Air Kerma Strength Measurement of a Cs-137 Radioisotope Using a Seven-Distance Ionization Technique and Comparison with the Gamma Spectroscopy Method

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Abstract

Brachytherapy describes a process where radioactive sources are inserted directly into the target area of a patient to treat disease. Before they can be used for treatment, brachytherapy sources must be calibrated such that medical physicists know their exact air kerma strength - a quantity given by manufacturers as a standard. Each individual source must be measured before use. Therefore, medical physicists must have an efficient technique for measuring air kerma strength. The goal of this project was to build a system that uses a "seven-distance" ionization measurement technique to measure the air kerma strength of a cesium-137 source. Results obtained using this method were also compared to those obtained using a gamma spectroscopy technique.

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Executive Summary

Brachytherapy is a form of radiation therapy that treats diseases such as cancer by placing radioactive sources inside of a patient. Sources can be placed either inside of or directly next to diseased tissue to kill unhealthy cells. However, before sources can be used, medical physicists must measure their dosimetric output, so as to know how it will react with the human body. The quantity that is measured for source calibration is called air kerma strength, which measures the amount of energy transfered to a volume of air that is surrounded by a vacuum and is at some distance from the source. To measure the air kerma strength of a source, medical physicists typically use what is called the "seven-distance" measurement technique, which requires a specialized, precisely built apparatus. Worcester Polytechnic Institute (WPI) lacks such an apparatus, and therefore cannot take measurements to assist in brachytherapy research.

The goal of this project was to build an apparatus that is able to take accurate air kerma strength measurements using the seven-distance measurement technique. By assembling this apparatus, I was able to provide WPI's radiation laboratory with the means to take air kerma strength measurements of brachytherapy research, thus aiding the university's brachytherapy research opportunities. Additionally, by constructing this apparatus, I have given WPI's radiation laboratory the ability to measure the air kerma strength of brachytherapy sources on behalf of other institutions. Finally, this apparatus will also be used to research new methods of air kerma strength measurement.

To complete this project, I had to carefully select the materials used in the construction of the apparatus so as to minimize error in measurement. I then had to carefully design and construct the apparatus in such a way that it was able to take accurate measurements while still being easy to use. Included in the design of the apparatus is the type of ionization chamber used and the types of materials used for supporting structures. Once the apparatus was fully built, I measured the air kerma strength of a non-brachytherapy cesium-137 source using the seven-distance measurement technique. To test that the apparatus was functional and taking accurate measurements, I then repeated my measurements using a new method called the gamma spectroscopy technique.

By comparing the results obtained using the seven-distance measurement technique to those calculated using the gamma spectroscopy technique, I was able to determine that the seven-distance apparatus that I built for this project was fully functional. The two measurements agreed well, allowing me to conclude that the apparatus can now be used for air kerma strength measurements of brachytherapy sources in WPI's radiation laboratory.

Table of Contents

Table of Figures

Table of Tables

1 Introduction

According to research by the National Cancer Institute, the average person in the United States has an approximate 40% chance of developing cancer at some point during his/her life. Of those diagnosed with some form of cancer, about one in five will die from the disease [1]. These high rates of development have made cancer the second most common cause of death in the United States [2]. Because of this, researchers are continually seeking more effective treatment options.

One form of cancer treatment involves the use of radiation. This type of treatment is called radiation therapy, and it comes in two varieties. Radiation can be delivered to a patient either externally using beams, or internally using implanted radioactive sources. The use of internal sources of radiation is referred to as brachytherapy. The sources used in brachytherapy are extremely small and are inserted into a target area using a catheter. This form of treatment allows target areas of a patient's body to be irradiated from the inside out, effectively killing tumor cells while delivering a smaller dose to healthy tissues. Brachytherapy sources (also called seeds) must be used according to treatment plans that outline the placement and time frame of the treatments for specific individuals. These treatment plans ensure maximum dose to target tissue while maintaining minimal exposure to healthy tissue.

