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Every organism on Earth is exposed to ionizing radiation. Food, water, air, rocks, soil, medical procedures, building materials and, of course, ubiquitous background cosmic radiation contribute in varying levels and types of radiation to our total radiation exposure. In 1987 and 2006, the National Council on Radiation Protection, (NCRP) undertook the task of attempting to estimate the total annual background radiation to which humans in the United States are exposed. My research sought to verify the NCRP estimates using a series of coordinated measurements of gamma radiation from sea level to over 14,000 feet altitude taken at multiple locations in the Continental United States. With one exception on Pikes Peak, the actual data recorded were found to be lower than the data points predicted by the NCRP. This was the case even though the gamma spectrometer employed was demonstrated to be 124X more sensitive than existing devices. The observed variances from predicted levels ranged from a maximum of 2.1 millisievert to a minimum of 0.4 millisievert.

UBIQUITOUS BACKGROUND RADIATION IN THE UNITED STATES: COMPARING NCRP ESTIMATES TO READINGS TAKEN AT SELECTED LOCATIONS IN THE CONTINENTAL UNITED STATES USING GAMMA SPECTROMETRY

by

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Approved by

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TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER I: INTRODUCTION

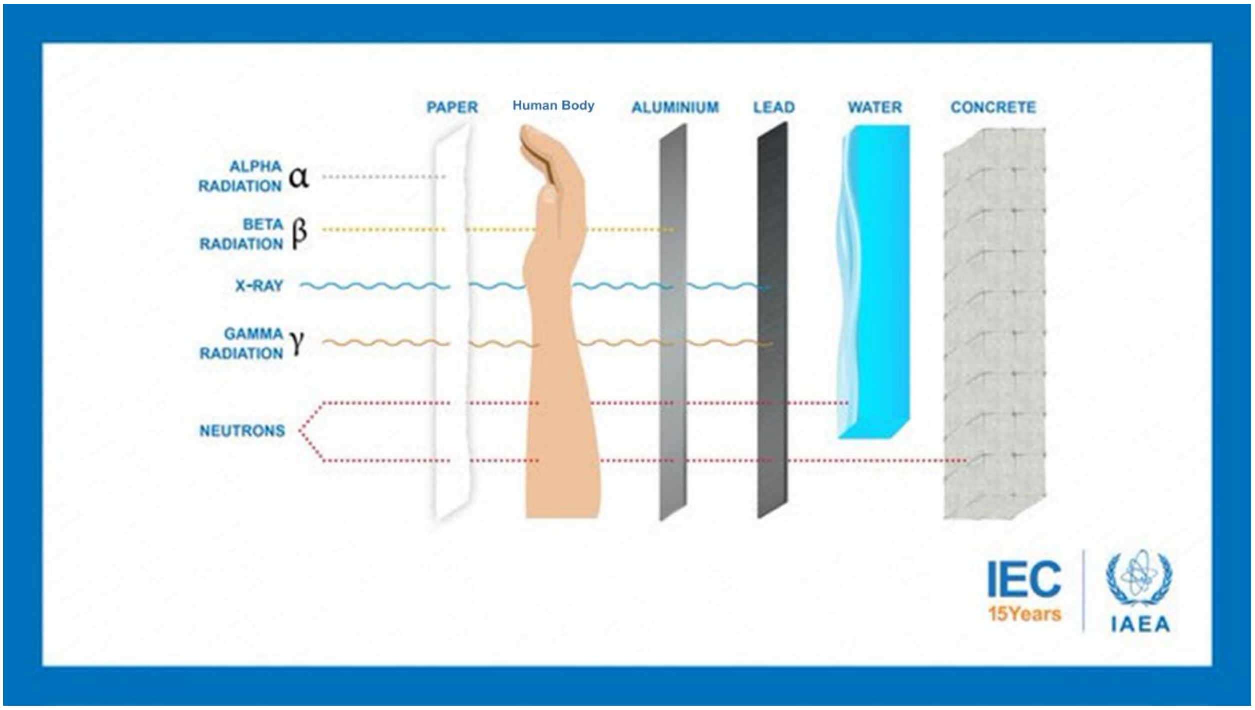
The Earth is radioactive. Many of the elements from which the Earth was formed are radioactive. This naturally occurring radioactivity is present in the air, soil, flora, rocks, and water. It finds its way into our bodies through the air we breathe, the water we drink, the food we consume, medical procedures, and countless man-made objects, from building materials to electronic devices.

Earth is also exposed to radiation from outer space. The majority of this radiation is from the Sun, but other sources in space contribute as well. The vast majority of this radiation is blocked by the magnetic fields surrounding Earth, and by Earth's atmosphere though some does reach the planet's surface. This natural radiation, whether from outer space, or Earth is referred to by physicists as 'ubiquitous background radiation'.

The National Council on Radiation Protection (NCRP) is tasked with estimating the amount of ionizing radiation the average American receives annually. These estimates are comprehensive with regard to factors which determine total exposure. The NCRP has published two reports on the amount of ionizing radiation received by the public, Report 94 in 1987, and Report 160 in 2006. In addition, several ancillary reports have been published which focus on specific sources of ionizing radiation, e.g. medical procedures, occupational exposure, and nuclear power production. (NCRP, 1987) (NCRP, 1989) (NCRP, 1989)

This study compares estimated numbers calculated by the NCRP to actual readings taken with the GSD-2100 Gamma Spectrometer from Sea Level to over 14,000 feet elevation.

Figure 1. Chart explaining how different emitters react to different materials (Source: IAEA)



Measuring Biological Effects of Ionizing Radiation

Parts of the body absorb radiation at different rates. Bones are more dense and absorb more radiation than soft tissues such as organs and muscles. This results in bones registering as white on x-rays, while muscles and organs appear semitranslucent, or grey.

To deal with this and allow more accurate measurement of the ionizing radiation to which patients are exposed, Rolf Maximillian Sievert developed the concept of "effective dose" in 1925 while at Radiumhemmet Institute at Solna, Sweden as a measure of estimating the total body exposure to ionizing radiation received when a portion of the body is exposed. Sievert was one of the founders of the International X-Ray and Radium Protection Committee in 1928. This group would eventually become the International Council on Radiation Protection and Measurements. Effective dose, as defined by the International Council on Radiation Protection and Measurements, or ICRP, in Publication 28, “is used to normalize partial-body irradiation relative to whole-body irradiation” (ICRP, 1978).

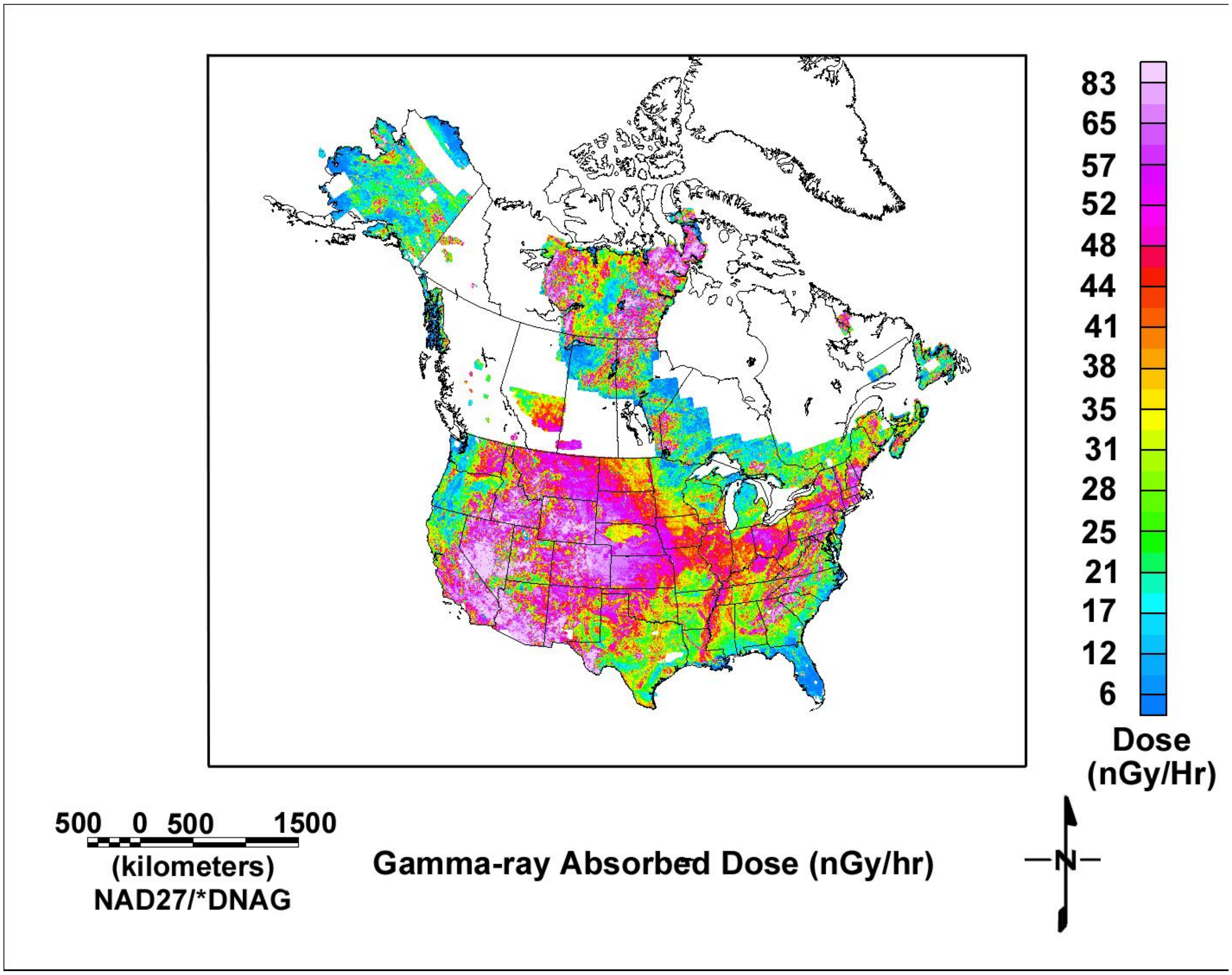
The formula for effective dose is $E = \sum W_T H_T$, where W_T represents the tissue weighting factor. Tissue Weighting Factor accounts for the relative radiation detriment for the organ or tissue from the stochastic health effect (NCRP, 1991). H_T represents equivalent dose, the radiation-weighted product of the absorbed dose. Additionally, a comparison of various activities and medical procedures has been developed by the NCRP. This is known as Background Equivalent Radiation Time, or BERT. BERT was defined by Professor J.R. Cameron while at the University of Wisconsin in 1991 (Cameron, 1991). We know this number because of the work done by the NCRP on ubiquitous background radiation. During a CT scan, the body will absorb ten millisievert (mSv) of radiation. This is the same amount of radiation a person would receive taking 500 transcontinental flights or 3.5 years of normal living. According to Report 160, the average American will receive 3.11 millisieverts of ubiquitous background radiation annually.

When measuring the amount of radiation an individual has received, there are measurements which are used for different situations, such as accounting for differences in tissue density and the form of radiation to which a person is exposed. Also, different units of measurement have been created to account for ionizing vs. non-ionizing radiation[1] and the type of dose received. Because all NCRP estimates of ubiquitous background radiation are expressed as effective dose, all readings for this study have been converted to effective dose to facilitate comparison. The units of measurement employed in calculating effective dose are sievert and roentgen. Roentgen (R) is the traditional unit of measurement for ionizing radiation, adopted by

[1] There are two forms of radiation: Ionizing and Non-Ionizing. Ionizing Radiation has energy sufficient to remove electrons from an atom, or to ionize it. Non-Ionizing Radiation does not possess enough energy to remove electrons. Non-Ionizing Radiation includes visible light, and some bands of infrared and microwave. For simplicity, all references to radiation in this paper are, in fact, “ionizing radiation”.

the ICRP in 1928. A roentgen is defined as the electrical charge released by ionizing radiation in a specified amount of air. The most common instrument which measures roentgen is the ion chamber. Ion chambers are used to measure the ionizing radiation in a specified volume of air. This unit of measurement was named in honor of Wilhelm Röentgen, who discovered X-Rays or Röentgen Rays as they were called at the time of discovery in 1895. Röentgen discovered x-rays while performing a test involving cathode ray tubes and barium platinocyanide paint on cardboard. Röentgen noticed what he described as sparkling on the paint when electrodes were run through the cathode ray tubing. Milliroentgen (mR) was used as the original measurement for ionizing radiation. Milliroentgen is defined as the electric charge released by ionizing radiation in a specified volume of air. A Geiger Muller counter is another common instrument used to measure ionizing radiation. The Geiger Muller counter is a radiation detection instrument which consists of a gas filled cylinder containing two electrodes. When ionizing radiation passes through the gas, it displaces electrons. These electrons become attracted to the electrodes, which creates an electrical pulse. These pulses are measured and counted, with the number of pulses indicating the strength of the radiation field. It is named after the inventors Hans Geiger and W. Muller, who invented the device in the 1920s. It measures radiation in Sievert or Roentgen.

Figure 2. Map presented in NCRP Report 160 of the estimated exposure to background radiation from a survey done by the US Geological Survey (Duval, 2005)



The GSD-2100

In 2018, Dr. Jonathan Dowell, physicist at Los Alamos National Laboratory in New Mexico, completed development of the GSD-2100 Lighthouse Gamma Spectrometer. The GSD-2100 is used for security purposes by members of Los Alamos Emergency Response Team in cooperation with government agencies to detect unauthorized sources of radioactive material.

