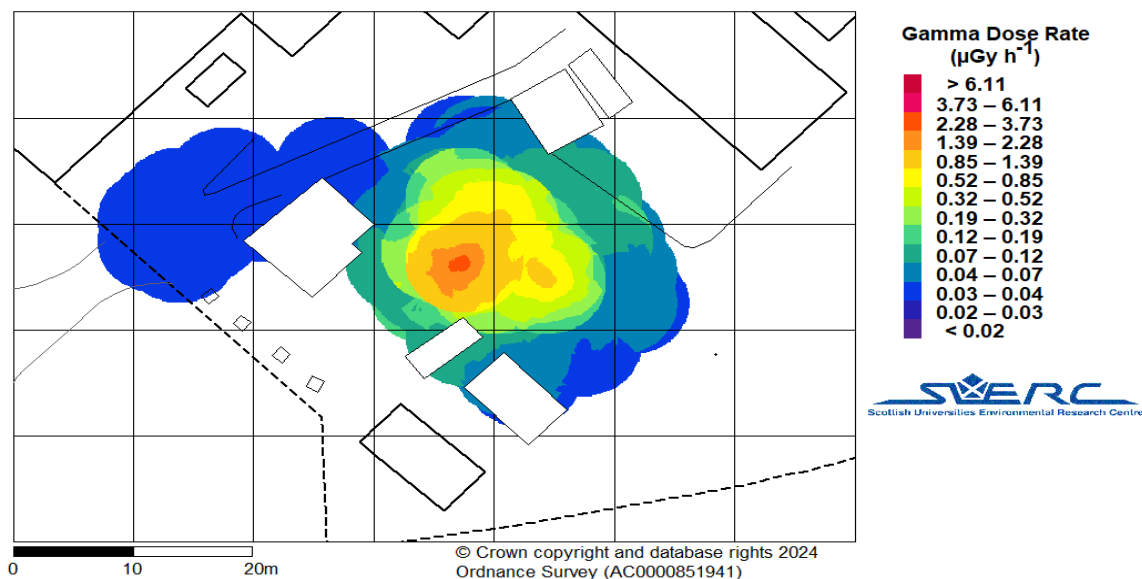


Figure 5.13. Dose rate distributions on rear area to Scottish Universities Environmental Research Centre with the ^{60}Co source deployed, measured using the backpack system.

5.4.2.1.4 Salt as Passive dosimeter arrays outside with deployed gamma source

The results of the experiments investigating the viability of employing ordinary table salt as a passive dosimeter for an accurate assessment of the radiation contribution from the source are

shown in Table 5.7. The study involved 40 dosimeters exposed to a gamma source for 135 hours. Following the completion of this exposure period, the dosimeters were retrieved for analysis. Each sachet was dispensed onto two aluminium planchettes. The optically stimulated luminescence (OSL) signal was then measured for each sample. These counts were then converted into dose values using a pre-established calibration curve (slope $39600.76 \pm 2750.11 \text{ c mGy}^{-1}$). The absorbed dose (D) for each sample was calculated using the following formula: $D(\text{mGy}) = \text{OSL Signal (counts)} / \text{Slope (counts/mGy)}$. The dose rates were determined by dividing these by the exposure period (135 h). The fading correction factor derived from the decay curve in Figure 5.4 was calculated to be 0.97. This coefficient was deemed negligible as it indicated an insignificant change in the dose value following correction. Consequently, it was disregarded in the analysis, as it did not contribute meaningfully to the correction of the measured radiation dose.

The spatial distribution of doses (mGy) from the salt dosimeters are shown in Figure. 5.14, with a range of 0.1320 ± 0.009 to 0.052 ± 0.004 mGy. Dosimeters that were situated in close proximity to the centrally located source recorded higher doses, whereas those that were located at a greater distance exhibited a significant decrease in the measured radiation levels. This change in dose illustrates the salt's capacity to distinguish between radiation levels in the experimental areas. The data clearly illustrates the correlation between the dosimeter's position in regard to the radiation source and the measured dose. Dosimeter 98, positioned close to the centrally placed radiation source, reported higher doses, with the highest measured value being 0.1320 ± 0.009 mGy. As the distance from the source increased, a significant reduction in the measured radiation levels was seen. The lowest measured dose of 0.052 ± 0.004 mGy was recorded at the farthest distant locations from the source by dosimeter 57 as shown in Table 5.7. The salt dosimeters demonstrated enough sensitivity to identify and measure radiation levels following deployment of the gamma source. The significant variation in dose at different places demonstrates remarkable spatial resolution, providing an extensive mapping of the radiation environment. The minimal error ranges (± 0.009 mGy for the maximum doses and ± 0.004 mGy for the minimum) indicate a good level of precision in the measurements.

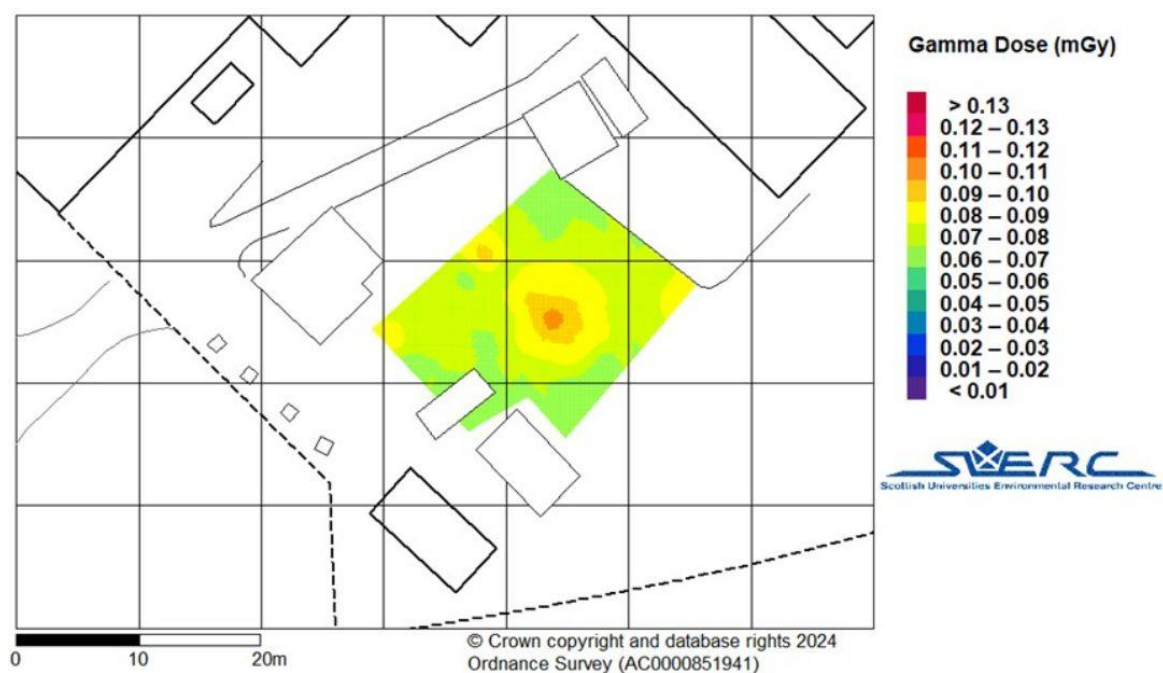


Figure 5.14. A map of the gamma radiation dose distribution throughout the investigated area. This map was generated following a 135-hour exposure period to a gamma source

Table 5.7 Mean and standard deviation of photon counts, dose and dose rate recorded using the SUERC portable OSL reader at 470 nm, from NaCl an area A, after deployed gamma source

X	Y	Salt .N	OSL Counts Average of two aliquots	Dose mGy	Dose rate $\mu\text{Gy/h}$	Net Dose mGy	Net $\mu\text{Gy/h}$
264425	653226	20	2709 $\pm$ 40.37	0.068 $\pm$ 0.005	0.507 $\pm$ 0.003	0.031 $\pm$ 0.005	0.228 $\pm$ 0.036
264423	653224	22	2694 $\pm$ 28.77	0.068 $\pm$ 0.005	0.504 $\pm$ 0.003	0.053 $\pm$ 0.005	0.393 $\pm$ 0.035
264419	653221	26	4268 $\pm$ 46.25	0.108 $\pm$ 0.008	0.798 $\pm$ 0.004	0.055 $\pm$ 0.008	0.405 $\pm$ 0.056
264417	653219	27	2245.5 $\pm$ 34.54	0.057 $\pm$ 0.004	0.42 $\pm$ 0.002	0.008 $\pm$ 0.004	0.063 $\pm$ 0.03
264415	653217	30	3286.5 $\pm$ 43.49	0.083 $\pm$ 0.006	0.615 $\pm$ 0.003	0.018 $\pm$ 0.006	0.135 $\pm$ 0.043
264415	653216	32	2851 $\pm$ 41.44	0.072 $\pm$ 0.005	0.533 $\pm$ 0.003	0.021 $\pm$ 0.005	0.152 $\pm$ 0.038
264411	653214	34	3746 $\pm$ 38.1	0.095 $\pm$ 0.007	0.701 $\pm$ 0.004	0.063 $\pm$ 0.007	0.466 $\pm$ 0.049
264424	653223	45	2379.5 $\pm$ 37.49	0.06 $\pm$ 0.004	0.445 $\pm$ 0.002	0.009 $\pm$ 0.004	0.07 $\pm$ 0.032
264422	653221	47	3189.5 $\pm$ 43.01	0.081 $\pm$ 0.006	0.597 $\pm$ 0.003	0.027 $\pm$ 0.006	0.198 $\pm$ 0.042
264420	653219	50	2623.5 $\pm$ 32.51	0.066 $\pm$ 0.005	0.491 $\pm$ 0.003	0.012 $\pm$ 0.005	0.092 $\pm$ 0.035
264416	653216	52	2826 $\pm$ 36.35	0.071 $\pm$ 0.005	0.529 $\pm$ 0.003	0.019 $\pm$ 0.005	0.14 $\pm$ 0.037
264413	653213	55	2753.5 $\pm$ 37.21	0.07 $\pm$ 0.005	0.515 $\pm$ 0.003	0.006 $\pm$ 0.005	0.042 $\pm$ 0.036
264412	653212	57	2044.5 $\pm$ 35.4	0.052 $\pm$ 0.004	0.382 $\pm$ 0.002	0.006 $\pm$ 0.004	0.046 $\pm$ 0.027
264426	653221	70	3019 $\pm$ 40.36	0.076 $\pm$ 0.005	0.565 $\pm$ 0.003	0.026 $\pm$ 0.005	0.196 $\pm$ 0.04
264424	653219	72	2967 $\pm$ 37.64	0.075 $\pm$ 0.005	0.555 $\pm$ 0.003	0.01 $\pm$ 0.005	0.074 $\pm$ 0.039
264422	653217	73	3852 $\pm$ 46.94	0.097 $\pm$ 0.007	0.721 $\pm$ 0.004	0.038 $\pm$ 0.007	0.282 $\pm$ 0.051
264421	653216	76	2917 $\pm$ 41.7	0.074 $\pm$ 0.005	0.546 $\pm$ 0.003	0.007 $\pm$ 0.005	0.054 $\pm$ 0.039
264417	653212	80	3086 $\pm$ 42.38	0.078 $\pm$ 0.006	0.577 $\pm$ 0.003	0.039 $\pm$ 0.006	0.289 $\pm$ 0.041
264414	653210	82	2379 $\pm$ 38.5	0.06 $\pm$ 0.004	0.445 $\pm$ 0.002	0.014 $\pm$ 0.004	0.1 $\pm$ 0.032
264419	653214	89	2425 $\pm$ 38.46	0.061 $\pm$ 0.004	0.454 $\pm$ 0.002	0.004 $\pm$ 0.004	0.031 $\pm$ 0.032
264414	653210	91	3363 $\pm$ 44.17	0.085 $\pm$ 0.006	0.629 $\pm$ 0.003	0.029 $\pm$ 0.006	0.215 $\pm$ 0.044
264425	653219	94	3611.5 $\pm$ 45.22	0.091 $\pm$ 0.006	0.676 $\pm$ 0.004	0.054 $\pm$ 0.006	0.4 $\pm$ 0.048
264426	653218	96	3452.5 $\pm$ 44.31	0.087 $\pm$ 0.006	0.646 $\pm$ 0.003	0.029 $\pm$ 0.006	0.213 $\pm$ 0.046
264424	653216	98	5225 $\pm$ 57.97	0.132 $\pm$ 0.009	0.977 $\pm$ 0.005	0.07 $\pm$ 0.009	0.522 $\pm$ 0.069
264423	653214	100	3308.5 $\pm$ 43.58	0.084 $\pm$ 0.006	0.619 $\pm$ 0.003	0.024 $\pm$ 0.006	0.181 $\pm$ 0.044
264420	653212	102	2833.5 $\pm$ 41.13	0.072 $\pm$ 0.005	0.53 $\pm$ 0.003	0.04 $\pm$ 0.005	0.299 $\pm$ 0.038
264418	653211	104	2672 $\pm$ 40.52	0.067 $\pm$ 0.005	0.5 $\pm$ 0.003	0.022 $\pm$ 0.005	0.165 $\pm$ 0.035
264416	653209	106	2160.5 $\pm$ 36.92	0.055 $\pm$ 0.004	0.404 $\pm$ 0.002	0.006 $\pm$ 0.004	0.043 $\pm$ 0.029
264432	653219	115	2681.5 $\pm$ 39.77	0.068 $\pm$ 0.005	0.502 $\pm$ 0.003	0.033 $\pm$ 0.005	0.242 $\pm$ 0.036
264430	653217	119	2808.5 $\pm$ 41.51	0.071 $\pm$ 0.005	0.525 $\pm$ 0.003	0.025 $\pm$ 0.005	0.188 $\pm$ 0.037
264426	653214	121	2311 $\pm$ 37.24	0.058 $\pm$ 0.004	0.432 $\pm$ 0.002	0.017 $\pm$ 0.004	0.128 $\pm$ 0.031
264426	653214	123	4894 $\pm$ 38.04	0.124 $\pm$ 0.009	0.915 $\pm$ 0.005	0.076 $\pm$ 0.009	0.564 $\pm$ 0.064
264423	653211	125	2718 $\pm$ 40.26	0.069 $\pm$ 0.005	0.508 $\pm$ 0.003	0.028 $\pm$ 0.005	0.208 $\pm$ 0.036
264421	653208	127	2785.5 $\pm$ 40.92	0.07 $\pm$ 0.005	0.521 $\pm$ 0.003	0.029 $\pm$ 0.005	0.217 $\pm$ 0.037
264419	653207	129	2743 $\pm$ 40.53	0.069 $\pm$ 0.005	0.513 $\pm$ 0.003	0.019 $\pm$ 0.005	0.14 $\pm$ 0.036
264434	653218	138	3652 $\pm$ 45.52	0.092 $\pm$ 0.006	0.683 $\pm$ 0.004	0.036 $\pm$ 0.007	0.267 $\pm$ 0.048
264431	653215	141	2864.5 $\pm$ 40.54	0.072 $\pm$ 0.005	0.536 $\pm$ 0.003	0.017 $\pm$ 0.005	0.124 $\pm$ 0.038
264426	653209	144	2265.5 $\pm$ 37.25	0.057 $\pm$ 0.004	0.424 $\pm$ 0.002	0.008 $\pm$ 0.004	0.057 $\pm$ 0.03
264428	653212	142	2348.5 $\pm$ 38.12	0.059 $\pm$ 0.004	0.439 $\pm$ 0.002	0.009 $\pm$ 0.004	0.064 $\pm$ 0.031
264424	653208	148	2799.5 $\pm$ 38.42	0.071 $\pm$ 0.005	0.524 $\pm$ 0.003	0.005 $\pm$ 0.005	0.037 $\pm$ 0.037
Average			2993.99 $\pm$ 40.32	0.076 $\pm$ 0.005	0.56 $\pm$ 0.003	0.026 $\pm$ 0.005	0.193 $\pm$ 0.04

Comparisons of dose rates determined from static backpack system measurements and the passive dosimeter system for 11 positions with the gamma source deployed are shown in Table 5.8. There are slight differences between the dose rates measured by the two systems. The backpack system usually reports higher dose rates than the passive dosimeter system. The backpack system, providing real-time measurements, ranges from 0.120 ± 0.003 to 1.58 ± 0.0105 $\mu\text{Sv/h}$, reflecting high sensitivity to spatial variations during measurement. In contrast, the passive dosimeter system yields more consistent values (0.432 ± 0.002 to 0.915 ± 0.002 $\mu\text{Sv/h}$), integrating dose over time with lower variability. The backpack system shows a wider range of values compared to the passive dosimeters. The passive dosimeter measurements show variation across different locations in a heterogeneous radiation field, while the backpack system generally has higher uncertainty values compared to the passive dosimeter system. Dosimeter number 73 shows the largest discrepancy, with the backpack system reading more than twice the passive dosimeter reading. The backpack system provides instantaneous radiation measurements, while Passive dosimeters measure accumulated radiation over an extended period, which could explain their more consistent readings. The discrepancies between the two systems highlight the importance of understanding the strengths and limitations of each system. The combination of these two systems could provide both immediate, high-sensitivity detection (backpack) and reliable long-term exposure data (passive dosimeters), enhancing overall radiation assessment capabilities.

Table 5.8 Dose rate of 12 dosimeters from both systems after the deployed gamma source.

Dosimeters number	Dose rate $\mu\text{Sv/h}$ using backpack system	Dose rate $\mu\text{Sv/h}$ using passive dosimeters
73	1.58 ± 0.0105	0.720 ± 0.004
100	0.870 ± 0.008	0.618 ± 0.003
76	0.749 ± 0.008	0.545 ± 0.002
52	0.308 ± 0.005	0.528 ± 0.002
50	0.183 ± 0.004	0.491 ± 0.002
47	0.120 ± 0.003	0.596 ± 0.003
72	0.322 ± 0.005	0.555 ± 0.003
96	0.977 ± 0.005	0.645 ± 0.003
121	0.152 ± 0.003	0.432 ± 0.002
123	0.801 ± 0.007	0.915 ± 0.002
125	0.124 ± 0.003	0.508 ± 0.002

Figure 5.14 shows the dose rate obtained by 40 passive dosimeters after deployment of the gamma source to 135 hours in the field. The passive dosimeters indicate a time-integrated dose rate, representing cumulative exposure throughout the location with a range of 0.02 to 6.11 $\mu\text{Gy}/\text{dosimeter}$ 98, positioned nearest to the source, registered the highest net dose rate, which was $0.522 \pm 0.101 \mu\text{Gy}/\text{h}$, confirming its proximity to the radiation source. All dosimetry at area A gave lower net dose rates. A clear trend was observed where net dose rates decreased with increasing distance from the source, as shown in Figure 5.14.

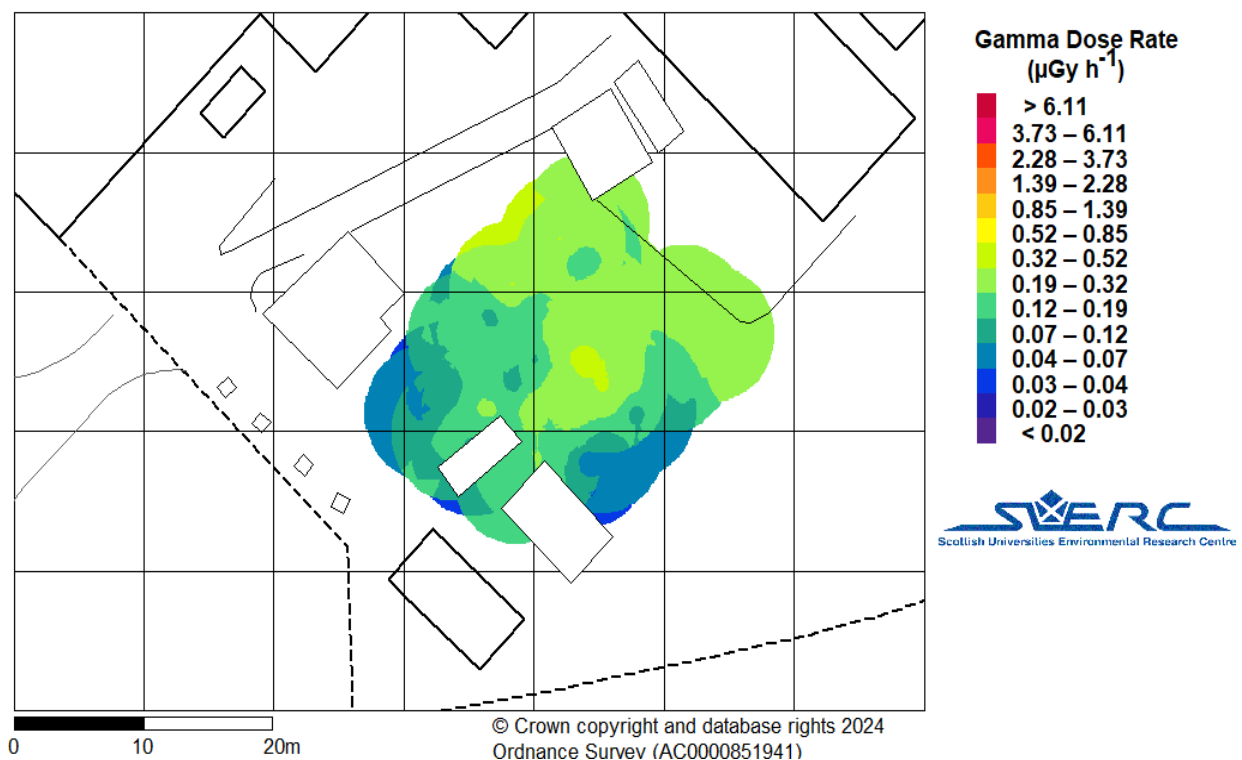


Figure 5.15. Net dose rate distributions on rear area to Scottish Universities Environmental Research Centre measured using salt dosimeters with the ^{60}Co source deployed.

Understanding the spatial distribution of radiation is crucial following a nuclear or radiological event, as it helps in assessing the exposure levels of both the public and emergency responders. This assessment is essential for directing protective actions, including evacuation or sheltering, and for reducing health hazards. Furthermore, it supports the examination of the incident's extensive impact, including environmental and long-term health effects. The accurate mapping of radiation levels facilitates informed decision-making and effective resource allocation during emergencies. It also aids in planning recovery efforts and mitigating future risks. Overall, this process is fundamental to safeguarding lives and ensuring a coordinated response to such incidents. This experiment successfully demonstrated the capability of the salt

dosimeter array to detect and quantify an anthropogenic radiation field superimposed on natural background radiation and accurately map the spatial distribution of a locally controlled radiation source and the ability of passive dosimeters to record the variations in dose rates across different distances from the source. The results demonstrate that passive dosimeters align effectively with the backpack system, positioning this approach as a complementary tool for dose assessment during accidents. Its sensitivity, cost-effectiveness, and ease of widespread deployment enhance its utility alongside real-time backpack measurements. The successful implementation of this salt dosimeter array using passive dosimeter arrays using salt in an outdoor setting has several important implications. The use of common salt as a dosimeter material offers a low-cost alternative to traditional dosimetry systems, potentially enabling more widespread radiation monitoring. The ability to map both natural background and artificial radiation fields suggests that salt dosimeters could be valuable in various scenarios, including environmental surveys, nuclear site monitoring, and emergency response situations. The 135-hour exposure period demonstrates the potential for these dosimeters to be used in extended monitoring campaigns without the need for constant human presence or power supply.

5.4.3 Complex radiation field inside a busy laboratory with an accelerator at the Scottish Universities Environmental Research Centre

The final experiment aimed to map the spatial distribution of the complex radiation fields emitted by a 5 MV tandem accelerator in the SUERC Accelerator Mass Spectrometry (AMS) laboratory (figure 5.16). These accelerators are known to produce low-level radiation from the acceleration of charged particles, especially during beam conditioning short-duration high-intensity radiation events. The experiment utilized a novel approach by employing table salt as a passive dosimeter material for detailed radiation field characterization in complex scientific environments. The experiment includes both baseline background radiation measurements and integrated measurements during radiation events associated with accelerator operations, with an array of dosimeters to allow analysis of the spatial distribution of radiation fields.

One hundred seventy salt samples were prepared and positioned approximately 50 cm above the accelerator tank (2.5 x 8 m) using a net with 50 cm spacing between each detector (Figure 5.17). The spatial coordinates of each dosimeter were recorded relative to the exterior walls of the laboratory to facilitate subsequent radiation field mapping. The exposure period lasted 3336 hours, from November 10, 2023, to March 28, 2024, to register the integrated background radiation of the AMS laboratory while the tandem accelerator was shut for maintenance. After 3336 hours, 55 samples were collected. The full contents of each sachet were emptied onto two 30 mm diameter aluminium planchettes for OSL signal recording.

To assess the dosimeter array's response to a complex radiation field in an active laboratory setting, controlled Irradiations were applied to the remaining 115 dosimeters positioned above the accelerator tank, which underwent exposure to various radiation events related to beam conditioning over a duration of 1944 hours, as outlined in Table 5.1, which lists the dates of short intense radiation bursts with their approximate duration and dose rates. Subsequent to exposure, the samples were collected and then the contents of each sachet were emptied onto two 30 mm diameter aluminium planchettes for recording OSL signals.

Dose normalization is crucial in OSL measurements for several reasons: a- sensitivity variations that different samples or even different aliquots of the same sample can have varying sensitivities to radiation. b- Normalization allows for comparison between different samples or measurements. c- It helps in calibrating the OSL response to known doses. Therefore, a stronger beta source was used to investigate dose normalization for the samples. The samples recorded the radiation signal inside the AMS laboratory, primarily from the accelerator. After that, a

laboratory dose of 100 mGy using a 0.62 GBq ^{90}Sr of surface area 4 cm² mounted in a shielded irradiator with a working distance of 7.5 cm was given to 20 samples spread on the 40 aluminium planchettes for dose normalization. After irradiation, samples were stored under dark conditions at room temperature for 24 hours to allow any unstable signal components to decay before measurement. This waiting period is crucial as it allows for the stabilisation of the OSL signal. Following the stabilisation period, the OSL dosimeters were read out again for the sensitivity comparison involving analysing the OSL response before and after the 100 mGy dose. This comparison provides information on the dosimeter's sensitivity to higher doses. The 100 mGy dose serves as a calibration point for each sample. No further preheating was undertaken at this stage. Calibration for the beta source using quartz has been described previously by Francoz (2023) and Alghamdi et al. (2022).

Table 5.9 shows radiation events for salt dosimeters inside the Accelerator Mass Spectrometry (AMS) laboratory, showing the date and approximate duration of each event and the dose rate measured in the control room.

Date	Duration	Dose rate $\mu\text{Sv/h}$
26-05	45 min	1.3
29-05	30 min	0.99
29-05	40 min	0.47
29-05	8 h 34 min	1.28-1.8
6-06	45 min	0.86
10-06	33 min	1.279
12-06	35 min	1.612
13-06	25 min	0.853

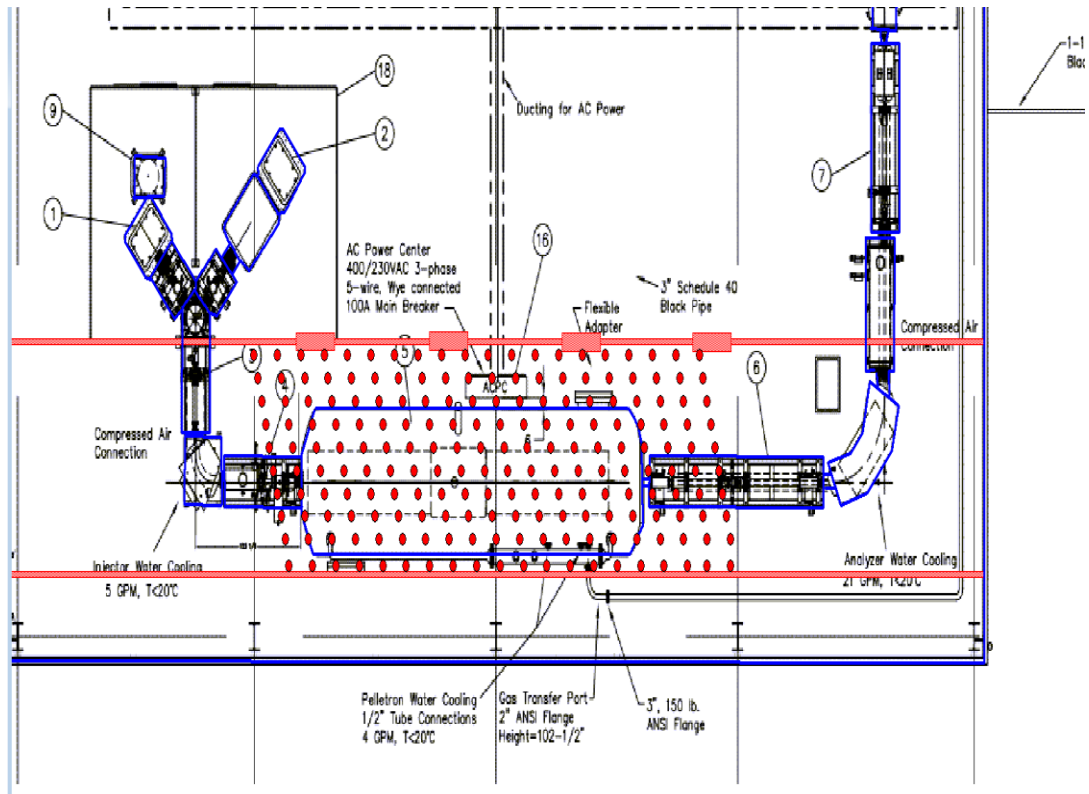


Figure 5.16 A floor plan of the AMS accelerator hall.



Figure 5.17 Photo of deployed dosimeters above the tandem suspended on a net.

5.4.3.1 Results

5.4.3.1.1 Background Radiation Measurements inside the laboratory

During the accelerator's maintenance shutdown, background doses were measured using 55 salt dosimeters to establish a baseline for subsequent experiments, which were deployed above the accelerator tank for 3336 hours, as shown in Figure 5.18. The radiation dose for each dosimeter was measured using optically stimulated luminescence (OSL) signals. For this process, each dosimeter sachet was carefully dispensed onto two separate aluminium planchettes to ensure consistent and accurate readings. The OSL counts obtained from these measurements were then converted into dose values using a calibration slope of 39600.76 ± 2750.11 (c mGy⁻¹), as established in Section 5.3.1 from prior experimental data. The absorbed dose (D) for each sample was calculated using the following formula: $D(\text{mGy}) = \text{OSL Signal (counts)} / \text{Slope (counts/mGy)}$. The fading correction factor derived from the decay curve in Figure 5.4 was calculated to be 0.946803139. This coefficient was deemed negligible as it indicated an insignificant change in the dose value following correction. Consequently, it was disregarded in the analysis, as it did not contribute meaningfully to the correction of the measured radiation dose.

The laboratory's background radiation dose was assessed by passive dosimetry to create a baseline for future studies. The average dose rate was measured at 0.0274 ± 0.0003 $\mu\text{Gy/h}$, indicative of the natural radiation environment. Meanwhile, film badges (Luxel+ radiation dosimeters) utilised at many laboratory locations documented a reduced average background dose rate of 0.0143 ± 0.0002 $\mu\text{Gy/h}$ throughout the same duration. Results have shown variability in dose rate between the passive dosimeters and film badge inside the laboratory, approximately 48% lower than the passive dosimetry result, potentially reflecting variability in the response of dosimeters to radiation or some background radiation accumulated values may have been recorded on the surface of the accelerator due to the close distance between passive dosimeters and accelerator. The gamma dose distribution is shown in Figure 5.18, a comparison of gamma dose levels measured inside a laboratory using a passive dosimeter to measure background dose inside the Laboratory. The map displays a range of gamma dose levels inside the laboratory during the period of measurement, indicating dose values ranging from 0.02 mGy to 0.26 mGy. The dose decreases as you move away from the centre, with the highest values concentrated in the central region. The surrounding areas show progressively lower dose rates, closer to the centre to less than 0.02 mGy in the outermost regions. The

observed data indicate that elevated radiation levels are highest in the central region of the tank, even when the accelerator is not operational, which is likely due to residual photons and protons from activated materials, as observed in the data. This finding is significant for understanding the spatial distribution of radiation within the laboratory environment. The presence of high radiation levels in the middle of the tank suggests that residual radiation may be the result of previous accelerator operations or the inherent properties of the materials used in the tank. Understanding this distribution is crucial for developing effective radiation protection strategies

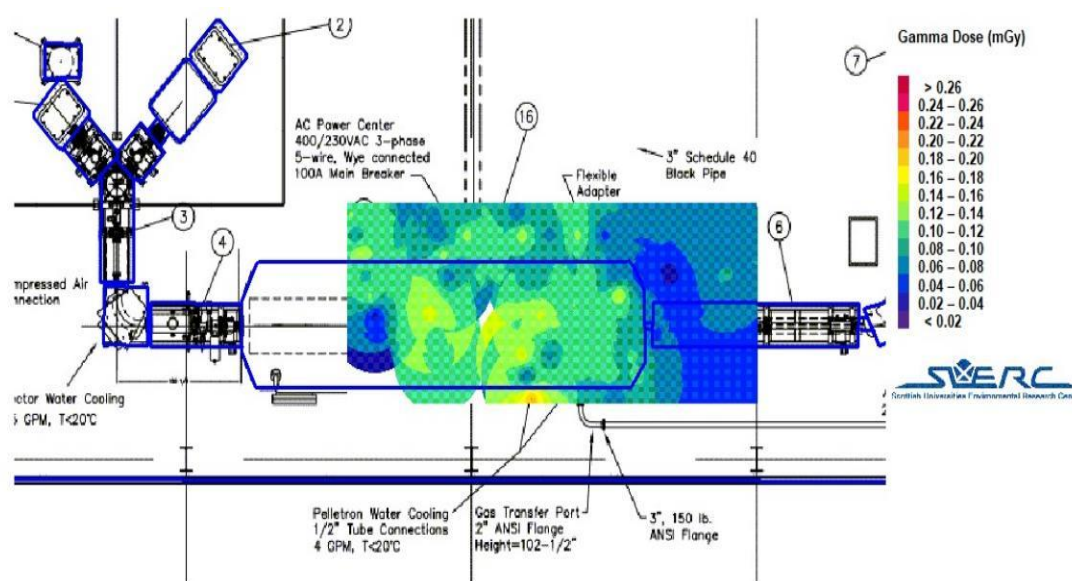


Figure 5.18. A map of the gamma radiation dose distribution above the accelerator during the accelerator's maintenance shutdown. This map was generated following a 3336 hours exposure period to radiation.