Treatment plans require that dose rates are exactly known in order to protect the patient while effectively killing diseased cells. However, brachytherapy sources can fall within a wide range of activities as specified by the manufacturer. More specifically, two brachytherapy seeds from the same batch of seeds can have outputs that vary by up to 11% of the manufacturer's specified output for that batch. According to the American Association of Physicists in Medicine (AAPM), it is the job of the medical physicist to verify the output of seeds before they are used for brachytherapy [3]. To calibrate sources, the AAPM recommends that physicists measure what is called the *air kerma strength* of each source. Air kerma strength is indirectly related to the dose rate of the source in air, but is much more easily measured. For this reason, air kerma strength is often used as a calibration standard for brachytherapy sources.

The method of air kerma strength measurement that is most commonly used today is called the "seven-distance" measurement technique. This technique measures the charge created in air by a source over seven distances, hence its name. Seven-distance apparatuses are generally difficult to set up, as they require high precision in their assembly. Additionally, because they take measurements in air, scattering and attenuation of the radiation released by sources requires correction factors to obtain an accurate result [4]. Another technique, called the gamma spectroscopy method, instead measures the number of times a source emits each photon energy in its emission spectrum in a given time interval. Using this information, and by summing over all photon energies, one can calculate the air kerma strength of any low dose-rate source. However, this method is relatively new, and so many working laboratories do not currently implement it. Before it can be commonly used, the accuracy of this method needs to be confirmed by testing.

The goal of this project was to build an apparatus to perform seven-distance measurements of the air kerma strength of a non-brachytherapy cesium-137 source. Furthermore, I repeated this measurement using the gamma spectroscopy method in order to ensure the

accuracy of the seven-distance apparatus. The seven-distance apparatus that I built for this project will also allow measurements of various sources to be easily made by qualified students and faculty at WPI. Additionally, this apparatus can be used to more thoroughly investigate new methods of air kerma strength measurement, such as the gamma spectroscopy system.

2 Background

In order to understand the importance of measuring the air kerma strength of a brachytherapy source, one must first understand the basics of radiation, radiation therapy, and radiation dosimetry. In this section, these and other topics will be discussed to give the reader an adequate background to understand the measurements taken for this project and their importance to the medical physics community.

2.1 Structure of the Atom

It is well known that the atom is one of the most basic units of matter, consisting of a nucleus and a surrounding cloud of negatively charged electrons. The nucleus of an atom contains most of the atom's mass, and consists of electrically neutral neutrons and positively charged protons. The net positive charge of the nucleus binds to the negative charge of the electron cloud through the electromagnetic force. The Bohr model of the atom (which is considered to be loosely correct) is shown in Fig. 1.

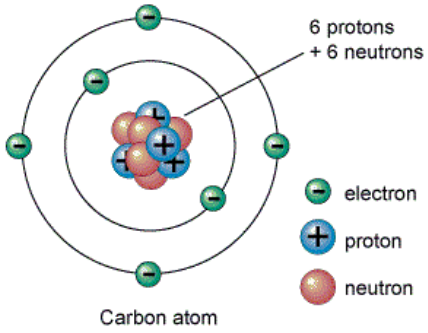

Figure 1: The Bohr model of an atom.[1]

Because only protons and neutrons make up the atomic nucleus, these particles are classified as nucleons. There exists a force that causes interaction between nucleons, which is called the nuclear force (also called nucleon-nucleon interaction or the residual strong force). This force is responsible for the formation of atomic nuclei, because it is attractive at distances around 1 femtometer (fm) between the nucleons' centers, and repulsive at distances shorter than 0.7 fm. This balance keeps nuclei from collapsing while also holding the particles together [5].

[1]This image courtesy of http://www.universetoday.com/82128/parts-of-an-atom/.

The masses of all three of the aforementioned particles that make up an atom are as follows:

$$m_{\text{proton}} = 938.27 \text{ MeV/c}^2$$
$$m_{\text{neutron}} = 939.57 \text{ MeV/c}^2$$
$$m_{\text{electron}} = 0.511 \text{ MeV/c}^2$$

For convenience, we write the masses of these particles in terms of millions of electron-volts (MeV) per the speed of light squared (c^2) using the famous mass-energy relation from special relativity, $E = mc^2$. It is worth nothing that the proton and neutron are approximately 2000 times more massive than the electron, and so in most cases, electrons can be neglected when considering the mass of an atom. One can also write out the approximate mass of nucleons ($m_{\text{nucleon}} = 931.502$ MeV) in terms of the standardized mass unit that is typically used in nuclear physics; this unit is called the unified atomic mass and is denoted by the character u. One unit of unified atomic mass is approximately equivalent to the mass a nucleon, or $1u = 931.502$ MeV.