I became aware of the GSD-2100 through a Los Alamos press release and contacted Dr. Dowell for more details. After several discussions about my research interests in remote sensing, Dr. Dowell offered the long-term use of a GSD-2100 for my research.

Measuring 3.4” wide, 3.4” high, 5.35” long, and weighing 20.5 pounds, the gamma spectrometer’s sensitivity and accuracy is achieved through the use of a Silicon Photomultiplier (SiPM) detector array surrounded by tungsten shielding. The combination of the directional SiPM array and the tungsten shielding allows the GSD-2100 to be very precise in measuring both background and gamma radiation. Since its development, the GSD has been used by organizations for threat detection and source containment. For example, a hospital could use the GSD-2100 to identify where a source outbreak occurred, and which employees spread the source unknowingly. For this project, this study took advantage of the GSD’s sensitivity and the directional aspect.

The multichannel analyzer allows for the GSD-2100 to pick up multiple wavelengths of radiation accurately. This is important in detecting ubiquitous background radiation, both natural and man made, since each element has a different wavelength depending on the atomic number. The ARM processor running at 160MHz allows the GSD to analyze the incoming data quicker. The counting rate of 33Hz allows for the GSD to display near real-time data compared to an Ion Chamber, this is advantageous in the field as it allows a more ready identification of radiation hotspots.

The QControl software used with the GSD-2100 was developed by the team at Los Alamos and Questra Instruments, in Tucson, Arizona. QControl displays the data from the GSD in real-time. It also calculates average counts per second, and can make calculations to account for background radiation when scanning for sources of gamma radiation. There are two forms of graphs available on QControl, one looking at total radiation detected and a graph displaying the average radiation rate.

The GSD-2100 spectrometer achieves the directionality of its detection through tungsten shielding surrounding the reader. This shielding protects the reader from stray gamma emitters and focuses the scan in a single direction with tungsten shielding limiting the cone of detection to a 35 degree field.

The sensitivity and directionality of the GSD provides a clear advantage over traditional detectors such as Geiger-Muller Counters and Ion Chambers. Additionally, the ability to detect emitters through lead shielding is advantageous. The GSD-2100 has been used to detect radionucleotides in rainwater in New Mexico and Hawaii for a PhD. Dissertation. The research in question found an increase in radionucleotides in areas around the Trinity Site in New Mexico.

Two additional tests of the GSD-2100's capability were conducted prior to beginning my field work. Both tests were carried out at Novant Health Systems Presbyterian Hospital with the supervision of Radiation Safety Officer and Physicist Brian Cripe, MSAP, CHP.

Test one was to determine the GSD's 'Cone of Detection'. To do this two radioactive sources, Thorium-232 and Cesium-137, both strong gamma emitters, were used. Each source was placed forty feet from the GSD and moved around the room while maintaining a forty foot distance from the detector. Once radioactive output dropped below a set limit of 500 gammas per second, the source was deemed to be outside the cone of detection. From these two tests, the cone of detection for the GSD-2100 was determined to be 35 degrees.

Second, the sensitivity of the GSD was compared to that of an Ion Chamber during a radiation therapy session. The session employed a 20.5 milliliter dose of Lutathera, Lutetium-177 (Lu-177). Both detectors were placed in a separate room 30 feet from the radioactive source. The room was shielded by two, ¾ inch sheets of lead and 2 inches of dry wall. The Ion Chamber registered 20 micro roentgen an hour while the GSD registered 25 milliroentgen. Converting milliroentgen to microroentgen gives 2,500 microroentgen per hour for the GSD, making the GSD-100 124X more sensitive than the Ion Chamber.

The QControl software used with the GSD-2100 was developed by the physicists at Los Alamos and Questra Instruments, in Tucson, Arizona. QControl displays the data from the GSD in real-time. The software is able to calculate the average counts per second, along with being able to discriminate against specific sources such as barium-131. Two forms of graphs are available on QControl, one for total radiation detected and one for average radiation rate.

To create additional graphs, OriginLab, a graphics package designed by Origin Software in Cambridge, Massachusetts was used. The program allows for the creation of a wide range of detailed graphs using data input by the user. The program can import data through a variety of file types including Excel spreadsheets, CSV files, and HTML tables. I attempted to import directly from QControl, but was unable to do so due to QControl's format. I attempted to write a code to allow the direct transfer of data between QControl and OriginLab, but was unsuccessful. A workaround was developed to transfer the data to a text file which could then be transferred to an Excel spreadsheet, then imported to OriginLab. This process was time consuming, but effective in producing a useable graph. One additional benefit was the ability to calculate an average between ascent and descent from the Excel spreadsheet. After importing the data, I completed the graphs showing the data from the scans I made at UNC-Greensboro, Wilmington, NC, Pikes' Peak, and Mt. Evans.

Figure 3. The GSD-2100 (Source: Los Alamos National Laboratory)

Figure 4. Configuration used for testing GSD's Cone of Detection and sensitivity

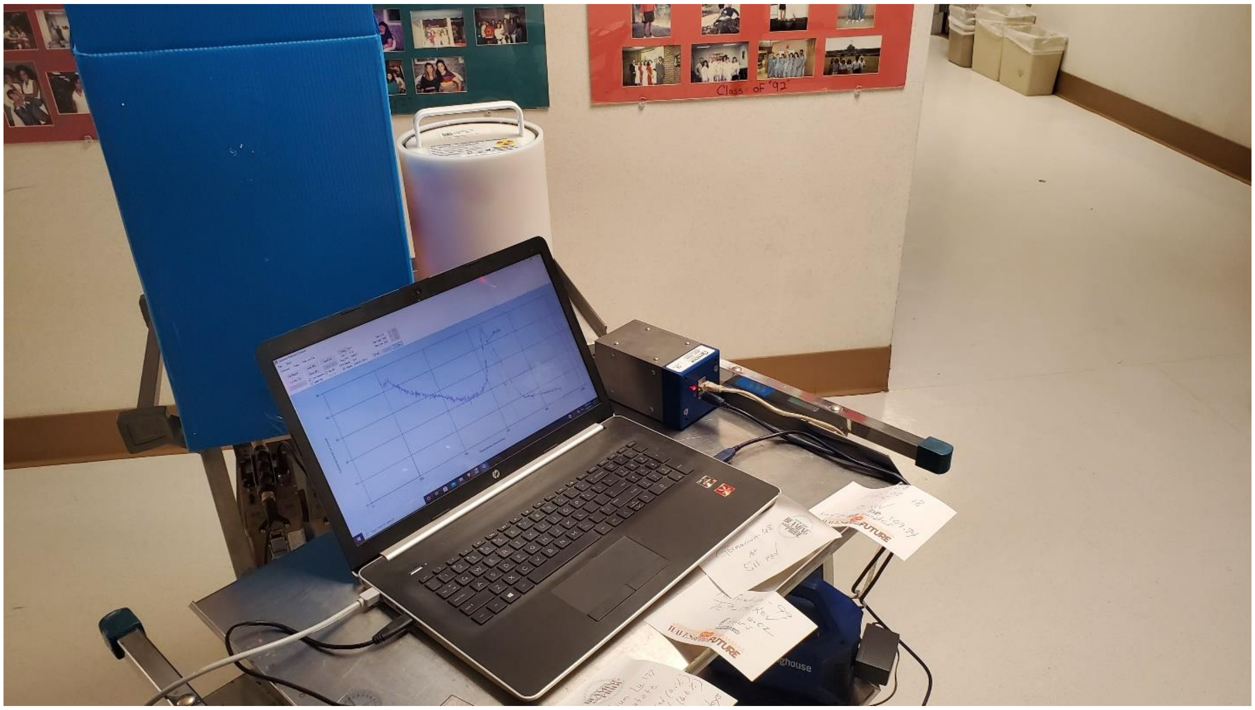
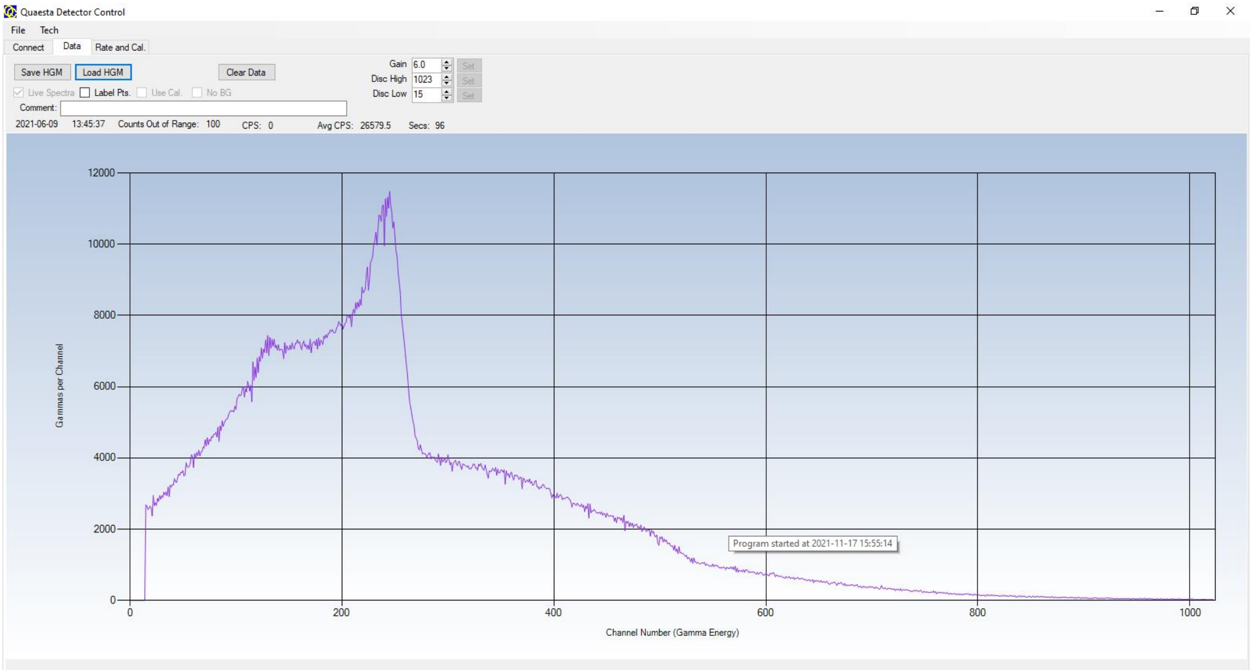


Figure 5. Result of GSD scan of Lutathera® treatment



CHAPTER II: COMPARING NCRP UBIQUITOUS BACKGROUND RADIATION ESTIMATES TO READINGS TAKEN AT UNC-GREENSBORO, WILMINGTON, NC, PIKES PEAK, AND MT. EVANS

Literature Review

My study compares the estimates presented by the NCRP in Report 160 to measurements taken in the continental United States. Estimates of all radiation exposure were updated in Report 160, the most significant increases were noted in radiation from medical procedures, technical, and occupational exposure. According to Dr. Kenneth Kase, senior vice president of the NCRP at the time Report 160 was published, the average American in the 2000's was exposed to seven times more ionizing radiation from medical procedure than the average American in the 1980's when Report 94 was published. The increase in exposure came from medical procedures involving x-rays and Computed Tomography (CT) scans. Additionally, exposure from technology and occupational sources had increased since the 1980s, with medical contributing 39% of occupational radiation, followed by high altitude commercial aviation at 38%.

Little has been written on the GSD as the device is only four years old and to my knowledge only two people outside of Los Alamos National Laboratories (LANL) have used the device, myself and Damien Milazzo of the University of New Mexico. "Lighthouse Project Saddlebags: Survey of Trinity Site" is an internal memo from Los Alamos National Laboratory which details Dowell and his team from Los Alamos taking several GSDs to the Trinity Site in New Mexico. The Trinity Site was chosen being the location of the nuclear tests in 1945. Since 1945, Los Alamos scientists have monitored the Trinity Site radiation levels and have compiled comprehensive data on these levels. Five locations at the site were tested: Ground Zero, the soil preservation shed, the perimeter fence, the pedestrian walkway, and the visitor parking lot. High levels of radioactivity around the ground zero pylon necessitated the use of a HAZMAT robot to carry the 2X2 array of GSDs around the pylon. 58 scans were made at Ground Zero, 11 around the perimeter fence, and 2 in the soil preservation shed. The duration of the scans ranged from as little as 10 second to as long as 5 minutes. (Dowell, 2018)

The readings of the pylon at Ground Zero registered over 1,000 counts per second, with traces of europium-152 and cesium-137 found in the area. This discovery is significant because europium-152 is the product of neutron activation in soil and cesium-137 is a direct product of the nuclear blasts at Trinity. (Dowell, 2018)

A problem arose when the team noticed the door to the Soil Preservation Shed was too small to accommodate the 2X2 array they had constructed. The solution was to use a single GSD with the HAZMAT robot extending its arm through the shed door. The first scan in the Soil Preservation scan was of the Trinitite pile at the doorway. Trinitite is the glassy residue leftover from the Trinity nuclear explosion as a result of sand from the desert floor being superheated. This scan read slightly lower than those at ground zero and contained traces of cesium-137 and europium-152. However, the scan of a patch of soil six feet from the trinitite yielded an interesting result. The counts per second for this patch of soil were 400 counts lower than the surrounding areas outside the shed, but still contained traces of cesium-137 and europium-152. Such a steep dropoff of counts so close to the ground zero pylon was unexpected. The next site was a combination of the pedestrian walkway leading to the perimeter fence and visitor parking lot. Here, there was a consistent decrease in counts per second leading out to the parking lot, along with a decrease in levels of cesium and europium. The counts per second in this area ranged from 427 counts per second at the gate to ground zero to as low as 80 counts per second in the Northeast corner of the parking lot (Dowell, 2018). The final scan was done around the perimeter fence and yielded results similar to scans done around ground zero. One scan site along the fence on the west side of the site did show an abundance of trinitite.