5.4.3.1.2 Dose Calculations During Accelerator Operation

The results from a map illustrating the distribution of radiation dose inside a busy laboratory at the Scottish Universities Environmental Research Centre are shown in Figure 5.19. This figure illustrates the spatial distribution of radiation levels during exposure, utilizing salt as a dosimeter in a complex radiation field near an accelerator. The dose values within the laboratory range from 0.14 mGy to 0.73 mGy as in Figure 5.19. Salt (NaCl) proved to be an effective radiation-sensitive material for dosimetry in the laboratory's complex mixed radiation field. The dosimeters exhibited a clear response to the radiation, with measurement values varying depending on their distance from the radiation source. The findings showed a spatial distribution of radiation levels within the laboratory, with higher doses recorded near the

accelerator the primary radiation source and lower doses further away. Specifically, Dosimeter 62 recorded the highest dose value before of 0.757 ± 0.052 mGy, reflecting its placement closest to the accelerator or in an area of elevated radiation. In contrast, the lowest value was 0.095 ± 0.007 mGy recorded by dosimeter 45. The uncertainties (± 0.052 and ± 0.0066 mGy) show reliable precision in the measurements. This variation could stem from uneven source distribution or distance differences. The wide range between the highest and lowest values demonstrates the significant variation in radiation levels throughout the laboratory space, which confirms the ability of the passive dosimeter to be sensitive to radiation and map the spatial distribution of a complex radiation field emitted by a 5 MV tandem accelerator.

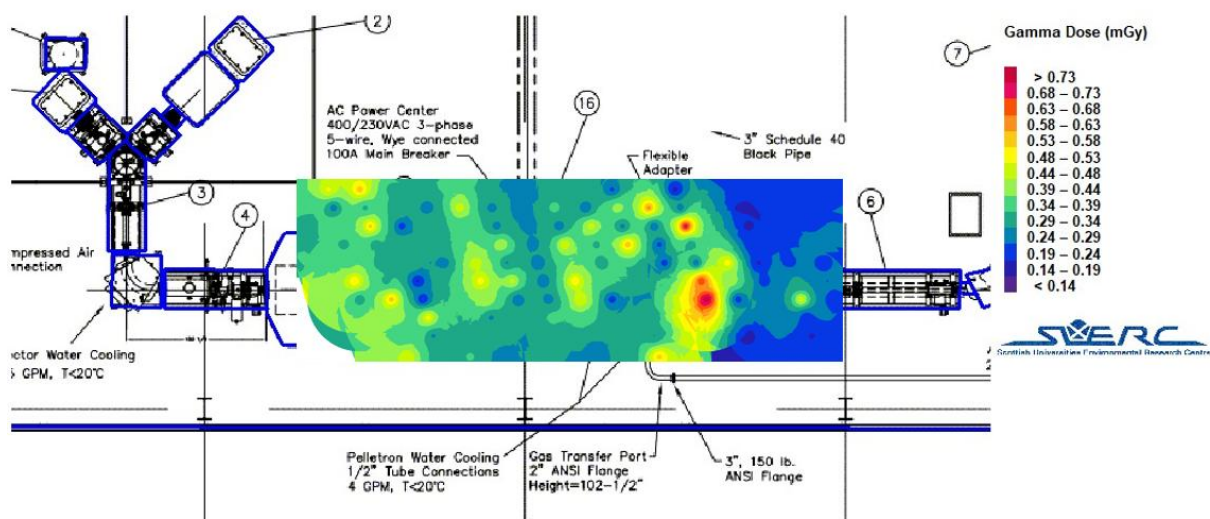


Figure 5.19. A map of the gamma radiation dose distribution above the accelerator. This map was generated following a 1444 hours exposure period to radiation.

5.4.3.1.3 Net dose Radiation Field Distribution

The results of a map of the distribution of net dose of using salt as a dosimeter in a complex radiation field inside a busy laboratory with an accelerator at the Scottish Universities Environmental Research Centre are shown in Figure 5.20. To determine the net radiation dose attributable to the radiation events inside the laboratory during operation, the average background radiation recorded within the laboratory was subtracted from the measured dose, providing a clearer assessment of the dosimeter's response to the applied radiation. The net dose (mGy) was calculated using a dosimeter exposed to radiation by subtracting the average dose rate for non-irradiated samples, which was 0.027 ± 0.0002 $\mu\text{Gy h}^{-1}$. Over 3336 hours, which was determined during the accelerator's maintenance shutdown. The accelerator laboratory recorded a net average dose of 0.275 ± 0.026 mGy, 0.0939 ± 0.010 $\mu\text{Gy h}^{-1}$ using

passive dosimeters, while the Luxel⁺ radiation dosimeters deployed inside the building recorded the average dose rate of radiation in the laboratory for the same period of $0.0145 \pm 0.0002 \mu\text{Gy h}^{-1}$. The higher readings from salt dosimeters compared to film badges suggest their increased sensitivity to radiation and closer proximity to the source.

These results highlight the utility of salt-based dosimetry for mapping radiation fields in complex environments like accelerator facilities. The method appears to be sensitive enough to detect low-level radiation and capable of distinguishing between areas of varying radiation intensity. This approach could be valuable for radiation protection purposes and radiation emergency response, helping to identify high-exposure areas and inform safety protocols in such facilities. It's worth noting that while this method shows promise, factors such as the specific type of radiation (e.g., photons, neutrons) and potential interferences in a busy laboratory environment should be considered when interpreting the results

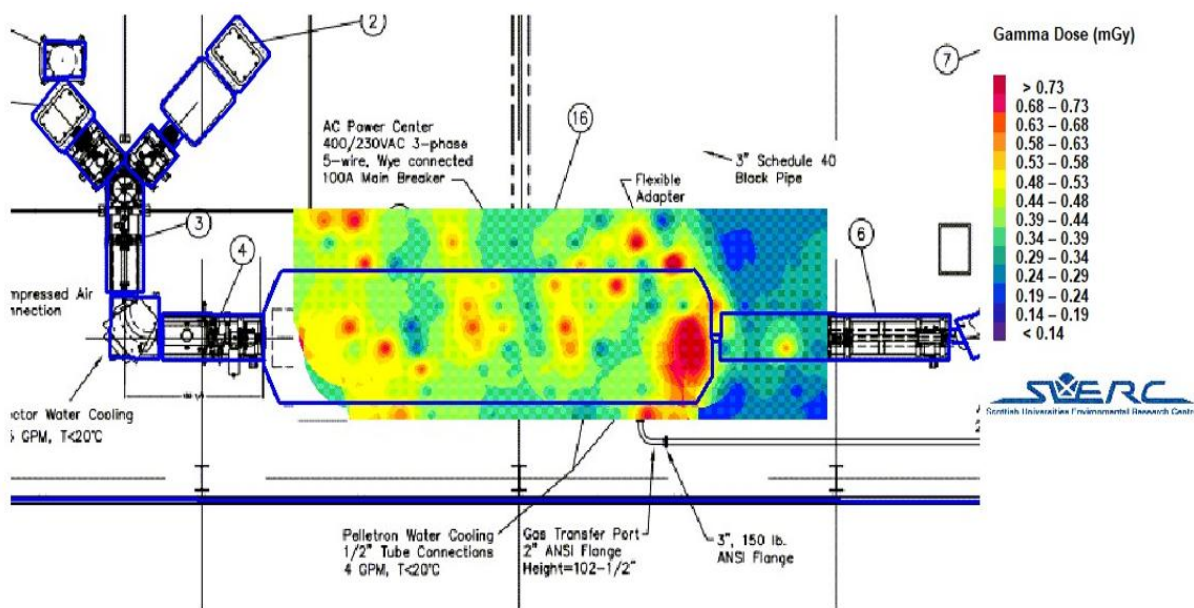


Figure 5.20. Net dose mGy distributions inside a busy laboratory with an accelerator determined from the net dose rates from 115 dosimeters deployed above the accelerator.

Dose normalization

The results of the experiments investigating the dose normalization where the samples have been given 100 mGy with ⁹⁰Sr are shown in Table 5.10, which includes dose rates before and after dose normalization (before normalization → applied 100 mGy → post-normalization results). The OSL signal intensity after applying a 100 mGy beta dose ranged between (1210936.5 ± 778.71 to 2122910.5 ± 103.10) counts with the average signal around

1609446.67 $\pm$ 48814.41 counts with some variation. In contrast, The OSL signal intensity before dose normalization ranged between (4274.5 $\pm$ 26.43 to 29973.5 $\pm$ 123.41) counts. The average signal is much lower, around 9254.37 $\pm$ 1202.21 counts, indicating the samples absorbed some radiation inside the laboratory from an accelerator which the absorbed dose (D, in mGy) was calculated as $D = (\text{OSL Signal before normalization} - \text{Background}) / \text{Calibration Slope}$, where the calibration slope is 39600.76 $\pm$ 2750.11 counts/mGy (from Section 5.3.2.1). The approximate values of the dose received by the laboratory samples ranged between (1.41 $\pm$ 0.005 to 0.2668 $\pm$ 0.001) mGy, which were calculated by comparing the signal inside the laboratory to the normalized signal. The annual dose rate, calculated from the approximate dose range, was about 1.20 $\pm$ 0.01 to 6.36 $\pm$ 0.03 mGy/a, with an average of 2.52 $\pm$ 0.23 mGy/a that is equivalent to 0.28 $\pm$ 0.03 μ Gy/h on average. Sample 61 shows a significantly higher dose (6.362 $\pm$ 0.026 mGy/a), which indicates a hotspot closest to the accelerator or in an area of high radiation. The wide range of OSL signals which was inside the laboratory (4274.5 to 29,973 counts) indicates varying levels of radiation exposure in the complex radiation field, and the variation in OSL signals after the 100 mGy dose (1210936.5 to 2122910.5 counts) suggests differences in sensitivity between samples. The normalization process helps to account for these sensitivity differences, allowing for more accurate dose estimations. This experiment demonstrates the capability of OSL using salt dosimeters to measure low-level radiation doses in a complex field environment. The normalization process is crucial for accounting for sensitivity variations between samples and improving the accuracy of dose estimations.

Table 5.10 Mean and standard deviation of dose normalization results recorded using the SUERC portable OSL reader at 470 nm, from NaCl inside a busy laboratory with an accelerator

Dosimeters number	OSL after normalization Counts Average of two aliquots	OSL Before normalization Counts Average of two aliquots	Approx. Dose mGy	mGy/a
5	1622600.5 $\pm$ 901.43	6311.5 $\pm$ 58.66	0.39 $\pm$ 0	1.75 $\pm$ 0.02
12	1541420.5 $\pm$ 878.58	6596.5 $\pm$ 59.78	0.43 $\pm$ 0	1.93 $\pm$ 0.02
21	1602176.5 $\pm$ 895.75	4274.5 $\pm$ 26.43	0.27 $\pm$ 0	1.2 $\pm$ 0.01
54	1605605.5 $\pm$ 896.75	7289.5 $\pm$ 62.58	0.45 $\pm$ 0	2.05 $\pm$ 0.02
61	2122910.5 $\pm$ 1031.1	29973.5 $\pm$ 123.42	1.41 $\pm$ 0.01	6.36 $\pm$ 0.03
69	1299307 $\pm$ 806.74	5947 $\pm$ 57.38	0.46 $\pm$ 0	2.06 $\pm$ 0.02
80	1305545.5 $\pm$ 808.68	8059 $\pm$ 65.56	0.62 $\pm$ 0.01	2.78 $\pm$ 0.02

97	1210936.5 ± 778.71	5712.5 ± 56.5	0.47 ± 0	2.13 ± 0.02
99	1573922.5 ± 887.73	10252 ± 73.4	0.65 ± 0	2.94 ± 0.02
100	1587320 ± 891.55	9160.5 ± 69.89	0.58 ± 0	2.6 ± 0.02
101	1749482.5 ± 935.96	11706 ± 78.45	0.67 ± 0	3.02 ± 0.02
125	1686329.5 ± 918.93	7953.5 ± 65.14	0.47 ± 0	2.13 ± 0.02
132	1681157.5 ± 917.48	8299 ± 66.37	0.49 ± 0	2.22 ± 0.02
133	1714888.5 ± 926.63	7654.5 ± 64.15	0.45 ± 0	2.01 ± 0.02
137	1430529.5 ± 846.32	7227 ± 62.05	0.51 ± 0	2.28 ± 0.02
142	1400385 ± 837.43	9267.5 ± 70.19	0.66 ± 0.01	2.98 ± 0.02
143	1821266 ± 955.01	8253.5 ± 66.19	0.45 ± 0	2.04 ± 0.02
161	1612198 ± 898.56	10967.5 ± 75.66	0.68 ± 0	3.07 ± 0.02
168	1889830 ± 972.73	10484.5 ± 74.18	0.55 ± 0	2.5 ± 0.02
180	1731122 ± 931.2	9698 ± 71.83	0.56 ± 0	2.52 ± 0.02
Average	1609446.68 ± 48814.5	9254.38 ± 1202.21	0.56 ± 0.05	2.53 ± 0.23

5.5 Discussion and conclusions

This chapter reinforces the potential of sodium chloride (NaCl) as a valuable material for accidental and retrospective dosimetry and shows the potential to use it as new method for radiological or nuclear emergency dosimetry. Its ubiquity in domestic and professional settings, coupled with its robust optically stimulated luminescence (OSL) response to radiation exposure, underscores its significance in the field. The dosimetric properties of NaCl, as demonstrated in this research and corroborated by previous studies, highlight its promising applications in radiation detection and measurement (e.g., Ekendahl and Judas, 2011; Thomsen et al., 2002; Bernhardsson et al., 2009; Christiansson et al., 2012; Alghamdi et al., 2022 ; Alghamdi et al., 2024).

My research (Alghamdi et al., 2022) has substantiated the efficacy of common salt as a dosimetric material when used in conjunction with a portable OSL reader. This method proves to be both swift and accurate for dose measurements below 100 µGy, offering the significant advantage of on-site analysis without the need for remote laboratory facilities. My empirical investigations have elucidated the optimal conditions for measuring radiation-induced OSL signals in NaCl, including crucial factors such as signal stability over time and the effects of environmental variables like light exposure and humidity (Alghamdi et al., 2024).

This chapter presents a pioneering pilot investigation and field trials that practically demonstrate salt dosimeters' potential and utility in mapping radiation fields and measuring

doses received by individuals to simulate a realistic scenario, comparing their efficacy a portable gamma spectrometry system(Backpack system). Our research encompasses three distinct scenarios: a controlled laboratory experiment, an outdoor environmental assessment, and a complex radiation field evaluation in an operational accelerator facility. In this chapter aim to augment the toolkit available to emergency responders, offering a complementary method to existing instrumental measurements that enhances spatial and temporal resolution in dose mapping. This cost-effective and accessible approach to radiation dosimetry has the potential to significantly improve decision-making processes in emergency response scenarios, from evacuation strategies to medical triage and long-term health monitoring.

The controlled experiment utilising ^{60}Co , done on a restricted scale in a laboratory environment, provided significant findings into the dosimetric characteristics of salt. The average initial dose was 0.393 ± 0.027 mGy, increasing to 0.527 ± 0.037 mGy after fading adjustment, with an average computed dose of 0.515 ± 0.007 mGy. This validates with theoretical estimates, showing an error margin below 3%. This agreement represents a reliable measurement method, and the fading factor employed reflects the real dosage in respect to the measured dose. These encouraging findings suggest potential for further investigation, including scaling up to larger areas, testing in varied environmental conditions, examining responses to different radiation types, and evaluating long-term stability in more complex radiation fields beyond the laboratory setting.

To evaluate salt as a passive dosimeter in outdoor conditions, 200 signals-cleared samples using a lightbox were sealed in black plastic and distributed across the three areas for 1776 hours during winter, exposing them to diverse weather conditions. After three months, 100 samples were retrieved and analyzed. The salt dosimeters successfully recorded natural radiation dose rates, accurately reflecting each area's characteristics. The experiment across areas C, B, and A shows initial dose estimates of 0.051 ± 0.004 mGy, 0.049 ± 0.004 mGy, and 0.035 ± 0.003 mGy, respectively, which increase to fading-corrected doses of 0.055 ± 0.004 mGy, 0.053 ± 0.004 mGy, and 0.038 ± 0.003 mGy, confirming the fading coefficient has a small effect on the results of this experiment. The consistency of measurements across locations validated the method's reliability. A comparative assessment was conducted to evaluate radiation measurements obtained through two distinct methodologies: a mobile gamma spectrometry apparatus and a passive dosimeter using salt. The experiment across areas A, B, and C demonstrates consistent trends in radiation dosimetry using salt, with initial dose rate estimates of 0.0278 ± 0.0019 $\mu\text{Gy/h}$, 0.0288 ± 0.0020 $\mu\text{Gy/h}$, and 0.0307 ± 0.0021 $\mu\text{Gy/h}$, respectively,

rising slightly to fading-corrected doses of $0.0300 \pm 0.0022 \mu\text{Gy/h}$, $0.0312 \pm 0.002 \mu\text{Gy/h}$, and 0.0328 ± 0.002 . In comparison, the portable system, when deployed in identical locations, registered average readings of 0.0341 ± 0.0004 , 0.0292 ± 0.0003 , and $0.0385 \pm 0.0003 \mu\text{Gy/h}$, respectively, within its operational parameters. This investigation underscores the potential of utilizing arrays of salt-based dosimeters for mapping background radiation in natural settings. The findings suggest that this approach could serve as a promising complement or alternative to traditional field radiation monitoring methods.

A controlled radiation experiment was conducted in a designated outdoor area using a nominal 17 MBq ^{60}Co source to simulate a locally controlled radiation field and assess the response of the 40 dosimeters array after the radiation exposure over 135 hours. To provide complementary data and assess temporal variations in background radiation, additional spectrometric measurements were performed. These supplementary readings also served to independently verify the spatial distribution of the radiation field generated by the source, allowing for comparison with the dosimeter array results. This pilot experiment successfully demonstrated the effectiveness of a salt-based dosimeter array for detecting and mapping radiation fields in an outdoor setting. The array accurately captured both natural background radiation and an artificially introduced source, showing sensitivity to dose rate variations across different distances. This novel approach, using common salt as a dosimetric material, offers a cost-effective alternative to traditional systems, potentially enabling more widespread radiation monitoring. The 135-hour exposure period highlights the array's suitability for extended, unattended monitoring campaigns. The successful implementation of this method suggests promising applications in environmental surveys, nuclear site monitoring, and emergency response scenarios, expanding the toolkit available for radiation detection and measurement in various field conditions.

The third experiment aimed to map the spatial distribution of a complex radiation field emitted by a 5 MV tandem accelerator during specific operational modes. The assessment of background radiation via passive dosimetry established a baseline dose rate of $0.0274 \pm 0.0003 \mu\text{Gy/h}$, reflecting the natural radiation environment. Spatial mapping revealed gamma dose levels ranging from 0.02 mGy to 0.26 mGy, with a clear decrease from the central region outward, consistent with radiation attenuation principles. Dose level variation after exposing samples to radiation events was observed across multiple measurements, reflecting differences in exposure intensity and sample positioning. Readings ranged from 0.14 mGy to 0.73 mGy. These variations emphasize the sensitivity of passive dosimetry in detecting event-specific

radiation changes. Salt (NaCl) proved to be an effective radiation-sensitive material for dosimetry in the laboratory's complex mixed radiation field. The dosimeters showed a clear response to the radiation, with measurements varying based on their proximity to the radiation source. Analysis of the collected data revealed a nuanced pattern of radiation distribution within the confines of the laboratory. As anticipated, the dosimeters in close proximity to the accelerator - the primary source of radiation - registered higher levels of radiation. Conversely, detectors situated at increasing distances from this focal point demonstrated a progressive attenuation in recorded doses, aligning with theoretical predictions of radiation field behaviour. Such detailed spatial information is crucial for implementing effective radiation protection measures and optimizing the layout of workspaces within accelerator laboratories and other radiation facilities. The successful application of salt-based dosimetry in this complex environment underscores its potential as a cost-effective and readily available tool for radiation monitoring in research and industrial settings.

This chapter has conclusively demonstrated that dosimetry using the integration of active backpack radiation detection systems with passive salt-based dosimeters represents a new innovative method that could potentially lead to a significant improvement in radiological emergency response capabilities. This innovative method, which integrates real-time mobile monitoring with long-term cumulative exposure assessment, provides a more detailed and nuanced comprehension of radiation levels during nuclear incidents. In order to fully realise the potential of this integrated methodology, it is necessary to address several critical considerations, including the following: the development of protocols for the integration and analysis of data from both systems that should account for the temporal and spatial variations inherent in the two measurement systems, enabling a cohesive interpretation of the radiological emergency, the proper calibration of both active and passive systems to maintain data accuracy, and the training of personnel on the deployment, operation, and interpretation of results from both detector types that may affect the performance of both systems to ensure that emergency responders and technical personnel are proficient in the deployment, operation, and interpretation of both detection systems. The comprehension of the strengths and limitations of each method and their mutual complementarity is a component of this. It is imperative to conduct a comprehensive evaluation of environmental elements that might influence system performance is essential. This encompasses the assessment of the influence of terrain,

meteorological conditions, and background radiation on both active and passive detection methods, as well as the development of suitable operational guidelines or correction factors.

The integrated approach of integrating active rucksack surveys with passive salt dosimetry has the potential to substantially improve the accuracy, reliability, and comprehensiveness of radiological assessments during nuclear emergencies by addressing these considerations. In addition to enhancing immediate response capabilities, this methodology also furnishes valuable data for the scientific comprehension of radiation exposure patterns and the management of long-term consequences. By utilising the assets of both active and passive detection technologies, this innovative approach improves the capacity to safeguard public health and safety during nuclear emergencies. Future research should concentrate on the optimisation of the synergy between these complementary systems, the exploration of advanced data fusion techniques, and the assessment of the efficacy of this integrated approach in a variety of emergency scenarios. These innovative methodologies will be essential in enhancing our capacity to manage radiological incidents effectively and protect public health and that of responders as the field of nuclear emergency response continues to develop.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

In the event of a significant radiological or nuclear catastrophe presenting a broad radiation hazard, a prompt and thorough first assessment is essential to evaluate the threat level and guide emergency response efforts. This rapid assessment helps the prioritisation of measures to safeguard public health, and mitigate the disaster's impact effectively. This assessment should include determining the nature of the incident, delineating affected areas, identifying individuals who may have been impacted (triage), and estimating the radiation doses received by first responders and the general public. Obtaining timely and accurate radiation dose measurements is essential for effective response and management. Two distinct but equally essential dose ranges must be addressed: doses in the range of 0.5–3 Gy, which are essential for identifying individuals requiring urgent medical intervention, and very low doses, which are crucial for providing reassurance to the public, mitigating widespread panic, and encouraging a confident return to affected areas at the end of the recovery phase. Having reviewed many aspects of radiological emergency response in chapter 2 it was concluded that there were important research opportunities to develop and assess luminescence dosimetry approaches suitable for real-time or near real-time applications during the early stages of emergency response. Luminescence measurements of common materials had already emerged as promising approaches for dose determination using laboratory instrumentation after the early stages. This thesis present new work investigating common materials in combination with portable instruments which have the potential for rapid deployment during emergencies. Portable instruments capable of delivering quick results could significantly enhance on-site decision-making during emergencies and enhance the ability of emergency responders to assess radiation risks accurately and efficiently. This capability raises several important research questions, which have guided the work presented in this thesis. These questions focus on optimizing luminescence techniques for both high and low dose ranges, improving the portability and efficiency of measurement devices, and ensuring the reliability of results in real-

world scenarios with the goal of developing a complementary method to existing instrumental measurements, thereby enhancing the spatial resolution of dose mapping.

The study focused on addressing several critical questions outlined in the introduction (Chapter 1)

1. Can portable optically stimulated luminescence (OSL) instruments provide accurate low-dose assessments in radiological or nuclear emergencies?
2. Is rapid on-site measurement feasible using these systems, particularly in radiation emergencies or major radiation accidents?
3. What are the luminescence properties of the studied materials and how do they perform with portable instruments?
4. What are the comparative advantages and disadvantages of different dosimeter materials examined in this research?
5. How precise are dose estimates from radiometric mapping using two-dimensional arrays of optical salt dosimeters compared to radiological surveys using backpack systems?

To address these questions, this investigation centred on new work on salt and talc as potential dosimetric materials, as detailed in Chapters 3,4 and 5 of the thesis.

The research described in Chapter 3 addresses research questions 1-4 by examining the luminescence characteristics of salt as a viable material. The portable instruments' effectiveness in measuring optically stimulated luminescence (OSL) signals in sodium chloride (NaCl) were evaluated, benchmarking their sensitivity against laboratory equipment. The work described in Chapter 3 aimed to determine if these portable devices can provide adequate initial dose assessments in field conditions, where the reader unit is subjected to outdoor environmental factors such as temperature variation, humidity, and light exposure, potentially eliminating the need for sample transportation to remote laboratories. The chapter presents investigation of key OSL properties of NaCl, including signal stability over time in sections 3.3.3 and the effects of light exposure and humidity 3.3.5 and 3.3.6, respectively. Thermoluminescence (TL) analysis was conducted to better understand trap parameters and predict the impact of varying environmental conditions in sections 3.3.4. This work resulted in the publication of two peer – reviewed papers highlighting the sensitivity of the dosimetric response (which enables micro-gray detection limits), and assessing the signal stability under different conditions.

The research presented in Chapter 4 focused on investigating the luminescence properties of talc, a widely available material, to assess its potential as a dosimetric material for radiation dose measurement, addressing research Questions 1–4. Utilizing portable instruments, the study evaluated key dosimetric characteristics, including sensitivity, detection limits, and dose-response relationships, as detailed in Sections 4.3.1 and 4.3.2. These investigations addressed fundamental questions regarding the material's suitability for practical applications in radiation dosimetry. Furthermore, the stability of the optically stimulated luminescence (OSL) signals was systematically examined over extended time intervals, up to 128 days post-irradiation, as discussed in Section 4.3.3. Additionally, the impact of light exposure on the OSL signals—referred to as light bleaching—was explored in Section 4.3.5, which also answered research questions 1-3. As a geological material talc is more physically stable than salt, however in unprepared form it was found to exhibit residual signals of greater magnitude than the dose range of interest. In this study it was shown that thermal annealing at 400 °C for one hour removes these residual signals after which the material is capable of registering doses in 0.5 to 2 Gy region, which are critical to medical triage.

Chapter 5 specifically aimed to answer research question 5 by the first comprehensive field trial to practically demonstrate the utility of salt dosimeters in mapping radiation fields. Definition of the spatial extent of radiation fields is important to emergency response for several reasons. As discussed in chapter 2 it is important for supporting decisions on shelter or evacuation, managing the safety of responders, and may be a proxy for measuring the doses received by individuals. My experiments included three distinct scenarios: a controlled laboratory experiment (section 5.4.1), an outdoor environmental assessment (section 5.4.2), and a complex radiation field evaluation in an operational accelerator facility (section 5.4.3).

Findings indicate, as presented in section 3.3.4, that dosimetry using common salt with a portable OSL reader is a quick and effective method for determining doses in the μGy to 100 mGy, operable in field settings under battery power. Responses from pulsed IRSL and portable OSL instruments were compared. OSL measurements showed a detection limit of $7\mu\text{Gy}$, while the other tested instruments had detection limits ranging from 30 to $340\mu\text{Gy}$. For the most sensitive systems, dose responses were measured in the 0-500 μGy range, revealing a linear response across this range. The OSL signals exhibit complex stability patterns, showing rapid initial signal loss over 4-8 days, followed by signal recovery starting around 60 days post-irradiation. From day 8 to day 64, the findings show consistent stability, which is essential for accurately estimating doses during both the initial and subsequent phases of managing

radiological emergencies, methods for accounting for signal instability over shorter and longer time scales have been demonstrated. The experimental findings presented in sections (3.3.5 and 3.3.6) demonstrate that the optically stimulated luminescence (OSL) signals of salt are significantly influenced by environmental factors, particularly light exposure and elevated humidity. Both conditions were observed to cause a near-complete loss of the OSL signal, highlighting the material's sensitivity to its surroundings. These results underscore the necessity of protecting salt-based dosimeters from light and moisture during signal accumulation, as well as during sample handling, to preserve the integrity of the measured dose. This also provides a mechanism to remove prior naturally induced signals before deployment. To address these challenges, a practical approach for protecting salt samples from light exposure and the impact of relative humidity has been developed, with the salt packets sealed in black plastic shrink wrap. This method addresses two key challenges in preserving salt for dosimetry applications, particularly in field applications where environmental factors pose significant challenges to sample preservation. These characteristics, combined with salt's widespread availability and low cost, support its potential use in prompt emergency assessments and as a retrospective dosimeter for doses below 100 μGy . The chapter concludes that this approach offers a promising solution for on-site radiation measurements in emergency scenarios. This analysis provides insights into the practical applications and limitations of field-based OSL measurements in common salt.

Experimental talc results using white powders packed from Luzenac Pharma's packing line have explained the presence of a significant geological residual signal in talc from primary quarry sources. This can be removed thermally but only by means of high-temperature treatment up to 400 °C for one hour. The TL analysis of the samples up to 500°C revealed a previously unidentified peak in the range of 450°C to 500°C, specifically centred at 470°C, which had not been observed in earlier studies, which could explain the need for a high temperature treatment to remove geological OSL signals. This finding underscores the importance of applying sufficiently high temperatures in the processing or resetting of talc-based materials to ensure accurate measurements or complete signal removal. Further examination of this peak may yield an expanded understanding of charge trapping and recombination mechanisms in talc, refined OSL dosimetry methodologies using talc, and superior differentiation between geological and artificially created radiation signals. . Furthermore, once residual signals are eliminated, the material has sufficient sensitivity to detect doses and is a suitable material for emergency and retrospective dosimetry. The results

reported here have specified that portable instruments can make dose determinations more rapidly and conveniently than laboratory-based instruments in the significantly wide range of 0.5-3 Gy, which is critical to medical triage in emergencies. The detection limit of preheated/prepared talc was 2 mGy using the blue LEDs in the SUERC Portable OSL Reader, which, combined with a linear dose-response in the 0–1500 mGy range and the absence of a native signal makes this a potentially useful dosimetric material. Although the fading rate at room temperature was found to be fast (beginning at 6% after 24 hours and losing 65% of its original value after 128 days of storage in the dark at room temperature), the period from 8 to 16 days covers much of the period of interest for dose reconstruction in the early stages of radiological emergency response. However, for initial responses within the first week of an emergency, the observed signal loss should be accounted for in the interpretation of results. This significant signal instability suggests the presence of multiple trap depths within talc; such behaviour necessitates the incorporation of fading correction factors tailored to the time elapsed between irradiation and measurement, as an uncorrected signal loss could lead to systematic underestimation of doses, particularly in retrospective dosimetry applications. Additionally, the zeroing behaviour poses further challenges. Incomplete zeroing due to environmental factors, such as exposure to light or temperature fluctuations, could leave residual signals that overlap with those induced by a recent radiation event. This overlap complicates the ability to accurately distinguish between background dose contributions (e.g., from natural radiation accumulated over time) and acute doses from a specific incident, potentially compromising the method's specificity. Furthermore, light exposure (simulated daylight) results in an extremely rapid loss of OSL signals, as with the similar bleaching seen in salt this would necessitate protecting the material from light during deployment and sample handling. The results are sufficiently favourable to conclude that these characteristics, together with the widespread availability and low cost of talc, support its use for prompt emergency assessment to medical triage and as a retrospective dosimeter above 10s of mGy.

Finally, the field trials to practically demonstrate the utility of the passive dosimeters in mapping radiation fields and measuring doses received by individuals to simulate a realistic scenario were reported in Chapter 5. This has highlighted the viability of salt-based dosimeter arrays for mapping background radiation in natural environments and complex radiation fields. The results represent a groundbreaking pilot investigation, introducing an innovative approach through field trials that effectively highlight the potential and practicality of salt dosimeters. This has conclusively demonstrated the use of passive dosimeters for mapping radiation fields

and accurately measuring individual doses, simulating real-world scenarios with promising results. The experiments have covered three diverse scenarios — a controlled laboratory experiment, an outdoor environmental assessment, and a complex radiation field evaluation within an operational accelerator facility — underscoring the versatility and reliability of this cutting-edge technique.

The controlled experiment using ^{60}Co , which was conducted on a limited scale within the laboratory setting, offered valuable insights into the dosimetry properties of salt and its potential for greater-scale applications. The results validate that the adjusted dosage closely aligns with theoretical estimates, exhibiting an error margin of less than 3%. This agreement represents a reliable measurement method, and the correction factors applied were appropriately determined, providing strong evidence that the experimental results are both reproducible and trustworthy.