Next, Dowell and his team travelled to the Sierra Oscuras, located approximately 35 miles Northwest of the Trinity Site to compare the Trinity Site scans to those of a nearby geologic formation. The Sierra Oscuras contain a high percentage of granite and granite contains high amounts of natural radioactive material. Three sites were scanned near the town of Lemitar, New Mexico, with each scan lasting around 10 minutes. As with the Trinity Site, traces of europium-152 were found since europium is naturally occurring in granite. Traces of europium-154 were also found in the Oscuras, yet this element was absent from the Trinity Site. Dr. Dowell offered two possible explanations for this, either the neutron activation cross section for europium-154 is greater than that of europium-152, or the half-life for europium-154 is significantly shorter than europium-152. As expected, the Trinity Site radiation levels were 15 to 20 times higher than surrounding areas and there was a considerable dropoff in counts per second as distance from the ground zero pylon increased.

Damien Milazzo, a member of the team present at the Trinity Site, used the GSD for his PhD. Dissertation in Earth and Planetary Science at the University of New Mexico, "Radionuclides in Rainwater and Their Impact on Background Radiation". Milazzo's hypothesis was nuclear waste had been disposed of improperly, leading to leakage into surface water and would therefore increase the counts per second observed in rainwater. He suggested when irradiated surface water evaporates, the radionuclides present will be absorbed into the atmosphere where they would be spread by storms, and potentially mask emissions from other hazardous sources. While all water affects radiation levels, the radionuclides present in rainwater add attenuation which affects the accuracy in reading background radiation levels (Milazzo, 2018).

Using steel plates to provide additional attenuation, Milazzo built a testing enclosure for the GSD. Before taking rainwater samples, he obtained base readings using “non rainwater water”, i.e., groundwater. Comparing these groundwater readings to rainwater, Milazzo found an increase of 1% in rainwater. Milazzo used eleven test sites across New Mexico, including Los Alamos National Laboratory, and nine sites located on Kona Island in Hawaii. These sites were selected in order to capture as many unique lithologies as possible in New Mexico and Hawaii. At each site in New Mexico, three soil samples were taken and each placed into a 25cm steel tube. From these readings, he found an increase of counts per second in rainwater sets ranging from 30% to 3%, with the highest peaks being found at the Los Alamos site. Getting rainwater samples in New Mexico proved difficult, so Milazzo travelled to Hawaii around the time the Kilauea volcano was erupting. Because he was unable to travel with his enclosure used in New Mexico, Milazzo had to construct a second enclosure for use in Hawaii. Two control scans were performed, one on the west side of Kona Island, which according to Milazzo had not seen rain for three weeks prior to his arrival, and a bucket which he planned to use to collect rainwater samples. Nine buckets were placed along State Road 200 and were marked to prevent tampering. Multiple scans were performed at each site to ensure accurate readings as the radionuclides in the water have short half-lives. After analysis, Milazzo noticed a difference in notable peaks between the non-rainwater and rainwater scans. At the scan site on Kona Beach, Milazzo observed peaks in the 1275, 1325, and 1530 KeV ranges. For the rainwater scans, Milazzo observed notable peaks at the 225, 490, 600, and 1460 KeV ranges. These peaks line up with the gamma emissions of naturally occurring radionuclides such as potassium, uranium, and thorium (Milazzo, 2018).

Milazzo repeated this experiment during the monsoon season in New Mexico to see if he could produce similar results. He found many similar peaks between the rainwater samples of New Mexico and Hawaii. Additionally, increases in counts per second were seen at all sites involving rainfall. These increases ranged from 3% to as high as 30%, which seemed to verify Milazzo's hypothesis that radionuclides present in rainwater would lead in an increase in radioactivity.

As part of the Accident Tolerant Fuel Program at Idaho National Laboratory, a new gamma spectrometer was developed in 2019 for a Transient Reactor Test Facility, or TREAT. The system, known as the Separate Effects Test Holder, or SETH, was developed by the team of Drs. Luis Giraldo, Tommy Holschuh, Scott Thompson, Jay Hix, James Johnson, and David Chichester. This system was developed to scan nuclear fuel for contamination post-irradiation. In their paper "TREAT Fuel Motion Summary Report-SETH A-E Experiments", descriptions of the new spectrometer are given and the results of the tests the spectrometer underwent are analyzed. The system uses a high-purity germanium detector, along with a collimator and mechanical positioning stages. The shielding includes four 4-inch tungsten bricks and four 2-inch lead bricks. While the GSD weighs around twenty pounds with the tungsten shielding attached, the SETH gamma-ray scanning system weighs approximately eighty pounds (Ocampo, 2019). In order to test the efficiency of the system, a europium-152 source was used at fifty centimeters from the center of the detector. Additionally, a simulation was completed measuring energies between 200 keV and 1500 keV to compare to the readings and examine how the detector would do at higher frequencies. They found the detector lost efficiency at higher frequencies, around

1000 keV. The efficiency still fell within expected parameters. The next test completed was the dead time evaluation. Dead time is defined as the total time after each event in which the detector is unable to record another event. For the GSD-2100, the dead time is between 30 to 100 nanoseconds. This is critical for a directional radiation detector since a shorter dead time means a more accurate reading and a better directional capability. As expected, the results showed the detector had a longer dead time at higher counts, since the processing unit had to deal with more data, with a dead time of approximately 80 nanoseconds (Ocampo, 2019). For benchmark testing and fission calculations, used fuel rodlets from a pressurized water reactor were tested with enriched $U0_2$ at a level of 4.9% enrichment. The pellet rodlets were placed in five Separate Effects Test Holders and were scanned at different energy ranges. SETH-A was used as a baseline to determine the energy coupling factor calorimetry for the rest of the SETHs, receiving approximately 100 megajoules of energy for 20 seconds. SETH-B comprised of three separate test, SETH-B1, SETH-B1-R2, and SETH-B2. SETH-B1 was subjugated to the same amount of energy as SETH-A, around 100 megajoules for 20 seconds. In order to cause an increase in temperature, SETH-B1-R2 was subject to the same amount of energy as SETH-B1 but for a longer period, around 25 seconds. SETH-B2 was subjected to a higher amount of energy, 143 megajoules, but for only 10 seconds. To yield an increased specimen temperature, SETH-C received the same amount of energy as SETH-B2 but received that energy for 20 seconds. SETH-D received around 500 megajoules of energy and maintained the energy for slightly longer than SETH-C with the purpose of reaching the cladding's melting point of 1850^0C, lasting 25 seconds. Finally, SETH-E was subjected to the same amount of energy as SETH-D, but for a significantly longer period, lasting 40 seconds. This was done in order to allow the cladding to be deformed at a maximum temperature of 2113^0C. The results of this test showed the detector performed as expected even under the harsh conditions seen in SETHs D and E. In these two later tests, massive power spikes were observed. But according to the team, this result was expected (Ocampo, 2019).

One of Dr. Stewart Carlyle Bushong's earliest papers related to my study because it covered the composition and distribution of background radiation, "The Composition and Spatial Distribution of Background Radiation". This experiment was performed while he was Teaching Fellow at the University of Pittsburgh in 1964. Bushong set up his test site in the boiler room of Presbyterian Hospital to prior to the installation of a full body scanner. The first experiment of the study involved the directional nature of background radiation, similar to what my study covers. Bushong took six scans at different directions: up, down, North, South, East, and West. For his experiments, Bushong scanned at three different energy ranges: 0-400 KeV, 0.2-2.7 MeV, and 0-4 MeV. From these tests, Bushong was able to determine there was no direction which predominates background radiation. Additionally, there were no sources in the boiler room which would interfere with the installation of a full body scanner (Bushong, 1964). The next test performed by Bushong was an analysis of the soil to determine the amount of radium and potassium-40 present. To calibrate the scanner for the scan, samples of uranium, thorium, and potassium were scanned. While there was no apparent relation to depth observed, the type of rock formation beneath had a far greater effect. Bushong states the rock formations in the Pittsburgh area primarily consist of a sedimentary origin, primarily limestone, clay, and sandstones (Bushong, 1964). For air measurements, Bushong conducted two separate analyses of high volume membrane filters in the boiler room, one at a 20 minute decay rate and the other at a 24 hour decay rate. After his analysis, Bushong determined radium and potassium-40 made up 84 and 15 percent of the total spectra respectively. Bushong's final analysis involved measuring cosmic radiation with an unshielded reader with an energy range of 0-8 MeV. Following all analysis, Bushong determined radium in the air contributed to 89 percent of all background radiation. Ultimately, Bushong was not able to determine any factors which would affect the installation of a full body scanner.

Methodology

After completing initial testing of the GSD-2100, the first step of the current study was to employ the GSD-2100 to survey ubiquitous background radiation on the UNC-Greensboro campus. This was a repeat of a radiation survey I conducted of the campus in 2018 using a Geiger-Muller Counter.

The campus was divided into twenty-five grid squares and using GPS a single read site was determined within each square. Read sites varied between squares to accommodate buildings, building floor plans, traffic patterns, and vegetation. Background radiation readings were obtained for each grid square. Data were recorded for one minute in each square while the gamma spectrometer was rotated 360-degrees to cover the entire square. Between 2018 and 2022, the only change which had occurred to the area examined was the McIver Building. In 2018 the building had been demolished with debris still present and in 2022 the new structure was in place.

A comparison of the data obtained in the two scans is presented in Figure 3. As seen in the chart, 2018 scans show a spike to 33 counts per second around the 100 KeV range. The scans in this range were taken in grid square 2 near a rock garden on campus. Scanning the same location with the more sensitive GSD-2100 yielded a higher spike of 54 counts per second. This spike could be the result of radioactive material present in the rock.

A notable difference was my scan results of McIver Building in grid square 15 being higher in 2018 rather than 2022, as seen around the 150 KeV range. The 2018 scans were at 40 to 45 counts per second, while the 2022 scans were at 20 to 25 counts per second. When 2018 scans were performed, the old McIver Building was being demolished. In grid square 16, I found a spike in 2022 up to 50 counts per second which I did not observe in 2018. This spike is seen around the 225 KeV range on Figure 3. I am unable to provide an explanation for this spike since I was unable to identify a source at this location. It is possible the higher reading in 2018 was the result of radioactive elements in the construction material, but lack of access to the demolition site prevented me from a detailed scanning of the materials to determine if such was the case. These scans provided the basis for my conversion formula for Gammas Per Second to milliroentgen.

Before readings were taken at Pikes Peak and Mt. Evans, solar activity levels were checked because Coronal Mass Ejections could affect readings. Mass Coronal Ejections have been known to increase levels of ionizing background radiation.

Figure 6. Grid System used to determine read sites on the UNC-Greensboro campus

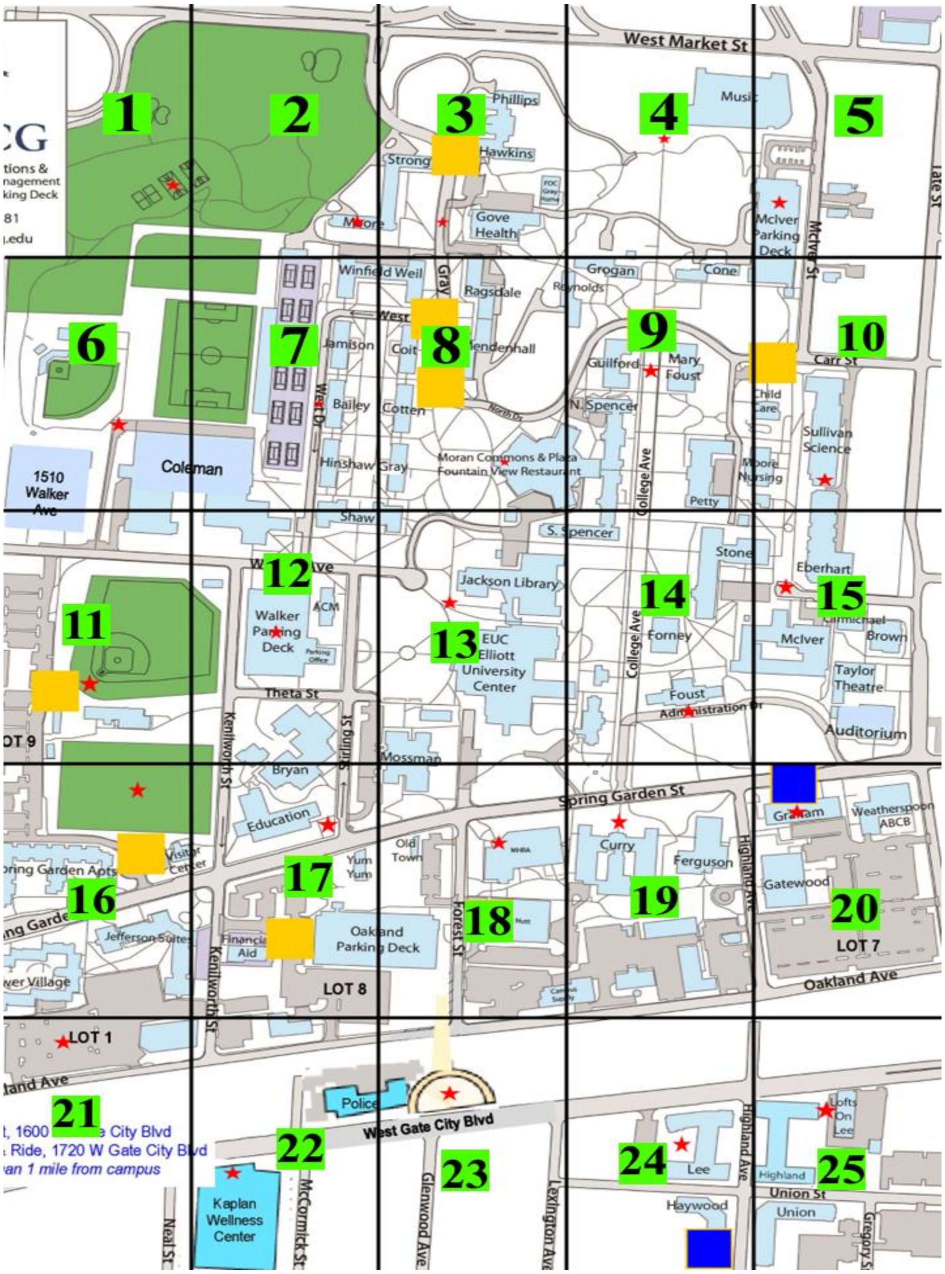
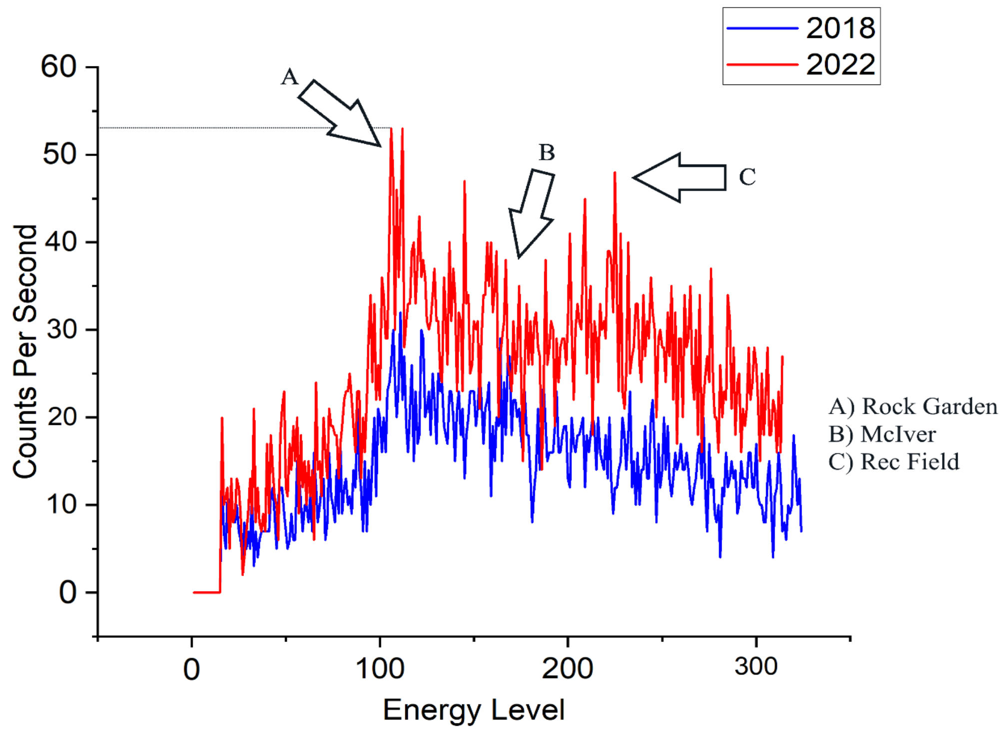


Figure 7. Chart comparing readings taken on the campus of UNC-Greensboro using a Geiger-Mueller Counter (2018) and the GSD-2100 (2022)



Experimental Design

Given the previous research conducted on the UNC-Greensboro campus, the ideal situation would have been to take readings on the main campus from ground level to altitudes of 15,000 feet or higher. Two options were considered and rejected. First, a weather balloon would have provided the necessary payload at reasonable cost, but would have lacked adequate control and introduced the unacceptable possibility of losing, or damaging the GSD-2100. Second, a heavy lift drone was considered. This option would have provided the navigational control required to safely take readings with acceptable risk of damage to the equipment. Unfortunately, the cost of a UAV capable of lifting an equipment payload of almost one hundred pounds was prohibitive.

Pikes Peak and Mt. Evans in Colorado were selected as alternatives because of their summit height and the fact, in both cases, a road gave access to the summit so equipment could be mounted on a vehicle allowing for continuous readings during ascent and descent.

For readings on Pikes Peak and Mt. Evans, the GSD was mounted to a tripod and placed on the passenger side of a truck along with a video camera. The GSD was connected to a laptop running QControl which was monitored throughout the experiment. Additionally, a GPS was set up to record the position of the GSD-2100.

Figure 8. The GSD-2100 setup on Pikes Peak

For UNC-Greensboro, 25 locations were chosen based on a grid system. Locations were varied between indoor and outdoor sites. At the chosen locations, the GSD was placed on a tripod and rotated 360 degrees for one minute in order to scan the general area. The GSD is connected to a laptop running QControl, which was monitored throughout the scan.

In Wilmington, a similar grid system was employed with 20 locations on the campus of UNC-Wilmington and 5 locations at Wrightsville Beach. Locations were varied between indoor and outdoor areas. Each scan lasted one minute while the GSD was rotated 360 degrees to read the general area.

UNC-Greensboro Campus

Initial readings with the GSD-2100 were taken Saturday, October 17th, 2020 since the campus would not be as busy and I could more easily move around campus. Using the same grid system employed for the 2018 study, readings were taken in each of the 25 grids. Total exposure time was one minute while rotating the GSD through 360 degrees to get a reading for the entire grid. Using the Lighthouse Detection Software, the data was translated into a readable Excel format in order to make conversions and compare the findings to estimated numbers. A set of second readings were taken a week later on Saturday, October 24th, 2020. The same process was repeated and then combined the two tables in order to determine averages. One of the objectives was to identify any "hot spots" on campus, or areas where the radiation exposure is significantly higher than the estimates. If any area with an average over 5 millisieverts were found, this would be concerning and would need to be reported to the administration immediately.

In my 2018 study, a grid square 15 was located at the demolition site of the old McIver Building in an attempt to identify radioactive materials used in the old building. During the scans in 2018, an Ion chamber and Geiger-Muller Counter were utilized. While there were no major spikes, the radiation levels at the demolition site were higher than the campus average, 4 milliroentgen at the site and 2.97 milliroentgen for the campus average. When I returned in 2022 with the GSD-2100, the new McIver building had been completed. I was able to reach the approximate location of my 2018 scan, and found the reading to be 2.3 milliroentgen, lower than my 2018 reading of 4 milliroentgen, while the campus average was 2.89 milliroentgen vs. 2.97 in 2018. It is possible the higher levels of radiation in 2018 could be caused the higher amount of radioactive materials in the old building materials compared to modern building materials. In 2018, I was unable to conduct a thorough study of the building material since my access to the building was limited due to construction.

The unit of measure used to measure radiation exposure is the traditional unit of roentgen. The unit of measure used to measure effective and equivalent dose is the SI unit of sievert. These standards of measure are readily convertible one to another. However, gammas per second, the unit of measurement used by the GSD, does not have a standard conversion available. The NCRP reports are in Roentgen while the GSD measures radiation in Gammas Per Second (GPS). In order to compare the estimates made by NCRP Reports 94 and 160 to the actual readings from the GSD-2100, a new conversion would have to be calculated. For this, a scan which had previously been done with a Geiger Counter and Ion Chamber was taken with the GSD-2100. Fortunately, these scans had been taken on the campus of UNC-Greensboro. These scans were taken at the exact locations which were scanned with the Geiger Counter and Ion Chamber, then compare the results. The result: 10 Gammas per second equaled 1 milliroentgen.

In conclusion, the readings taken with the GSD in 2022 were very similar to readings taken in 2018. The more sensitive GSD-2100 presented advantages when taking readings. For example, the directional nature of the spectrometer makes it capable of locating the source of a hot spot on campus if one were present. The SiPM sensor in the GSD is more sensitive and capable of detecting a wider range of radiation sources than a Geiger-Muller Counter.

Wilmington, NC

Getting readings at sea level is critical to the experiment since it gives a baseline for the analysis of altitude's role in the NCRP's estimation of 2.5 milliroentgen. For this experiment, 20 locations at the campus of UNC-Wilmington and along the beach at Wrightsville Beach, which is across the inlet from Wilmington, were selected as read sites.

The first read sites were located near the police department at a nearby resident hall, Loggerhead. From here, readings were at several different locations around campus including the Student Union and DePaolo Hall. After readings were taken at UNC-Wilmington, new read sites were established at nearby Wrightsville Beach. The first Wrightsville Beach read site was set up on the pier and moved further inland. The readings in Wilmington and Wrightsville Beach were found to be the closest to the estimates made by the NCRP. While the NCRP estimates in the Outer Banks are 2.5 milliroentgen, the readings were at 2.1 milliroentgen.

Pike's Peak

Pikes' Peak is unique in that it is owned and operated by the City of Colorado Springs. With over 23 million visitors in 2021, Pike's Peak is the most popular of Colorado's mountains with peaks of 14,000 feet or higher. Locally, they are referred to as "14'ers".

Approximately six months prior to my visit I began the process if obtaining approval from the city, and my request was approved by Ms. Katherine Severson, Ranger Supervisor. On the day scheduled for me to take readings I arrived at the park before 8 a.m. and met with Ms. Severson and spent about an hour outlining the research study and how the Pike's Peak readings would fit in the complete project. I demonstrated the equipment for the Rangers and explained each item, particularly the GSD-2100. The Park Rangers advised me of areas I was not permitted to scan. These areas were the three reservoirs along the road: The North Catamount Reservoir, The South Catamount Reservoir, and The Crystal Creek Reservoir. These reservoirs are owned by the city of Colorado Springs, and the city has contracted with a third party to manage and monitor the reservoirs. In the opinion of the city, were I to scan these reservoirs, it might be construed as a breach in the contract between the city and the third party.

At the end of the day, I returned to the Ranger Station and spent another hour sharing and explaining the readings. During our conversation, the Rangers shared that many visitors expressed concern about being exposed to radiation on the summit. They also said each year, a group of "environmentalists" stage a protest at the park where they warn radiation kills trees on the summit and makes people sick and kills them. I told them a person could live on the summit for 3.5 years and receive no more radiation than they would in a CT scan. After I explained the reading, the Rangers expressed their intention to share this information in the future when visitors expressed concerns.

In order to get a complete scan and more data points, readings were taken during both the ascent and descent of the mountain. Scanning twice allowed the data to be validated, identify any spikes in the readings, and the corresponding location on the mountain. The GSD-2100 was set up in the back seat of a truck along with a video camera to have a visual to compare numbers. No major hot spots were found on the mountain, however two areas where the readings briefly spiked were observed near the summit. After reviewing the video footage, I was able to determine rock outcroppings above the tree line to be the cause of the spikes.