We evaluated salt as a passive dosimeter in outdoor settings. 200 samples were zeroed using a lightbox and sealed in black plastic, and placed across three areas for 1776 hours during winter, exposing them to varied weather. After three months, we retrieved and analyzed 100 samples. The salt dosimeters successfully recorded natural radiation dose rates, accurately reflecting each area's characteristics. Also, in a controlled experiment, we exposed 40 dosimeters to a 17 MBq ^{60}Co source for 135 hours, simulating an artificial radiation field that could be present in some emergency scenarios, and confirmed their reliable response under environmental conditions. A comparison with mobile gamma spectrometry validated the consistency of this method. This pioneering pilot study demonstrated that salt dosimeters effectively detected and mapped radiation, capturing both natural and artificial sources with sensitivity to dose variations. This innovative, cost-effective approach proved suitable for prolonged monitoring, suggesting its potential for environmental surveys, nuclear site oversight, and emergency response applications. The results indicate that this approach could effectively complement conventional field radiation monitoring techniques. The results conclusively demonstrate that integrating active backpack radiation detection systems with passive salt-based dosimeters offers an innovative method for enhancing radiological emergency response capabilities.

Salt (NaCl) proved to be an effective radiation-sensitive material for dosimetry to map the spatial distribution of a complex radiation field emitted by a 5 MV tandem accelerator during specific operational modes using 115 dosimeter which deployed above the accelerator. The salt dosimeters responded clearly to radiation, with measurements reflecting their distance from the

source. Data analysis uncovered a detailed radiation distribution pattern within the lab, where dosimeters near the end of the accelerator where the beam has maximum energy recorded higher doses, while those farther away showed a gradual decrease, consistent with expected radiation behaviour. This successful use of salt-based dosimetry highlighted its value as an affordable, accessible tool for radiation monitoring in research and industrial contexts.

Research question 4, related to the strengths and weaknesses of this new method, was addressed in Chapters 3 and 4. The main advantage is portability - deployment where needed, reducing time to transport samples. Battery operation is a bonus, removing reliance on power provision at any field response base. That these instruments are also sensitive enough to make quick measurements with low detection limits and dose ranges that include important triage doses makes them a useful contribution to the tools available to emergency responders. Also important that these are simple measurements; you can rapidly train a lot of people to run these instruments. A secondary advantage is that portable readers are relatively cheap compared to laboratory instruments. That means that it's feasible to deploy multiple systems to further increase measurement throughput. But using multiple instruments raises cross-calibration issues due to differences in diode power or photomultiplier response—particularly when instruments from different manufacturers are used. Common materials measured on all instruments would address these instrumental variations, and therefore need to be considered as part of the system - these could be geological samples (eg: like our Morar sand or granulite), maybe better to be irradiated salt or talc (or other materials being measured) as these better match the dosimeter being used. If necessary, it may be sufficient to simply dig some sediment up from nearby and mix it well and use this as a common material.

This new method will provide retrospective dose assessments in situations where real-time monitoring was not feasible, create a radiation dosimetry method that is both cost-effective and broadly accessible and promoting more well-informed decision-making in the areas of medical triage, evacuation, and long-term health monitoring. The use of everyday materials as dosimeters offers several advantages. Firstly, these materials are ubiquitous, ensuring widespread availability in emergency situations. Secondly, they are cost-effective, potentially allowing for large-scale deployment of dosimeters without significant financial burden. Possibility of rapid measurements of dose using field deployed instruments with minimal sample preparation, hence removing need to transport samples to a distant lab for measurement. Lastly, their familiarity to the general public could reduce anxiety and increase cooperation in emergency response scenarios. However, the research also acknowledged potential challenges.

These include variations in material purity and composition, which could affect dosimetric accuracy, and the need for careful handling and storage to prevent contamination or signal loss. The study also considered the limitations of portable instruments in terms of sensitivity and precision compared to laboratory-grade equipment. While these dosimeters are invaluable for reconstructing radiation exposure after the fact, their temporal resolution is inherently limited by the integration time required for measurements. For instance, a 10-second measurement using a backpack-style dosimeter can achieve significantly higher temporal resolution compared to passive dosimeters, which typically integrate doses over hours or even days. However, these passive dosimeters offer unique advantages in terms of spatial resolution. Their low cost and ease of deployment make it feasible to distribute them in large numbers across a wide area, enabling detailed and high-resolution dose mapping. This stands in contrast to conventional passive dosimeters, such as those based on alumina, which are often more resource-intensive to deploy in large quantities.

The rapid assessment and analysis of results using approaches similar to those described in this work is vital for making decisions based on real-time information during the response to radiological and nuclear disasters and conducting subsequent analyses of the incident's impact. However, it is also acknowledged that this approach has some weaknesses. The use of salt and talc in emergency dosimetry, while potentially beneficial, introduces several challenges such as their common presence in the environment may lead to confusion between incident-related and background materials. Variability in salt or talc composition and response characteristics may lead to uncertainties in dose assessments. Investigations of the properties of each specific salt is warranted prior to use in dosimetric applications, this would identify whether a general response curve is applicable or whether a curve specific to that salt would be needed. For initial responses within the first week of an emergency, the observed signal loss is significant and should be accounted for in interpretation of early results. Salt is highly sensitive to light exposure and higher levels of humidity, both of which result in almost complete loss of OSL signal which leads to a requirement to protect salt from both light exposure and elevated humidity while signals accumulate, and for sample handling to minimise light exposure and excess humidity. Moreover, the rapid fading of the OSL signal poses a significant challenge, as it necessitates the prompt collection of samples following a radiation incident. Delays in sample retrieval could result in the loss of critical dosimetric information, thereby compromising the accuracy of dose reconstruction. This temporal constraint highlights the importance of establishing efficient protocols for sample collection and storage in the immediate aftermath of

an accident. As the talc used is natural and obtained from quarries, it is expected that there will be great variability in the composition of the samples. This may mean that there will be a variety of fading rates and hence it cannot be expected that a universal dose response or fading curve may be constructed. One such approach is the Δ OSL technique, utilised in the DEPot Project (Dosimetric Emergency Protocol), which establishes an emergency dosimetry method using metastable luminescence signals from quartz (Palczewski et al., 2024).

The combined approach, which integrates real-time mobile monitoring with long-term cumulative exposure assessment, offers a more comprehensive understanding of radiation levels during nuclear incidents. However, the effectiveness of this integrated approach depends not only on understanding the individual strengths and weaknesses of each component but also on addressing the significant challenges of harmonizing data from diverse measurement systems. Even combining data from the same types of instruments can be difficult due to variations in processing techniques, sensitivities, and fields of view. For example, EU-funded projects in the late 1990s and early 2000s aimed to standardize airborne survey data collected by different teams using similar NaI detectors, highlighting the complexities of data integration. The challenge becomes even greater when attempting to correlate data from different types of instruments, such as airborne surveys, ground-based mobile measurements, static gamma-ray spectrometers, non-spectrometric dose rate instruments, soil samples, and integrating dosimeters. To fully realize the potential of this method, it is essential to develop comprehensive operational protocols tailored for field deployment, including specific procedures for sample preparation and measurement under varying environmental conditions such as temperature and humidity. Precise correction factors are necessary to account for signal variability due to light exposure and moisture. Additionally, standardized calibration methods using reference irradiated materials are critical to ensure consistency across multiple portable reader units. These elements are vital for ensuring the accuracy, reliability, and comparability of dose assessments in diverse radiation scenarios. By addressing these challenges, the integrated dosimetry approach can be optimized for practical application in radiological emergency response and environmental monitoring. As nuclear emergency response continues to evolve, these novel methods will play a vital role in improving our ability to manage radiological incidents effectively and safeguard public health.

This study has demonstrated that salt and talc are suitable materials for emergency and retrospective dosimetry, which can be read using portable instruments. Both materials offer practical advantages, including widespread availability and ease of use, making them viable

candidates for large-scale deployment in radiological emergencies. However, several key considerations must be addressed to ensure their optimal performance. Pre-calibrating bulk supplies is essential to establish reliable dose-response relationships and ensure consistency across measurements. Additionally, protective measures are necessary to safeguard the signal. Salt must be shielded from light exposure and moisture, while talc also requires protection from light to maintain its dosimetric properties. Furthermore, the inherent fading of the optically stimulated luminescence (OSL) signal over time necessitates the development of appropriate correction factors to account for this effect. Deployment strategies should be carefully designed, considering factors such as sample collection timelines and environmental conditions. By addressing these considerations, salt and talc can be effectively utilized as robust and accessible dosimetric materials in both emergency and retrospective radiation monitoring scenarios.

6.2 Future work

The work presented in this thesis was primarily aimed at enhancing the response to nuclear and radiation emergencies through the use of new rapid methods of dosimetry using a portable reader using luminescence techniques with common materials (specifically salt and talc). There is further work that could be carried out to improve the protocols used or fully understand the luminescence emission and dose absorption mechanisms in salt and talc investigated. More broadly, this study also raised some questions that have not been answered yet.

1- It is known that rock salts show very large variations in luminescence intensities, reflecting the variability of impurities in these materials. Whether table salt from other batches or suppliers also shows large variations is currently unknown. This is important to know whether a calibration is needed for each batch of salt used, or whether a generic calibration could give useful data in an emergency.

2- The results of the signal stability experiments conducted with salt indicate that the signal strength decreased over the first four days before increasing during the 8 to 256-day period. This pattern has also been reported by other researchers in their studies of different salt samples (Alghamdi, 2024; Christiansson et al., 2014; Singh et al., Biernacka et al., 2018). Further investigation into this complex fading phenomenon could help further understand the underlying physical processes and optimize measurement protocols.

3- The talc used for this work was a single sample from a single mine. Previous work at high doses on a small number of samples indicated that there is significant variability between different sources of talc. While the principle of using talc for emergency dosimetry has been demonstrated here, it would be necessary to fully understand the variabilities between talcs, including kinetic parameters that influence signal stability, for both talc as mined and talc incorporated into other products such as tablets, cosmetic products and baby powders. Noting that the fading of OSL shown in this work is multi-component, it would be useful to explore combined thermal and optical readout procedures with a view to simplifying the fading behaviour. Also to investigate whether the influence of the most thermally-stable residual geological components, can be reduced by changing readout wavelengths or by using combined thermal and optical readout.

4. Extend the dose-response curves of these dosimeters into the triage range and beyond, ensuring their applicability across a wide spectrum of radiation doses. This would enhance their utility in emergency scenarios.

5- Research into optimized packaging solutions is essential to protect the dosimeters from environmental factors such as light and humidity, which can compromise signal integrity.

6. Integrating data from these dosimeters with other measurement systems—such as real-time monitoring devices, airborne surveys, and soil samples. Some further work on defining precise details for the use of such systems in nuclear or radiological emergency response is still required and integrating with other systems.

7-The applied fading correction was derived from laboratory conditions, which may not accurately reflect the outdoor environment. The effects of temperature, humidity, water changes, and electron equilibrium on the dosimeter's response are still ambiguous. Future studies should consider these variables to enhance the precision of outdoor radiation assessments utilising passive dosimeters.

8-As part of future research, it would be highly valuable to extend this work by employing stronger radiation sources. It would be expected that dosimetry mapping would register the radiation field from the source more clearly and enhance the sensitivity and accuracy of the measurements with stronger sources.

Overall, the work presented in this thesis, despite obvious avenues for further research noted above, has demonstrated the feasibility of using portable OSL systems with both salt and talc

as potential dosimeters, adding to the range of techniques which are available for use in radiological and nuclear emergency management.

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Appendix :Salt

Backgrounds, sensitivities and detection limits, Photo-stimulated luminescence food instrument PPSL								
N	sample							
1	STD PAPRIKA	53644	+/-	236	POSITIVE	53388	+/-	236
2	STD UNIRRAD PAP	1412	+/-	59	INTERMEDIATE	1156	+/-	59
3	ETEST	317	+/-	49	NEGATIVE	61	+/-	49
4	SALT1	365	+/-	50	NEGATIVE	109	+/-	50
5	SALAT2	335	+/-	49	NEGATIVE	79	+/-	49
6	SALAT3	392	+/-	50	NEGATIVE	136	+/-	50
7	SALAT4	295	+/-	49	NEGATIVE	39	+/-	49
8	SALAT5	318	+/-	49	NEGATIVE	62	+/-	49
9	SALAT6	381	+/-	50	NEGATIVE	125	+/-	50
10	SALAT7	277	+/-	49	NEGATIVE	21	+/-	49
11	SALAT8	534	+/-	51	NEGATIVE	278	+/-	51
12	SALAT8	399	+/-	50	NEGATIVE	143	+/-	50
13	SALAT 10	395	+/-	50	NEGATIVE	139	+/-	50
14	ETEST	235	+/-	48	NEGATIVE	-21	+/-	48
15	Test-pap	48004	+/-	224	POSITIVE	47748	+/-	224
16	Test pap-un	1188	+/-	57	INTERMEDIATE	932	+/-	57
17	Test2-paa-un	1429	+/-	59	INTERMEDIATE	1173	+/-	59
18	Test3-pap-un	1186	+/-	57	INTERMEDIATE	930	+/-	57
19	Set1-1-Irradiated	213401	+/-	464	POSITIVE	213145	+/-	464
20	Set1-2-Irradiated	277085	+/-	528	POSITIVE	276829	+/-	528
21	Set1-3-Irradiated	133813	+/-	369	POSITIVE	133557	+/-	369
22	Set1-4-Irradiated	263907	+/-	516	POSITIVE	263651	+/-	516
23	Set1-5-irradiated	351807	+/-	595	POSITIVE	351551	+/-	595
24	Set1-6-Irradiated	262366	+/-	514	POSITIVE	262110	+/-	514
25	Set1-7-Irradiated	295970	+/-	546	POSITIVE	295714	+/-	546
26	Set1-8-Irradiated	374565	+/-	614	POSITIVE	374309	+/-	614
27	Set1-9-Irradiated	349211	+/-	593	POSITIVE	348955	+/-	593
28	Set1-10-Irradiated	270208	+/-	522	POSITIVE	269952	+/-	522

Backgrounds, sensitivities and detection limits, Portable OSL 1											
N.	Samples	IRSL		IRSL_dep		PSP	OSL		OSL_dep	PSP	IRSL/OSL
1	set2-1	131	36.48	13.56	37.29	30	-212	34.29	1.94	47	-0.62
2	set2-2	-21	40.68	-0.62	-0.62	-13	-183	36.89	1.73	-33	0.11
3	set2-3	-104	36.44	0.65	0.49	-66	-72	31.75	4.54	-88	1.44
4	Set2-4	56	46.13	5.22	19.11	30	-272	42.10	0.80	-7	-0.21
5	Set2-5	-71	38.07	-0.08	-0.36	-16	-12	34.93	-0.40	-72	5.92
6	Set2-6	-54	37.60	0.13	0.57	25	-247	34.89	1.08	-1	0.22
7	Set2-7	7	38.56	-1.27	-1.69	10	-176	36.22	1.63	2	-0.04
8	Set2-8	66	40.22	1.75	2.38	-54	-168	34.87	1.00	-42	-0.39
9	Set2-9	-65	37.93	0.59	0.76	-14	-79	35.17	0.27	-47	0.82
10	Set2-10	13	36.29	-1.72	-2.81	10	-47	35.68	14.67	4	-0.28
11	empty	-10	31.78	-1.53	-2.18	-15	-4	31.18	-0.91	-11	2.50
12	empty2	-864	83.28	0.62	0.13	-412	-735	71.22	0.76	-498	1.18
13	empty2	-1256	111.93	0.56	0.11	-532	-985	93.93	0.66	-994	1.28
14	Set1-Irradiated	822801	918.46	3.37	0.01	1096	82239	319.08	1.30	-297	10.00
15	Set2 Irradiated	916322	968.64	3.32	0.01	1233	97170	343.36	1.29	-302	9.43
16	Set3 Irradiated	569320	763.12	3.22	0.01	918	59026	268.65	1.27	29	9.65

17	Set4 Irradiated	824808	917.71	3.24	0.01	2098	92112	334.04	1.28	522	8.95
18	Set5 Irradiated	440916	670.79	3.21	0.01	746	47965	240.30	1.28	185	9.19
19	Set6 Irradiated	533587	738.41	3.11	0.01	828	59012	265.76	1.27	-12	9.04
20	Set7 Irradiated	551224	749.82	3.14	0.01	1343	59664	268.39	1.27	339	9.24
21	Set8 Irradiated	537484	741.47	3.14	0.01	1027	61381	272.16	1.29	97	8.76
22	Set9 Irradiated	375791	619.31	3.11	0.01	876	42005	225.20	1.27	238	8.95
23	Set10 Irradiated	486934	705.05	3.10	0.01	986	54489	255.56	1.28	163	8.94

Backgrounds, sensitivities and detection limits, Portable OSL 2											
N.	sample	IRSL		IRSL_de		PSP	OSL		OSL_de	PSP	IRSL/OSL
1	empty-	63	31.9218	0.2115	0.4354	75.00	213.00	35.62	0.4295	25.00	0.2958
2	empty2	272	37.5233	-0.0251	-0.084	-26.0	138.00	37.81	6.6667	39.00	1.9710
3	empty3	-182	33.9706	0.8384	0.3170	32.00	-112.00	36.55	0.1089	28.00	1.6250
4	set1	-6	35.1852	-0.8182	-0.978	-29.0	829.00	43.27	2.7854	-50.00	-0.0072
5	Set2	-23	32.6343	3.6000	17.333	30.00	845.00	43.32	3.2250	-14.00	-0.0272
6	Set3	-148	37.0405	8.2500	14.151	8.00	420.00	44.81	5.1765	17.00	-0.3524
7	Set4	199	33.0303	0.3916	0.1702	17.00	611.00	41.98	4.0917	65.00	0.3257
8	Set5	6	34.0881	-0.3333	-2.811	-31.0	667.00	41.41	2.2857	-27.00	0.0090
9	Set6	-166	34.6699	0.6436	0.2904	14.00	497.00	43.18	8.5577	0.00	-0.3340
10	set7	-119	35.2278	3.4074	3.3476	42.00	610.00	43.42	3.7287	-21.00	-0.1951
11	Set8	135	32.9697	0.6667	0.3443	48.00	642.00	43.05	4.7321	65.00	0.2103
13	Set10	-125	33.2114	1.3148	0.7199	-7.00	662.00	43.61	5.4902	3.00	-0.1888
14	empty	272	35.5106	0.8636	0.5030	-14.0	-9.00	36.70	-1.2000	-7.00	13.6667
15	Set1 Irr	50570	228.670	3.5666	0.0396	100.0	2510056.	1585.20	10.2338	271.00	0.0201
16	Set2 Irr	41673	207.935	3.6068	0.0444	151.0	1999099.	1414.81	10.8285	263.00	0.0208
17	Set3 Irr	40485	205.885	3.6433	0.0460	14.00	2088170.	1445.92	10.4961	157.00	0.0194
18	Set4 Irr	49262	225.721	3.5145	0.0394	36.00	2556317.	1599.60	10.4000	183.00	0.0193
19	Set5 Irr	42555	211.686	3.5199	0.0431	30.00	2308964.	1520.52	10.2332	196.00	0.0184
20	Set6 Irr	40122	204.738	3.5177	0.0441	51.00	2167443.	1473.15	10.6065	240.00	0.0185
21	Set7 Irr	43829	213.703	3.5589	0.0427	52.00	2424848.	1558.19	10.4448	323.00	0.0181
22	Set8 Irr	35191	191.726	3.5893	0.0483	58.00	2003743.	1416.42	10.5716	235.00	0.0176
23	Set9 Irr	49341	226.673	3.4292	0.0383	2.00	2701524.	1644.54	10.5255	245.00	0.0183
24	Set10 I	39952.	203.725	3.4450	0.0427	66.00	2272332.	1508.30	10.4161	275.00	0.0176

Dose response: Portable OSL 470 nm

Portable OSL 470 nm, 0uGy									
N.	Samples	OSL		OSL_dep		PSP		IRSL/OSL	
1	P-1	3138	68.10286	4.573712	0.311678	48	24.75884	0.023901	0.011862
2	P-2	4096	72.41547	4.979562	0.273905	27	23.34524	0.053223	0.00871
3	P-3	3228	67.4092	4.416107	0.27948	-19	24.75884	0.009603	0.011688
4	P-4	3172	70.93659	4.27787	0.295399	-269	32.80244	-0.16204	-0.01593
5	P-5	4121	74.35725	5.389147	0.322834	5	25.45584	-0.01747	-0.00881
6	P-6	3608	73.10267	4.876221	0.322049	74	25.4951	0.031042	0.010937
7	P-7	3168	68.1469	5.285714	0.387296	-6	24.04163	0.007891	0.012328
8	P-8	3643	72.76675	4.596006	0.287448	113	24.83948	0.041724	0.010128
9	P-9	3013	67.23838	3.859677	0.247861	7	24.04163	-0.00996	-0.01264
10	p-10	4149	75.53145	5.201794	0.311443	8	24.04163	-0.01012	-0.00928

Portable OSL 470 nm, 20uGy									
N.	Samples	OSL		OSL_dep		PSP		IRSL/OSL	
1	P-1	3855	72.5741	4.099206	0.222803	59	24.75884	0.01323	0.00909
2	P-2	3227	68.81134	4.204839	0.268219	74	24.08319	0.007127	0.010891
3	P-3	2777	64.81512	3.976703	0.271876	44	26.1725	0.03601	0.013248
4	P-4	4304	76.02631	4.92022	0.274347	88	24.83948	0.018587	0.008069
5	P-5	3928	73.15736	4.447989	0.249153	49	23.34524	0.010183	0.009067
6	P-6	2401	64.69158	3.326126	0.246698	83	24.08319	-0.07289	-0.01501
7	P-7	4110	74.47147	5.217852	0.308978	40	26.1725	0.000243	0.008695
8	P-8	2924	68.49818	3.998291	0.279355	65	25.4951	-0.00616	-0.0132
9	P-9	2522	65.74192	3.887597	0.302143	92	24.83948	-0.02617	-0.01467
10	p-10	3020	67.32013	4.392857	0.30205	36	26.1725	0.037417	0.01277
		312	40.59557	2.058824	0.630952	1	22.62742	0.086538	0.118691

Portable OSL 470 nm, 50uGy									
N.	Samples	OSL		OSL_dep		PSP		IRSL/OSL	
1	P-1	5277	80.77747	5.662879	0.283789	-90	24.08319	-0.02388	-0.0073
2	p-2	4756	79.04429	5.375335	0.293275	41	24.75884	0.042893	0.008261
3	P-3	4296	74.75293	4.586476	0.239563	-61	24.75884	-0.01466	-0.00894
4	P-4	5200	85.01765	6.133059	0.365633	101	26.90725	-0.00904	-0.00764
5	P-5	5481	81.95731	5.716912	0.279859	-14	24.04163	0.041051	0.007133
6	p-6	4604	77.48548	5.99696	0.35147	37	24.75884	0.025413	0.008048
7	P-7	5743	85.50439	5.103082	0.23883	15	26.87006	-0.00644	-0.00668
8	P-8	5533	83.62416	5.674306	0.284512	54	24.08319	0.00235	0.006408
9	P-9	4795	79.34104	5.419009	0.2956	-21	24.75884	-0.01877	-0.00807
10	p-10	5220	81.1172	5.428571	0.272767	51	23.34524	0.028161	0.006929

Sample	OSL		OSL_dep		PSP	IRSL/OSL	
1	7240	92.64988	6.921225	0.315153	19	0.003591	0.004969
2	8382	98.11218	7.082932	0.291211	16	0.011453	0.004264
3	6781	91.46037	6.785304	0.331298	60	0.02743	0.00578
4	7534	94.45634	7.380423	0.341222	4	0.009955	0.005051
5	7333	96.13012	8.16625	0.440981	104	0.012273	0.005426
6	6816	91.60786	7.018824	0.347902	30	0.005722	0.005673
7	7195	92.0163	6.880613	0.310283	39	0.019597	0.004934
8	7186	91.18114	6.477627	0.276837	32	0.042444	0.005056
9	7452	94.08507	6.54251	0.285235	-25	-0.00738	-0.0051
10	7308	93.74433	6.337349	0.278193	13	0.003831	0.005222

Samples	OSL		OSL_dep		PSP		IRSL/OSL	
p-1	12752	118.7434	8.431953	0.292247	11	22.62742	0.00494	0.0029
P-2	10526	109.0229	8.604015	0.34332	-99	26.24881	-0.01007	-0.00386
p-3	10345	108.706	8.623256	0.353822	55	24.75884	0.01421	0.003619
P-4	13442	122.1065	8.826023	0.307149	64	24.08319	0.009076	0.002718
P-5	11462	112.9336	8.771526	0.331154	7	24.04163	0.012214	0.003271
p-6	12339	116.1163	6.770151	0.209165	14	23.34524	0.030797	0.003119
P-7	13375	121.3219	9.011228	0.313805	25	24.75884	0.02385	0.002964
P-8	11266	111.5078	8.333886	0.304449	-34	24.75884	0.01864	0.003459
P-9	11606	113.2696	8.544408	0.312563	54	22.67157	0.029209	0.003175
P-10	11483	113.7497	8.789429	0.338759	34	21.93171	0.001742	0.003188

Portable OSL 470 nm, 500uGy								
Samples	OSL		OSL_dep		PSP		IRSL/OSL	
P-1	27521	170.4846	11.19902	0.28237	3	25.45584	0.012936	0.001581
P-2	21436	150.7183	10.43863	0.289406	-7	24.04163	0.012129	0.001849
P-3	24825	162.2128	10.98118	0.290807	-18	24.75884	0.012004	0.001738
P-4	26141	166.1355	9.648065	0.230743	86	24.83948	0.018783	0.001538
P-5	24788	162.5792	10.76459	0.285912	-3	25.45584	0.008835	0.001748
P-6	24942	162.4623	10.12489	0.255325	91	24.08319	0.020006	0.001602
P-7	22979	155.7915	9.492694	0.240319	-58	26.1725	0.008225	0.001802
P-8	25242	163.3095	9.315488	0.223018	51	22.67157	0.018501	0.001633
P-9	24334	160.6923	9.354894	0.230533	-15	25.45584	0.00789	0.001715
P-10	29807	177.5134	10.62066	0.250706	57	25.4951	0.01134	0.00143

Dose response: Portable IRSL 890 nm

Portable IRSL 890 nm, 0 uGy							
N.	Samples	IRSL		IRSL_dep		PSP	
0	P-1	1559	57.40209	3.157333	0.320479	4	24.75884
2	P-2	1074	54.89991	4.264706	0.746522	-47	26.1725
3	P-3	1630	57.18391	2.97561	0.27735	-54	24.08319
4	P-4	903.00	51.91339	5.496403	1.305469	-60	25.4951
5	P-5	950	55.91064	5.737589	1.459608	-18	26.87006
6	P-6	1106	53.79591	3.495935	0.50913	-9	25.45584

Portable IRSL 890 nm, 20 uGy							
N.	Samples	IRSL		IRSL_dep		PSP	
0	P-1	1625	57.62812	3.526462	0.364511	-16	24.75884
2	P-2	1741	62.58594	3.692722	0.402992	-36	26.87006
3	P-3	1544	58.99152	3.541176	0.400845	4	25.45584
4	P-4	1528	60.69596	4.457143	0.611374	-67	26.90725
5	P-5	1534	57.98	3.85443	0.452052	-47	24.75884
6	P-6	1555	58.84726	3.070681	0.317653	49	25.4951
7	P-7	728	49.95998	2.294118	0.384125	-22	24.75884
8	P-8	1446	58.46366	4.277372	0.579486	15	26.1725
9	P-9	1615	59.01695	4	0.462721	-27	25.45584
10	P-10	1114	58.42944	4.654822	0.897386	-65	27.58623

Portable IRSL 890 nm, 50 uGy							
N.	Samples	IRSL		IRSL_dep		PSP	
1	P-1	3169	72.56032	2.31139	0.123513	-60	26.90725
2	P-2	1329	56.61272	2.712291	0.298805	-1	25.45584
3	P-3	1563	60.58878	3.824074	0.462389	-7	26.87006
4	P-4	1618.00	60.77829	4.411371	0.563377	25	26.1725
5	P-5	1693	59.94164	4.068862	0.459622	-3	25.45584
6	P-6	2686	66.64833	2.501956	0.149192	3	25.45584
7	P-7	1497	61.13101	3.973422	0.522671	-20	26.87006
8	P-8	1538	60.44833	3.703364	0.44594	37	26.1725
9	P-9	1388	58	3.506494	0.435634	-22	26.1725
10	P-10	1947	64.14827	2.155592	0.16463	-6	26.87006

Portable IRSL 890 nm, 100 uGy							
N.	Samples	IRSL		IRSL_dep		PSP	
0	P-1	2046	60.87693	3.280335	0.268508	-11	24.04163
2	P-2	2128	64.99231	4.644562	0.485774	-78	26.90725
3	P-3	2590	67.80855	4.058594	0.327134	-96	26.24881
4	P-4	2158	62.01613	2.799296	0.204548	-32	24.75884
5	P-5	2326	64.01562	3.09507	0.226645	-59	24.75884
6	P-6	2341	63.66318	3.02926	0.216365	-20	24.75884
7	P-7	2010	62.6578	3.466667	0.309831	-29	26.1725
8	P-8	2351	64.92303	3.461101	0.269915	-132	25.6125
9	P-9	1972	63.62389	3.268398	0.294974	-83	26.90725

Portable IRSL 890 nm, 200 uGy							
N.	Sample	IRSL		IRSL_dep		PSP	
1	1	2634	68.10286	3.932584	0.306891	-37	26.1725
2	2	632	50.23943	1.17931	0.18909	-27	25.45584
3	3	2837	70.60453	4.111712	0.316708	-47	26.90725
4	4	2646	70.09993	4.167969	0.348633	43	27.58623
5	5	2573	68.76772	3.712454	0.292396	3	26.87006
6	6	2292	67.14164	3.42471	0.286032	16	26.87006
8	7	2414	65.16134	3.140652	0.22712	-16	25.45584
9	8	2508	68.08818	3.078049	0.22333	-112	26.24881
10	9	2326	67.42403	3.776181	0.329321	-53	26.90725
11	10	3014	71.40028	2.702703	0.159229	-27	26.1725

Portable IRSL 890 nm, 500 uGy							
N.	Sample	IRSL		IRSL_dep		PSP	
1	P-1	5980	88.79189	3.274482	0.125326	-14	25.45584
2	P-2	4221	82.73452	4.22401	0.255294	-54	29
3	P-3	5133	85.00	3.421189	0.151285	21	26.1725
4	P-4	4329	81.09871	3.355131	0.169245	-38	27.58623
5	P-5	5214	85.94184	2.764621	0.111391	19	26.87006
6	P-6	4496	81.61	3.460317	0.170667	-93	26.90725
7	P-7	4074	79.10752	3.302006	0.171739	62	26.90725
8	P-8	3940	78.53662	3.277959	0.175073	51	27.58623
9	P-9	3730	75.80237	2.889468	0.148209	10	26.1725
10	P-10	4533	83.64807	2.89433	0.134944	20	28.28427

Dose response: Pulsed PSL 880 nm

Portable IRSL 890 nm, 0 uGy			
N.	Filename	Sample Label	Counts
1	SALT0034.psl	sat1	1353
2	SALT0035.psl	sat2	1199
3	SALT0036.psl	sat3	1242
4	SALT0037.psl	sat4	1467
5	SALT0038.psl	sat5	1292
6	SALT0039.psl	sat6	1511
7	SALT0040.psl	sat7	1248
8	SALT0041.psl	sat8	1376
9	SALT0042.psl	sat9	1278
10	SALT0043.psl	sat1	1272

Portable IRSL 890 nm, 20 uGy			
N.	Filename	Sample Label	Counts
1	SALT0044.psl	sat1 20uGy	1352
2	SALT0045.psl	sat2 20uGy	1204
3	SALT0046.psl	sat3 0uGy	1382
4	SALT0047.psl	sat4 20uGy	985
5	SALT0048.psl	sat5 20uGy	1352
6	SALT0049.psl	sat6 20uGy	1143
7	SALT0050.psl	sat7 20uGy	1459
8	SALT0051.psl	sat8 20uGy	1268
9	SALT0052.psl	sat9 20uGy	1334
10	SALT0053.psl	sat10 20uGy	1077

Portable IRSL 890 nm, 50 uGy			
N.	Filename	Sample Label	Counts
1	SALT0054.psl	sat1 50uGy	1461
2	SALT0055.psl	sat2 50uGy	1673
3	SALT0056.psl	sat3 50uGy	1380
4	SALT0057.psl	sat4 50uGy	1616
5	SALT0058.psl	sat5 50uGy	1369
6	SALT0059.psl	sat6 50uGy	1294
7	SALT0060.psl	sat7 50uGy	1535
8	SALT0061.psl	sat8 50uGy	1606
9	SALT0062.psl	sat9 50uGy	1433
10	SALT0063.psl	sat10 50uGy	1503

Portable IRSL 890 nm, 100 uGy			
N.	Filename	Sample Label	Counts
1	SALT0064.psl	sat1 100uGy	1764
2	SALT0065.psl	sat2 100uGy	1523
3	SALT0066.psl	sat3 100uGy	1722
4	SALT0067.psl	sat4 100uGy	1707
5	SALT0068.psl	sat5 100uGy	2005
6	SALT0069.psl	sat6 100uGy	1610
7	SALT0070.psl	sat7 100uGy	1704
8	SALT0071.psl	sat8 100uGy	1607
9	SALT0072.psl	sat9 100uGy	1546
10	SALT0073.psl	sat10 100uGy	1825

Portable IRSL 890 nm, 200 uGy			
N.	Filename	Sample Label	Counts
1	SALT0074.psl	sat1 200uGy	1942
2	SALT0075.psl	sat2 200uGy	2309
3	SALT0076.psl	sat3 200uGy	2134
4	SALT0077.psl	sat4 200uGy	1858
5	SALT0078.psl	sat5 200uGy	1765
6	SALT0079.psl	sat6 200uGy	2000
7	SALT0080.psl	sat7 200uGy	1955
8	SALT0081.psl	sat8 200uGy	2393
9	SALT0082.psl	sat9 200uGy	2306
10	SALT0083.psl	sat10 200uGy	1718

Portable IRSL 890 nm, 500 uGy			
N.	Filename	Sample Label	Counts
1	SALT0084.psl	sat1 500uGy	3649
2	SALT0085.psl	sat2 500uGy	4022
3	SALT0086.psl	sat3 500uGy	4236
4	SALT0087.psl	sat4 500uGy	3773
5	SALT0088.psl	sat5 500uGy	4176
6	SALT0089.psl	sat6 500uGy	3263
7	SALT0090.psl	sat7 500uGy	3221
8	SALT0091.psl	sat8 500uGy	3390
9	SALT0092.psl	sat9 500uGy	3463
10	SALT0093.psl	sat10 500uGy	3293

Signal stability tests using 10 mGy with ^{60}Co

After 4 days								
N.	Sample	OSL		OSL dep		PSP		
1	Empty1	423	45.83667	1.238095	0.273485	43	28.9655	0.101655
2	Empty2	352	46.26013	0.833333	0.22106	22	29.89983	0.0625
3	Empty3	384	45.07771	0.714286	0.175205	-44	28.7054	-0.11458
4	salt2	84129	293.249	6.098296	0.062673	85	30.54505	0.00101
5	salt3	99148	317.8144	6.058304	0.056765	3	30.4795	3.03E-05
6	salt4	113051	339.0678	6.205749	0.054831	16	30.95158	0.000142
7	salt5	141015	378.123	6.256098	0.049494	95	31.32092	0.000674
8	salt6	115773	342.9504	6.042153	0.052263	117	30.34798	0.001011
9	salt7	83267	291.4979	6.014321	0.061684	106	29.18904	0.001273
10	salt8	117196	344.987	6.053202	0.052098	160	30.16621	0.001365
11	salt9	100085	319.2914	6.201396	0.058514	105	30.51229	0.001049
12	salt10	105607	327.8643	6.062596	0.055109	88	30.72458	0.000833

After 8 days								
N.	Sample	OSL		OSL dep		PSP		
1	salt2	164407	407.8909	6.108877	0.044279	182	31.36877	0.001107
2	salt3	187871	435.8635	6.120371	0.041396	73	32.44996	0.000389
3	salt4	153267	394.1484	6.230258	0.047198	121	32.29551	0.000789
4	salt5	177478	424.0519	6.188837	0.043475	203	34.21988	0.001144
5	salt6	182717	429.8151	6.217737	0.042879	54	31.81195	0.000296
6	salt7	181810	428.8963	6.131202	0.042304	197	32.72614	0.001084
7	salt8	153267	393.9949	6.230258	0.047198	121	32.29551	0.000372
8	salt9	177478	423.8125	6.188837	0.043475	203	34.21988	0.000766
9	salt10	182717	429.7523	6.217737	0.042879	54	31.81195	0.000901
10	salt11	181810	428.6665	6.131202	0.042304	197	32.72614	0.000754

After 16 days								
N.	Sample	OSL		OSL dep		PSP		
1	Empty3	447	32.32646	1.041096	0.150873	39	17.29162	0.087248
2	salt1	168238	411.3806	6.478574	0.046939	90	22.31591	0.000535
3	salt2	156690	396.9509	6.19785	0.045801	150	20.97618	0.000957
4	salt3	211504	460.8557	6.068984	0.038199	166	21.0238	0.000785
5	salt4	194877	442.6793	6.197407	0.041034	140	23.32381	0.000718
6	salt5	190251	437.1487	6.151756	0.041015	98	20.59126	0.000515
7	salt6	174173	418.7159	5.875069	0.040461	209	23.97916	0.0012
8	salt7	186264	432.7078	6.048513	0.04064	238	22.04541	0.001278
9	salt8	182036	427.7242	6.06881	0.041193	92	21.35416	0.000505
10	salt9	182851	428.6735	6.299733	0.0433	155	21.33073	0.000848
11	salt10	225490	475.8718	6.413289	0.039901	164	21.9545	0.000727

After 32 days								
N.	Sample	OSL		OSL dep		PSP		
1	EMPTY1	169	24.22808	0.656863	0.200067	-11	14.45683	-0.06509
2	SALT1	31911	180.7844	6.038156	0.099674	-82	19.64688	-0.00257
3	SALT2	292115	541.4102	6.486673	0.035547	173	22.47221	0.000592
4	SALT3	225585	475.7615	6.018824	0.036545	216	19.54482	0.000958
5	SALT4	279809	529.9821	6.443708	0.036025	198	23.15167	0.000708
6	SALT5	175396	419.8547	6.316703	0.044346	107	21	0.00061
7	SALT6	209166	458.3034	6.389458	0.041232	186	20.92845	0.000889
8	SALT7	227277	477.5552	6.17211	0.037657	159	19.77372	0.0007
9	SALT8	253557	504.3203	6.121787	0.035249	211	19.77372	0.000832
10	SALT9	177955	422.6926	6.134753	0.042198	61	18.89444	0.000343
11	SALT10	214800	464.3318	6.854609	0.044784	180	20.04994	0.000838

After 64 days								
N.	Sample	OSL		OSL dep		PSP		
1	EMPTY1	638	38.34058	1.860987	0.241536	-58	20.39608	-0.09091
2	EMPTY1	63	25.55386	9.5	29.51224	43	17.17556	0.68254
3	SALT1	539654	735.5039	6.273847	0.024951	378	25.6125	0.0007
4	SALT2	224222	474.4829	6.433677	0.040191	192	21.35416	0.000856
5	SALT3	217115	466.9186	6.153471	0.038426	183	21.18962	0.000843
6	SALT4	294794	543.8658	6.04979	0.032184	254	22.31591	0.000862
7	SALT5	293942	543.3102	6.233003	0.033588	164	24.93993	0.000558
8	SALT6	292535	541.8884	5.929646	0.03144	202	23.5372	0.000691
9	SALT7	276738	527.0009	5.97442	0.032664	238	22.27106	0.00086
10	SALT8	300432	549.0756	5.980784	0.031404	302	22.93469	0.001005
11	SALT9	302152	550.8956	5.981331	0.031345	247	25.82634	0.000817
12	SALT10	316838	563.7961	6.101125	0.031377	198	22.67157	0.000625

After 128days								
N.	Sample	OSL		OSL dep		PSP		
1	EMPTY1	87	26.73948	0.298507	0.302832	-48	17.72005	-0.55172
2	salt1	388967	624.5695	6.423459	0.030353	178	23.66432	0.000458
3	salt2	344485	587.7882	6.437871	0.032364	189	22.47221	0.000549
4	salt3	310524	558.3171	6.326444	0.033351	235	24.43358	0.000757
5	salt4	315323	562.4509	6.457265	0.034007	236	22.67157	0.000748
6	salt5	339328	583.3044	6.208855	0.031016	172	21.40093	0.000507
7	salt6	296185	545.2477	6.579135	0.036022	199	23.55844	0.000672
8	salt7	279150	529.3317	6.44142	0.036006	101	22.82542	0.000362
9	sal8	324637	570.6198	6.419596	0.03323	235	22.02272	0.000724
10	salt9	352323	595.3831	6.500703	0.032487	-205	32.84814	-0.00058
11	salt10	295269	544.4217	6.406537	0.034773	161	23.72762	0.000545
12	SALT10	316838	563.7961	6.101125	0.031377	198	22.67157	0.000625

After 256days								
N.	Sample	OSL		OSL_dep		PSP		
1	EMPTY1	153	25.47548	2.4	1.054823	44	15.74802	0.287582
2	EMPTY2	4306	69.77105	0.989834	0.032074	51	16.76305	0.011844
3	salt1	438451	663.1161	6.817198	0.031039	254	25.21904	0.000579
4	salt2	539918	736.1182	6.469398	0.026041	210	31.241	0.000389
5	salt3	483047	695.9691	6.171658	0.025788	267	25.74879	0.000553
6	salt4	484661	697.2855	5.529092	0.022183	251	27.80288	0.000518
7	salt5	493387	703.438	6.690426	0.028498	205	26.81418	0.000415
8	salt6	394842	629.2885	6.695525	0.031882	127	24.10394	0.000322
9	salt7	479962	693.7233	6.544674	0.028039	293	25.39685	0.00061
10	SALT8	459330	678.7164	6.620952	0.029149	365	25.74879	0.000795
11	SALT9	368829	608.1192	6.710765	0.033106	228	22.13594	0.000618
12	SALT10	458909	678.2544	6.772322	0.030046	292	23.66432	0.000636

Signal stability tests using 200 mGy with ⁹⁰Sr

After one day								
N.	Sample	OSL		OSL_dep		PSP		
1	EMPTY1	190	25.80698	1.209302	0.330614	-16	15.42725	-0.08421
2	empty2	251	25.671	0.780142	0.16307	-12	14.28286	-0.04781
3	salt1	4058157	2015.918	6.481563	0.009496	2502	53.70289	0.000617
4	salt2	2699788	1644.339	6.221619	0.01101	1744	45.07771	0.000646
5	salt3	3504910	1873.402	6.34725	0.009927	2101	48.6107	0.000599
6	salt4	3187502	1786.592	6.367017	0.010454	1809	46.95743	0.000568
7	salt5	2972325	1725.267	6.260322	0.01058	1744	45.93474	0.000587
8	salt6	2988838	1730.118	6.2604	0.010551	1685	47.27579	0.000564
9	salt7	3025211	1740.623	6.371354	0.010745	1955	47.73887	0.000646
10	salt8	2186545	1479.846	6.483299	0.012945	1408	41.23106	0.000644
11	salt9	3445994	1857.698	6.344904	0.010009	2074	50.23943	0.000602
12	salt10	2416972	1555.826	6.329799	0.011912	1410	42.56759	0.000583

After two days								
N.	Sample	OSL		OSL_dep		PSP		
1	salt1	2127868	1459.815	6.380742	0.012836	1298	39.94997	0.00061
2	salt2	2557699	1600.486	6.253723	0.011392	1652	43.909	0.000646
3	salt3	2098553	1449.789	6.359083	0.012869	1348	40.84116	0.000642
4	salt4	2323669	1525.513	6.256975	0.01196	1461	41.96427	0.000629
5	salt5	2377465	1543.111	6.246093	0.011796	1423	43.16248	0.000599
6	salt6	2234253	1495.867	6.092214	0.01176	1381	41.02438	0.000618
7	salt7	2658620	1631.747	6.319667	0.011334	1611	44.59821	0.000606

8	salt8	2184106	1478.923	6.284797	0.012409	1340	39.42081	0.000614
9	salt9	1756099	1326.267	6.213653	0.013632	1169	37.98684	0.000666
10	salt10	2264908	1506.142	6.465532	0.012671	1402	42.16634	0.000619

After four days								
N.	Sample	OSL		OSL_dep		PSP		
1	empty1	136	26.30589	3	1.789048	64	16.67333	0.470588
2	salt1	1713793	1310.335	6.005167	0.01318	1346	39.89987	0.000785
3	salt2	1509234	1229.617	6.198346	0.01466	1040	36.90528	0.000689
4	salt3	2076525	1442.158	6.071356	0.012145	1362	40.59557	0.000656
5	salt4	1808355	1345.971	6.111892	0.013138	1212	40.5216	0.00067
6	saltt5	1957306	1400.211	6.217924	0.012926	1327	40.53394	0.000678
7	salt6	2569445	1604.214	6.078068	0.010936	1804	45.03332	0.000702
8	salt7	1736627	1319.019	5.963192	0.012966	1260	39.89987	0.000726
9	salt8	1982818	1409.426	6.002984	0.012244	1354	42.80187	0.000683
10	salt9	2002800	1416.407	6.17672	0.012663	1377	41.29165	0.000688
11	salt10	1519071	1233.559	6.281905	0.014875	893	36.04164	0.000588

After eight days								
N.	Sample	OSL		OSL_dep		PSP		
1	salt1	1697201	1303.969	6.117012	0.013581	1283	39.58535	0.000756
2	salt2	1441660	1201.76	6.251847	0.015174	941	35.81899	0.000653
3	salt3	1943225	1395.156	6.227727	0.012999	1268	40.22437	0.000653
4	salt4	1838519	1357.018	6.287411	0.013538	1190	38.60052	0.000647
5	salt5	1646749	1284.482	6.396864	0.01466	1284	39.64846	0.00078
6	salt6	1471880	1214.377	6.145291	0.014677	1104	37.62978	0.00075
7	salt7	1701868	1305.879	5.971212	0.013129	1378	41.54516	0.00081
8	salt8	1698969	1304.523	6.233719	0.013919	1083	37.48333	0.000637
9	salt9	1610459	1270.141	6.24453	0.014333	1037	37.40321	0.000644
10	salt10	1505784	1228.147	6.505952	0.015679	994	35.77709	0.00066

After 16 days								
N.	Sample	OSL		OSL dep		PSP		
1	EMPTY1	265	28.82707	1.676768	0.397701	15	16.8226	0.056604
2	salt1	2024479	1424.233	7.472254	0.01638	1444	44.49719	0.000713
3	salt2	1729986	1316.59	6.151806	0.013557	1226	41.37632	0.000709
4	salt3	1639241	1281.511	6.105787	0.013779	1021	38.923	0.000623
5	salt4	1864116	1366.861	5.772545	0.011986	1566	45.78209	0.00084
6	salt5	1724934	1314.584	6.266398	0.013916	1027	39.9875	0.000595
7	salt6	2288115	1514.067	6.232905	0.011997	1470	46.28175	0.000642
8	salt7	1396052	1182.79	6.243864	0.0154	860	38.34058	0.000616
9	salt8	2176937	1476.884	6.052384	0.011817	1432	46.08687	0.000658
10	salt9	2732764	1654.785	5.92607	0.010254	2158	52.66878	0.00079
11	salt10	2793082	1672.888	5.933976	0.010158	2032	52.30679	0.000728

After 32 days								
N.	Sample	OSL		OSL dep		PSP		
1	EMPTY1	122	27.23968	0.876923	0.395927	-30	17.60682	-0.2459
2	EMPTY2	42	24.93993	0.235294	0.536667	-18	17.02939	-0.42857
3	SALT1	1960917	1401.726	5.966056	0.012217	1638	44.27189	0.000835
4	SALT2	2451159	1567.116	5.909675	0.010786	2056	48.43552	0.000839
5	SALT3	3088158	1758.866	6.238696	0.010339	2100	52.21111	0.00068
6	SALT4	1832493	1355.162	5.957786	0.012618	1553	44.55334	0.000847
7	SALT5	2034237	1427.584	6.098792	0.012357	1688	43.35897	0.00083
8	SALT6	1954180	1399.432	5.99215	0.012315	1669	45.98913	0.000854
9	SALT7	1610348	1270.223	6.218281	0.014262	1261	39.48417	0.000783
10	SALT8	2152478	1468.522	6.168953	0.012201	1686	45.16636	0.000783
11	SALT9	1800253	1343.057	6.118917	0.013194	1351	42.13075	0.00075
12	SALT10	2444740	1565.133	6.001274	0.011028	1932	49.49747	0.00079

After 64 days								
N.	Sample	OSL		OSL dep		PSP		
1	EMPTY1	122	27.23968	0.876923	0.395927	-30	17.60682	-0.2459
2	EMPTY1	1323	42.13075	0.971684	0.061918	-22	15.0333	-0.01663
3	SALT1	2754805	1661.334	6.139945	0.010717	2217	51.11751	0.000805
4	SALT2	2442254	1564.29	6.057824	0.011177	2074	48.72371	0.000849
5	SALT3	2467420	1572.217	6.169085	0.011394	1891	47.1487	0.000766
6	SALT4	2725602	1652.392	6.21198	0.010943	2075	48.97959	0.000761
7	SALT5	1958183	1400.657	6.214693	0.012921	1532	42.75512	0.000782
8	SALT6	2605813	1615.644	6.21584	0.011201	1974	47.39198	0.000758
9	SALT7	2035614	1428.09	6.146743	0.012485	1616	43.74929	0.000794
10	SALT8	2218530	1490.8	6.389779	0.012605	1572	44.47471	0.000709
11	SALT9	2298066	1517.221	6.184016	0.011842	1657	44.12482	0.000721
12	SALT10	1453585	1206.755	6.396965	0.015596	962	36.55133	0.000662

After 128 days								
N.	Sample	OSL		OSL dep		PSP		
1	EMPTY1	138	24.85961	0.916667	0.332545	-32	15.49193	-0.23188
2	EMPTY1	591	34.04409	0.900322	0.103801	22	16.8523	0.037225
3	SALT1	3261159	1807.46	6.177747	0.009931	2648	53.62835	0.000812
4	SALT2	3140847	1773.068	8.20241	0.014919	991	38.22303	0.000316
5	SALT3	2444540	1564.413	7.867471	0.015972	1060	37.73592	0.000434
6	SALT4	3348581	1830.734	8.34035	0.014789	1097	38.76854	0.000328
7	SALT5	2610182	1616.301	8.330509	0.01672	781	33.51119	0.000299
8	SALT6	2391642	1547.197	8.586008	0.018221	685	33	0.000286
9	SALT7	3880453	1970.792	7.874232	0.012683	1470	42.23742	0.000379
10	SALT8	2632967	1623.397	8.117995	0.016063	906	35.01428	0.000344
11	SALT9	3543848	1883.356	8.186784	0.014007	1157	39.88734	0.000326
12	SALT10	2766485	1664.12	8.97219	0.018022	764	37.49667	0.000276
13	SALT11	4103365	2026.634	8.227369	0.013106	1081	44.05678	0.000263

After 256 days								
N.	Samples	OSL		OSL dep		PSP		
1	EMPTY1	124	23.19483	4.391304	3.264957	49	14.38749	0.395161
2	SALT1	3990190	1999.183	6.244209	0.009106	2915	57.19266	0.000731
3	SALT2	4934232	2223.139	6.189876	0.008092	3681	63.69458	0.000746
4	SALT3	3042411	1745.453	6.666961	0.011398	1801	45.79301	0.000592
5	SALT5	3590031	1896.308	6.256839	0.009626	2551	54.56189	0.000711
6	SALT6	4157597	2040.63	6.234151	0.0089	3023	57.33236	0.000727
7	SALT7	3839877	1961.008	6.175288	0.009138	2421	53.2635	0.00063
8	SALT8	5118356	2264	6.501269	0.008491	3243	60.57227	0.000634
9	SALT9	4609530	2148.553	6.515395	0.008975	2906	58.10336	0.00063
10	SALT10	3429336	1853.363	6.327391	0.010001	2459	53	0.000717
11	SALT11	4164851	2042.214	6.52407	0.009457	2585	53.78662	0.000621

Impact of light exposure

Storage Darkroom, 24 hours								
N.	Samples	OSL		OSL_dep		PSP		
1	empty	166	25.96151	2.074074	0.792113	42	15.93738	0.253012
1	empty2	55	27.76689	-3.03704	-2.30443	46	18.92089	0.836364
1	clean	239	43.94315	-2.62585	-0.65123	528	29.08608	2.209205
1	clean2	771	36.15245	1.153631	0.108549	-12	16.37071	-0.01556
1	salt1	184620	430.8944	5.704678	0.03772	253	22.91288	0.00137
1	salt2	174824	419.1706	5.845106	0.039984	166	20.97618	0.00095
1	salt3	163389	405.2197	5.948288	0.042338	131	20.17424	0.000802
1	salt4	184373	430.2848	5.960098	0.039917	148	19.64688	0.000803
1	salt5	173218	417.2865	5.904416	0.040753	185	21.33073	0.001068
Mean		176084.8		5.872517				
Std dev		8839.335		0.104104				
Std Err		2946.45		0.0347				
% SE		5.019931		1.772737				

Storage daylight, 2.5hours								
N.	Samples	OSL		OSL_dep		PSP		
1	salt1	1254	42.56759	1.339552	0.092837	21	16.70329	0.016746
1	salt2	1093	40.45986	1.077947	0.080023	34	16.49242	0.031107
1	salt3	1065	41.3884	1.320261	0.105744	82	18	0.076995
1	salt4	949	40.13726	1.147059	0.09785	49	18.19341	0.051633
1	salt5	818	38.704	1.210811	0.116872	88	18.43909	0.107579
Mean		1035.8		1.219126				
Std dev		163.33		0.11172				
Std Err		54.4433		0.03724				
% SE		15.76849		9.163925				

Storage daylight, 5 hours								
N.	Samples	OSL		OSL_dep		PSP		
1	empty	78	28.74022	-2.77273	-1.4367	144	19.33908	1.846154
1	salt1	911	38.03945	1.06576	0.089137	14	16.37071	0.015368
1	salt2	947	38.5357	1.104444	0.090239	27	16.40122	0.028511
1	salt3	887	38.79433	1.228643	0.110001	101	17.5784	0.113867
1	salt4	855	36.94591	1.209302	0.106229	61	15.96872	0.071345
1	salt5	863	39.23009	0.988479	0.089883	-18	18.38478	-0.02086
Mean		892.6		1.119326				
Std dev		37.48066		0.100322				
Std Err		12.4936		0.03344				
% SE		4.199043		8.962679				

Storage daylight, 24 hours								
		OSL		OSL_dep		PSP		
1	Salt1	628	35.80503	1.188153	0.137434	51	18.08314	0.08121
1	Salt2	626	36.11094	1.514056	0.185116	47	18.41195	0.07508
1	Salt3	766	36.30427	1.447284	0.143814	58	16.61325	0.075718
1	Salt4	776	35.86084	1.409938	0.137966	119	15.96872	0.153351
1	Salt5	699	35.36948	0.879032	0.089067	26	16.61325	0.037196
Mean		699		1.287693				
Std dev		72.09022		0.259116				
Std Err		24.0301		0.08637				
% SE		10.31334		20.12253				

Storage daylight, 24 hours using black heat-shrink								
N.	Samples	OSL		OSL_dep		PSP		
1	salt6	150799	389.4342	6.027963	0.044897	84	20.73644	0.000557
1	salt7	199511	447.655	5.786088	0.036842	110	21.0238	0.000551
1	salt8	204077	452.8256	5.857657	0.037094	179	22.06808	0.000877
1	salt9	202719	451.2616	6.098004	0.039305	177	21.42429	0.000873
1	salt10	187107	433.5539	5.818271	0.038365	145	20.76054	0.000775
Mean		188842.6		5.917597				
Std dev		22297.89		0.137368				
Std Err		7432.63		0.04579				
% SE		11.80766		2.321355				

Relative humidity effect during storage

Relative humidity (%), 32 , 32 days							
Samples	OSL		OSL_dep		PSP		
Empty	104	26.83282	0.094736842	0.193654	-18	17.54993	-0.17308
Empty	157	23.51595	0.784090909	0.236202	28	14.07125	0.178344
SALT1	227202	478.1862	6.450711615	0.040113	-12	27.01851	-5.3E-05
SALT2	278804	528.9291	6.160571194	0.033926	233	21.93171	0.000836
SALT3	263122	513.8112	6.165631808	0.034926	142	20.97618	0.00054
SALT4	289258	538.8302	5.925017955	0.031584	208	23.2379	0.000719
SALT5	224163	474.2816	5.992856252	0.036399	104	19.74842	0.000464
Mean	256509.8		6.138				
Std dev	29658.30		0.203				
Std Err	9886.10		0.067				
% SE	11.56		3.313				

Relative humidity (%), 32 , 64 days							
Samples	OSL	OSL_dep		PSP			
Empty	28	25.49509757	-29	-534.238	29	17.63519	1.035714
Empty2	182	25.57342371	0.700935	0.209163	-42	15.36229	-0.23077
SALT1	360021	600.9018223	6.142282	0.029696	239	23.04344	0.000664
SALT2	288737	538.2685204	6.007329	0.032173	126	22.31591	0.000436
EMPTY3	195	26.13426869	0.741071	0.209481	-62	15.6205	-0.31795
SALT3	338432	582.585616	6.311283	0.031773	185	22.06808	0.000547
SALT4	314399	543.8575181	6.213468	0.032156	10089	#NUM!	0.03209
SALT5	334771	579.5092752	5.887584	0.029085	254	23.02173	0.000759
SALT6	305287	553.3416666	6.233603	0.032888	146	21.2132	0.000478
SALT7	361717	602.2698731	6.298567	0.030657	248	22.49444	0.000686
SALT8	362527	603.0530657	6.182593	0.029879	281	23.93742	0.000775
SALT9	345775	588.9541578	6.149725	0.030346	168	23.36664	0.000486
SALT10	309338	557.1947595	6.327159	0.033384	156	23.74868	0.000504
Mean	301927.1818		5.681333				
Std dev	103147.4899		1.643813				
Std Err	34382.49662		0.54794				
% SE	34.16303535		28.93357				
Std Err	% SE						
32542.13344	22.149						

Relative humidity (%), 52 , 32 days							
Samples	OSL		OSL_dep		PSP		
Empty	2	14.07124728	1	14.07125	0	9.899495	0
salt10	515	26.70205985	3.023438	0.395993	1	9.949874	0.001942
salt7	525	26.88865932	3.007634	0.387858	1	9.949874	0.001905
salt9	541	27.14774392	2.977941	0.374486	2	9.899495	0.003697
salt2	573	27.80287755	2.979167	0.361535	2	10	0.00349
salt8	539	27.14774392	2.992593	0.378182	1	9.949874	0.001855
salt3	545	27.29468813	2.949275	0.368966	2	10	0.00367
SALT6	598	28.24889378	2.883117	0.335531	2	10	0.003344
salt4	495	26.32489316	2.867188	0.377865	1	9.949874	0.00202
salt1	542	27.20294102	2.927536	0.365333	1	9.949874	0.001845
salt5	534	27.05549852	2.955556	0.374041	1	9.949874	0.001873
Mean	540.7		2.956344				
Std dev	28.65523028		0.051235				

Std Err	9.551743426		0.01708				
% SE	5.299654203		1.733044				

Relative humidity (%), 53 using black shrink,10 days							
Samples	OSL		OSL_dep		PSP		
empty	183	25.23886	1.815385	0.578759	47	15.06651917	0.256830601
empty	235	25.86503	0.766917	0.172456	-3	14.73091986	-0.012765957
salt	129122	406.448	6.394723	0.046609	19	22.11334439	0.000115697
salt	119223	409.9707	6.381858	0.046051	92	20.49390153	0.000550121
salt	126250	409.0697	6.446571	0.046815	146	19.84943324	0.000876614
salt	130303	413.6798	6.210729	0.043949	88	20.34698995	0.000516726
salt	116429	409.0318	6.227727	0.044649	109	20.46948949	0.000654777
salt	124318	432.1736	6.280287	0.043126	-233	33.36165464	-0.001262544
salt	121905	414.6529	6.267372	0.044412	109	20.42057786	0.000637043
salt	128127	422.9622	6.633011	0.046981	114	18.86796226	0.000639784
salt	123019	427.7768	5.784623	0.038567	46	21.77154106	0.000252685
Mean	124299.6		5.739382				
Std dev	4648.145		1.760694				
Std Err	1549.38		0.5869				
% SE	3.73947		30.67741				

Appendix: Talc

Heating to 450 to remove the signal										
samples	IRSL		IRSL_dep		PSP	OSL		OSL_dep	PSP	IRSL/OSL
Empty	23	33.63034	-0.47727	-0.58794	21	375	40.6325	2.04878	42	0.061333
UN.R	74410	276.4164	1.455532	0.011015	127	3736944	1939.228	1.757154	5416	0.019912
D9 2	86209	297.807	1.51221	0.010685	364	5800877	2418.481	1.611223	11423	0.014861
D9 3	58957	247.0243	1.50977	0.01294	140	3478349	1873.357	1.574894	7263	0.01695
D9 3	61526	251.7975	1.477391	0.012338	205	4220242	2063.546	1.416373	9026	0.014579
D9 4	121643	352.152	1.537719	0.009118	334	5458458	2345.923	1.629371	10632	0.022285
D9 5	78487	284.3079	1.584785	0.011805	200	4183954	2054.14	1.594092	8298	0.018759
D9 6	80480	287.6943	1.464101	0.010669	354	5564110	2369.666	1.579984	12230	0.014464
D9 7	128893	363.6771	1.605109	0.009326	416	5846703	2428.954	1.614592	12437	0.022045
D9 8	80334	287.162	1.485736	0.010842	330	4505556	2131.684	1.615372	9098	0.01783
D9 9	103427	326.5563	1.484196	0.009567	487	5435730	2342.173	1.606915	11708	0.019027
D9 10	75364	277.8345	1.462071	0.010985	265	4206856	2060.281	1.614986	9018	0.017915
Mean	87532		1.512309			4870084		1.58578		
Std dev	23459.07		0.049532			841342.8		0.061889		
Std Err	7819.689		0.016511			280447.6		0.02063		
% SE	26.80056		3.275234			17.27574		3.902778		

Heating to 450 to remove the signal										
samples	IRSL		IRSL_dep		PSP	OSL		OSL_dep	PSP	IRSL/OSL
after450	-76	31.74902	0.407407	0.453987	41	515	40.03748	1.278761	1	-0.14757
after450	-117	32.72614	4.85	5.915851	93	694	43.56604	0.922438	4	-0.16859
after450	109	32.51154	-5.95455	-5.86194	-17	530	39.57272	0.766667	22	0.20566
after450	-13	32.78719	-0.13333	-1.57113	2	537	42.53234	0.778146	46	-0.02421
after450	-101	33.68976	0.507463	0.402125	-5	454	41.30375	0.868313	4	-0.22247
after450	60	32.18695	1.307692	1.439598	-44	696	41.32796	0.817232	9	0.086207
after450	136	28.49561	0.402062	0.21804	29	653	41.3884	1.213559	96	0.20827
after450	123	32.10919	1.795455	1.050969	55	684	41.71331	0.853659	37	0.179825
after450	30	32.09361	-0.48276	-0.42304	64	566	43.0581	1.25498	72	0.053004
after450	39	31.85906	-2.625	-2.55096	8	661	39.81206	1.021407	-13	0.059002
Mean	29.55556		-0.037			608.3333		0.944044		
Std dev	92.0083		2.988753			88.28505		0.181914		
Std Err	30.6694		0.99625			29.4283		0.06064		
% SE	311.3063		-8078.53			14.51261		19.26968		

Backgrounds, sensitivities and detection limits, Portable OSL 1, 980 OSL										
	IRSL		IRSL_dep		PSP	OSL		OSL_dep	PSP	IRSL/OSL
Empty 1	75	31.9217794	0.211538462	0.435447092	75	213	35.62303	0.42953	25	0.295775
Empty 2	281	36.52332608	-0.025089	-0.084934	-26	138	37.81534	6.666667	39	1.971014
D9 1 Back.G	406076	642.4577807	1.403954535	0.004508624	959	42136	223.392	1.236281	273	9.63727
D9 2 Back.G	551759	747.2770571	1.37998473	0.00378773	1276	53772	250.8944	1.23761	628	10.26108
D 1	483929	704.2109059	1.476961898	0.004384588	2782	51719	261.937	1.304563	1227	9.35689
D 2	506983	721.4533942	1.437769871	0.004163204	3128	58489	277.9874	1.287049	1319	8.668006
D 3	540061	744.1619447	1.435746404	0.004024861	3183	60357	281.4694	1.297651	1288	8.947777
D 4	647092	813.8623962	1.485202283	0.003812731	3558	70022	302.7375	1.301917	1587	9.241267
D 5	420429	656.829506	1.414801413	0.004490818	2373	45018	244.6262	1.282281	957	9.339131
D 6	602679	786.5462478	1.391033016	0.003682989	3546	62712	290.5443	1.26528	1432	9.610266
D7	485076	706.0878132	1.419235143	0.004198726	2911	50934	262.7737	1.301166	1158	9.523619
D 8	548243	749.5218476	1.438304439	0.004001048	2983	56935	273.8156	1.287189	1125	9.629279
D 9	423380	659.654455	1.422331819	0.00450493	2579	47471	251.9425	1.316223	1060	8.918708
D10	460844	688.093017	1.410864595	0.004279124	2785	54236	267.2452	1.308406	1139	8.497013

Backgrounds, sensitivities and detection limits, Portable OSL 2, 470 OSL										
	IRSL		IRSL_dep		PSP	OSL		OSL_dep	PSP	IRSL/OSL
Empty 1	-160	33.97058	0.838384	0.317008	32	-112	36.55133	0.108911	28	1.625
Empty 2	23	33.63034	-0.47727	-0.58794	21	375	40.6325	2.04878	42	0.061333333
D9 1 Back.G	74410	276.4164	1.455532	0.011015	127	3736944	1939.228	1.757154	5416	0.019911992
D9 2 Back.G	406076	642.4578	1.403955	0.004509	959	42136	223.392	1.236281	273	9.637269793
D9 3Back.G	551759	747.2771	1.379985	0.003788	1276	53772	250.8944	1.23761	628	10.26108384
D9 1	86209	297.807	1.51221	0.010685	364	5800877	2418.481	1.611223	11423	0.014861374
D9 2	58957	247.0243	1.50977	0.01294	140	3478349	1873.357	1.574894	7263	0.016949708
D9 3	61526	251.7975	1.477391	0.012338	205	4220242	2063.546	1.416373	9026	0.014578785
D9 4	121643	352.152	1.537719	0.009118	334	5458458	2345.923	1.629371	10632	0.022285231
D9 5	78487	284.3079	1.584785	0.011805	200	4183954	2054.14	1.594092	8298	0.018759049
D9 6	80480	287.6943	1.464101	0.010669	354	5564110	2369.666	1.579984	12230	0.014464128
D9 7	128893	363.6771	1.605109	0.009326	416	5846703	2428.954	1.614592	12437	0.022045416
D9 8	80334	287.162	1.485736	0.010842	330	4505556	2131.684	1.615372	9098	0.017829986
D9 9	103427	326.5563	1.484196	0.009567	487	5435730	2342.173	1.606915	11708	0.019027251
D9 10	75364	277.8345	1.462071	0.010985	265	4206856	2060.281	1.614986	9018	0.017914566