Figure 9. Ascent of Pikes' Peak as seen on QControl

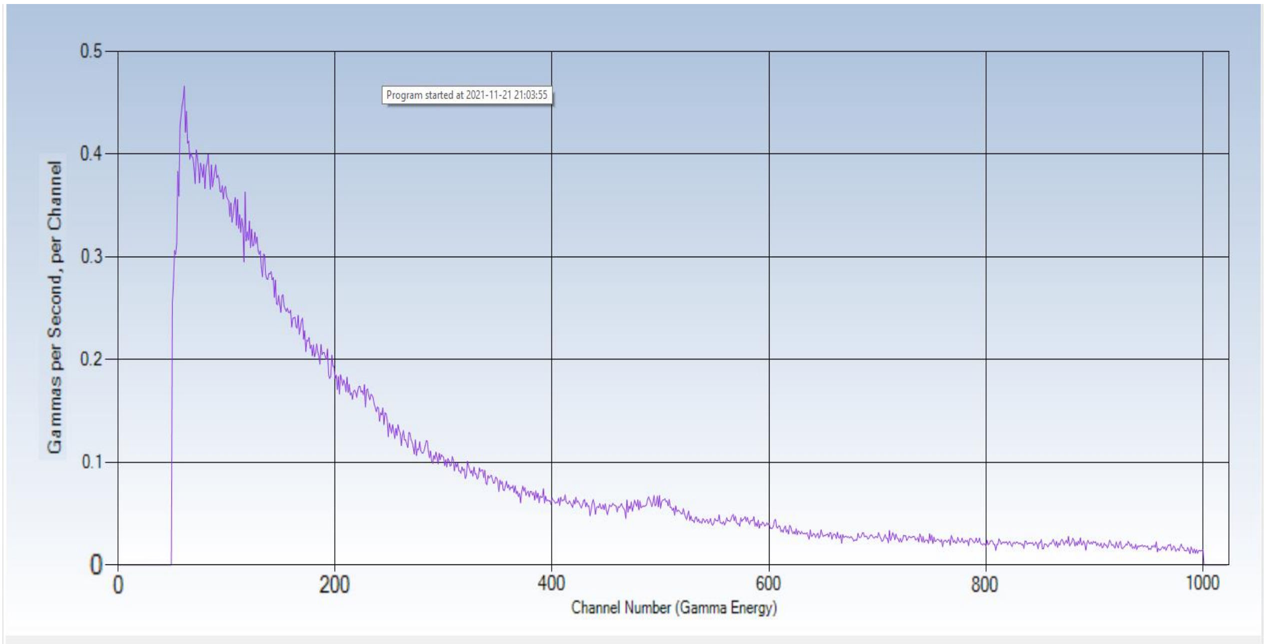
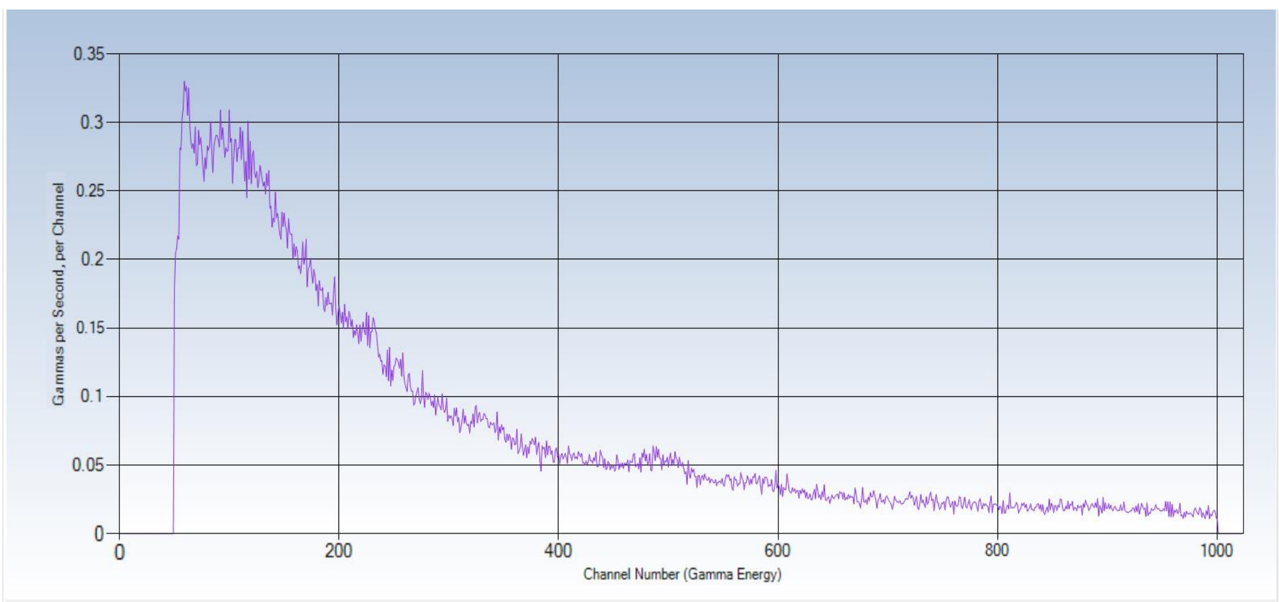


Figure 10. Descent of Pikes' Peak as seen on QControl



Mt. Evans

The readings of Mt. Evans were conducted in the same way as the readings of Pikes Peak. Readings were taken on both the ascent and descent. Mt. Evans is slightly higher than

Pike’s Peak and the road up to the summit is longer by 10 miles. Because of this difference in height and length, an adjustment to the analysis had to be made. While the difference between the two mountains is small, this difference could lead to an error in the analysis. The readings were lower than NCRP by 2.1 milliroentgen, with NCRP estimates at 8 milliroentgen while my readings measured 5.9 milliroentgen. While this is not considered significant since it does not fall within the five to ten millisievert range set by the NCRP, it is interesting to note all scans made resulted in lower than estimated readings.

Figure 11. Ascent of Mt. Evans as seen on QControl

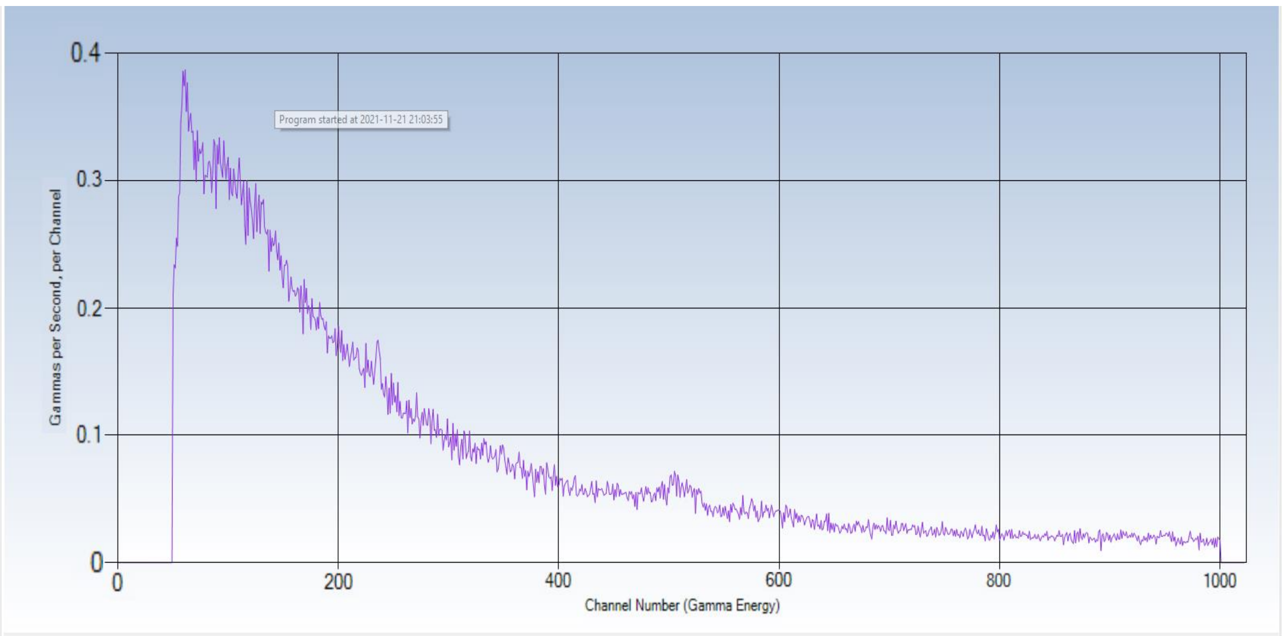
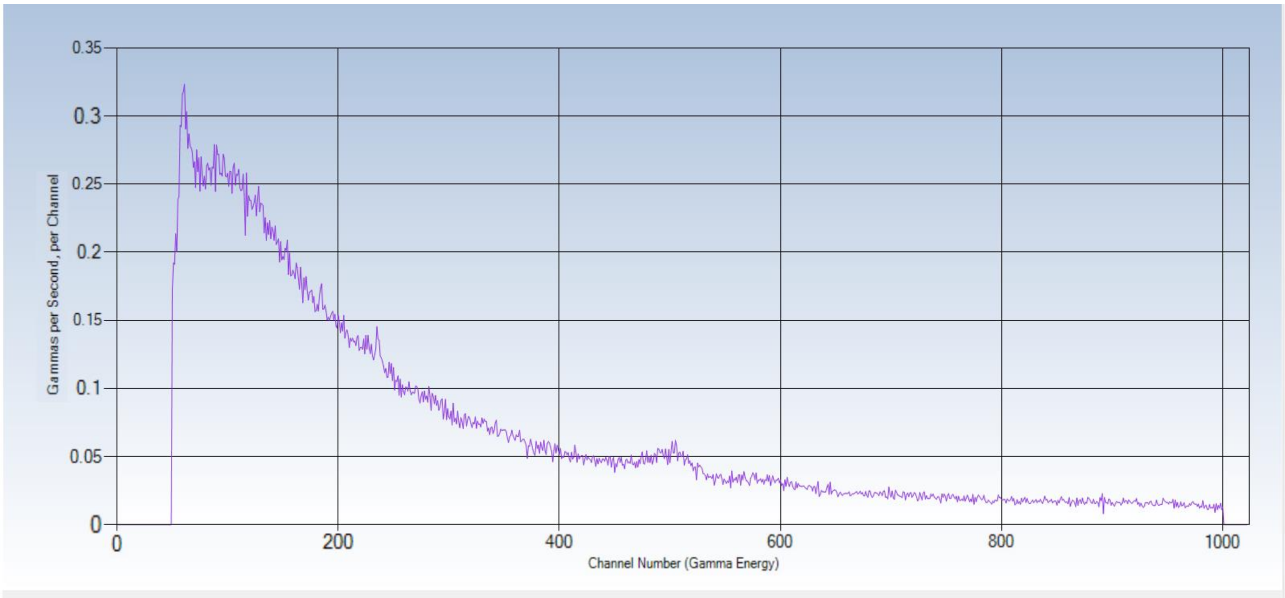


Figure 12. Descent of Mt. Evans as seen on QControl



Statistical Analysis

GPS readings, along with a complete video record, were coordinated with all GSD-2100 readings to form a complete data record and to make it possible to identify the exact point at which any reading was obtained. My scans at Pikes Peak and Mt. Evans had different altitudes for start and end points. Pikes Peak's summit is 14,115 feet and has a prominence of 5,530 feet, while Mt. Evans' summit is 14,271 feet with a prominence of 7,000 feet. By wedding NCRP estimates to US Geological Survey data, I was able to match estimated readings precisely on the roads on both Pikes Peak and Mt. Evans (Duval, 2005). NCRP estimates and readings taken, for both Pikes Peak and Mt. Evans were sorted by altitude in 200-foot increments, then compared.

Because NCRP estimates are presented in nanogray, they must be converted to milliroentgen. Since a direct conversion from nanogray to milliroentgen is unavailable, I first converted nanogray to millisievert, then converted millisievert into milliroentgen.

My hypothesis was the actual ionizing radiation would be higher than the NCRP estimates. This seemed a reasonable assumption after my initial test of the GSD-2100 showed it to be 124X more sensitive than an Ion Chamber. When the actual readings were, in fact, lower than the NCRP estimates I determined to continue with the analysis even though my original hypothesis was obviously incorrect. In order to complete the analysis, a One-Way ANOVA test was performed comparing two sets of variables: the NCRP estimates and observed data from my readings. A One-Way ANOVA test is a statistical method used to compare the means of two or more variables. After converting Gammas Per Second to milliroentgen, the ANOVA was performed at the confidence level of .05. The p-score for all 3 read sites fell below the .05 limit. The p-score is a measure of probability used to For Pikes Peak, a p-score of 0.0001 was achieved with a f-ratio value of 30.12. The standard deviation for Pike's Peak was 0.6964. For Mt. Evans, a p-score of 0.0001 was achieved with an f-ratio value of 21.49. The standard deviation for Mt. Evans was 0.7853. For Wilmington, a p-score of 0.0001 was achieved with an f-ratio value of 19.41. The standard deviation for Wilmington was 0.5891. There was no significant difference, higher or lower, between the estimates and the readings taken.

Figure 13. Graph showing radiation levels at Pike's Peak

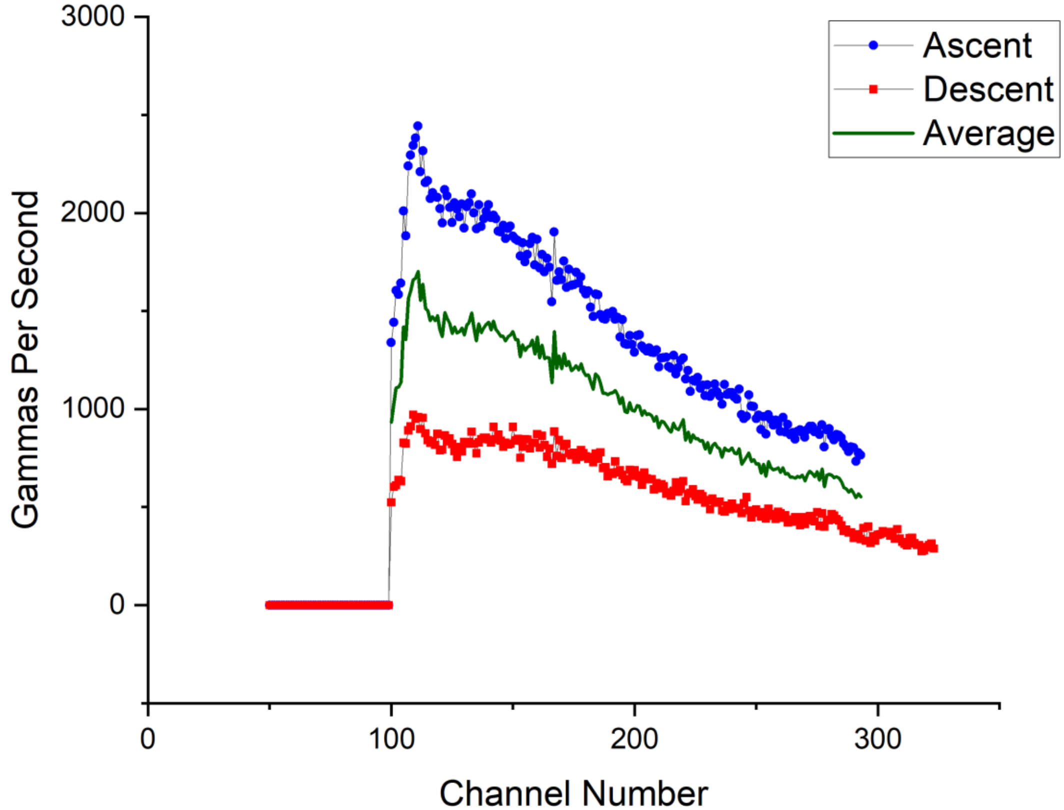


Figure 14. Graphs showing radiation levels at Pike's Peak during ascent based on altitude.