Backgrounds, sensitivities, and detection limits using heated talc

Backgrounds, sensitivities and detection limits, Portable OSL 1, 980 OSL										
	IRSL		IRSL_dep		PSP	OSL		OSL_dep	PSP	IRSL/OSL
Empty 1	248	28.49561	0.620915	0.152542	21	-32	28.07134	4.333333	64	-7.75
Empty 2	63	31.92178	0.211538	0.435447	75	213	35.62303	0.42953	25	0.295775
Empty 1	272	37.52333	-0.02509	-0.08493	-26	138	37.81534	6.666667	39	1.971014
D9 1 Back.G	-182	33.97058	0.838384	0.317008	32	-112	36.55133	0.108911	28	1.625
D9 1 Back.G	-155	44.55334	1.094595	0.631292	15	-36	43.54308	-0.42857	-52	4.305556
D9 3 Back.G	98	38.07887	0.849057	0.666156	-22	72	34.58323	1.181818	-57	1.361111
D9 4 Back.G	-185	35.70714	1.202381	0.470643	-15	12	36.05551	-0.63636	-43	-15.4167
S1	6030	84.79387	1.681192	0.049427	12	832	45.47527	1.337079	19	7.247596
S2	253	43	3.362069	1.78086	63	-323	36.94591	0.691099	23	-0.78328
S3	1151	53.54437	2.307471	0.258337	-67	17	38.32754	0.214286	-66	67.70588
S4	662	47.56049	1.769874	0.279979	34	7	37.45664	-1.2	-51	94.57143
S5	2119	60.68773	1.632298	0.09879	-17	333	42.67318	3.111111	-19	6.363363
S6	2078	57.56735	1.465006	0.083785	-19	330	37.97368	1.820513	-31	6.29697
S7	626	50.81338	1.832579	0.332807	-125	87	37.40321	2.222222	-161	7.195402
S8	1014	53.34791	1.560606	0.173663	-58	72	38.72983	0.090909	-101	14.08333
S9	526	45.49725	1.348214	0.239762	20	-128	38.0526	0.560976	8	-4.10938

Backgrounds, sensitivities and detection limits, Portable OSL 2, 470 OSL										
	IRSL		IRSL_dep		PSP	OSL		OSL_dep	PSP	IRSL/OSL
Empty 1	53	31.06445	-0.13115	-0.35041	-10	286	33.85262	1.150376	-13	0.185315
Empty 2	10	34.14674	-0.58333	-1.15534	31	112	35.60899	0.577465	0	0.089286
Empty 1	222	29.22328	2.313433	0.749367	10	348	34.4093	1.011561	51	0.637931
D9 1 Back.G	72	31.74902	23	166.5653	-2	612	38.47077	0.918495	-17	0.117647
D9 1 Back.G	-10	31.08054	-1.90909	-4.34624	-4	377	38.94868	0.953368	41	-0.02653
D9 3 Back.G	119	32.41913	-0.08462	-0.16485	-17	372	41.42463	1.369427	103	0.319892
D9 4 Back.G	-107	33.06055	0.138298	0.259862	-48	610	40.47221	0.92429	-43	-0.17541
s1	91	39.58535	0.123457	0.340455	37	10634	109.7725	2.040892	-15	0.008557
s2	335	43.02325	1.392857	0.370821	5	8028	97.52948	2.239709	-8	0.041729
s3	348	42.23742	2.192661	0.644362	105	10992	112.6233	2.264627	64	0.031659
s4	245	39.81206	3.083333	1.471495	-7	8169	99.36297	2.237812	91	0.029991
s5	191	43.25506	1.546667	0.747719	-8	9727	107.0841	2.238016	15	0.019636
s6	62	39.67367	-0.13889	-0.38339	52	7408	94.80506	2.104778	17	0.008369
s7	91	36.31804	6	11.73272	55	10310	108.379	2.019034	52	0.008826
s8	135	39.63584	0.421053	0.316163	53	9407	104.1297	2.154594	0	0.014351
s9	113	38.63936	6.533333	11.71524	19	7290	93.58419	2.212869	22	0.015501

Dose response

0mGy using IRSL 10 SAMPLES											
	IRSL		IRSL_dep		PSP		OSL		OSL_dep	PSP	IRSL/OSL
EMPTY1	-84.00	33.11	0.38	0.42	9.00	25.46	-188.00	30.66	0.94	-13.00	0.45
EMPTY2	-159.00	32.76	0.77	0.33	30.00	26.17	-142.00	31.97	1.54	-17.00	1.12
EMPTY3	94.00	29.29	0.74	0.48	9.00	23.35	29.00	28.86	3.83	10.00	3.24
s1	-124.00	35.89	1.82	1.21	-13.00	26.87	-185.00	33.39	0.65	-28.00	0.67
s2	-6.00	33.26	-1.29	-1.83	-82.00	25.50	-35.00	32.51	-3.06	-5.00	0.17
s3	-155.00	44.55	1.09	0.63	15.00	29.70	-36.00	43.54	-0.43	-52.00	4.31
s4	-48.00	35.61	0.60	0.98	-37.00	26.17	-61.00	32.66	0.61	-47.00	0.79
s5	-66.00	34.61	0.53	0.65	-24.00	26.17	-135.00	33.06	1.76	-9.00	0.49
s6	-6.00	38.55	-0.25	-3.52	-91.00	26.91	-151.00	34.37	0.31	-40.00	0.04
s7	-14.00	37.76	1.80	11.00	4.00	26.87	-43.00	37.16	4.38	-4.00	0.33
s8	-72.00	34.06	0.33	0.48	-16.00	25.46	-182.00	33.44	0.61	17.00	0.40
s9	98.00	38.08	0.85	0.67	-22.00	26.17	72.00	34.58	1.18	-57.00	1.36
s10	-73.00	36.92	0.55	0.64	-39.00	26.17	-124.00	32.98	0.88	-56.00	0.59

0mGy using OSL 10 SAMPLES											
	IRSL		IRSL_dep		PSP		OSL		OSL_dep	PSP	IRSL/OSL
empty	-147.00	31.83	1.30	0.58	-14.00	21.93	195.00	35.82	0.29	-18.00	-0.75
empty	129.00	31.83	3.61	2.91	5.00	19.80	451.00	35.93	1.59	-11.00	0.29
empty	-110.00	30.69	1.12	0.63	73.00	21.26	223.00	37.67	0.80	36.00	-0.49
s1	-234.00	35.75	0.64	0.21	14.00	23.35	540.00	45.25	1.25	-1.00	-0.43
s2	-51.00	31.58	0.06	0.48	-22.00	20.52	700.00	40.50	1.33	-27.00	-0.07
s3	-83.00	34.89	0.66	0.59	-31.00	21.93	427.00	40.68	0.84	-18.00	-0.19
s4	-159.00	32.70	0.73	0.31	65.00	22.67	416.00	43.22	1.58	56.00	-0.38
s5	-3.00	31.89	-1.14	-1.64	-37.00	20.52	798.00	41.88	1.18	-16.00	0.00
s6	-49.00	32.48	3.08	6.26	-30.00	21.93	728.00	41.28	1.08	-32.00	-0.07
s7	-153.00	33.15	1.13	0.49	-21.00	21.93	555.00	40.39	0.62	-44.00	-0.28
s8	-92.00	32.80	-93.00	-2249.48	54.00	21.26	630.00	42.02	0.75	-8.00	-0.15
s9	-156.00	34.35	3.33	2.42	80.00	22.67	569.00	43.09	1.12	-12.00	-0.27
s10	50.00	33.14	0.43	0.72	-46.00	21.26	544.00	40.84	1.22	19.00	0.09

200mGy using IRSL 10 SAMPLES											
	IRSL		IRSL_dep		PSP		OSL		OSL_dep	PSP	IRSL/OSL
empty	-147.00	31.83	1.30	0.58	-14.00	21.93	195.00	35.82	0.29	-18.00	-0.75
empty	129.00	31.83	3.61	2.91	5.00	19.80	451.00	35.93	1.59	-11.00	0.29
empty	-110.00	30.69	1.12	0.63	73.00	21.26	223.00	37.67	0.80	36.00	-0.49
S1	6030.00	84.79	1.68	0.05	12.00	25.46	832.00	45.48	1.34	19.00	7.25
S2	253.00	43.00	3.36	1.78	63.00	27.59	-323.00	36.95	0.69	23.00	-0.78
S3	1151.00	53.54	2.31	0.26	-67.00	28.32	17.00	38.33	0.21	-66.00	67.71
S4	662.00	47.56	1.77	0.28	34.00	27.59	7.00	37.46	-1.20	-51.00	94.57
S5	2119.00	60.69	1.63	0.10	-17.00	27.59	333.00	42.67	3.11	-19.00	6.36
S6	2078.00	57.57	1.47	0.08	-19.00	26.17	330.00	37.97	1.82	-31.00	6.30
S7	626.00	50.81	1.83	0.33	-	125.00	29.07	87.00	2.22	-	161.00
S8	1014.00	53.35	1.56	0.17	-58.00	28.32	72.00	38.73	0.09	-	101.00
S9	526.00	45.50	1.35	0.24	20.00	27.59	-128.00	38.05	0.56	8.00	-4.11

200mGy using OSL 10 SAMPLES											
	IRSL		IRSL_dep		PSP		OSL		OSL_dep	PSP	IRSL/OSL
s1	91.00	39.59	0.12	0.34	37.00	23.35	10634.00	109.77	2.04	-15.00	0.01
s2	335.00	43.02	1.39	0.37	5.00	24.04	14028.00	97.53	2.24	-8.00	0.04
s3	348.00	42.24	2.19	0.64	105.00	23.43	11992.00	112.62	2.26	64.00	0.03
s4	245.00	39.81	3.08	1.47	-7.00	22.63	12869.00	99.36	2.24	91.00	0.03
s5	191.00	43.26	1.55	0.75	-8.00	24.04	13727.00	107.08	2.24	15.00	0.02
s6	62.00	39.67	-0.14	-0.38	52.00	23.35	11408.00	94.81	2.10	17.00	0.01
s7	91.00	36.32	6.00	11.73	55.00	21.93	10310.00	108.38	2.02	52.00	0.01
s8	135.00	39.64	0.42	0.32	53.00	23.35	12607.00	104.13	2.15	0.00	0.01
s9	113.00	38.64	6.53	11.72	19.00	22.63	11290.00	93.58	2.21	22.00	0.02

500mGy using IRSL 10 SAMPLES											
	IRSL		IRSL_dep		PSP		OSL		OSL_dep	PSP	IRSL/OSL
empty	-109.00	29.44	1.60	0.94	12.00	24.76	1.00	29.07	-1.10	-33.00	-109.00
empty	100.00	30.53	-0.19	-0.16	54.00	24.08	272.00	21.63	0.06	-23.00	-0.37
empty	18.00	30.23	-0.22	-0.94	6.00	24.04	-56.00	30.59	1.95	24.00	-0.32
s1	3738.00	102.83	1.82	0.11	-27.00	45.25	57.00	80.85	-2.84	-89.00	65.58
s2	2406.00	113.23	2.07	0.23	-166.00	54.49	192.00	93.49	0.33	-371.00	-12.53
s3	3732.00	85.42	1.80	0.09	-15.00	35.36	183.00	61.51	2.00	9.00	20.39
s4	1912.00	74.86	1.72	0.15	-67.00	36.07	41.00	58.28	-1.59	-84.00	46.63
s5	1789.00	65.40	1.67	0.13	-14.00	31.11	126.00	51.71	-43.00	15.00	14.20
s6	2263.00	71.52	1.70	0.12	-55.00	33.24	300.00	52.92	0.48	-88.00	7.54
s7	1638.00	69.56	1.55	0.14	-28.00	33.94	230.00	55.55	0.72	-86.00	7.12
s8	2278.00	76.59	1.66	0.12	95.00	35.38	15.00	58.13	-1.58	-56.00	151.87
s9	3725.00	81.22	1.54	0.07	28.00	33.24	408.00	56.32	1.43	-27.00	9.13

500mGy using OSL 10 SAMPLES											
	IRSL		IRSL_dep		PSP		OSL		OSL_dep	PSP	IRSL/OSL
empty	15.00	33.51	-4.00	-19.3	101.00	21.40	-17	36.54	-0.54	61.00	-0.88
empty	-81.00	34.28	0.69	0.61	46.00	21.93	68	35.33	1.52	-19	-1.19
empty	-589.00	23.64	0.11	0.04	27.00	21.93	220	35.27	0.56	-31	-2.68
s1	706.00	46.97	1.47	0.20	11.00	23.35	30144	178.38	2.55	44	0.02
s2	305.00	42.72	1.07	0.30	28.00	23.35	26620	168.19	2.60	37	0.01
s3	819.00	44.12	1.57	0.18	16.00	21.21	30309	177.73	2.44	38	0.03
s4	346.00	39.32	1.15	0.26	-62.00	21.26	29484	175.43	2.57	23	0.01
s5	309.00	41.48	1.34	0.37	-19.00	23.35	25816	165.02	1.99	1	0.01
s6	282.00	42.26	1.27	0.39	46.00	23.35	31084	181.15	2.54	57	0.01
s7	400.00	38.11	1.74	0.36	-79.00	20.62	27408	168.56	2.49	-12	0.01
s8	530.00	44.47	0.95	0.16	-24.00	23.35	27647	170.37	2.60	-17	0.02
s9	579.00	40.83	1.85	0.29	-14.00	21.21	30593	178.17	2.33	16	0.02
s10	511.00	43.30	1.99	0.39	25.00	23.35	29059	174.59	2.45	15	0.02

1000mGy using IRSL 10 SAMPLES											
	IRSL		IRSL_dep		PSP		OSL		OSL_dep	PSP	IRSL/OSL
empty	-140.00	34.47	0.41	0.27	-30	26.17	-43.00	32.51	-0.33	-57	3.26
empty	-63.00	33.06	6.88	20.72	5	25.46	-99.00	32.82	1.48	5	0.64
empty	-212.00	36.06	0.77	0.27	20	26.87	-250.00	34.84	0.87	-12	0.85
s1	5142.00	106.52	1.60	0.07	41	43.84	414.00	80.76	1.21	-24	12.42
s2	4506.00	92.66	1.70	0.07	-18	36.77	537.00	68.04	2.68	3	8.39
s3	4431.00	109.67	1.54	0.08	-123	48.10	371.00	84.94	0.83	-188	11.94
s4	5660.00	100.92	1.75	0.07	-47	38.90	386.00	70.27	1.01	7	14.66
s5	6014.00	114.90	1.72	0.07	-37	46.67	461.00	85.87	2.36	-69	13.05
s6	2921.00	131.44	1.75	0.17	-89	62.94	-711.00	112.93	0.56	-223	-4.11
s7	3581.00	110.40	1.70	0.11	14	50.21	-47.00	90.25	0.04	-104	-76.19
s8	3334.00	118.67	1.54	0.12	-71	55.15	13.00	98.88	-1.45	-246	256.46
s9	4341.00	132.29	1.74	0.12	-26	60.81	-159.00	110.30	-0.15	-209	-27.30

1000mGy using OSL 10 SAMPLES											
	IRSL		IRSL_dep		PSP		OSL		OSL_dep	PSP	IRSL/OSL
empty	132.00	29.73	1.44	0.68	-42.00	19.10	142.00	36.58	0.61	111.00	0.93
empty2	-118.00	32.59	0.62	0.37	-5.00	21.21	270.00	35.81	0.67	-42.00	-0.44
empty3	16.00	34.53	-0.20	-1.23	-28.00	21.93	330.00	35.86	1.54	-55.00	0.05
s1	920.00	49.48	1.30	0.14	-10.00	24.04	59511.00	247.59	2.58	66.00	0.02
s2	681.00	47.34	1.62	0.24	20.00	24.04	61565.00	252.07	2.50	104.00	0.01
s3	572.00	54.95	1.41	0.28	-30.00	28.28	61610.00	252.76	2.64	-43.00	0.01
s4	842.00	48.76	0.99	0.11	12.00	24.04	55601.00	239.90	2.40	104.00	0.02
s5	851.00	52.56	1.86	0.26	42.00	26.17	57457.00	244.43	2.54	94.00	0.01
s6	553.00	53.30	1.57	0.32	8.00	26.87	61119.00	252.01	2.59	26.00	0.01
s7	573.00	51.86	1.26	0.23	-27.00	26.17	59883.00	249.45	2.61	56.00	0.01
s8	685.00	50.29	0.88	0.13	-3.00	25.46	62370.00	253.75	2.63	44.00	0.01
s9	746.00	59.55	1.40	0.23	12.00	29.70	66327.00	262.73	2.78	-25.00	0.01
s10	1193.00	73.19	1.83	0.25	-93.00	35.38	62888.00	257.20	2.78	225.00	0.02

1500mGy using IRSL 10 SAMPLES											
	IRSL		IRSL_dep		PSP		OSL		OSL_dep	PSP	IRSL/OSL
EMPTY	-142.00	38.60	0.48	0.32	-96.00	27.66	162.00	35.36	0.40	-136.00	-0.88
empty	189.00	34.54	0.99	0.36	3.00	24.76	-14.00	33.20	0.08	28.00	-13.50
EMPTY	-51.00	36.89	0.06	0.55	-101.00	26.25	20.00	35.04	-7.67	-51.00	-2.55
S1	5663.00	105.05	1.51	0.06	-3.00	41.01	542.00	75.51	1.50	-53.00	10.45
S2	5186.00	119.09	1.48	0.07	-49.00	50.91	496.00	93.34	1.60	-195.00	10.46
S3	5510.00	101.22	1.67	0.07	42.00	38.90	726.00	72.26	0.99	-60.00	7.59
S4	5424.00	108.39	1.66	0.07	87.00	43.86	330.00	80.91	1.32	-27.00	16.44
S6	5504.00	117.83	1.51	0.07	59.00	49.50	140.00	93.38	2.18	50.00	39.31
S7	4918.00	234.34	3.65	0.58	-1685	113.36	-1784	192.76	0.47	-2764	-2.76
S8	6063.00	123.77	1.59	0.07	64.00	51.62	322.00	97.95	3.81	4.00	18.83
S9	5830.00	129.24	1.56	0.07	60.00	55.87	160.00	105.01	-4.48	-1.00	36.44
S10	5261.00	114.21	1.38	0.06	-60.00	48.08	455.00	88.47	1.49	-103.00	11.56

1500mGy using OSL 10 SAMPLES											
	IRSL		IRSL_dep		PSP		OSL		OSL_dep	PSP	IRSL/OSL
empty	57.00	34.19	1.59	2.06	-20	21.21	207.00	36.48	0.82	3.00	0.28
empty	-90.00	34.26	2.91	3.29	-74	22.67	137.00	34.13	1.25	-59.00	-0.66
empty	-99.00	34.71	3.71	4.59	-12	22.63	217.00	37.59	0.52	-27.00	-0.46
s1	900.00	79.87	1.65	0.32	-80	39.62	84992.00	332.55	2.78	246.00	0.01
s2	900.00	52.73	1.31	0.16	24	25.46	84031.00	293.57	2.50	68.00	0.01
s3	1096.00	54.15	1.49	0.15	55	25.50	90910.00	305.69	2.44	175.00	0.01
s4	657.00	53.82	0.93	0.15	8	26.87	91850.00	307.00	2.47	39.00	0.01
s5	637.00	54.56	1.65	0.31	-45	27.59	87625.00	299.93	2.49	-2.00	0.01
s6	1954.00	62.63	1.71	0.12	-10	25.46	85308.00	295.72	2.54	44.00	0.02
s7	761.00	50.29	1.01	0.13	-34	24.76	83989.00	293.59	2.39	110.00	0.01
s8	771.00	61.25	1.09	0.17	-23	30.41	94136.00	311.83	2.66	30.00	0.01
s9	822.00	56.44	1.48	0.21	33	27.59	88598.00	301.88	2.56	43.00	0.01
s10	990.00	52.90	1.43	0.16	0.00	25.46	79492.00	285.88	2.47	107.00	0.01

Signal stability tests

Signal stability tests after one day								
Empty	OSL		OSL_dep		PSP		IRSL/OSL	
Empty	160	44.136153	2.018867925	1.315462284	28	27.58622845	0.53125	0.300441
Empty	296	44.2266888	0.86163522	0.259410038	-32	26.17250466	0.118243	0.145323
s1	170	44.5196586	0.328125	0.254275772	-23	26.17250466	-0.64118	-0.30051
s2	55029	239.117126	2.172614586	0.020440615	137	28.42534081	0.010504	0.000849
s3	63544	256.452725	2.180062056	0.019051775	193	27.80287755	0.01484	0.000772
s4	70702	270.403402	2.090122378	0.017166123	129	29.06888371	0.008996	0.000713
s5	53804	235.949147	2.132692868	0.020163524	110	27.65863337	0.022359	0.000958
s6	62291	254.383569	2.053330719	0.017957671	131	29.06888371	0.00838	0.00079
s7	55151	239.330316	2.058507098	0.01913879	122	27.65863337	0.011169	0.000863
s8	70986	270.750808	2.076449684	0.016983089	41	30.41381265	0.005212	0.000708
s9	66000	260.952103	2.144504264	0.018292129	105	27.65863337	0.013576	0.00077
s10	51218	231.538334	2.084306877	0.020256028	-1	28.28427125	0.003319	0.000989

Signal stability tests after two days								
Empty	OSL		OSL_dep		PSP		IRSL/OSL	
Empty	232	39.8497177	1.12844037	0.389573328	41	23.34523506	-0.56896552	-0.17101
Empty	287	39.0256326	0.93918919	0.255747525	27	24.75883681	0.233449477	0.124561
S1	365	39.8622629	1.5	0.344956694	-34	24.75883681	-0.11506849	-0.10025
S2	64773	257.792552	2.10245234	0.017969219	125	25.61249695	0.012798543	0.000695
S3	60474	249.050196	2.06243986	0.018174321	60	26.17250466	0.008482984	0.000707
S4	57254	242.515979	2.11230702	0.019234272	57	26.90724809	0.011649841	0.000782
S5	60122	249.050196	2.0441519	0.01810284	157	27.01851217	0.008316423	0.000702
S6	55616	239.340761	2.17878372	0.020285788	64	24.75883681	0.016272296	0.000868
S7	58680	245.446532	2.09935034	0.018853699	121	24.8394847	0.01141786	0.000714
S8	55433	238.480607	2.13854603	0.019821315	68	25.49509757	0.010372883	0.000754
S9	60636	249.887975	2.08988993	0.01848413	140	27.01851217	0.011148493	0.000725
S10	46798	220.177201	2.11695751	0.0214456	123	24.8394847	0.013205693	0.00091
S10	56143	240.331022	2.07885934	0.019077031	60	25.49509757	0.013216251	0.000822

Signal stability tests after Four days								
Empty	OSL		OSL_dep		PSP		IRSL/OSL	
Empty	232	39.8497177	1.128440367	0.389573328	41	23.34523506	-0.56897	-0.17101
Empty	287	39.0256326	0.939189189	0.255747525	27	24.75883681	0.233449	0.124561
S1	365	39.8622629	1.5	0.344956694	-34	24.75883681	-0.11507	-0.10025
S2	64773	257.792552	2.102452342	0.017969219	125	25.61249695	0.012799	0.000695
S3	60474	249.050196	2.062439864	0.018174321	60	26.17250466	0.008483	0.000707
S4	57254	242.515979	2.112307023	0.019234272	57	26.90724809	0.01165	0.000782
S5	60122	249.050196	2.044151899	0.01810284	157	27.01851217	0.008316	0.000702
S6	55616	239.340761	2.178783722	0.020285788	64	24.75883681	0.016272	0.000868
S7	58680	245.446532	2.099350341	0.018853699	121	24.8394847	0.011418	0.000714
S8	55433	238.480607	2.138546031	0.019821315	68	25.49509757	0.010373	0.000754
S9	60636	249.887975	2.089889931	0.01848413	140	27.01851217	0.011148	0.000725
S10	46798	220.177201	2.116957506	0.0214456	123	24.8394847	0.013206	0.00091
S11	56143	240.331022	2.078859336	0.019077031	60	25.49509757	0.013216	0.000822

Signal stability tests after eight days								
	OSL		OSL_dep		PSP		IRSL/OSL	
Empty	92	36.66060556	1.24390244	1.00830714	39	22.6715681	0.184782609	0.370026943
Empty	311	32.35737937	1.41085271	0.30413701	-18	21.21320344	0.292604502	0.101101828
Empty	365	39.86226286	1.5	0.34495669	-34	24.75883681	0.115068493	-0.10025449
S1	41745	207.549994	2.21288386	0.02388433	124	24.20743687	0.016864295	0.000943793
S2	53017	233.1630331	1.93902101	0.01804926	67	24.08318916	0.022804006	0.000907974
S3	54305	236.9071548	2.03329051	0.01894929	145	25	0.008139214	0.000756054
S4	55054	238.046214	2.031441	0.01875146	116	26.2488095	0.014930795	0.000808783
S5	51854	230.768282	2.03275237	0.01930926	-2	25.45584412	0.013557295	0.000888109
S6	44486	214.5180645	1.99246603	0.02045242	88	26.2488095	0.016994111	0.000992464
S7	51482	229.8912787	1.97291679	0.0187046	56	25.49509757	0.024455149	0.000958427
S8	56205	239.7102418	2.10079444	0.0192283	61	24.75883681	0.052788898	0.001144667
S9	47399	221.4113818	2.06789644	0.02070191	180	25	0.022637608	0.000944009
S10	49585	225.8251536	2.68059679	0.02764398	96	24.8394847	0.035877786	0.001080913

Signal stability tests after 16 days								
	OSL		OSL_dep		PSP		IRSL/OSL	
Empty	151	34.6265794	1.359375	0.643773784	-18	22.627417	-0.09271523	-0.22127
Empty	157	34.5398321	3.48571429	2.450999439	0	22.627417	-0.21656051	-0.20717
Empty	232	39.8497177	1.12844037	0.389573328	41	23.34523506	-0.56896552	-0.17101
S1	44378	214.443466	2.07625121	0.021523585	74	24.08318916	0.053968182	0.001397
S2	23791	159.044019	2.13658537	0.030923627	28	25.45584412	0.034550881	0.001991
S3	38424	199.53947	1.96252891	0.021641205	37	26.17250466	0.025270664	0.001232
S4	45256	215.925913	1.96236172	0.019868017	90	23.43074903	0.007998939	0.000819
S5	39819	202.778204	1.96316416	0.02122174	69	24.08318916	0.022752957	0.001109
S6	39247	201.789494	2.14857601	0.023860431	173	25	0.053583713	0.001396
S7	47106	220.022726	2.2353022	0.022696647	52	23.34523506	0.093151616	0.001631
S8	38642	200.064989	2.06877382	0.022961272	87	24.8394847	0.020211169	0.001108
S9	50643	227.567572	2.01769753	0.01931623	-12	24.04163056	0.021483719	0.000948
S10	86247	296.949491	2.05862118	0.015154571	165	27.01851217	0.021763076	0.000655
S11	12846	118.110118	1.41647856	0.026506768	43	24.08318916	0.017982251	0.00266

Signal stability tests after 32 days								
	OSL		OSL_dep		PSP		IRSL/OSL	
Empty	102	35.5808937	2.77777778	2.710563108	25	23.34523506	-0.34313725	-0.3365
Empty	142	32.0936131	0.84415584	0.385314876	40	21.9317122	1.323943662	0.367374
Empty	296	44.2266888	0.86163522	0.259410038	-32	26.17250466	0.118243243	0.145323
S1	42815	211.60104	1.86963807	0.019477884	80	26.2488095	0.038514539	0.001353
S2	43763	213.820018	1.95556156	0.020294352	198	26.40075756	0.018920092	0.001024
S3	43776	211.801794	1.91956783	0.019623051	33	23.34523506	0.016287463	0.000935
S4	43427	211.497045	1.96147027	0.02026886	109	24.8394847	0.03246828	0.00111
S5	39328	202.326469	1.87317358	0.020310973	46	26.17250466	0.015688568	0.001152
S6	37225	196.247293	1.95436508	0.021858564	45	26.17250466	0.039328408	0.001378
S7	44515	213.876132	1.91004772	0.01937931	106	23.43074903	0.017949006	0.000904
S8	38545	199.351448	1.89029694	0.02061696	9	24.75883681	0.013464781	0.001065

Signal stability tests after 64 days								
	OSL		OSL_dep		PSP		IRSL/OSL	
Empty	1334	48.8876262	1.07465008	0.078862426	-27	23.34523506	-0.06596702	-0.02471
Empty	75	33.2716095	2.125	2.28424461	-23	23.34523506	-0.52	-0.49609
Empty	102	35.5808937	2.77777778	2.710563108	25	23.34523506	-0.34313725	-0.3365
S1	39607	202.007426	1.75125035	0.018613418	27	23.34523506	0.012750271	0.001011
S2	39741	202.526541	1.89784162	0.020411632	92	24.08318916	0.046048162	0.001337
S3	35957	193.889144	1.82680818	0.020685872	84	25.49509757	0.011736241	0.001156
S4	33854	186.874289	1.91467929	0.022336979	13	24.04163056	0.015241921	0.001159
S5	44871	215.524941	1.91389051	0.019434314	107	24.8394847	0.028682222	0.001109
S6	38842	200.364668	1.86128913	0.020201761	-15	25.45584412	0.012640956	0.001111
S7	42683	209.559061	1.94812819	0.020267848	32	24.75883681	0.012674835	0.000952
S8	32032	182.603395	2.00882961	0.024431358	86	24.08318916	0.014266983	0.001181
S9	28691	172.183042	1.86165968	0.023507402	6	23.34523506	0.015823777	0.001301

Signal stability tests after 128 days							
	OSL		OSL_dep		PSP		
Empty	171	22.8254244	0.92134831	0.24718495	-19	13.22875656	-0.11111111
Empty	55	24.3104916	0.03773585	0.327027663	-30	16.37070554	-0.54545455
S1	22571	152.371257	1.55039548	0.021502411	85	17.97220076	0.003765894
S2	28019	169.342848	1.67919296	0.021059978	111	18.13835715	0.003961597
S3	17206	134.4247	1.4965177	0.023933358	48	20.78460969	0.002789725
S4	17163	133.187837	1.52063445	0.024236505	138	16.97056275	0.008040552
S5	19667	142.720006	1.51335463	0.022495789	53	18.734994	0.00269487
S6	10953	107.121426	1.56992023	0.031659214	73	16.15549442	0.006664841
S7	25230	160.636235	1.48155798	0.019263403	51	16.94107435	0.002021403
S8	24644	159.492947	1.53122432	0.020350971	145	19.92485885	0.005883785
S9	29751	174.507879	1.62910923	0.019742563	97	18.734994	0.003260395

Impact of light exposure

Impact of light exposure after 2.5 hours								
	OSL		OSL_dep		PSP		IRSL/OSL	
Empty	151	34.62658	1.359375	0.643774	-18	22.62742	-0.09272	-0.22127
Empty	157	34.53983	3.485714	2.450999	0	22.62742	-0.21656	-0.20717
Empty	194	36.02777	1.425	0.551894	-90	22.02272	-1.15464	-0.28094
s1	1810	53.49766	1.134434	0.067292	-48	25.4951	-0.05359	-0.01878
S2	2116	56.63921	1.489412	0.082427	-12	22.62742	0.00189	0.015985
S3	1720	54.69918	1.395543	0.091063	41	23.34524	-0.0314	-0.0189
S4	1515	53.46962	1.179856	0.083836	99	22.02272	-0.00594	-0.02023
S5	1779	51.3712	1.277849	0.07472	-53	23.34524	-0.01855	-0.01813
S6	1832	53.29165	1.173191	0.068628	-34	23.34524	-0.03275	-0.018

Impact of light exposure after 5 hours								
	OSL		OSL_dep		PSP		IRSL/OSL	
Empty	151	34.6265794	1.359375	0.643773784	-18	22.627417	-0.09271523	-0.22127
Empty	157	34.5398321	3.48571429	2.450999439	0	22.627417	-0.21656051	-0.20717
Empty	171	34.9141805	1.06024096	0.433456289	36	21.9317122	0.356725146	0.195721
S1	1761	53.3010319	1.33554377	0.08234652	-22	23.34523506	-0.07041454	-0.01847
S2	1513	47.9687398	1.28895613	0.08284594	-51	23.34523506	-0.00396563	-0.02075
S3	1515	50.6260802	1.20203488	0.080955572	46	22.6715681	0.089768977	0.021088
S4	1076	46.6476152	1.04952381	0.091053053	15	22.627417	-0.08550186	-0.02885
S5	1664	51.8844871	1.18372703	0.074282662	-43	23.34523506	-0.05048077	-0.02014
S6	1664	51.1859356	1.48729447	0.094658089	4	22.627417	0.010216346	0.018594
S7	1314	47.8121324	1.22711864	0.09016985	30	21.9317122	0.059360731	0.023309
S8	910	45.5411901	1.28643216	0.130938265	3	22.627417	0.052747253	0.038158
S9	1089	45.2658812	1.46938776	0.126589349	-44	23.34523506	-0.09641873	-0.02976

Impact of light exposure after 24 hours								
	OSL		OSL_dep		PSP		IRSL/OSL	
Empty	151	34.62658	1.359375	0.643774	-18	22.62742	-0.09272	-0.22127
Empty	157	34.53983	3.485714	2.450999	0	22.62742	-0.21656	-0.20717
Empty	157	34.53983	3.485714	2.450999	0	22.62742	-0.21656	-0.20717
s1	832	43.45112	1.242588	0.131416	-82	23.43075	-0.125	-0.04349
s2	910	45.54119	1.286432	0.130938	3	22.62742	0.052747	0.038158
S3	735	46.55105	1.296875	0.167514	61	22.67157	-0.20952	-0.04572
S4	647	45.15529	1.107492	0.155065	31	24.75884	-0.20711	-0.05402
S5	735	46.55105	1.296875	0.167514	61	22.67157	-0.20952	-0.04572
S6	647	45.15529	1.107492	0.155065	31	24.75884	-0.20711	-0.05402
S7	1089	45.26588	1.469388	0.126589	-44	23.34524	-0.09642	-0.02976