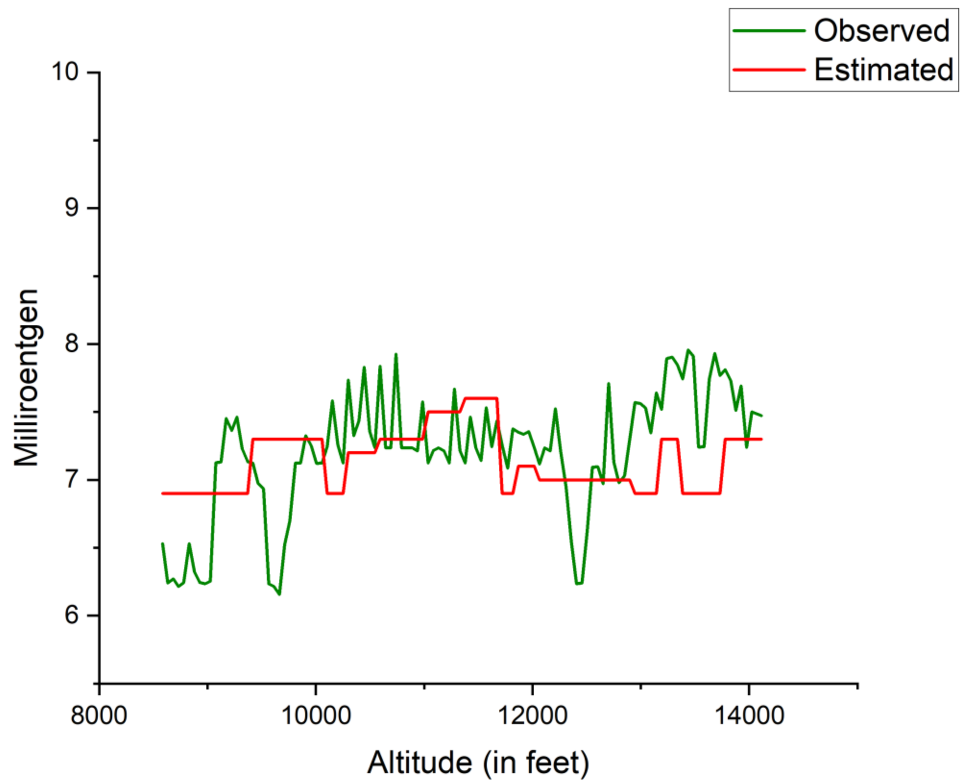


Figure 15. Graphs showing radiation levels at Pike's Peak during descent based on altitude.

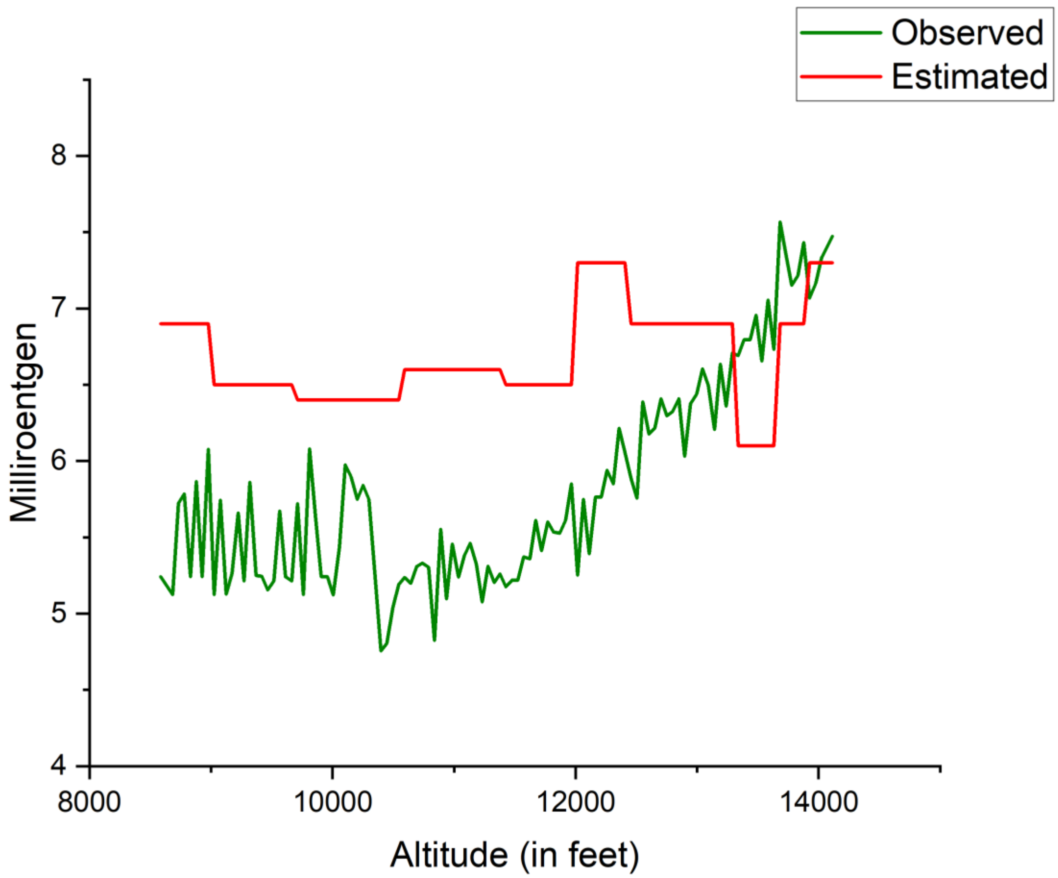


Figure 16. ANOVA Test Results for Pikes Peak

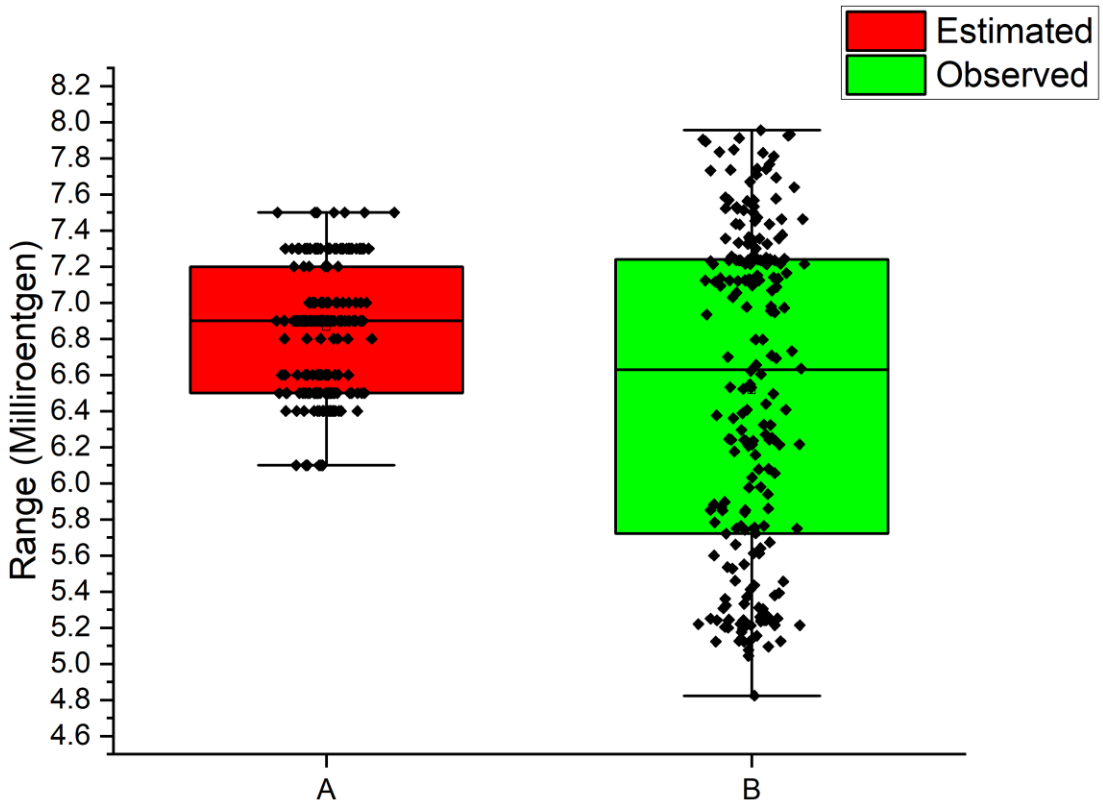


Figure 17. Graph showing radiation levels at Mt. Evans

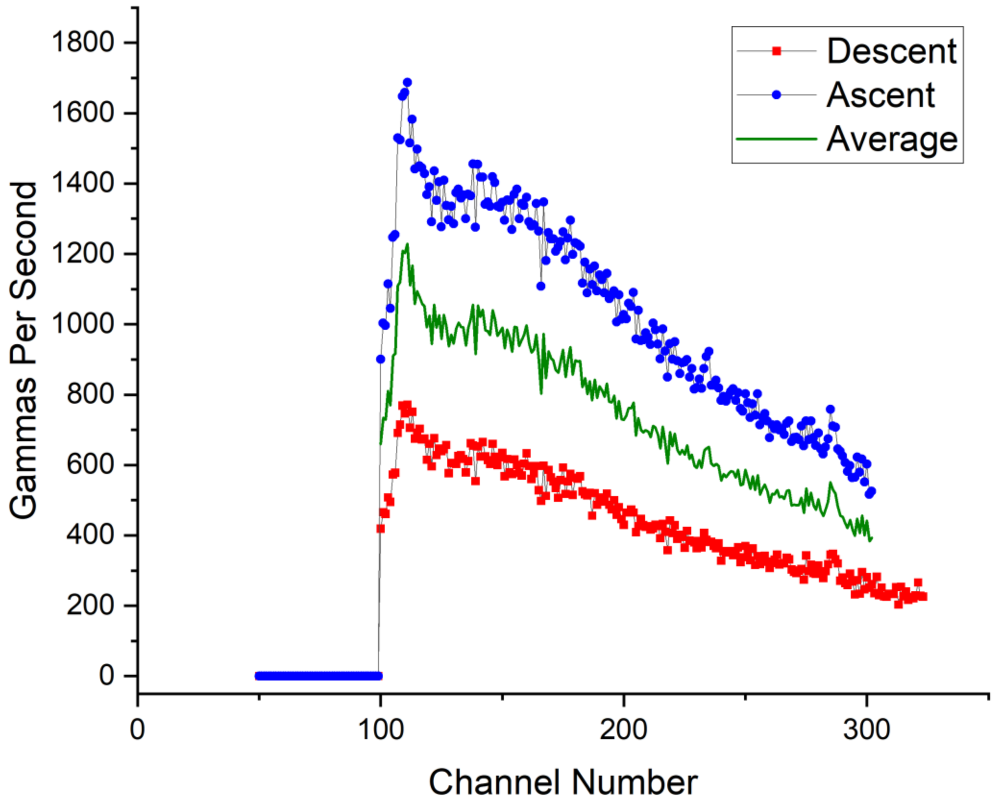


Figure 18. Graph showing radiation levels at Mt. Evans during ascent based on altitude.