Impact of light exposure after 48 hours								
	OSL		OSL_dep		PSP		IRSL/OSL	
Empty	171	34.9141805	1.060240964	0.433456289	36	21.93171	0.356725	0.195721
Empty	232	39.8497177	1.128440367	0.389573328	41	23.34523506	-0.56897	-0.17101
Empty	232	39.8497177	1.12844037	0.389573328	41	23.34523506	-0.56896552	-0.17101
s1	223	43.53159772	1.143442623	0.191395582	25	23.34524	-0.10707	-0.06727
S1	421	41.77319715	1.476470588	0.307165364	37	23.34524	0.047506	0.082281
s2	437	44.32832052	0.977375566	0.198318831	70	24.08319	-0.40732	-0.0855
S2	368	41.56921938	1.942731278	0.272561337	8	22.62742	0.047904	0.04883
S3	467	41.60528813	1.340350877	0.171240062	-5	23.34524	0.065967	0.050521
S5	638	40.42276586	0.876470588	0.111600195	0	24.04163	0.03605	0.050086
S6	433	38.88444419	1.211180124	0.133545543	2	22.62742	0.276685	0.046682
S7	291	38.45776905	0.903100775	0.141900937	-19	21.93171	-0.01426	-0.06622

Appendix salt as dosimeters

Dose response

	OSL		OSL_dep		PSP	
empty chamber	96	25.01999	3.571429	2.838439	-37	16.27882
empty chamber	105	26.01922	0.129032	0.198758	-38	16.91153

0mGy	OSL		OSL_dep
S1	2214	51.7880295	2.84375
S2	482	32.03123476	1.200913242
S3	1775	47.50789408	3.708222812
S4	674	33.91164992	1.653543307
S5	459	31.12876483	1.17535545
Mean	1120.8		2.116356962

25 mGy	OSL		OSL_dep
s1	662184	814.4323	6.842623
s2	709265	843.0308	6.736986
s3	842475	918.7486	6.598353
s4	868920	932.8848	6.99551
s5	819247	906.0304	6.627146
Mean	780418.2		6.760123

50 mGy	OSL		OSL_dep
S1	1138698	1068.006554	6.62221538
S2	2187141	1479.819246	6.712361904
S3	1895231	1377.666505	6.828783279
S4	1104979	1052.070815	6.535677508
S5	1805239	1344.414743	6.875608043
Mean	1626257.6		6.714929223

100 mGy	OSL		OSL_dep
S1	4717531	2173.236987	6.394643288
S2	4446815	2110.226291	6.226821448
S3	2627407	1622.142719	6.293389221
S4	6006605	2452.490367	6.25813195
S5	6692123	2588.497054	6.249595116
Mean	3930584.333		6.304951319

Dose response

Dose response from beta irradiated using a blue OSL portable reader (blue) , from sets of five individual planchettes of salt exposed to beta doses from 0–100 mGy

		OSL		OSL_dep		PSP	
	empty chamber	96	25.01999	3.571429	2.838439	-37	16.27882
	empty chamber	105	26.01922	0.129032	0.198758	-38	16.91153
25 mGy using OSL 5 SAMPLES							
	s1	662184	814.4323	6.842623	0.025329	350	23.62202
	s2	709265	843.0308	6.736986	0.023964	324	26.79552
	s3	842475	918.7486	6.598353	0.021379	562	28.49561
	s4	868920	932.8848	6.99551	0.022783	379	26.01922
	s5	819247	906.0304	6.627146	0.021808	486	28.67054
Mean		780418.2		6.760123			
Std dev		89768.31		0.163249			
Std Err		29922.77		0.054416			
% SE		11.50259		2.41488			
50 mGy using OSL 5 SAMPLES							
	s1	1138698	1068.007	6.622215	0.018466	612	31.14482
	s2	2187141	1479.819	6.712362	0.013563	1166	36.90528
	s3	1895231	1377.667	6.828783	0.014925	1037	36.97296
	s4	1104979	1052.071	6.535678	0.018414	669	30.61046
	s5	1805239	1344.415	6.875608	0.015428	866	33.25658
Mean		1626258		6.714929			
Std dev		481772		0.140991			
Std Err		160590.7		0.046997			
% SE		29.62458		2.099667			
100 mGy using OSL 5 SAMPLES							
	s1	4717531	2173.237	6.394643	0.008639	2336	52.09607
	s4	4446815	2110.226	6.226821	0.008587	2704	55.85696
	s5	2627407	1622.143	6.293389	0.011336	1604	44.38468
	s2	6006605	2452.49	6.258132	0.007438	3542	63.65532
	s3	6692123	2588.497	6.249595	0.007031	3663	64.00781
Mean		3930584		6.304951			
Std dev		1136673		0.084506			
Std Err		378890.9		0.028169			
% SE		28.91867		1.340315			
% SE		4.795137		2.71295			
0 mGy using OSL 5 SAMPLES							
	s1	2214	51.78803	2.84375	0.157983	-20	15.29706
	s1	482	32.03123	1.200913	0.16293	68	16.49242
	s2	1775	47.50789	3.708223	0.265885	-7	15.52417
	s4	674	33.91165	1.653543	0.179984	50	15.42725
	s5 0	459	31.12876	1.175355	0.161158	25	15.96872
Mean		1120.8		2.116357			
Std dev		816.8137		1.11813			
Std Err		272.2712		0.37271			
% SE		7.87774		52.83275			

x	Y	Nacl dose rate	Strr.	Backpack dose rate	Strr.
264393.50	653212.50	0.02614	0.00110	0.03915	0.00539
264393.50	653213.50	0.02596	0.00113	0.04028	0.00372
264393.50	653214.50	0.02659	0.00121	0.04019	0.00312
264393.50	653215.50	0.02545	0.00130	0.03881	0.00435
264394.50	653207.50	0.03676	0.00151	0.03822	0.00625
264394.50	653208.50	0.03140	0.00104	0.03648	0.00639
264394.50	653209.50	0.03079	0.00101	0.04096	0.01129
264394.50	653210.50	0.02941	0.00086	0.04364	0.01127
264394.50	653211.50	0.02843	0.00088	0.04208	0.00851
264394.50	653212.50	0.02724	0.00102	0.04256	0.00716
264394.50	653213.50	0.02583	0.00118	0.04216	0.00584
264394.50	653214.50	0.02599	0.00105	0.04089	0.00482
264394.50	653215.50	0.02668	0.00107	0.04004	0.00420
264394.50	653216.50	0.02559	0.00131	0.03930	0.00309
264394.50	653217.50	0.02561	0.00132	0.03841	0.00192
264394.50	653218.50	0.02607	0.00187	0.03750	0.00092
264395.50	653206.50	0.03826	0.00193	0.03673	0.00801
264395.50	653207.50	0.03438	0.00113	0.04187	0.00575
264395.50	653208.50	0.03284	0.00101	0.04229	0.00543
264395.50	653209.50	0.03160	0.00093	0.04323	0.00797
264395.50	653210.50	0.03038	0.00088	0.04252	0.00708
264395.50	653211.50	0.02930	0.00087	0.04326	0.00850
264395.50	653212.50	0.02767	0.00097	0.04868	0.01292
264395.50	653213.50	0.02645	0.00113	0.04940	0.01105
264395.50	653214.50	0.02603	0.00104	0.04365	0.00724
264395.50	653215.50	0.02619	0.00106	0.04173	0.00806
264395.50	653216.50	0.02598	0.00120	0.03906	0.00424
264395.50	653217.50	0.02567	0.00136	0.03809	0.00201
264395.50	653218.50	0.02607	0.00187	0.03702	0.00105
264396.50	653205.50	0.03881	0.00160	0.03845	0.01191
264396.50	653206.50	0.03784	0.00137	0.04261	0.01299
264396.50	653207.50	0.03495	0.00117	0.04086	0.00785
264396.50	653208.50	0.03370	0.00096	0.04333	0.00541
264396.50	653209.50	0.03278	0.00094	0.04595	0.00414
264396.50	653210.50	0.03114	0.00094	0.04496	0.00588
264396.50	653211.50	0.03011	0.00102	0.04571	0.00711
264396.50	653212.50	0.02870	0.00084	0.05022	0.01117
264396.50	653213.50	0.02765	0.00085	0.04890	0.00971
264396.50	653214.50	0.02657	0.00119	0.04452	0.00692
264396.50	653215.50	0.02624	0.00123	0.04196	0.01089
264396.50	653216.50	0.02607	0.00127	0.03809	0.00807
264396.50	653217.50	0.02573	0.00140	0.03731	0.00324
264396.50	653218.50	0.02607	0.00187	0.03663	0.00106
264396.50	653219.50	0.02607	0.00187	0.03556	0.00131
264397.50	653204.50	0.03983	0.00282	0.03312	0.00589

264397.50	653205.50	0.03542	0.00130	0.04211	0.01253
264397.50	653206.50	0.03415	0.00109	0.04446	0.01054
264397.50	653207.50	0.03450	0.00100	0.04270	0.00717
264397.50	653208.50	0.03441	0.00101	0.04364	0.00452
264397.50	653209.50	0.03402	0.00104	0.04540	0.00325
264397.50	653210.50	0.03163	0.00092	0.04595	0.00388
264397.50	653211.50	0.02937	0.00096	0.04614	0.00708
264397.50	653212.50	0.02889	0.00083	0.04695	0.00641
264397.50	653213.50	0.02839	0.00083	0.04417	0.00504
264397.50	653214.50	0.02770	0.00103	0.04179	0.00455
264397.50	653215.50	0.02700	0.00112	0.03927	0.00569
264397.50	653216.50	0.02618	0.00126	0.03750	0.01243
264397.50	653217.50	0.02618	0.00119	0.03707	0.00349
264397.50	653218.50	0.02607	0.00187	0.03651	0.00149
264397.50	653219.50	0.02607	0.00187	0.03494	0.00163
264398.50	653203.50	0.02414	0.00174	0.03238	0.00452
264398.50	653204.50	0.02994	0.00129	0.03613	0.00638
264398.50	653205.50	0.03337	0.00113	0.04193	0.00794
264398.50	653206.50	0.03399	0.00112	0.04409	0.00676
264398.50	653207.50	0.03461	0.00101	0.04404	0.00382
264398.50	653208.50	0.03512	0.00106	0.04530	0.00386
264398.50	653209.50	0.03554	0.00125	0.04936	0.00662
264398.50	653210.50	0.03400	0.00107	0.04882	0.00918
264398.50	653211.50	0.03090	0.00081	0.04582	0.00742
264398.50	653212.50	0.02961	0.00092	0.04530	0.00624
264398.50	653213.50	0.02897	0.00099	0.04152	0.00360
264398.50	653214.50	0.02881	0.00087	0.03936	0.00366
264398.50	653215.50	0.02766	0.00094	0.03801	0.00290
264398.50	653216.50	0.02631	0.00119	0.03740	0.00276
264398.50	653217.50	0.02662	0.00140	0.03713	0.00233
264398.50	653218.50	0.02607	0.00187	0.03643	0.00228
264399.50	653202.50	0.02506	0.00180	0.02793	0.00892
264399.50	653203.50	0.02873	0.00119	0.03146	0.01197
264399.50	653204.50	0.02912	0.00122	0.03747	0.02199
264399.50	653205.50	0.03135	0.00093	0.03969	0.00996
264399.50	653206.50	0.03304	0.00100	0.04310	0.00434
264399.50	653207.50	0.03435	0.00112	0.04473	0.00384
264399.50	653208.50	0.03536	0.00114	0.04433	0.00570
264399.50	653209.50	0.03566	0.00111	0.04649	0.05240
264399.50	653210.50	0.03487	0.00103	0.04550	0.01107
264399.50	653211.50	0.03386	0.00104	0.04225	0.02347
264399.50	653212.50	0.03176	0.00093	0.04161	0.00377
264399.50	653213.50	0.03018	0.00093	0.03783	0.00198
264399.50	653214.50	0.02986	0.00087	0.03731	0.00231
264399.50	653215.50	0.02835	0.00090	0.03699	0.00141
264399.50	653216.50	0.02675	0.00136	0.03629	0.00149

264399.50	653217.50	0.02672	0.00137	0.03723	0.00209
264399.50	653218.50	0.02607	0.00187	0.03640	0.00201
264400.50	653202.50	0.02595	0.00108	0.02970	0.00618
264400.50	653203.50	0.02812	0.00101	0.03361	0.00984
264400.50	653204.50	0.02839	0.00088	0.03877	0.01008
264400.50	653205.50	0.02972	0.00081	0.03931	0.00631
264400.50	653206.50	0.03093	0.00092	0.04282	0.00344
264400.50	653207.50	0.03313	0.00116	0.04439	0.00393
264400.50	653208.50	0.03497	0.00133	0.04393	0.00771
264400.50	653209.50	0.03406	0.00095	0.04348	0.01315
264400.50	653210.50	0.03443	0.00102	0.04226	0.00814
264400.50	653211.50	0.03501	0.00134	0.04088	0.00527
264400.50	653212.50	0.03361	0.00109	0.03961	0.00276
264400.50	653213.50	0.03183	0.00095	0.03724	0.00177
264400.50	653214.50	0.03105	0.00087	0.03529	0.00160
264400.50	653215.50	0.02877	0.00108	0.03307	0.00213
264400.50	653216.50	0.02685	0.00136	0.03333	0.00216
264400.50	653217.50	0.02607	0.00187	0.03628	0.00206
264401.50	653202.50	0.02702	0.00099	0.03351	0.00318
264401.50	653203.50	0.02704	0.00091	0.03719	0.00520
264401.50	653204.50	0.02794	0.00080	0.03929	0.00346
264401.50	653205.50	0.02750	0.00084	0.03940	0.00273
264401.50	653206.50	0.02794	0.00094	0.04038	0.00239
264401.50	653207.50	0.02977	0.00092	0.04146	0.00349
264401.50	653208.50	0.03183	0.00093	0.04251	0.00441
264401.50	653209.50	0.03133	0.00098	0.04160	0.00286
264401.50	653210.50	0.03198	0.00099	0.04141	0.00292
264401.50	653211.50	0.03343	0.00103	0.03987	0.00232
264401.50	653212.50	0.03367	0.00103	0.03748	0.00135
264401.50	653213.50	0.03231	0.00095	0.03655	0.00146
264401.50	653214.50	0.02975	0.00106	0.03473	0.00265
264401.50	653215.50	0.03107	0.00131	0.03212	0.00314
264401.50	653216.50	0.02763	0.00198	0.03199	0.00214
264402.50	653202.50	0.02793	0.00089	0.03597	0.00330
264402.50	653203.50	0.02748	0.00089	0.03860	0.00407
264402.50	653204.50	0.02751	0.00087	0.03977	0.00355
264402.50	653205.50	0.02703	0.00089	0.04021	0.00204
264402.50	653206.50	0.02698	0.00087	0.03965	0.00309
264402.50	653207.50	0.02861	0.00081	0.03976	0.00445
264402.50	653208.50	0.02984	0.00088	0.04039	0.00252
264402.50	653209.50	0.03041	0.00096	0.03998	0.00177
264402.50	653210.50	0.03092	0.00098	0.03919	0.00109
264402.50	653211.50	0.03203	0.00093	0.03724	0.00136
264402.50	653212.50	0.03292	0.00096	0.03644	0.00126
264402.50	653213.50	0.03265	0.00143	0.03623	0.00160
264402.50	653214.50	0.03233	0.00139	0.03461	0.00378

264402.50	653215.50	0.03350	0.00171	0.03307	0.00230
264403.50	653202.50	0.02838	0.00097	0.03741	0.00347
264403.50	653203.50	0.02805	0.00094	0.03893	0.00696
264403.50	653204.50	0.02769	0.00090	0.03984	0.00383
264403.50	653205.50	0.02705	0.00099	0.04021	0.00233
264403.50	653206.50	0.02779	0.00081	0.04004	0.00316
264403.50	653207.50	0.02830	0.00089	0.03935	0.00408
264403.50	653208.50	0.02915	0.00110	0.03949	0.00303
264403.50	653209.50	0.02993	0.00093	0.03906	0.00173
264403.50	653210.50	0.03122	0.00091	0.03762	0.00118
264403.50	653211.50	0.03223	0.00090	0.03649	0.00101
264403.50	653212.50	0.03120	0.00118	0.03572	0.00088
264403.50	653213.50	0.03375	0.00173	0.03583	0.00075
264403.50	653214.50	0.03407	0.00176	0.03453	0.00074
264404.50	653202.50	0.02915	0.00112	0.03821	0.00366
264404.50	653203.50	0.02872	0.00119	0.03927	0.00431
264404.50	653204.50	0.02834	0.00104	0.03937	0.00218
264404.50	653205.50	0.02806	0.00086	0.04005	0.00166
264404.50	653206.50	0.02903	0.00104	0.03981	0.00158
264404.50	653207.50	0.02916	0.00103	0.03859	0.00150
264404.50	653208.50	0.02878	0.00097	0.03795	0.00186
264404.50	653209.50	0.02936	0.00093	0.03753	0.00190
264404.50	653210.50	0.03029	0.00096	0.03754	0.00118
264404.50	653211.50	0.03069	0.00102	0.03713	0.00073
264404.50	653212.50	0.03127	0.00113	0.03653	0.00062
264404.50	653213.50	0.03333	0.00169	0.03575	0.00064
264405.50	653202.50	0.02971	0.00129	0.03807	0.00343
264405.50	653203.50	0.02934	0.00117	0.03900	0.00275
264405.50	653204.50	0.02889	0.00100	0.03895	0.00147
264405.50	653205.50	0.02882	0.00098	0.03915	0.00115
264405.50	653206.50	0.02918	0.00109	0.03888	0.00094
264405.50	653207.50	0.02913	0.00111	0.03836	0.00105
264405.50	653208.50	0.02860	0.00091	0.03774	0.00158
264405.50	653209.50	0.02853	0.00083	0.03719	0.00291
264405.50	653210.50	0.02936	0.00097	0.03698	0.00147
264405.50	653211.50	0.02948	0.00096	0.03618	0.00077
264405.50	653212.50	0.02933	0.00124	0.03499	0.00059
264405.50	653213.50	0.03124	0.00223	0.03247	0.00079
264405.50	653214.50	0.03124	0.00223	0.02460	0.00140
264406.50	653202.50	0.03003	0.00148	0.03696	0.00229
264406.50	653203.50	0.02991	0.00136	0.03713	0.00184
264406.50	653204.50	0.02932	0.00111	0.03810	0.00120
264406.50	653205.50	0.02897	0.00129	0.03841	0.00103
264406.50	653206.50	0.02900	0.00107	0.03830	0.00103
264406.50	653207.50	0.02901	0.00093	0.03802	0.00116
264406.50	653208.50	0.02886	0.00080	0.03770	0.00160

264406.50	653209.50	0.02961	0.00090	0.03720	0.00197
264406.50	653210.50	0.02979	0.00098	0.03633	0.00173
264406.50	653211.50	0.03022	0.00118	0.03560	0.00077
264406.50	653212.50	0.02818	0.00136	0.03213	0.00075
264406.50	653213.50	0.02693	0.00157	0.02460	0.00140
264406.50	653214.50	0.02605	0.00146	0.02460	0.00140
264406.50	653215.50	0.03124	0.00223	0.02460	0.00140
264407.50	653202.50	0.03011	0.00149	0.03703	0.00183
264407.50	653203.50	0.02973	0.00122	0.03761	0.00175
264407.50	653204.50	0.02939	0.00111	0.03827	0.00131
264407.50	653205.50	0.02920	0.00122	0.03853	0.00159
264407.50	653206.50	0.02918	0.00102	0.03812	0.00166
264407.50	653207.50	0.02970	0.00081	0.03722	0.00149
264407.50	653208.50	0.03030	0.00091	0.03607	0.00186
264407.50	653209.50	0.03043	0.00094	0.03581	0.00185
264407.50	653210.50	0.03046	0.00104	0.03565	0.00118
264407.50	653211.50	0.02893	0.00131	0.03425	0.00093
264407.50	653212.50	0.02858	0.00132	0.02733	0.00119
264407.50	653213.50	0.02773	0.00121	0.02460	0.00140
264407.50	653214.50	0.02583	0.00143	0.02468	0.00110
264407.50	653215.50	0.02482	0.00132	0.02475	0.00099
264407.50	653216.50	0.02430	0.00103	0.02490	0.00141
264407.50	653217.50	0.02442	0.00176	0.02490	0.00141
264407.50	653218.50	0.02442	0.00176	0.03020	0.00154
264407.50	653219.50	0.02442	0.00176	0.03020	0.00154
264408.50	653202.50	0.02992	0.00136	0.03697	0.00144
264408.50	653203.50	0.02992	0.00119	0.03776	0.00120
264408.50	653204.50	0.02975	0.00115	0.03761	0.00159
264408.50	653205.50	0.02966	0.00109	0.03747	0.00249
264408.50	653206.50	0.03008	0.00090	0.03734	0.00196
264408.50	653207.50	0.03049	0.00087	0.03605	0.00185
264408.50	653208.50	0.03038	0.00091	0.03428	0.00161
264408.50	653209.50	0.03051	0.00108	0.03518	0.00212
264408.50	653210.50	0.02965	0.00118	0.03583	0.00156
264408.50	653211.50	0.02976	0.00139	0.03236	0.00078
264408.50	653212.50	0.02911	0.00150	0.02683	0.00140
264408.50	653213.50	0.02741	0.00116	0.02549	0.00102
264408.50	653214.50	0.02591	0.00095	0.02582	0.00064
264408.50	653215.50	0.02404	0.00103	0.02453	0.00068
264408.50	653216.50	0.02384	0.00101	0.02450	0.00077
264408.50	653217.50	0.02200	0.00121	0.02439	0.00083
264408.50	653218.50	0.02442	0.00176	0.02445	0.00099
264408.50	653219.50	0.02442	0.00176	0.02760	0.00104
264408.50	653220.50	0.02442	0.00176	0.02760	0.00104
264408.50	653221.50	0.02703	0.00138	0.03084	0.00078
264408.50	653222.50	0.02951	0.00211	0.03218	0.00073

264409.50	653202.50	0.02981	0.00130	0.03703	0.00069
264409.50	653203.50	0.02973	0.00127	0.03742	0.00069
264409.50	653204.50	0.02941	0.00111	0.03699	0.00112
264409.50	653205.50	0.03020	0.00085	0.03650	0.00167
264409.50	653206.50	0.03052	0.00092	0.03593	0.00164
264409.50	653207.50	0.03076	0.00096	0.03263	0.00215
264409.50	653208.50	0.03059	0.00096	0.03129	0.00213
264409.50	653209.50	0.02985	0.00122	0.03308	0.00304
264409.50	653210.50	0.02958	0.00115	0.03485	0.00203
264409.50	653211.50	0.02967	0.00129	0.03312	0.00160
264409.50	653212.50	0.02893	0.00137	0.03082	0.00156
264409.50	653213.50	0.02619	0.00103	0.02852	0.00161
264409.50	653214.50	0.02457	0.00082	0.02571	0.00063
264409.50	653215.50	0.02392	0.00080	0.02509	0.00073
264409.50	653216.50	0.02368	0.00092	0.02459	0.00087
264409.50	653217.50	0.02273	0.00111	0.02439	0.00067
264409.50	653218.50	0.02417	0.00135	0.02444	0.00064
264409.50	653219.50	0.02531	0.00111	0.02460	0.00084
264409.50	653220.50	0.02574	0.00108	0.02500	0.00141
264409.50	653221.50	0.02620	0.00112	0.02756	0.00113
264409.50	653222.50	0.02951	0.00211	0.03052	0.00064
264409.50	653223.50	0.02951	0.00211	0.03164	0.00059
264409.50	653224.50	0.02951	0.00211	0.03282	0.00087
264410.50	653202.50	0.03080	0.00219	0.03572	0.00054
264410.50	653203.50	0.02994	0.00152	0.03589	0.00060
264410.50	653204.50	0.03047	0.00109	0.03569	0.00079
264410.50	653205.50	0.03050	0.00100	0.03556	0.00118
264410.50	653206.50	0.03074	0.00115	0.03411	0.00166
264410.50	653207.50	0.03092	0.00099	0.03109	0.00165
264410.50	653208.50	0.03110	0.00109	0.02954	0.00193
264410.50	653209.50	0.02999	0.00117	0.02985	0.00330
264410.50	653210.50	0.02951	0.00116	0.03078	0.00282
264410.50	653211.50	0.02875	0.00092	0.03271	0.00251
264410.50	653212.50	0.02708	0.00089	0.03114	0.00379
264410.50	653213.50	0.02438	0.00077	0.02934	0.00427
264410.50	653214.50	0.02325	0.00080	0.02655	0.00306
264410.50	653215.50	0.02408	0.00072	0.02480	0.00139
264410.50	653216.50	0.02557	0.00077	0.02434	0.00069
264410.50	653217.50	0.02449	0.00110	0.02423	0.00081
264410.50	653218.50	0.02417	0.00116	0.02440	0.00067
264410.50	653219.50	0.02517	0.00112	0.02464	0.00086
264410.50	653220.50	0.02580	0.00108	0.02572	0.00113
264410.50	653221.50	0.02650	0.00117	0.02627	0.00129
264410.50	653222.50	0.02647	0.00110	0.02959	0.00071
264410.50	653223.50	0.02770	0.00152	0.03085	0.00083
264410.50	653224.50	0.02733	0.00145	0.03091	0.00174

264410.50	653225.50	0.02702	0.00139	0.03135	0.00151
264411.50	653203.50	0.02839	0.00203	0.03294	0.00059
264411.50	653204.50	0.03089	0.00156	0.03313	0.00084
264411.50	653205.50	0.03069	0.00134	0.03290	0.00086
264411.50	653206.50	0.03063	0.00114	0.03197	0.00095
264411.50	653207.50	0.03101	0.00110	0.03052	0.00131
264411.50	653208.50	0.03175	0.00127	0.02871	0.00133
264411.50	653209.50	0.03071	0.00105	0.02822	0.00331
264411.50	653210.50	0.02939	0.00086	0.02938	0.00367
264411.50	653211.50	0.02833	0.00094	0.03783	0.00547
264411.50	653212.50	0.02664	0.00086	0.03477	0.01133
264411.50	653213.50	0.02352	0.00077	0.02844	0.00847
264411.50	653214.50	0.02370	0.00075	0.02612	0.00455
264411.50	653215.50	0.02530	0.00066	0.02476	0.00148
264411.50	653216.50	0.02602	0.00080	0.02422	0.00069
264411.50	653217.50	0.02550	0.00115	0.02428	0.00080
264411.50	653218.50	0.02520	0.00117	0.02446	0.00089
264411.50	653219.50	0.02595	0.00103	0.02469	0.00064
264411.50	653220.50	0.02576	0.00101	0.02565	0.00091
264411.50	653221.50	0.02669	0.00117	0.02650	0.00136
264411.50	653222.50	0.02704	0.00126	0.03103	0.00138
264411.50	653223.50	0.02708	0.00132	0.03174	0.00123
264411.50	653224.50	0.02723	0.00143	0.03014	0.00145
264411.50	653225.50	0.02682	0.00137	0.03086	0.00150
264411.50	653226.50	0.02659	0.00135	0.03249	0.00098
264412.50	653203.50	0.02839	0.00203	0.02998	0.00187
264412.50	653204.50	0.03063	0.00157	0.03081	0.00152
264412.50	653205.50	0.03002	0.00138	0.03164	0.00105
264412.50	653206.50	0.03011	0.00123	0.03030	0.00079
264412.50	653207.50	0.03031	0.00123	0.02756	0.00087
264412.50	653208.50	0.03164	0.00130	0.02613	0.00089
264412.50	653209.50	0.03106	0.00109	0.02750	0.00205
264412.50	653210.50	0.02977	0.00080	0.02864	0.00263
264412.50	653211.50	0.02854	0.00094	0.03428	0.00790
264412.50	653212.50	0.02744	0.00082	0.03347	0.00832
264412.50	653213.50	0.02627	0.00073	0.02749	0.00428
264412.50	653214.50	0.02630	0.00068	0.02627	0.00266
264412.50	653215.50	0.02681	0.00066	0.02515	0.00048
264412.50	653216.50	0.02684	0.00075	0.02446	0.00048
264412.50	653217.50	0.02618	0.00095	0.02444	0.00078
264412.50	653218.50	0.02591	0.00093	0.02448	0.00082
264412.50	653219.50	0.02589	0.00095	0.02492	0.00054
264412.50	653220.50	0.02620	0.00091	0.02590	0.00075
264412.50	653221.50	0.02698	0.00132	0.02662	0.00189
264412.50	653222.50	0.02722	0.00140	0.02925	0.00171
264412.50	653223.50	0.02641	0.00123	0.03126	0.00103

264412.50	653224.50	0.02576	0.00119	0.03045	0.00086
264412.50	653225.50	0.02615	0.00113	0.03133	0.00092
264412.50	653226.50	0.02592	0.00109	0.03199	0.00128
264412.50	653227.50	0.02445	0.00125	0.03368	0.00239
264413.50	653203.50	0.02839	0.00203	0.02988	0.00177
264413.50	653204.50	0.03045	0.00158	0.02983	0.00244
264413.50	653205.50	0.02992	0.00123	0.03033	0.00091
264413.50	653206.50	0.02968	0.00128	0.02926	0.00072
264413.50	653207.50	0.02949	0.00136	0.02647	0.00103
264413.50	653208.50	0.03032	0.00107	0.02554	0.00108
264413.50	653209.50	0.03021	0.00092	0.02720	0.00123
264413.50	653210.50	0.03003	0.00098	0.02737	0.00215
264413.50	653211.50	0.02907	0.00077	0.02705	0.00394
264413.50	653212.50	0.02799	0.00075	0.02690	0.00427
264413.50	653213.50	0.02748	0.00094	0.02689	0.00251
264413.50	653214.50	0.02828	0.00081	0.02635	0.00131
264413.50	653215.50	0.02885	0.00077	0.02479	0.00040
264413.50	653216.50	0.02866	0.00073	0.02477	0.00043
264413.50	653217.50	0.02802	0.00073	0.02486	0.00052
264413.50	653218.50	0.02673	0.00083	0.02521	0.00049
264413.50	653219.50	0.02560	0.00100	0.02517	0.00065
264413.50	653220.50	0.02613	0.00090	0.02527	0.00086
264413.50	653221.50	0.02750	0.00130	0.02575	0.00143
264413.50	653222.50	0.02729	0.00139	0.02681	0.00096
264413.50	653223.50	0.02583	0.00109	0.02916	0.00056
264413.50	653224.50	0.02509	0.00106	0.02996	0.00058
264413.50	653225.50	0.02479	0.00099	0.03117	0.00076
264413.50	653226.50	0.02560	0.00108	0.03165	0.00126
264413.50	653227.50	0.02450	0.00125	0.03291	0.00294
264413.50	653228.50	0.02455	0.00126	0.03274	0.00464
264413.50	653229.50	0.02498	0.00180	0.03138	0.00497
264414.50	653203.50	0.02839	0.00203	0.03023	0.00081
264414.50	653204.50	0.02966	0.00128	0.03039	0.00107
264414.50	653205.50	0.02897	0.00105	0.03018	0.00110
264414.50	653206.50	0.02906	0.00112	0.02906	0.00083
264414.50	653207.50	0.02896	0.00104	0.02665	0.00109
264414.50	653208.50	0.02931	0.00090	0.02487	0.00110
264414.50	653209.50	0.02977	0.00099	0.02425	0.00047
264414.50	653210.50	0.03002	0.00110	0.02582	0.00186
264414.50	653211.50	0.02941	0.00078	0.02472	0.00429
264414.50	653212.50	0.02897	0.00067	0.02499	0.00591
264414.50	653213.50	0.02910	0.00083	0.02578	0.00303
264414.50	653214.50	0.03070	0.00108	0.02493	0.00049
264414.50	653215.50	0.03046	0.00094	0.02517	0.00060
264414.50	653216.50	0.03024	0.00091	0.02476	0.00062
264414.50	653217.50	0.03019	0.00096	0.02508	0.00065

264414.50	653218.50	0.02838	0.00079	0.02548	0.00061
264414.50	653219.50	0.02671	0.00078	0.02544	0.00058
264414.50	653220.50	0.02638	0.00071	0.02560	0.00119
264414.50	653221.50	0.02639	0.00089	0.02599	0.00192
264414.50	653222.50	0.02549	0.00091	0.02717	0.00065
264414.50	653223.50	0.02460	0.00103	0.02880	0.00054
264414.50	653224.50	0.02417	0.00112	0.02929	0.00083
264414.50	653225.50	0.02411	0.00094	0.03002	0.00077
264414.50	653226.50	0.02450	0.00097	0.03121	0.00108
264414.50	653227.50	0.02458	0.00128	0.03179	0.00184
264414.50	653228.50	0.02462	0.00130	0.03187	0.00410
264414.50	653229.50	0.02498	0.00180	0.03077	0.00271
264414.50	653230.50	0.02498	0.00180	0.02993	0.00138
264415.50	653203.50	0.02839	0.00203	0.02964	0.00078
264415.50	653204.50	0.02646	0.00112	0.02968	0.00084
264415.50	653205.50	0.02791	0.00104	0.02948	0.00098
264415.50	653206.50	0.02846	0.00097	0.02842	0.00090
264415.50	653207.50	0.02854	0.00091	0.02585	0.00083
264415.50	653208.50	0.02846	0.00107	0.02360	0.00098
264415.50	653209.50	0.02851	0.00113	0.02370	0.00046
264415.50	653210.50	0.02936	0.00085	0.02403	0.00046
264415.50	653211.50	0.02924	0.00079	0.02392	0.00307
264415.50	653212.50	0.02954	0.00081	0.02412	0.00494
264415.50	653213.50	0.02977	0.00079	0.02458	0.00163
264415.50	653214.50	0.03096	0.00102	0.02471	0.00122
264415.50	653215.50	0.03021	0.00093	0.02503	0.00058
264415.50	653216.50	0.03036	0.00099	0.02481	0.00062
264415.50	653217.50	0.03113	0.00111	0.02550	0.00145
264415.50	653218.50	0.02944	0.00081	0.02588	0.00095
264415.50	653219.50	0.02778	0.00066	0.02629	0.00087
264415.50	653220.50	0.02655	0.00060	0.02632	0.00092
264415.50	653221.50	0.02493	0.00067	0.02628	0.00097
264415.50	653222.50	0.02369	0.00076	0.02692	0.00050
264415.50	653223.50	0.02390	0.00102	0.02826	0.00056
264415.50	653224.50	0.02397	0.00106	0.02913	0.00080
264415.50	653225.50	0.02388	0.00091	0.02935	0.00070
264415.50	653226.50	0.02368	0.00090	0.03023	0.00104
264415.50	653227.50	0.02340	0.00104	0.03090	0.00140
264415.50	653228.50	0.02328	0.00108	0.03138	0.00230
264415.50	653229.50	0.02255	0.00118	0.03102	0.00169
264415.50	653230.50	0.02219	0.00114	0.03039	0.00077
264415.50	653231.50	0.01957	0.00143	0.02999	0.00069
264416.50	653203.50	0.02308	0.00167	0.02908	0.00110
264416.50	653204.50	0.02582	0.00108	0.02894	0.00114
264416.50	653205.50	0.02535	0.00095	0.02894	0.00114
264416.50	653206.50	0.02679	0.00078	0.02699	0.00076

264416.50	653207.50	0.02734	0.00079	0.02495	0.00083
264416.50	653208.50	0.02767	0.00095	0.02433	0.00077
264416.50	653209.50	0.02757	0.00093	0.02408	0.00050
264416.50	653210.50	0.02820	0.00075	0.02418	0.00045
264416.50	653211.50	0.02927	0.00104	0.02427	0.00071
264416.50	653212.50	0.03001	0.00117	0.02445	0.00119
264416.50	653213.50	0.02938	0.00075	0.02471	0.00148
264416.50	653214.50	0.02943	0.00074	0.02464	0.00126
264416.50	653215.50	0.02882	0.00086	0.02498	0.00092
264416.50	653216.50	0.02898	0.00086	0.02525	0.00066
264416.50	653217.50	0.02951	0.00080	0.02565	0.00090
264416.50	653218.50	0.02881	0.00085	0.02586	0.00073
264416.50	653219.50	0.02787	0.00084	0.02624	0.00058
264416.50	653220.50	0.02647	0.00065	0.02607	0.00062
264416.50	653221.50	0.02405	0.00071	0.02601	0.00077
264416.50	653222.50	0.02249	0.00081	0.02732	0.00070
264416.50	653223.50	0.02306	0.00076	0.03015	0.00115
264416.50	653224.50	0.02357	0.00080	0.03055	0.00138
264416.50	653225.50	0.02359	0.00095	0.02861	0.00083
264416.50	653226.50	0.02373	0.00122	0.02917	0.00086
264416.50	653227.50	0.02354	0.00117	0.03002	0.00114
264416.50	653228.50	0.02276	0.00098	0.03074	0.00087
264416.50	653229.50	0.02214	0.00114	0.03075	0.00080
264416.50	653230.50	0.02180	0.00112	0.03016	0.00092
264416.50	653231.50	0.01957	0.00143	0.02948	0.00112
264416.50	653232.50	0.01957	0.00143	0.02973	0.00199
264417.50	653202.50	0.02308	0.00167	0.02820	0.00149
264417.50	653203.50	0.02308	0.00167	0.02820	0.00149
264417.50	653204.50	0.02300	0.00127	0.02820	0.00149
264417.50	653205.50	0.02450	0.00101	0.02802	0.00137
264417.50	653206.50	0.02535	0.00092	0.02627	0.00089
264417.50	653207.50	0.02554	0.00084	0.02532	0.00077
264417.50	653208.50	0.02581	0.00075	0.02365	0.00097
264417.50	653209.50	0.02624	0.00078	0.02394	0.00077
264417.50	653210.50	0.02645	0.00095	0.02444	0.00062
264417.50	653211.50	0.02756	0.00089	0.02455	0.00056
264417.50	653212.50	0.02817	0.00091	0.02487	0.00067
264417.50	653213.50	0.02804	0.00072	0.02535	0.00100
264417.50	653214.50	0.02798	0.00068	0.02478	0.00146
264417.50	653215.50	0.02820	0.00070	0.02438	0.00090
264417.50	653216.50	0.02879	0.00075	0.02513	0.00055
264417.50	653217.50	0.02884	0.00084	0.02526	0.00059
264417.50	653218.50	0.02849	0.00090	0.02547	0.00059
264417.50	653219.50	0.02789	0.00085	0.02557	0.00044
264417.50	653220.50	0.02726	0.00075	0.02519	0.00061
264417.50	653221.50	0.02531	0.00073	0.02555	0.00084

264417.50	653222.50	0.02339	0.00072	0.02682	0.00092
264417.50	653223.50	0.02335	0.00066	0.02860	0.00180
264417.50	653224.50	0.02329	0.00071	0.02941	0.00223
264417.50	653225.50	0.02386	0.00097	0.02835	0.00082
264417.50	653226.50	0.02420	0.00128	0.02881	0.00073
264417.50	653227.50	0.02385	0.00108	0.02969	0.00092
264417.50	653228.50	0.02289	0.00095	0.03082	0.00107
264417.50	653229.50	0.02139	0.00112	0.03162	0.00084
264417.50	653230.50	0.02126	0.00113	0.03113	0.00111
264417.50	653231.50	0.01957	0.00143	0.03048	0.00261
264417.50	653232.50	0.01957	0.00143	0.03055	0.00367
264418.50	653202.50	0.02308	0.00167	0.02820	0.00149
264418.50	653203.50	0.02308	0.00167	0.02820	0.00149
264418.50	653204.50	0.02603	0.00114	0.02820	0.00149
264418.50	653205.50	0.02533	0.00109	0.02798	0.00135
264418.50	653206.50	0.02446	0.00116	0.02623	0.00088
264418.50	653207.50	0.02425	0.00114	0.02571	0.00101
264418.50	653208.50	0.02516	0.00077	0.02459	0.00271
264418.50	653209.50	0.02562	0.00080	0.02521	0.00186
264418.50	653210.50	0.02544	0.00108	0.02552	0.00103
264418.50	653211.50	0.02580	0.00082	0.02511	0.00085
264418.50	653212.50	0.02608	0.00071	0.02528	0.00063
264418.50	653213.50	0.02659	0.00097	0.02552	0.00073
264418.50	653214.50	0.02723	0.00083	0.02474	0.00120
264418.50	653215.50	0.02793	0.00061	0.02389	0.00067
264418.50	653216.50	0.02866	0.00065	0.02489	0.00040
264418.50	653217.50	0.02924	0.00097	0.02517	0.00046
264418.50	653218.50	0.02885	0.00091	0.02542	0.00058
264418.50	653219.50	0.02860	0.00078	0.02529	0.00061
264418.50	653220.50	0.02846	0.00111	0.02457	0.00063
264418.50	653221.50	0.02668	0.00103	0.02489	0.00076
264418.50	653222.50	0.02428	0.00069	0.02623	0.00089
264418.50	653223.50	0.02289	0.00075	0.02704	0.00108
264418.50	653224.50	0.02211	0.00087	0.02752	0.03829
264418.50	653225.50	0.02270	0.00078	0.02784	0.00088
264418.50	653226.50	0.02303	0.00088	0.02925	0.00068
264418.50	653227.50	0.02310	0.00089	0.03053	0.00122
264418.50	653228.50	0.02172	0.00103	0.03140	0.00125
264418.50	653229.50	0.02169	0.00111	0.03198	0.00111
264418.50	653230.50	0.02230	0.00106	0.03198	0.00113
264418.50	653231.50	0.01957	0.00143	0.03143	0.00149
264418.50	653232.50	0.01957	0.00143	0.02993	0.00255
264418.50	653233.50	0.01957	0.00143	0.03021	0.00309
264419.50	653202.50	0.02308	0.00167	0.02820	0.00149
264419.50	653203.50	0.02745	0.00118	0.02739	0.00088
264419.50	653204.50	0.02689	0.00115	0.02749	0.00093

264419.50	653205.50	0.02590	0.00115	0.02721	0.00080
264419.50	653206.50	0.02483	0.00110	0.02620	0.00072
264419.50	653207.50	0.02425	0.00100	0.02592	0.00108
264419.50	653208.50	0.02467	0.00080	0.02566	0.00096
264419.50	653209.50	0.02487	0.00071	0.02640	0.00102
264419.50	653210.50	0.02492	0.00074	0.02627	0.00133
264419.50	653211.50	0.02345	0.00069	0.02497	0.00086
264419.50	653212.50	0.02309	0.00073	0.02490	0.00079
264419.50	653213.50	0.02556	0.00085	0.02454	0.00066
264419.50	653214.50	0.02673	0.00077	0.02454	0.00060
264419.50	653215.50	0.02717	0.00063	0.02455	0.00073
264419.50	653216.50	0.02805	0.00063	0.02495	0.00062
264419.50	653217.50	0.02910	0.00073	0.02549	0.00057
264419.50	653218.50	0.02935	0.00082	0.02547	0.00061
264419.50	653219.50	0.02942	0.00101	0.02531	0.00061
264419.50	653220.50	0.02838	0.00098	0.02455	0.00067
264419.50	653221.50	0.02697	0.00089	0.02453	0.00061
264419.50	653222.50	0.02512	0.00064	0.02585	0.00056
264419.50	653223.50	0.02304	0.00076	0.02664	0.00055
264419.50	653224.50	0.02219	0.00086	0.02730	0.00072
264419.50	653225.50	0.02285	0.00072	0.02777	0.00075
264419.50	653226.50	0.02315	0.00083	0.02887	0.00056
264419.50	653227.50	0.02223	0.00089	0.03115	0.00084
264419.50	653228.50	0.02114	0.00116	0.03239	0.00086
264419.50	653229.50	0.02132	0.00118	0.03207	0.00081
264419.50	653230.50	0.02221	0.00109	0.03157	0.00081
264419.50	653231.50	0.01957	0.00143	0.03102	0.00103
264419.50	653232.50	0.01957	0.00143	0.02893	0.00154
264419.50	653233.50	0.01957	0.00143	0.02879	0.00192
264420.50	653202.50	0.03046	0.00160	0.03003	0.00077
264420.50	653203.50	0.02853	0.00127	0.02975	0.00077
264420.50	653204.50	0.02847	0.00126	0.03027	0.00090
264420.50	653205.50	0.02813	0.00113	0.02991	0.00084
264420.50	653206.50	0.02702	0.00101	0.02928	0.00069
264420.50	653207.50	0.02518	0.00095	0.02801	0.00068
264420.50	653208.50	0.02439	0.00103	0.02588	0.00088
264420.50	653209.50	0.02489	0.00072	0.02562	0.00064
264420.50	653210.50	0.02465	0.00061	0.02542	0.00056
264420.50	653211.50	0.02226	0.00072	0.02458	0.00076
264420.50	653212.50	0.02206	0.00079	0.02469	0.00065
264420.50	653213.50	0.02506	0.00068	0.02462	0.00061
264420.50	653214.50	0.02619	0.00071	0.02477	0.00069
264420.50	653215.50	0.02551	0.00092	0.02482	0.00115
264420.50	653216.50	0.02727	0.00078	0.02519	0.00088
264420.50	653217.50	0.02941	0.00071	0.02562	0.00077
264420.50	653218.50	0.02994	0.00086	0.02575	0.00053

264420.50	653219.50	0.02950	0.00113	0.02575	0.00055
264420.50	653220.50	0.02838	0.00085	0.02528	0.00072
264420.50	653221.50	0.02742	0.00077	0.02491	0.00057
264420.50	653222.50	0.02522	0.00072	0.02530	0.00058
264420.50	653223.50	0.02308	0.00061	0.02608	0.00047
264420.50	653224.50	0.02218	0.00062	0.02722	0.00073
264420.50	653225.50	0.02344	0.00079	0.02775	0.00080
264420.50	653226.50	0.02520	0.00109	0.02841	0.00069
264420.50	653227.50	0.02402	0.00099	0.02995	0.00060
264420.50	653228.50	0.02206	0.00094	0.03127	0.00064
264420.50	653229.50	0.02244	0.00112	0.03192	0.00085
264420.50	653230.50	0.02254	0.00121	0.03164	0.00075
264420.50	653231.50	0.01957	0.00143	0.03074	0.00113
264420.50	653232.50	0.01957	0.00143	0.02947	0.00158
264420.50	653233.50	0.01957	0.00143	0.02913	0.00185
264421.50	653202.50	0.03698	0.00262	0.03087	0.00071
264421.50	653203.50	0.02972	0.00141	0.03172	0.00109
264421.50	653204.50	0.03017	0.00133	0.02901	0.00311
264421.50	653205.50	0.03103	0.00148	0.02904	0.00324
264421.50	653206.50	0.03104	0.00147	0.03112	0.00126
264421.50	653207.50	0.02809	0.00104	0.03024	0.00071
264421.50	653208.50	0.02600	0.00089	0.03153	0.00090
264421.50	653209.50	0.02582	0.00072	0.02602	0.00065
264421.50	653210.50	0.02537	0.00065	0.02577	0.00065
264421.50	653211.50	0.02496	0.00061	0.02553	0.00059
264421.50	653212.50	0.02499	0.00067	0.02539	0.00053
264421.50	653213.50	0.02707	0.00086	0.02584	0.00069
264421.50	653214.50	0.02801	0.00089	0.02565	0.00063
264421.50	653215.50	0.02767	0.00086	0.02542	0.00087
264421.50	653216.50	0.02950	0.00091	0.02583	0.00094
264421.50	653217.50	0.03147	0.00098	0.02601	0.00071
264421.50	653218.50	0.03112	0.00083	0.02654	0.00075
264421.50	653219.50	0.02990	0.00076	0.02651	0.00067
264421.50	653220.50	0.02888	0.00085	0.02608	0.00058
264421.50	653221.50	0.02827	0.00110	0.02577	0.00087
264421.50	653222.50	0.02537	0.00084	0.02600	0.00081
264421.50	653223.50	0.02186	0.00058	0.02630	0.00070
264421.50	653224.50	0.02044	0.00055	0.02663	0.00055
264421.50	653225.50	0.02367	0.00091	0.02628	0.00085
264421.50	653226.50	0.02722	0.00150	0.02782	0.00149
264421.50	653227.50	0.02599	0.00131	0.02975	0.00104
264421.50	653228.50	0.02362	0.00096	0.03077	0.00069
264421.50	653229.50	0.02388	0.00109	0.03161	0.00068
264421.50	653230.50	0.02382	0.00122	0.03039	0.00056
264421.50	653231.50	0.02383	0.00122	0.02947	0.00106
264421.50	653232.50	0.01957	0.00143	0.02952	0.00174

264422.50	653202.50	0.03698	0.00262	0.03063	0.00091
264422.50	653203.50	0.03698	0.00262	0.03350	0.00213
264422.50	653204.50	0.03124	0.00147	0.03121	0.00710
264422.50	653205.50	0.03275	0.00174	0.03162	0.04564
264422.50	653206.50	0.03346	0.00184	0.03468	0.00278
264422.50	653207.50	0.03133	0.00139	0.03225	0.00111
264422.50	653208.50	0.02795	0.00086	0.03421	0.00117
264422.50	653209.50	0.02697	0.00077	0.02600	0.00102
264422.50	653210.50	0.02638	0.00091	0.02558	0.00089
264422.50	653211.50	0.02640	0.00081	0.02592	0.00092
264422.50	653212.50	0.02716	0.00074	0.02586	0.00079
264422.50	653213.50	0.02967	0.00123	0.02627	0.00074
264422.50	653214.50	0.03081	0.00126	0.02604	0.00068
264422.50	653215.50	0.03044	0.00088	0.02578	0.00061
264422.50	653216.50	0.03201	0.00111	0.02640	0.00061
264422.50	653217.50	0.03371	0.00139	0.02634	0.00058
264422.50	653218.50	0.03197	0.00089	0.02676	0.00064
264422.50	653219.50	0.03012	0.00072	0.02677	0.00080
264422.50	653220.50	0.02944	0.00090	0.02656	0.00082
264422.50	653221.50	0.02833	0.00109	0.02661	0.00057
264422.50	653222.50	0.02591	0.00081	0.02652	0.00063
264422.50	653223.50	0.02120	0.00058	0.02659	0.00067
264422.50	653224.50	0.01684	0.00067	0.02668	0.00049
264422.50	653225.50	0.02132	0.00071	0.02609	0.00093
264422.50	653226.50	0.02508	0.00112	0.02763	0.00224
264422.50	653227.50	0.02540	0.00110	0.02938	0.00243
264422.50	653228.50	0.02377	0.00109	0.02985	0.00084
264422.50	653229.50	0.02485	0.00111	0.03071	0.00069
264422.50	653230.50	0.02501	0.00128	0.03050	0.00082
264422.50	653231.50	0.01957	0.00143	0.02980	0.00111
264422.50	653232.50	0.01957	0.00143	0.02912	0.00223
264423.50	653202.50	0.03698	0.00262	0.03011	0.00100
264423.50	653203.50	0.03419	0.00188	0.03309	0.00302
264423.50	653204.50	0.03247	0.00163	0.03295	0.00623
264423.50	653205.50	0.03190	0.00147	0.03179	0.00587
264423.50	653206.50	0.03191	0.00143	0.03211	0.00423
264423.50	653207.50	0.03033	0.00118	0.03007	0.00091
264423.50	653208.50	0.02845	0.00106	0.03022	0.00077
264423.50	653209.50	0.02764	0.00090	0.02613	0.00083
264423.50	653210.50	0.02707	0.00115	0.02606	0.00089
264423.50	653211.50	0.02730	0.00103	0.02600	0.00094
264423.50	653212.50	0.02807	0.00077	0.02599	0.00087
264423.50	653213.50	0.02973	0.00096	0.02613	0.00059
264423.50	653214.50	0.03110	0.00107	0.02635	0.00056
264423.50	653215.50	0.03177	0.00112	0.02683	0.00077
264423.50	653216.50	0.03273	0.00104	0.02691	0.00069

264423.50	653217.50	0.03249	0.00099	0.02644	0.00063
264423.50	653218.50	0.03145	0.00094	0.02673	0.00056
264423.50	653219.50	0.02995	0.00091	0.02694	0.00097
264423.50	653220.50	0.02946	0.00074	0.02720	0.00087
264423.50	653221.50	0.02826	0.00077	0.02739	0.00071
264423.50	653222.50	0.02643	0.00097	0.02697	0.00054
264423.50	653223.50	0.02376	0.00089	0.02691	0.00047
264423.50	653224.50	0.02044	0.00061	0.02701	0.00047
264423.50	653225.50	0.02145	0.00072	0.02703	0.00057
264423.50	653226.50	0.02289	0.00085	0.02760	0.00104
264423.50	653227.50	0.02392	0.00087	0.02921	0.00095
264423.50	653228.50	0.02369	0.00091	0.02987	0.00070
264423.50	653229.50	0.02489	0.00109	0.03011	0.00069
264423.50	653230.50	0.02446	0.00105	0.03024	0.00091
264423.50	653231.50	0.01957	0.00143	0.02906	0.00119
264424.50	653202.50	0.03698	0.00262	0.02798	0.00177
264424.50	653203.50	0.03369	0.00179	0.02950	0.00225
264424.50	653204.50	0.03350	0.00150	0.02961	0.00286
264424.50	653205.50	0.03148	0.00119	0.02820	0.00292
264424.50	653206.50	0.03062	0.00110	0.02825	0.00163
264424.50	653207.50	0.02950	0.00121	0.02839	0.00102
264424.50	653208.50	0.02879	0.00129	0.02820	0.00065
264424.50	653209.50	0.02829	0.00097	0.02665	0.00066
264424.50	653210.50	0.02750	0.00089	0.02597	0.00061
264424.50	653211.50	0.02748	0.00087	0.02540	0.00064
264424.50	653212.50	0.02748	0.00075	0.02552	0.00059
264424.50	653213.50	0.02863	0.00080	0.02574	0.00048
264424.50	653214.50	0.03013	0.00095	0.02633	0.00047
264424.50	653215.50	0.03220	0.00134	0.02704	0.00077
264424.50	653216.50	0.03226	0.00105	0.02717	0.00078
264424.50	653217.50	0.03141	0.00085	0.02725	0.00047
264424.50	653218.50	0.03021	0.00099	0.02745	0.00061
264424.50	653219.50	0.02920	0.00102	0.02752	0.00086
264424.50	653220.50	0.02925	0.00079	0.02773	0.00070
264424.50	653221.50	0.02860	0.00074	0.02760	0.00063
264424.50	653222.50	0.02703	0.00096	0.02733	0.00075
264424.50	653223.50	0.02593	0.00090	0.02746	0.00070
264424.50	653224.50	0.02430	0.00074	0.02771	0.00052
264424.50	653225.50	0.02285	0.00097	0.02850	0.00053
264424.50	653226.50	0.02303	0.00098	0.02983	0.00063
264424.50	653227.50	0.02413	0.00085	0.02995	0.00065
264424.50	653228.50	0.02379	0.00095	0.03087	0.00076
264424.50	653229.50	0.02602	0.00133	0.03004	0.00073
264424.50	653230.50	0.02635	0.00135	0.02890	0.00059
264425.50	653203.50	0.03308	0.00138	0.02810	0.00320
264425.50	653204.50	0.03205	0.00118	0.02782	0.00161

264425.50	653205.50	0.03169	0.00115	0.02751	0.00126
264425.50	653206.50	0.03062	0.00106	0.02747	0.00095
264425.50	653207.50	0.02938	0.00107	0.02728	0.00089
264425.50	653208.50	0.02882	0.00110	0.02675	0.00069
264425.50	653209.50	0.02840	0.00127	0.02672	0.00077
264425.50	653210.50	0.02849	0.00099	0.02615	0.00049
264425.50	653211.50	0.02815	0.00081	0.02565	0.00049
264425.50	653212.50	0.02752	0.00085	0.02490	0.00077
264425.50	653213.50	0.02696	0.00104	0.02523	0.00071
264425.50	653214.50	0.02811	0.00093	0.02607	0.00051
264425.50	653215.50	0.03041	0.00093	0.02663	0.00055
264425.50	653216.50	0.03133	0.00094	0.02722	0.00075
264425.50	653217.50	0.03149	0.00115	0.02735	0.00068
264425.50	653218.50	0.02991	0.00093	0.02755	0.00062
264425.50	653219.50	0.02903	0.00092	0.02806	0.00091
264425.50	653220.50	0.03074	0.00113	0.02829	0.00095
264425.50	653221.50	0.02978	0.00099	0.02793	0.00058
264425.50	653222.50	0.02809	0.00078	0.02776	0.00103
264425.50	653223.50	0.02748	0.00083	0.02790	0.00108
264425.50	653224.50	0.02730	0.00105	0.02843	0.00073
264425.50	653225.50	0.02557	0.00094	0.02948	0.00056
264425.50	653226.50	0.02449	0.00092	0.03054	0.00059
264425.50	653227.50	0.02486	0.00085	0.03073	0.00068
264425.50	653228.50	0.02733	0.00099	0.03142	0.00101
264425.50	653229.50	0.02786	0.00100	0.03003	0.00128
264425.50	653230.50	0.02122	0.00154	0.02854	0.00100
264426.50	653202.50	0.03286	0.00234	0.02625	0.00263
264426.50	653203.50	0.03286	0.00234	0.02624	0.00226
264426.50	653204.50	0.03268	0.00140	0.02640	0.00076
264426.50	653205.50	0.03162	0.00122	0.02636	0.00049
264426.50	653206.50	0.03122	0.00121	0.02665	0.00057
264426.50	653207.50	0.03118	0.00097	0.02672	0.00054
264426.50	653208.50	0.03033	0.00102	0.02690	0.00070
264426.50	653209.50	0.02952	0.00111	0.02713	0.00064
264426.50	653210.50	0.02938	0.00097	0.02643	0.00050
264426.50	653211.50	0.02966	0.00086	0.02522	0.00072
264426.50	653212.50	0.02848	0.00091	0.02468	0.00090
264426.50	653213.50	0.02664	0.00105	0.02527	0.00159
264426.50	653214.50	0.02780	0.00093	0.02627	0.00069
264426.50	653215.50	0.02965	0.00079	0.02647	0.00070
264426.50	653216.50	0.03106	0.00093	0.02691	0.00070
264426.50	653217.50	0.03146	0.00130	0.02717	0.00068
264426.50	653218.50	0.03060	0.00102	0.02746	0.00053
264426.50	653219.50	0.03084	0.00097	0.02830	0.00095
264426.50	653220.50	0.03226	0.00141	0.02842	0.00080
264426.50	653221.50	0.03038	0.00109	0.02793	0.00070

264426.50	653222.50	0.02855	0.00073	0.02839	0.00082
264426.50	653223.50	0.02825	0.00092	0.02893	0.00099
264426.50	653224.50	0.02900	0.00140	0.02982	0.00117
264426.50	653225.50	0.02780	0.00113	0.03062	0.00087
264426.50	653226.50	0.02717	0.00087	0.03050	0.00071
264426.50	653227.50	0.02884	0.00106	0.03006	0.00056
264426.50	653228.50	0.02951	0.00107	0.03074	0.00139
264426.50	653229.50	0.02749	0.00116	0.02997	0.00260
264427.50	653202.50	0.03286	0.00234	0.02358	0.00133
264427.50	653203.50	0.03286	0.00234	0.02397	0.00094
264427.50	653204.50	0.03175	0.00182	0.02563	0.00047
264427.50	653205.50	0.03138	0.00166	0.02586	0.00056
264427.50	653206.50	0.03267	0.00164	0.02622	0.00073
264427.50	653207.50	0.03250	0.00143	0.02667	0.00117
264427.50	653208.50	0.03189	0.00107	0.02693	0.00203
264427.50	653209.50	0.03113	0.00094	0.02738	0.00088
264427.50	653210.50	0.03090	0.00100	0.02703	0.00067
264427.50	653211.50	0.03062	0.00134	0.02545	0.00071
264427.50	653212.50	0.03015	0.00133	0.02475	0.00090
264427.50	653213.50	0.02907	0.00089	0.02545	0.00232
264427.50	653214.50	0.02846	0.00087	0.02627	0.00072
264427.50	653215.50	0.02882	0.00078	0.02640	0.00075
264427.50	653216.50	0.02991	0.00084	0.02670	0.00076
264427.50	653217.50	0.02978	0.00091	0.02687	0.00068
264427.50	653218.50	0.02957	0.00082	0.02672	0.00066
264427.50	653219.50	0.02975	0.00094	0.02728	0.00103
264427.50	653220.50	0.03004	0.00095	0.02823	0.00102
264427.50	653221.50	0.02965	0.00088	0.02916	0.00107
264427.50	653222.50	0.02814	0.00081	0.02972	0.00120
264427.50	653223.50	0.02750	0.00082	0.03012	0.00135
264427.50	653224.50	0.02875	0.00095	0.03043	0.00170
264427.50	653225.50	0.02947	0.00102	0.03064	0.00464
264427.50	653226.50	0.02967	0.00107	0.02980	0.00119
264427.50	653227.50	0.03066	0.00121	0.02908	0.00073
264427.50	653228.50	0.03114	0.00119	0.02975	0.00087
264427.50	653229.50	0.03155	0.00138	0.02962	0.00086
264427.50	653230.50	0.03549	0.00181	0.02919	0.00070
264428.50	653202.50	0.03286	0.00234	0.02445	0.00066
264428.50	653203.50	0.03286	0.00234	0.02508	0.00047
264428.50	653204.50	0.03286	0.00234	0.02543	0.00054
264428.50	653205.50	0.03321	0.00169	0.02570	0.00066
264428.50	653206.50	0.03317	0.00192	0.02611	0.00118
264428.50	653207.50	0.03332	0.00178	0.02674	0.00198
264428.50	653208.50	0.03422	0.00133	0.02697	0.00088
264428.50	653209.50	0.03484	0.00127	0.02714	0.00071
264428.50	653210.50	0.03320	0.00121	0.02705	0.00071

264428.50	653211.50	0.03190	0.00154	0.02595	0.00057
264428.50	653212.50	0.03096	0.00154	0.02547	0.00058
264428.50	653213.50	0.03035	0.00102	0.02544	0.00062
264428.50	653214.50	0.02912	0.00090	0.02590	0.00060
264428.50	653215.50	0.02905	0.00090	0.02644	0.00064
264428.50	653216.50	0.02851	0.00080	0.02679	0.00060
264428.50	653217.50	0.02834	0.00079	0.02681	0.00056
264428.50	653218.50	0.02825	0.00075	0.02729	0.00088
264428.50	653219.50	0.02829	0.00071	0.02740	0.00143
264428.50	653220.50	0.02783	0.00072	0.02860	0.00145
264428.50	653221.50	0.02715	0.00079	0.03071	0.00119
264428.50	653222.50	0.02627	0.00107	0.03096	0.00115
264428.50	653223.50	0.02707	0.00086	0.03118	0.00127
264428.50	653224.50	0.02880	0.00077	0.03071	0.00238
264428.50	653225.50	0.02998	0.00120	0.03024	0.00216
264428.50	653226.50	0.03055	0.00139	0.02882	0.00128
264428.50	653227.50	0.03146	0.00125	0.02842	0.00099
264428.50	653228.50	0.03278	0.00136	0.02924	0.00062
264428.50	653229.50	0.03569	0.00183	0.02925	0.00061
264428.50	653230.50	0.03604	0.00187	0.02969	0.00063
264428.50	653231.50	0.04018	0.00285	0.02898	0.00084
264429.50	653202.50	0.03286	0.00234	0.02429	0.00058
264429.50	653203.50	0.03286	0.00234	0.02559	0.00071
264429.50	653204.50	0.03286	0.00234	0.02543	0.00115
264429.50	653205.50	0.03498	0.00198	0.02549	0.00139
264429.50	653206.50	0.03421	0.00188	0.02584	0.00275
264429.50	653207.50	0.03488	0.00167	0.02635	0.00090
264429.50	653208.50	0.03743	0.00169	0.02686	0.00062
264429.50	653209.50	0.03925	0.00202	0.02650	0.00046
264429.50	653210.50	0.03659	0.00157	0.02623	0.00054
264429.50	653211.50	0.03357	0.00124	0.02533	0.00060
264429.50	653212.50	0.03172	0.00116	0.02543	0.00058
264429.50	653213.50	0.03092	0.00104	0.02539	0.00072
264429.50	653214.50	0.02957	0.00109	0.02606	0.00073
264429.50	653215.50	0.02842	0.00111	0.02662	0.00073
264429.50	653216.50	0.02719	0.00109	0.02677	0.00066
264429.50	653217.50	0.02680	0.00111	0.02700	0.00071
264429.50	653218.50	0.02676	0.00079	0.02832	0.00082
264429.50	653219.50	0.02655	0.00067	0.02852	0.00153
264429.50	653220.50	0.02638	0.00079	0.03031	0.00154
264429.50	653221.50	0.02637	0.00083	0.03184	0.00118
264429.50	653222.50	0.02605	0.00094	0.03148	0.00090
264429.50	653223.50	0.02746	0.00084	0.03157	0.00104
264429.50	653224.50	0.02854	0.00086	0.03098	0.00141
264429.50	653225.50	0.03009	0.00120	0.03022	0.00119
264429.50	653226.50	0.03118	0.00144	0.02897	0.00111

264429.50	653227.50	0.03343	0.00138	0.02910	0.00075
264429.50	653228.50	0.03473	0.00146	0.03004	0.00107
264429.50	653229.50	0.03541	0.00152	0.02949	0.00084
264429.50	653230.50	0.03609	0.00164	0.02999	0.00077
264429.50	653231.50	0.04018	0.00285	0.02944	0.00109
264429.50	653232.50	0.04018	0.00285	0.02995	0.00117
264430.50	653202.50	0.03286	0.00234	0.02340	0.00096
264430.50	653203.50	0.03286	0.00234	0.02474	0.00226
264430.50	653204.50	0.03286	0.00234	0.02537	0.00146
264430.50	653205.50	0.03612	0.00189	0.02537	0.00201
264430.50	653206.50	0.03655	0.00187	0.02568	0.00075
264430.50	653207.50	0.03829	0.00193	0.02561	0.00051
264430.50	653208.50	0.03938	0.00202	0.02592	0.00042
264430.50	653209.50	0.04128	0.00247	0.02474	0.00067
264430.50	653210.50	0.03914	0.00198	0.02433	0.00086
264430.50	653211.50	0.03636	0.00142	0.02515	0.00069
264430.50	653212.50	0.03270	0.00106	0.02368	0.00098
264430.50	653214.50	0.03025	0.00131	0.02480	0.00141
264430.50	653215.50	0.02953	0.00139	0.02480	0.00141
264430.50	653216.50	0.02737	0.00118	0.02738	0.00085
264430.50	653217.50	0.02620	0.00117	0.02777	0.00062
264430.50	653218.50	0.02581	0.00074	0.02921	0.00060
264430.50	653219.50	0.02583	0.00071	0.03053	0.00073
264430.50	653220.50	0.02611	0.00105	0.03172	0.00128
264430.50	653221.50	0.02629	0.00101	0.03271	0.00152
264430.50	653222.50	0.02640	0.00077	0.03259	0.00128
264430.50	653223.50	0.02712	0.00098	0.03162	0.00090
264430.50	653224.50	0.02817	0.00095	0.03025	0.00103
264430.50	653225.50	0.02990	0.00089	0.02967	0.00094
264430.50	653226.50	0.03225	0.00109	0.02956	0.00050
264430.50	653227.50	0.03601	0.00173	0.03000	0.00087
264430.50	653228.50	0.03653	0.00183	0.03048	0.00127
264430.50	653229.50	0.03617	0.00166	0.03009	0.00121
264430.50	653230.50	0.03643	0.00168	0.03140	0.00156
264430.50	653231.50	0.03739	0.00192	0.03130	0.00156
264430.50	653232.50	0.03705	0.00187	0.03130	0.00156
264431.50	653203.50	0.03286	0.00234	0.02406	0.00092
264431.50	653204.50	0.03286	0.00234	0.02523	0.00108
264431.50	653205.50	0.03726	0.00187	0.02525	0.00098
264431.50	653206.50	0.03805	0.00191	0.02544	0.00046
264431.50	653207.50	0.03964	0.00211	0.02524	0.00042
264431.50	653208.50	0.03967	0.00205	0.02510	0.00049
264431.50	653209.50	0.04049	0.00225	0.02440	0.00093
264431.50	653210.50	0.03853	0.00182	0.02416	0.00087
264431.50	653211.50	0.03604	0.00144	0.02440	0.00073
264431.50	653212.50	0.03336	0.00115	0.02431	0.00070