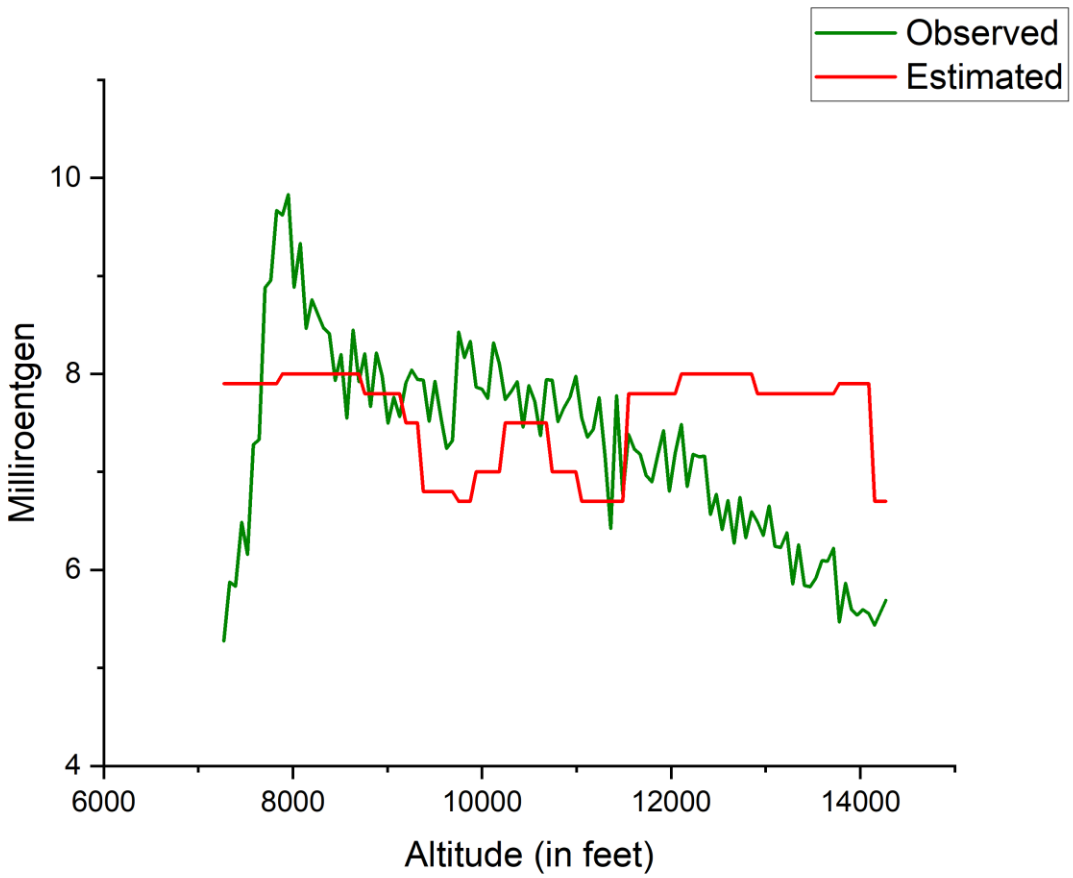


Figure 19. Graph showing radiation levels at Mt. Evans during descent based on altitude.

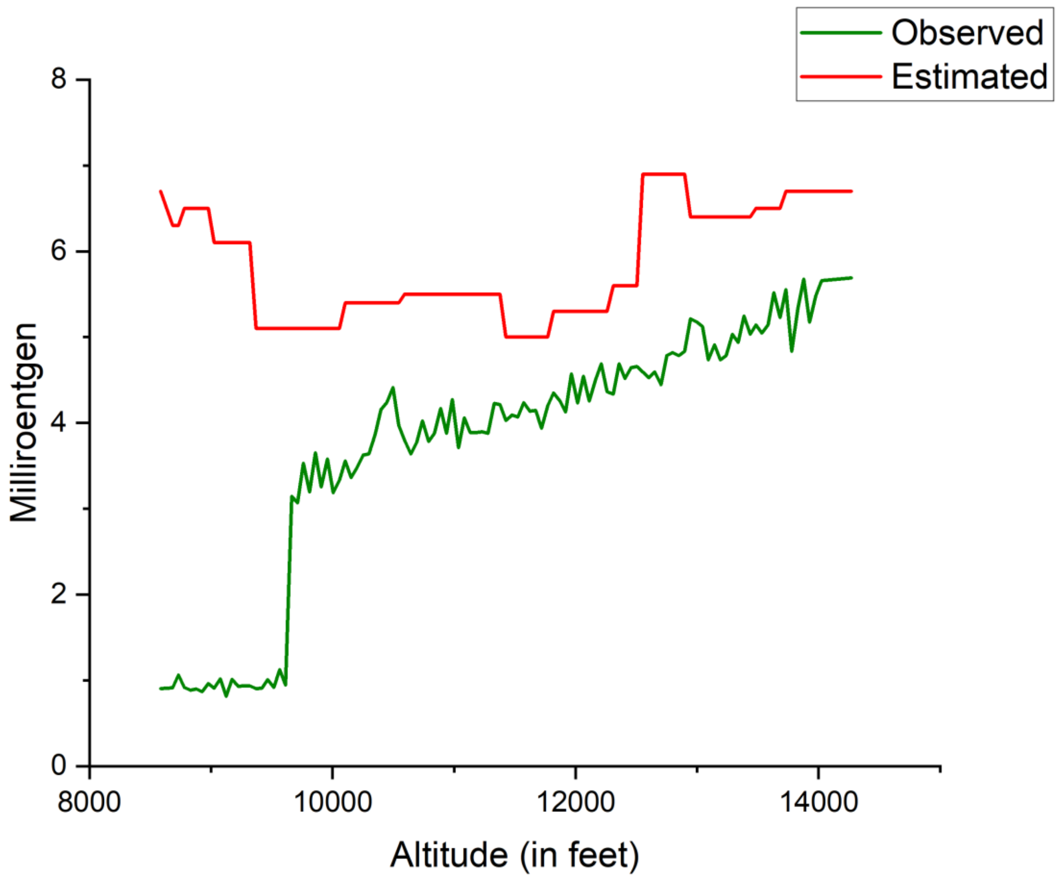


Figure 20. ANOVA Test Results for Mt. Evans

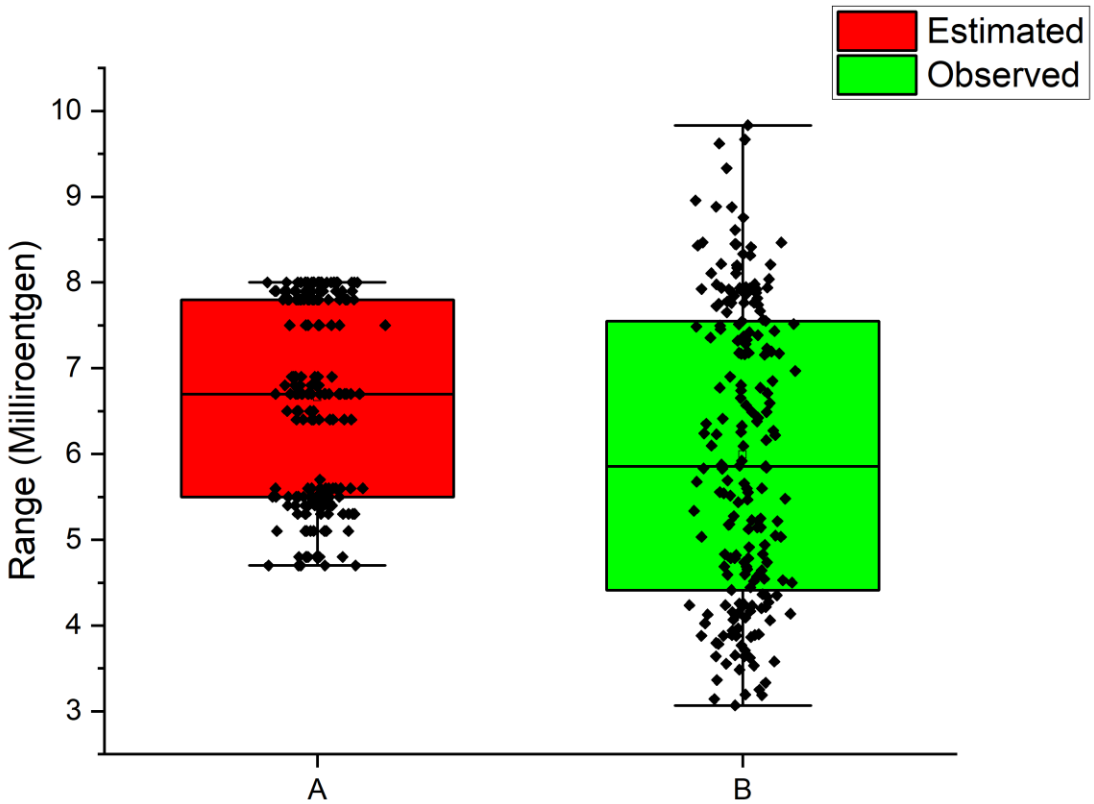


Figure 21. Graph showing radiation levels in Wilmington

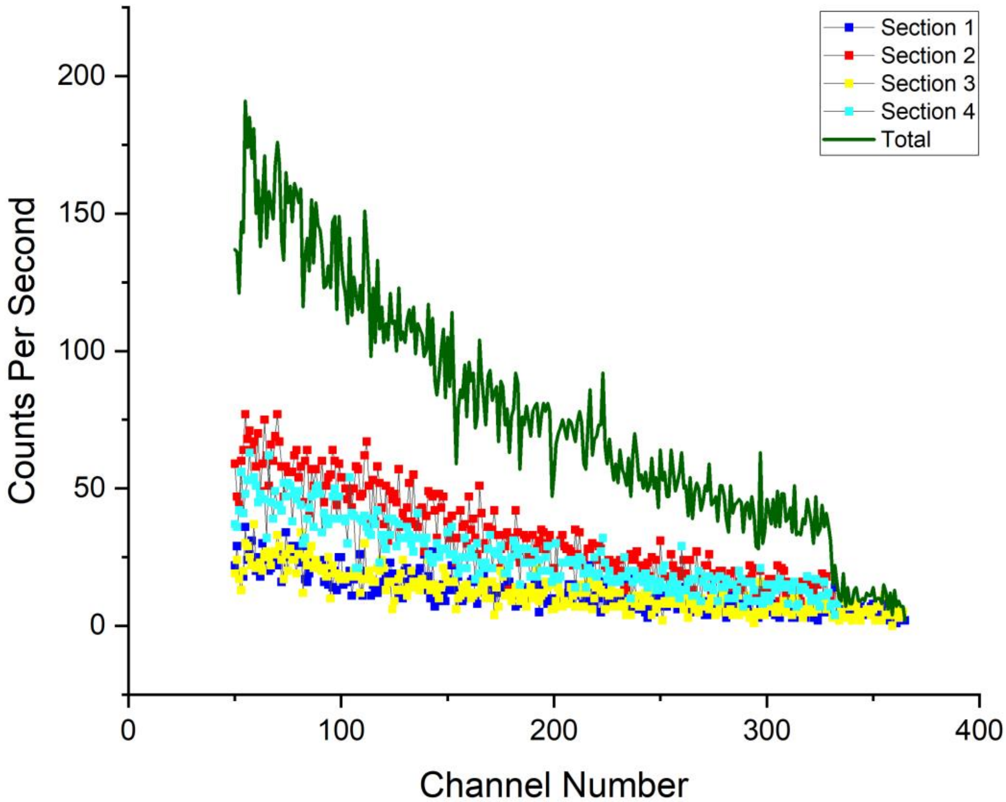
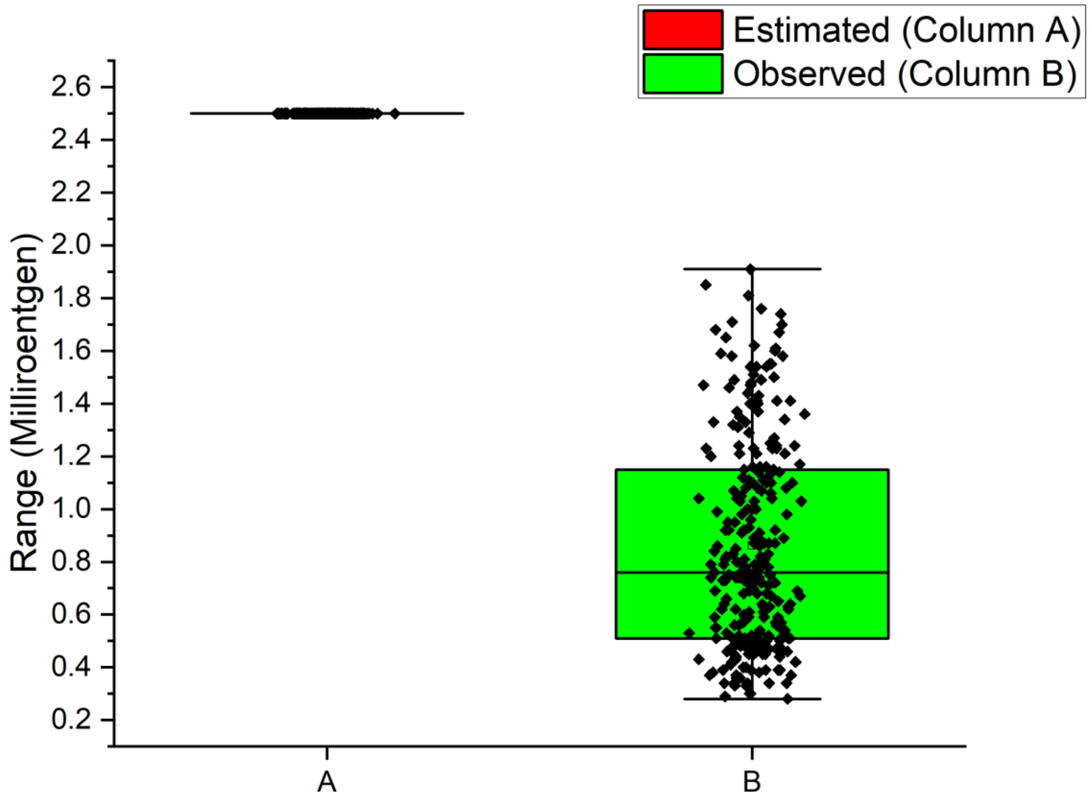


Figure 22. ANOVA Test Results for Wilmington



Findings

After analyzing the data collected and comparing the results to the estimate in both NCRP Reports, I found the actual numbers to be lower than the estimates. In Wilmington, the NCRP's estimate was 2.5 milliroentgen while actual readings measured 2.1 milliroentgen, a difference of 0.4 milliroentgen. On the UNC-Greensboro campus, the NCRP estimate is 3.5 milliroentgen while actual readings were 2.89 milliroentgen, a difference of 0.61 milliroentgen. Estimates for Pikes Peak were 8.5 milliroentgen, while the actual readings were 7 milliroentgen, a difference of 1.5 milliroentgen. NCRP estimates for Mt. Evans were 8 milliroentgen, while actual readings were 5.9 milliroentgen, a difference of 2.1 milliroentgen.