264431.50	653213.50	0.03187	0.00110	0.02375	0.00098
264431.50	653214.50	0.03000	0.00139	0.02480	0.00141
264431.50	653215.50	0.02971	0.00147	0.02595	0.00111
264431.50	653216.50	0.02770	0.00107	0.02646	0.00105
264431.50	653217.50	0.02567	0.00083	0.02844	0.00081
264431.50	653218.50	0.02385	0.00076	0.02987	0.00061
264431.50	653219.50	0.02388	0.00075	0.03124	0.00072
264431.50	653220.50	0.02515	0.00088	0.03137	0.00099
264431.50	653221.50	0.02559	0.00086	0.03218	0.00331
264431.50	653222.50	0.02566	0.00074	0.03224	0.00317
264431.50	653223.50	0.02671	0.00091	0.03156	0.00130
264431.50	653224.50	0.02792	0.00090	0.03032	0.00117
264431.50	653225.50	0.02988	0.00082	0.02978	0.00069
264431.50	653226.50	0.03241	0.00108	0.02954	0.00058
264431.50	653227.50	0.03584	0.00171	0.02966	0.00068
264431.50	653228.50	0.03662	0.00180	0.03009	0.00121
264431.50	653229.50	0.03567	0.00148	0.03140	0.00156
264431.50	653230.50	0.03478	0.00129	0.03140	0.00156
264432.50	653204.50	0.03286	0.00234	0.02525	0.00048
264432.50	653205.50	0.03806	0.00191	0.02507	0.00067
264432.50	653206.50	0.03884	0.00199	0.02489	0.00073
264432.50	653207.50	0.03830	0.00179	0.02463	0.00069
264432.50	653208.50	0.03898	0.00193	0.02460	0.00076
264432.50	653209.50	0.03876	0.00192	0.02554	0.00106
264432.50	653210.50	0.03668	0.00169	0.02557	0.00177
264432.50	653211.50	0.03403	0.00153	0.02497	0.00067
264432.50	653212.50	0.03301	0.00154	0.02477	0.00068
264432.50	653213.50	0.03175	0.00115	0.02493	0.00082
264432.50	653214.50	0.02939	0.00116	0.02505	0.00093
264432.50	653215.50	0.02861	0.00107	0.02525	0.00128
264432.50	653216.50	0.02732	0.00083	0.02569	0.00178
264432.50	653217.50	0.02558	0.00078	0.02876	0.00108
264432.50	653218.50	0.02350	0.00082	0.02970	0.00095
264432.50	653219.50	0.02341	0.00077	0.03139	0.00070
264432.50	653220.50	0.02480	0.00066	0.03166	0.00084
264432.50	653221.50	0.02527	0.00067	0.03145	0.00419
264432.50	653222.50	0.02463	0.00082	0.03134	0.00197
264432.50	653223.50	0.02579	0.00077	0.03133	0.00352
264432.50	653224.50	0.02796	0.00072	0.03079	0.00094
264432.50	653225.50	0.02960	0.00093	0.03044	0.00069
264432.50	653226.50	0.03108	0.00115	0.02984	0.00072
264432.50	653227.50	0.03319	0.00115	0.02999	0.00069
264432.50	653228.50	0.03439	0.00123	0.03140	0.00156
264432.50	653229.50	0.03455	0.00130	0.03140	0.00156
264433.50	653206.50	0.04392	0.00310	0.02476	0.00093
264433.50	653207.50	0.03912	0.00209	0.02452	0.00087

264433.50	653208.50	0.03849	0.00201	0.02466	0.00081
264433.50	653209.50	0.03705	0.00186	0.02596	0.00084
264433.50	653210.50	0.03471	0.00185	0.02599	0.00083
264433.50	653211.50	0.03263	0.00193	0.02416	0.00087
264433.50	653212.50	0.03214	0.00199	0.02416	0.00097
264433.50	653213.50	0.03163	0.00146	0.02529	0.00086
264433.50	653214.50	0.02916	0.00107	0.02532	0.00087
264433.50	653215.50	0.02811	0.00092	0.02546	0.00119
264433.50	653216.50	0.02739	0.00099	0.02610	0.00109
264433.50	653217.50	0.02662	0.00105	0.02885	0.00105
264433.50	653218.50	0.02535	0.00079	0.02996	0.00093
264433.50	653219.50	0.02504	0.00069	0.03102	0.00048
264433.50	653220.50	0.02575	0.00085	0.03138	0.00079
264433.50	653221.50	0.02584	0.00083	0.03061	0.00272
264433.50	653222.50	0.02508	0.00075	0.03079	0.00246
264433.50	653223.50	0.02605	0.00069	0.03123	0.00213
264433.50	653224.50	0.02866	0.00072	0.03075	0.00058
264433.50	653225.50	0.02977	0.00097	0.03059	0.00078
264433.50	653226.50	0.03049	0.00112	0.02980	0.00087
264433.50	653227.50	0.03169	0.00091	0.03040	0.00154
264434.50	653207.50	0.03797	0.00194	0.02497	0.00093
264434.50	653208.50	0.03709	0.00187	0.02510	0.00089
264434.50	653209.50	0.03566	0.00182	0.02531	0.00068
264434.50	653210.50	0.03390	0.00191	0.02536	0.00064
264434.50	653211.50	0.03256	0.00207	0.02425	0.00095
264434.50	653212.50	0.03217	0.00198	0.02549	0.00204
264434.50	653213.50	0.03106	0.00168	0.02686	0.00114
264434.50	653214.50	0.03011	0.00119	0.02595	0.00089
264434.50	653215.50	0.02798	0.00097	0.02648	0.00092
264434.50	653216.50	0.02761	0.00117	0.02762	0.00089
264434.50	653217.50	0.02735	0.00135	0.02917	0.00090
264434.50	653218.50	0.02647	0.00093	0.03080	0.00080
264434.50	653219.50	0.02595	0.00080	0.03085	0.00059
264434.50	653220.50	0.02623	0.00087	0.03116	0.00080
264434.50	653221.50	0.02637	0.00088	0.03061	0.00186
264434.50	653222.50	0.02636	0.00067	0.03047	0.00381
264434.50	653223.50	0.02724	0.00066	0.03090	0.00105
264434.50	653224.50	0.02894	0.00088	0.03067	0.00046
264434.50	653225.50	0.02967	0.00094	0.03108	0.00065
264434.50	653226.50	0.03046	0.00084	0.03040	0.00154
264434.50	653227.50	0.03172	0.00095	0.03040	0.00154
264435.50	653208.50	0.03146	0.00225	0.02475	0.00099
264435.50	653209.50	0.03146	0.00225	0.02428	0.00063
264435.50	653210.50	0.03146	0.00225	0.02514	0.00059
264435.50	653211.50	0.03146	0.00225	0.02585	0.00078
264435.50	653212.50	0.03146	0.00225	0.02696	0.00112

264435.50	653213.50	0.03087	0.00155	0.02731	0.00121
264435.50	653214.50	0.02983	0.00116	0.02630	0.00096
264435.50	653215.50	0.02808	0.00103	0.02645	0.00103
264435.50	653216.50	0.02741	0.00104	0.02856	0.00087
264435.50	653217.50	0.02682	0.00115	0.02943	0.00065
264435.50	653218.50	0.02645	0.00107	0.03061	0.00076
264435.50	653219.50	0.02625	0.00108	0.03036	0.00074
264435.50	653220.50	0.02613	0.00078	0.03071	0.00159
264435.50	653221.50	0.02627	0.00071	0.03058	0.00197
264435.50	653222.50	0.02711	0.00070	0.03027	0.00117
264435.50	653223.50	0.02826	0.00088	0.03052	0.00057
264435.50	653224.50	0.02888	0.00100	0.03052	0.00050
264435.50	653225.50	0.02960	0.00101	0.03083	0.00090
264435.50	653226.50	0.03041	0.00083	0.03040	0.00154
264436.50	653208.50	0.03146	0.00225	0.02327	0.00079
264436.50	653209.50	0.03146	0.00225	0.02337	0.00073
264436.50	653210.50	0.03146	0.00225	0.02451	0.00065
264436.50	653211.50	0.03146	0.00225	0.02541	0.00078
264436.50	653212.50	0.03146	0.00225	0.02601	0.00079
264436.50	653213.50	0.03049	0.00166	0.02594	0.00079
264436.50	653214.50	0.02924	0.00125	0.02605	0.00086
264436.50	653215.50	0.02863	0.00123	0.02550	0.00101
264436.50	653216.50	0.02630	0.00110	0.03050	0.00109
264436.50	653217.50	0.02637	0.00101	0.02925	0.00058
264436.50	653218.50	0.02621	0.00104	0.02958	0.00046
264436.50	653219.50	0.02600	0.00098	0.02935	0.00171
264436.50	653220.50	0.02565	0.00091	0.02965	0.00201
264436.50	653221.50	0.02593	0.00083	0.02989	0.00512
264436.50	653222.50	0.02727	0.00084	0.02962	0.00081
264436.50	653223.50	0.02842	0.00110	0.03012	0.00048
264436.50	653224.50	0.02866	0.00089	0.03039	0.00071
264436.50	653225.50	0.02921	0.00080	0.03050	0.00154
264437.50	653209.50	0.03146	0.00225	0.02251	0.00094
264437.50	653210.50	0.03146	0.00225	0.02442	0.00086
264437.50	653211.50	0.03146	0.00225	0.02589	0.00114
264437.50	653212.50	0.03146	0.00225	0.02620	0.00116
264437.50	653213.50	0.03146	0.00225	0.02532	0.00086
264437.50	653214.50	0.02992	0.00151	0.02481	0.00089
264437.50	653215.50	0.02762	0.00141	0.02522	0.00102
264437.50	653216.50	0.02682	0.00115	0.02688	0.00108
264437.50	653217.50	0.02667	0.00103	0.02899	0.00061
264437.50	653218.50	0.02630	0.00096	0.02905	0.00047
264437.50	653219.50	0.02608	0.00093	0.02882	0.00867
264437.50	653220.50	0.02558	0.00108	0.02910	0.00190
264437.50	653221.50	0.02584	0.00090	0.02948	0.00385
264437.50	653222.50	0.02669	0.00089	0.02960	0.00045

264437.50	653223.50	0.02747	0.00086	0.02985	0.00049
264437.50	653224.50	0.02828	0.00078	0.02948	0.00088
264437.50	653225.50	0.02875	0.00087	0.02960	0.00152
264437.50	653226.50	0.03004	0.00119	0.02960	0.00152
264438.50	653211.50	0.03146	0.00225	0.02596	0.00104
264438.50	653212.50	0.03146	0.00225	0.02589	0.00111
264438.50	653213.50	0.03146	0.00225	0.02363	0.00146
264438.50	653215.50	0.02755	0.00140	0.02484	0.00105
264438.50	653216.50	0.02659	0.00111	0.02726	0.00113
264438.50	653217.50	0.02637	0.00110	0.02892	0.00105
264438.50	653218.50	0.02602	0.00098	0.02886	0.00073
264438.50	653219.50	0.02614	0.00088	0.02832	0.00115
264438.50	653220.50	0.02579	0.00092	0.02857	0.00219
264438.50	653221.50	0.02613	0.00092	0.02897	0.00109
264438.50	653222.50	0.02644	0.00111	0.02912	0.00048
264438.50	653223.50	0.02695	0.00092	0.02934	0.00063
264438.50	653224.50	0.02759	0.00084	0.02960	0.00152
264438.50	653225.50	0.02779	0.00113	0.02960	0.00152
264438.50	653226.50	0.02877	0.00110	0.02960	0.00152
264438.50	653227.50	0.02978	0.00109	0.02960	0.00152
264439.50	653216.50	0.02667	0.00191	0.02688	0.00095
264439.50	653217.50	0.02553	0.00130	0.02896	0.00139
264439.50	653218.50	0.02552	0.00107	0.02886	0.00092
264439.50	653219.50	0.02543	0.00107	0.02868	0.00051
264439.50	653220.50	0.02591	0.00091	0.02871	0.00051
264439.50	653221.50	0.02605	0.00092	0.02864	0.00053
264439.50	653222.50	0.02639	0.00094	0.02859	0.00058
264439.50	653223.50	0.02672	0.00086	0.02863	0.00084
264439.50	653224.50	0.02693	0.00090	0.02930	0.00140
264439.50	653225.50	0.02749	0.00105	0.02960	0.00152
264439.50	653226.50	0.02807	0.00102	0.02960	0.00152
264439.50	653227.50	0.02890	0.00107	0.02960	0.00152
264440.50	653217.50	0.02441	0.00176	0.02818	0.00118
264440.50	653218.50	0.02553	0.00106	0.02844	0.00118
264440.50	653219.50	0.02551	0.00094	0.02835	0.00077
264440.50	653220.50	0.02552	0.00096	0.02788	0.00067
264440.50	653221.50	0.02606	0.00091	0.02745	0.00075
264440.50	653222.50	0.02609	0.00095	0.02770	0.00082
264440.50	653223.50	0.02629	0.00111	0.02780	0.00105
264440.50	653224.50	0.02626	0.00133	0.02912	0.00133
264440.50	653225.50	0.02673	0.00111	0.02930	0.00140
264440.50	653226.50	0.02719	0.00107	0.02960	0.00152
264440.50	653227.50	0.02828	0.00107	0.02960	0.00152
264441.50	653219.50	0.02530	0.00105	0.02920	0.00151
264441.50	653220.50	0.02537	0.00106	0.02600	0.00144
264441.50	653221.50	0.02545	0.00110	0.02600	0.00144

264441.50	653222.50	0.02571	0.00109	0.02630	0.00133
264441.50	653223.50	0.02581	0.00140	0.02648	0.00126
264441.50	653224.50	0.02607	0.00144	0.02780	0.00105
264441.50	653225.50	0.02639	0.00126	0.02849	0.00114
264441.50	653226.50	0.02702	0.00119	0.02960	0.00152
264441.50	653227.50	0.02752	0.00115	0.02960	0.00152
264442.50	653220.50	0.02573	0.00131	0.02516	0.00101
264442.50	653221.50	0.02571	0.00134	0.02542	0.00109
264442.50	653222.50	0.02589	0.00122	0.02581	0.00130
264442.50	653223.50	0.02586	0.00132	0.02613	0.00123
264442.50	653224.50	0.02586	0.00137	0.02711	0.00110
264442.50	653225.50	0.02593	0.00147	0.02780	0.00105
264442.50	653226.50	0.02604	0.00139	0.02720	0.00104
264442.50	653227.50	0.02614	0.00134	0.02480	0.00141
264442.50	653228.50	0.02620	0.00133	0.02480	0.00141
264443.50	653220.50	0.02563	0.00184	0.02488	0.00084
264443.50	653221.50	0.02563	0.00184	0.02482	0.00102
264443.50	653222.50	0.02563	0.00184	0.02505	0.00100
264443.50	653223.50	0.02563	0.00184	0.02528	0.00104
264443.50	653224.50	0.02593	0.00147	0.02530	0.00104
264443.50	653225.50	0.02597	0.00143	0.02540	0.00101
264443.50	653226.50	0.02604	0.00138	0.02498	0.00103
264443.50	653227.50	0.02563	0.00184	0.02495	0.00107
264443.50	653228.50	0.02563	0.00184	0.02495	0.00107
264444.50	653221.50	0.02563	0.00184	0.02432	0.00119
264444.50	653222.50	0.02563	0.00184	0.02429	0.00126
264444.50	653223.50	0.02563	0.00184	0.02468	0.00106
264444.50	653224.50	0.02563	0.00184	0.02494	0.00100
264444.50	653225.50	0.02563	0.00184	0.02502	0.00101
264444.50	653226.50	0.02563	0.00184	0.02499	0.00103
264444.50	653227.50	0.02563	0.00184	0.02490	0.00116
264445.50	653223.50	0.02563	0.00184	0.02410	0.00139
264445.50	653224.50	0.02563	0.00184	0.02410	0.00139
264445.50	653225.50	0.02563	0.00184	0.02505	0.00100

5.3.4 Complex radiation field that inside a busy laboratory with an accelerator at the Scottish Universities Environmental Research Centre.

Mean and standard deviation of dose rate recorded from unirradiated samples using the SUERC portable OSL reader at 470 nm, from AML Labtorey , after 3336 hour

x /cm	y /cm	y cm	z	N. dosimeters	OSL	Std.err	Dose mGy		Dose rate μGy/h	Std.err
19	-9	737	33	1	2939.0	41.9702	0.0742	0.0053	0.0222	0.0016
82	-30	716	5	2	3074.5	42.6468	0.0776	0.0055	0.0233	0.0016
38	-16	730	6	4	3249.5	43.2059	0.0821	0.0058	0.0246	0.0017
71	-34	712	9	6	2397.5	38.4090	0.0605	0.0043	0.0181	0.0013
92	-56	690	11	7	2345.0	37.5233	0.0592	0.0042	0.0178	0.0013
58	-35	711	3	10	2140.0	36.1040	0.0540	0.0039	0.0162	0.0012
112	-26	720	4	13	2822.0	41.0122	0.0713	0.0050	0.0214	0.0015
263	-16	730	7	30	2118.0	36.3524	0.0535	0.0038	0.0160	0.0011
133	-56	690	12	32	3184.0	43.8805	0.0804	0.0057	0.0241	0.0017
133	-56	690	12	33	1529.0	32.1947	0.0386	0.0028	0.0116	0.0008
69	-25	721	32	35	2565.5	39.3859	0.0648	0.0046	0.0194	0.0014
25	-50	696	16	36	2071.0	36.2974	0.0523	0.0037	0.0157	0.0011
46	-34	712	9	37	2104.5	36.3834	0.0531	0.0038	0.0159	0.0011
69	-28	718	10	38	1153.0	28.5570	0.0291	0.0021	0.0087	0.0006
82	-16	730	5	39	2502.5	38.8941	0.0632	0.0045	0.0189	0.0013
130	-30	716	26	40	2343.0	38.3667	0.0592	0.0042	0.0177	0.0013
46	-154	2146	71	43	2160.5	36.3559	0.0546	0.0039	0.0164	0.0012
29	-154	2146	74	44	2383.5	38.5195	0.0602	0.0043	0.0180	0.0013
50	-154	2146	71	45	5768.5	56.4247	0.1457	0.0102	0.0437	0.0031
73	-154	2146	68	47	3980.5	47.2467	0.1005	0.0071	0.0301	0.0021
108	-149	2151	69	48	3651.5	45.9102	0.0922	0.0065	0.0276	0.0019
134	-143	2157	72	49	4136.0	48.0104	0.1044	0.0073	0.0313	0.0022
166	-140	2160	72	50	4308.0	48.9132	0.1088	0.0076	0.0326	0.0023
181	-137	2163	72	55	4930.5	52.6284	0.1245	0.0087	0.0373	0.0026
97	-173	2127	34	56	4325.5	49.8874	0.1092	0.0077	0.0327	0.0023
116	-207	2093	31	57	4565.0	50.5173	0.1153	0.0081	0.0346	0.0024
128	-228	2072	28	58	4255.0	48.7596	0.1074	0.0075	0.0322	0.0023
163	-268	2032	8	60	2416.0	38.3732	0.0610	0.0043	0.0183	0.0013
92	-156	2144	28	64	2711.5	40.3454	0.0685	0.0049	0.0205	0.0015
152	-179	2121	32	65	3915.5	46.9867	0.0989	0.0070	0.0296	0.0021
8	-36	2264	3	72	4750.5	51.6406	0.1200	0.0084	0.0360	0.0025
24	-36	2264	6	73	2706.5	42.0803	0.0683	0.0049	0.0205	0.0015
40	-36	2264	11	74	5235.0	29.3245	0.1322	0.0092	0.0396	0.0028
56	-36	2264	15	75	3253.0	43.9943	0.0821	0.0058	0.0246	0.0017
72	-59	2241	20	76	5650.0	55.6687	0.1427	0.0100	0.0428	0.0030
88	-74	2226	25	77	2934.0	41.3461	0.0741	0.0052	0.0222	0.0016
103	-142	1170	4	110	6051.0	57.1577	0.1528	0.0107	0.0458	0.0032
133	-142	1170	18	111	2413.0	38.1248	0.0609	0.0043	0.0183	0.0013
186	-137	1175	23	113	7984.0	35.3058	0.2016	0.0140	0.0604	0.0042
209	-134	1178	23	114	3483.0	44.4522	0.0880	0.0062	0.0264	0.0019
243	-132	1180	23	115	5028.0	52.6735	0.1270	0.0089	0.0381	0.0027
110	-130	1182	23	116	3042.5	42.0387	0.0768	0.0054	0.0230	0.0016
129	-128	1184	23	117	2366.0	37.9078	0.0597	0.0043	0.0179	0.0013
151	-126	1186	23	118	5108.5	52.6047	0.1290	0.0090	0.0387	0.0027

161	-124	1188	23	119	2588.5	38.8877	0.0654	0.0046	0.0196	0.0014
44	-109	1203	18	121	5583.0	55.0318	0.1410	0.0099	0.0423	0.0030
62	-111	1201	18	122	6060.0	57.2014	0.1530	0.0107	0.0459	0.0032
84	-111	1201	18	123	4272.0	49.1477	0.1079	0.0076	0.0323	0.0023
110	-100	1212	18	124	4705.5	51.4174	0.1188	0.0083	0.0356	0.0025
139	-100	1212	18	125	4787.5	51.8676	0.1209	0.0085	0.0362	0.0025
169	-100	1212	18	126	3408.5	43.9744	0.0861	0.0061	0.0258	0.0018
189	-103	1209	18	128	5610.5	55.2653	0.1417	0.0099	0.0425	0.0030
239	-106	1206	18	129	3724.0	46.3195	0.0940	0.0066	0.0282	0.0020
262	-100	1212	18	154	4875.5	51.8917	0.1231	0.0086	0.0369	0.0026
84	-23	1057	42	163	1400.5	31.4205	0.0354	0.0026	0.0106	0.0008
Average					3619.382	43.94194144	0.091398531	0.00643912	0.027397641	0.001930192

Mean and standard deviation of dose rate recorded from irradiated samples using the SUERC portable OSL reader at 470 nm, from AML Labtorey , after 19444 hours

N.dosimetes	OSL	sstr	Dose mGy	Dose rate μGy/h	Std.err	Net dose (mGy)	STD.de	Net μGy/h	STD.de
2	5676.0	55.83	0.14	0.07	0.01	0.05	0.01	0.03	0.01
5	6311.5	58.66	0.16	0.05	0.00	0.07	0.01	0.04	0.01
9	8090.0	72.41	0.20	0.06	0.00	0.11	0.02	0.06	0.01
11	5418.0	54.04	0.14	0.04	0.00	0.05	0.01	0.02	0.01
12	6596.5	59.78	0.17	0.05	0.00	0.08	0.01	0.04	0.01
13	5487.0	54.71	0.14	0.04	0.00	0.05	0.01	0.02	0.01
14	6032.5	57.02	0.15	0.05	0.00	0.06	0.01	0.03	0.01
18	17171.0	53.35	0.43	0.13	0.01	0.34	0.03	0.18	0.02
20	9397.0	68.85	0.24	0.07	0.00	0.15	0.02	0.08	0.01
21	5074.5	26.43	0.13	0.04	0.00	0.04	0.01	0.02	0.01
22	4168.5	48.61	0.11	0.03	0.00	0.02	0.01	0.01	0.00
23	4942.5	66.36	0.12	0.04	0.00	0.03	0.01	0.02	0.01
26	5947.5	56.82	0.15	0.05	0.00	0.06	0.01	0.03	0.01
31	3986.0	48.26	0.10	0.03	0.00	0.01	0.01	0.01	0.00
32	3967.0	47.42	0.10	0.03	0.00	0.01	0.01	0.01	0.00
35	4941.5	34.90	0.12	0.04	0.00	0.03	0.01	0.02	0.01
36	4075.5	48.03	0.10	0.03	0.00	0.01	0.01	0.01	0.00
37	5656.0	55.38	0.14	0.04	0.00	0.05	0.01	0.03	0.01
40	7656.0	61.22	0.19	0.06	0.00	0.10	0.01	0.05	0.01
41	18887.0	97.23	0.48	0.14	0.01	0.39	0.03	0.20	0.02
42	13833.0	45.60	0.35	0.10	0.01	0.26	0.02	0.13	0.01
43	5432.0	55.30	0.14	0.04	0.00	0.05	0.01	0.02	0.01
44	4077.5	24.83	0.10	0.03	0.00	0.01	0.01	0.01	0.00
45	3746.0	35.23	0.09	0.03	0.00	0.00	0.01	0.00	0.00
51	7842.5	64.73	0.20	0.06	0.00	0.11	0.01	0.06	0.01
52	28202	87.87	0.71	0.04	0.21	0.01	0.62	0.05	0.32
53	9676.0	71.40	0.24	0.07	0.01	0.15	0.02	0.08	0.01
54	7289.5	62.58	0.18	0.06	0.00	0.09	0.01	0.05	0.01
60	26111.0	115.25	0.66	0.20	0.01	0.57	0.05	0.29	0.02
61	29973.5	123.42	0.76	0.23	0.02	0.67	0.05	0.34	0.03
65	23112.0	45.22	0.58	0.17	0.01	0.49	0.04	0.25	0.02
68	7016.0	61.05	0.18	0.05	0.00	0.09	0.01	0.04	0.01
69	5947.0	57.38	0.15	0.05	0.00	0.06	0.01	0.03	0.01
70	5832.5	56.34	0.15	0.04	0.00	0.06	0.01	0.03	0.01
71	6146.5	57.74	0.16	0.05	0.00	0.07	0.01	0.03	0.01
79	14354.0	62.23	0.36	0.11	0.01	0.27	0.03	0.14	0.01
80	8059.0	65.56	0.20	0.06	0.00	0.11	0.02	0.06	0.01
82	21504.0	76.34	0.54	0.16	0.01	0.45	0.04	0.23	0.02
83	9882.5	71.84	0.25	0.07	0.01	0.16	0.02	0.08	0.01
87	8755.0	68.33	0.22	0.07	0.00	0.13	0.02	0.07	0.01
89	20383.0	54.34	0.51	0.15	0.01	0.42	0.04	0.22	0.02
90	10474.5	74.45	0.26	0.08	0.01	0.17	0.02	0.09	0.01
91	6930.5	61.68	0.18	0.05	0.00	0.08	0.01	0.04	0.01
92	16765.0	61.40	0.42	0.13	0.01	0.33	0.03	0.17	0.02
93	10380.0	73.55	0.26	0.08	0.01	0.17	0.02	0.09	0.01
94	9224.0	70.17	0.23	0.07	0.00	0.14	0.02	0.07	0.01
95	11315.5	77.10	0.29	0.09	0.01	0.20	0.02	0.10	0.01
97	5712.5	56.50	0.14	0.04	0.00	0.05	0.01	0.03	0.01
99	10252.0	73.40	0.26	0.08	0.01	0.17	0.02	0.09	0.01
100	9160.5	69.89	0.23	0.07	0.00	0.14	0.02	0.07	0.01
101	11706.0	78.45	0.30	0.09	0.01	0.21	0.02	0.11	0.01
116	7469.0	63.33	0.19	0.06	0.00	0.10	0.01	0.05	0.01

117	17647.0	72.45	0.45	0.13	0.01	0.36	0.03	0.18	0.02
128	19664.0	65.45	0.50	0.15	0.01	0.41	0.03	0.21	0.02
130	17638.0	54.32	0.45	0.13	0.01	0.36	0.03	0.18	0.02
131	6688.0	59.98	0.17	0.05	0.00	0.08	0.01	0.04	0.01
132	8299.0	66.37	0.21	0.06	0.00	0.12	0.02	0.06	0.01
133	7654.5	64.15	0.19	0.06	0.00	0.10	0.01	0.05	0.01
134	7973.5	65.36	0.20	0.06	0.00	0.11	0.01	0.06	0.01
135	7867.0	64.90	0.20	0.06	0.00	0.11	0.01	0.06	0.01
136	7196.5	62.68	0.18	0.05	0.00	0.09	0.01	0.05	0.01
137	7227.0	62.05	0.18	0.05	0.00	0.09	0.01	0.05	0.01
140	7758.0	64.24	0.20	0.06	0.00	0.11	0.01	0.05	0.01
141	11536.0	42.11	0.29	0.09	0.01	0.20	0.02	0.10	0.01
142	9267.5	70.19	0.23	0.07	0.00	0.14	0.02	0.07	0.01
143	8253.5	66.19	0.21	0.06	0.00	0.12	0.02	0.06	0.01
144	7916.0	65.57	0.20	0.06	0.00	0.11	0.01	0.06	0.01
145	15543.0	63.89	0.39	0.12	0.01	0.30	0.03	0.16	0.01
146	8548.5	67.86	0.22	0.06	0.00	0.13	0.02	0.06	0.01
147	16236.0	57.86	0.41	0.12	0.01	0.32	0.03	0.16	0.01
148	7276.0	62.67	0.18	0.06	0.00	0.09	0.01	0.05	0.01
149	16719.0	49.91	0.42	0.13	0.01	0.33	0.03	0.17	0.02
150	12782.5	47.42	0.32	0.10	0.01	0.23	0.02	0.12	0.01
151	13444.0	43.54	0.34	0.10	0.01	0.25	0.02	0.13	0.01
152	16924.0	59.45	0.43	0.13	0.01	0.34	0.03	0.17	0.02
153	18760.0	42.92	0.47	0.14	0.01	0.38	0.03	0.20	0.02
154	15092.0	39.41	0.38	0.11	0.01	0.29	0.03	0.15	0.01
155	8447.5	67.17	0.21	0.06	0.00	0.12	0.02	0.06	0.01
156	7953.5	65.14	0.20	0.06	0.00	0.11	0.01	0.06	0.01
157	8000.5	65.64	0.20	0.06	0.00	0.11	0.01	0.06	0.01
158	9615.0	71.10	0.24	0.07	0.01	0.15	0.02	0.08	0.01
159	9396.0	70.79	0.24	0.07	0.00	0.15	0.02	0.08	0.01
160	7712.5	64.41	0.19	0.06	0.00	0.10	0.01	0.05	0.01
161	10967.5	75.66	0.28	0.08	0.01	0.19	0.02	0.10	0.01
163	10130.5	72.85	0.26	0.08	0.01	0.17	0.02	0.09	0.01
164	11320.5	76.84	0.29	0.09	0.01	0.20	0.02	0.10	0.01
165	10516.5	74.13	0.27	0.08	0.01	0.18	0.02	0.09	0.01
166	9854.5	72.00	0.25	0.07	0.01	0.16	0.02	0.08	0.01
167	5492.0	55.03	0.14	0.04	0.00	0.05	0.01	0.03	0.01
168	10153.0	73.17	0.26	0.08	0.01	0.17	0.02	0.09	0.01
168	10484.5	74.18	0.26	0.08	0.01	0.17	0.02	0.09	0.01
170	4042.0	48.00	0.10	0.03	0.00	0.01	0.01	0.01	0.00
171	4415.0	49.70	0.11	0.03	0.00	0.02	0.01	0.01	0.00
172	18484.0	72.17	0.47	0.14	0.01	0.38	0.03	0.19	0.02
173	8432.0	67.02	0.21	0.06	0.00	0.12	0.02	0.06	0.01
174	9199.5	70.13	0.23	0.07	0.00	0.14	0.02	0.07	0.01
175	20936.0	41.71	0.53	0.16	0.01	0.44	0.04	0.23	0.02
176	10375.0	73.63	0.26	0.08	0.01	0.17	0.02	0.09	0.01
177	20913.0	63.21	0.53	0.16	0.01	0.44	0.04	0.23	0.02
178	10053.5	72.36	0.25	0.08	0.01	0.16	0.02	0.08	0.01
180	9698.0	71.83	0.24	0.07	0.01	0.15	0.02	0.08	0.01
184	10389.0	74.21	0.26	0.08	0.01	0.17	0.02	0.09	0.01
185	21160.0	52.44	0.53	0.16	0.01	0.44	0.04	0.23	0.02
186	14031.0	85.43	0.35	0.11	0.01	0.26	0.03	0.14	0.01
187	11038.5	75.91	0.28	0.08	0.01	0.19	0.02	0.10	0.01
188	17388.0	61.70	0.44	0.13	0.01	0.35	0.03	0.18	0.02
189	18100.0	55.37	0.46	0.14	0.01	0.37	0.03	0.19	0.02
190	7472.5	63.24	0.19	0.06	0.00	0.10	0.01	0.05	0.01
191	12192.0	79.72	0.31	0.09	0.01	0.22	0.02	0.11	0.01
193	10209.0	73.72	0.26	0.08	0.01	0.17	0.02	0.09	0.01

194	12554.5	80.87	0.32	0.10	0.01	0.23	0.02	0.12	0.01
195	19708.0	44.98	0.50	0.15	0.01	0.41	0.03	0.21	0.02
196	9624.5	71.34	0.24	0.07	0.01	0.15	0.02	0.08	0.01
197	11103.0	53.50	0.28	0.08	0.01	0.19	0.02	0.10	0.01
198	10363.5	73.73	0.26	0.08	0.01	0.17	0.02	0.09	0.01