The study found the average amount of background radiation received on the UNC-Greensboro campus is approximately 2.89 millisieverts, which is below the average for the United States of 3.11 millisieverts. The hypothesis I felt was the most reasonable was the difference in season. Readings in 2018 were taken in the summer, while readings for this experiment were taken in late fall. This could have possibly led to a decline in radiation received via Ultraviolet radiation. The other hypothesis which seemed plausible was a difference in two of the read sites. Another read site which changed was the Faust Building, due to the fact I was unable to enter the building. I have been able to find a very slight difference in readings between indoor and outdoor spaces. Therefore, the decision to vary read sites was made in order to get a better understanding of the amount of background radiation received. Along with no hot spots being found, the readings matched the estimates.

The GSD-2100 was found to be 124X more sensitive than a Geiger-Muller counter, leading to precise readings. These precise readings aided the analysis. Additionally, the GSD's directionality has been shown to accurately show the location of radiation sources within a 35 degree cone. I have also theorized that the GSD's sensitivity could have led to the lower than estimated readings. Because I was able to get a more precise reading, the analysis was more accurate than the estimates made in NCRP Reports 94 and 160.

A One-Way ANOVA test was constructed to determine if a significant difference was present. I performed the ANOVA with a confidence level of .05. The p-score for all 3 read sites fell below the .05 limit. The p-score is a measure of probability used to For Pikes Peak, a p-score of 0.0001 was achieved with a f-ratio value of 30.12. The standard deviation for Pike's Peak was 0.6964. For Mt. Evans, a p-score of 0.0001 was achieved with an f-ratio value of 21.49. The standard deviation for Mt. Evans was 0.7853. For Wilmington, a p-score of 0.0001 was achieved with an f-ratio value of 19.41. The standard deviation for Wilmington was 0.5891. While I found differences between actual numbers and the estimated numbers presented in NCRP Reports 94 and 160, the differences were not sufficient to conclude the NCRP's estimations are incorrect.

CHAPTER III: CONCLUSION

With one exception, the readings at all locations were consistently lower than NCRP estimates. The exception was near the summit of Pikes Peak. At the altitude where the spike was observed, the estimate was 6.9 milliroentgen and the actual reading measured 7.92 milliroentgen. After comparing the video, GPS, and GSD reading, I feel confident the higher reading was the result of a large boulder outcropping above the tree line on the North slope of Pikes Peak. For Pikes' Peak, 8.5 milliroentgen was the NCRP's estimate while actual readings measured 7 milliroentgen, a difference of 1.5 milliroentgen. On Mt. Evans, the NCRP's estimate was 8 milliroentgen and actual readings measured 5.9 milliroentgen, a difference of 2.1 milliroentgen. For the UNC-Greensboro campus NCRP's estimate was 3.5 milliroentgen and actual readings measured 2.89 milliroentgen, a difference of 0.61 milliroentgen. In Wilmington, the NCRP's estimate was 2.5 milliroentgen while actual readings measured 2.1 milliroentgen, a difference of 0.4 milliroentgen. Readings on Mt. Evans had the highest difference from the NCRP's estimate at a 2.1 milliroentgen lower, while readings at Wilmington had the lowest difference at 0.4 milliroentgen lower.

The One-Way ANOVA test performed on the NCRP estimates and observed data showed the difference between estimated and observed data was not statistically significant at the .05 level of confidence. For Pikes' Peak, a p-score of 0.0001 was achieved with a f-ratio value of 30.12. The standard deviation for Pike's Peak was 0.6964. For Mt. Evans, a p-score of 0.0001 was achieved with an f-ratio value of 21.49. The standard deviation for Mt. Evans was 0.7853. For Wilmington, a p-score of 0.0001 was achieved with an f-ratio value of 19.41. The standard deviation for Wilmington was 0.5891. This is a bit of a surprise since particularly given the superior sensitivity of the GSD-2100 compared to current devices for detecting ionizing radiation. Still, that the estimates and observed data were as close as they were is evidence of the high quality of work produced by the NCRP.

How do we account for the disparity between NCRP estimates and the radiation levels actually recorded? The first possibility would be to attribute the lower current readings to radioactive half-life decay[2]. This seems plausible until we compare the data in NCRP's 1987 report to that of 2006. In the earlier report, the estimate is 3.0 millisievert and 3.11 millisievert in the later report. An increase of .11 millisievert. Clearly half-life is not a factor, or the later estimate would have been lower than the first.

The second option is to assert the difference between estimated and observed, while the observed is consistently lower, is too small to be of significance and without further studies conducted over a wider geographical area and over a longer time period no conclusion can be reached.

In considering possible options for further research, I have identified three possibilities:

1) In 2018 I designed a study of ubiquitous background radiation which would have placed dosimeters on one hundred students, faculty, and staff of UNC Greensboro for a period of one year to determine the actual dose of ionizing radiation they received. The data collected over a period of a year could then be compared to NCRP estimates for the UNC-Greensboro campus and to produce an ionizing radiation map of the campus. At the time I did not possess the sufficient funds to rent or purchase the dosimeters, so the study was put on hold. Having completed the current study, I

[2] Half-life is defined as the amount of time is required for a radioactive isotope to lose half of its atoms, or undergo radioactive decay. All radioactive materials, which contain unstable nuclei undergo radioactive decay, which is defined as the process in which an unstable nucleus loses energy by radiation. During this decay, the nucleus will emit one of three particles: alpha, beta, or gamma

would like to revisit the issue and explore securing funding for the dosimeters so the study can go forward.

2) Another option would be to proceed with the development of a heavy lift drome to wed to the GSD-2100. Early in my conversations with Dr. Dowell of Los Alamos, I mentioned using the GSD-2100 in such an application and he said the idea had merit and had in fact considered it himself, but his current research program would not afford him the time. Also, one of my faculty at Penn State, a U.S. Army colonel, who had worked for the Office of Threat Reduction, suggested that office would be more than willing to fund the line of research. In fairness, I feel I would have to obtain Dr. Dowell's approval before approaching another government agency for funding since Los Alamos funded development of the GSD.

   With a heavy lift drone the GSD could be employed to scan more territory for radiation leaks, or non-authorized sources of radiation, e.g. dirty bombs. A drone borne GSD could also be used to scan medical facilities for radiation leaks.

3) A third option would be a study of radioactivity in rainwater, groundwater, and snow in a defined portion of North Carolina using the GSD-2100, and producing a map of the respective radiation levels.

CHAPTER IV: GLOSSARY

Absorbed dose: energy (J) imparted to matter (kg) by ionizing radiation

Effective dose (E): sum of the products of equivalent dose to tissues and organs (H_T) and the weighting factor of each tissue and organ (W_T); Effective dose takes into account the differing radiosensitivities of tissues and organs

$\mathbf{E = \sum W_T H_T}$: Formula for Effective Dose

Effective dose equivalent (H_E): The sum over specified organs and tissues of the products of the mean dose equivalent in a tissue and the weighting factor for that tissue or organ

Equivalent dose (H_T): radiation-weighted sum the stochastic risks from ionizing radiation

$\mathbf{H_T = \sum W_R D_{T,R}}$: Formula for Equivalent Dose

Gammas Per Second: The unit of measurement used by the GSD-2100

Gamma rays: electromagnetic radiation emitted by the atomic nucleus; Gamma rays have high penetrating abilities compared to alpha and beta particles

Geiger-Muller Counter: an electronic instrument used for detecting and measuring ionizing radiation

GSD-2100: Gamma Spectrometry Device, Developed by Dr. Jonathan Dowell at Los Alamos National Laboratory in New Mexico

Gray (Gy): SI unit of absorbed dose. 1 Gy = 1 J kg^{-1}

Ion Chamber: a gaseous ionization detector used for the detection and measurement of various types of ionizing radiation, including X-rays, gamma rays, and beta particles; It consists of a gas-filled chamber with two electrodes, known as anode and cathode

Ionizing Radiation: A form of radiation which possesses enough energy to remove electrons from atoms. This process is known as ionizing an atom. This differs from non-ionizing radiation.

Lithology: Description of a rock unit's physical characteristics visible at outcrop, in hand or core samples

NCRP: National Council of Radiation Protection

Roentgen (R): traditional unit of ionizing radiation exposure adopted by the International Council for Radiation Protection (ICRP) in 1928; A roentgen is defined as the electrical charge released by ionizing radiation in a specified amount of air

Sievert (Sv): SI unit of effective dose and equivalent dose

SiPM: Silicon Photomultiplier detector array, the detector used in the GSD-2100

REFERENCES

Bushong, SC (1964). The Composition and Spatial Distribution of Background Radiation. Health Physics. Nov;(10) 731-742.

Beretka J, Matthew PJ (1985). Natural radioactivity of Australian building materials, industrial wastes and by-products. Health Physics. Jan;48(1):87-95.

National Council of Radiation Protection (1987). Report 92: *Public Radiation Exposure from Nuclear Power Generation in the United States*. 1987

National Council of Radiation Protection (1987). Report 93: *Ionizing Radiation Exposure of the Population of United States*.

National Council of Radiation Protection (1987). Report 94: *Exposure of the Population in the United States and Canada from Natural Background Radiation*.

National Council of Radiation Protection (1989). Report 100: *Exposure of the U.S. Population from Diagnostic Medical Radiation*.

National Council of Radiation Protection (1989). Report 101: *Exposure of the U.S. Population from Occupational Radiation*.

Cameron, J.R., A radiation unit for the public. Physics and Society 20 (1991)

National Council of Radiation Protection (1993). Report 116: *Limitation of Exposure to Ionizing Radiation*.

Ya-xin Yang, Xin-min Wu, Zhong-ying Jiang, Wei-xing Wang, Ji-gen Lu, Jun Lin, Lei-Ming Wang, Yuan-fu Hsia (2005) Radioactivity concentrations in soils of the Xiazhuang granite area, China, Applied Radiation and Isotopes, Volume 63, Issue 2, pgs 255-259

Duval, J.S., Carson, J.M., Holman, P.B., and Darnley, A.G., (2005). Terrestrial radioactivity and gamma-ray exposure in the United States and Canada: U.S. Geological Survey Open-File Report 2005-1413

National Council of Radiation Protection (2006). Report 160*: Ionizing Radiation Exposure of the Population of the United States*.

Fawzia Ahmad (2007) Natural radioactivity levels in building materials used in Egypt, Radiation Effects and Defects in Solids, 162:1, 43-52, DOI: 10.1080/10420150600968246

Shahbazi-Gahrouei, D., Gholami, M., & Setayandeh, S. (2013). A review on natural background radiation. Advanced biomedical research, 2, 65. https://doi.org/10.4103/2277-9175.115821

Dowell, Jonathan, Rittner, Christian, Milazzo, Damian, Kingsly, Adam, McKibbin, Peter, Seagraves, David. (2018). Los Alamos National Laboratory Internal Memo: Lighthouse Project Saddlebags: Survey of Trinity Site.

Milazzo, Damian (2018). Radionuclides in rainwater and their impact on background radiation. https://digitalrepository.unm.edu/eps_etds/247

International Atomic Energy Agency (2019). Philippines: Radiation-Processed Seaweed Increases Typhoon Resistance of Rice. https://www.iaea.org/newscenter/news/philippines-radiation-processed-seaweed-increases-typhoon-resistance-of-rice

Hae Young Lee, Seongjin Maeng, Seong Jin Park, Sang Hoon Lee, (2022) COMPARISON OF GAMMA ABSORBED DOSE RATES IN THE AIR MEASURED WITH A PORTABLE SURVEY METER AND THE SOIL RADIOACTIVITY MEASUREMENTS, *Radiation Protection Dosimetry*, Volume 198, Issue 20, December 2022, Pages 1529–1539, https://doi.org/10.1093/rpd/ncac195

T S Shashikumar, M N Ramachandra, Chandrashekar, Shivalinge Gowda, (2022) ESTIMATION OF INDOOR AND OUTDOOR EFFECTIVE DOSES AND LIFETIME CANCER RISK FROM GAMMA DOSE RATES IN AND AROUND MANDYA DISTRICT, KARNATAKA, *Radiation Protection Dosimetry*, Volume 198, Issue 20, December 2022, Pages 1540–1545, https://doi.org/10.1093/rpd/ncac199

Singapore National Environmental Agency (2021). Radiation Safety and Regulatory Information. https://www.nea.gov.sg/our-services/radiation-safety

Bushong, SC. (2024) Radiologic Science. 13th Edition. Elsevier