2.1.1 Atom Classification

Nuclei are generally characterized into species by two factors: the mass number, A, and the atomic number Z. A represents the total number of nucleons in a particular nucleus, and Z represents solely the number of protons in the same nucleus. For example, hydrogen has one proton in its nucleus, and no neutrons. Therefore, for hydrogen, $A = 1$ and $Z = 1$. There is also a third factor representing the number of neutrons in a nucleus, which is given by N such that $N = A - Z$. The standard notation for writing a chemical element X with parameters A and Z is called *nuclear notation*, shown by Fig. 2.

Figure 2: The general form of nuclear notation for an atom with mass number A, atomic number Z, and neutron number N.

An alternative to using this notation includes writing the element's abbreviation, followed by the number of neutrons in the particular atom. For example, a carbon atom containing 12 neutrons would be written as C-12 or 12-C.

In addition to the number of nucleons, atoms can also be classified according to their charge. Electrically neutral atoms are ones that contain the same number of electrons as they do protons, and therefore have no net charge. When an atom has a different number of electrons than it has protons, that atom is called an ion. Positive ions, which contain one less orbital electron than nuclear protons, are called cations. Negative ions, which contain more orbital electrons than nuclear protons, are called anions.

It is important to note that an element is defined by the number of protons in its nucleus. Though the number of electrons and neutrons might change, atoms with the same Z are considered the same element.

2.1.2 Isotopes and Nuclides

Different atomic species often have commonalities between the parameters A and N. To classify these atoms, names have been given to pairs of atoms that share a parameter.

Atoms that have the same number of protons (Z) but differing numbers of neutrons (N) are said to be isotopes of the same element. This is because elements are defined only by the parameter Z, meaning that different configurations of the parameters A and N will still be the same chemical element provided that Z has not changed. Hydrogen, as an example, has three naturally occurring isotopes: ${}^{1}_{1}\mathrm{H}$ (hydrogen), ${}^{2}_{1}\mathrm{H}$ (deuterium) and ${}^{3}_{1}\mathrm{H}$ (tritium). One can see that Z does not change between isotopes, and so N for these atoms must be 0, 1 and 2 respectively.

Isotopes that have unequal numbers of protons and neutrons seek to balance their proton-neutron ratio by emitting radiation to reach stability. Isotopes that undergo radioactive decay are called radioisotopes or radionuclides. Every isotope of every element has differing nuclear properties, and so they are called nuclides. All possible nuclides are compiled into what is called the Table of Nuclides, which can be seen in Fig. 3.

The Table of Nuclides arranges nuclides by their nuclear properties, and thus their radioactive behavior. In Fig. 3, the most stable nuclides are represented by the color red, and the least stable nuclides are represented by the color blue. Each small cube of color in this figure represents an individual nuclide.

2.2 Radiation

Radiation is defined as the release of energetic particles or waves by some source. Radiation comes in many forms and has many properties, all of which are essential to understanding the characteristics of radiation and its ability to interact with matter. Radiation is best known as a mechanism of transferring energy to a material, as this process can be biologically harmful, produce useful energy, or incur other noticeable effects. In this section, I will discuss how radiation is categorized, and how one is able to describe nuclides using its nuclear properties.

2.2.1 Types of Radiation

Radiation can be characterized in several ways. One of the most important descriptors of radiation is dependent on the way the radiation interacts with normal matter. Specifically, radiation that carries enough energy to free an orbital electron from an atom is considered *ionizing*. Non-ionizing radiation is any radiation that does not have this ability. Because ionizing radiation is much more practically useful than non-ionizing radiation, it is often simply referred to as "radiation" in fields that frequently use radiation. Ionizing radiation is biologically harmful because of its ability to liberate electrons and therefore break the bonds that hold molecules together.

In addition to being ionizing or non-ionizing, radiation can also take different physical forms. The three main types of radiation are alpha, beta and gamma. Each type has unique properties that make them ideal for specific applications. *Alpha radiation* (α), for example, is the release of two protons bound with two neutrons (identical to a helium nucleus) from the nucleus of a larger atom that has decayed. Alpha radiation has relatively low energy,

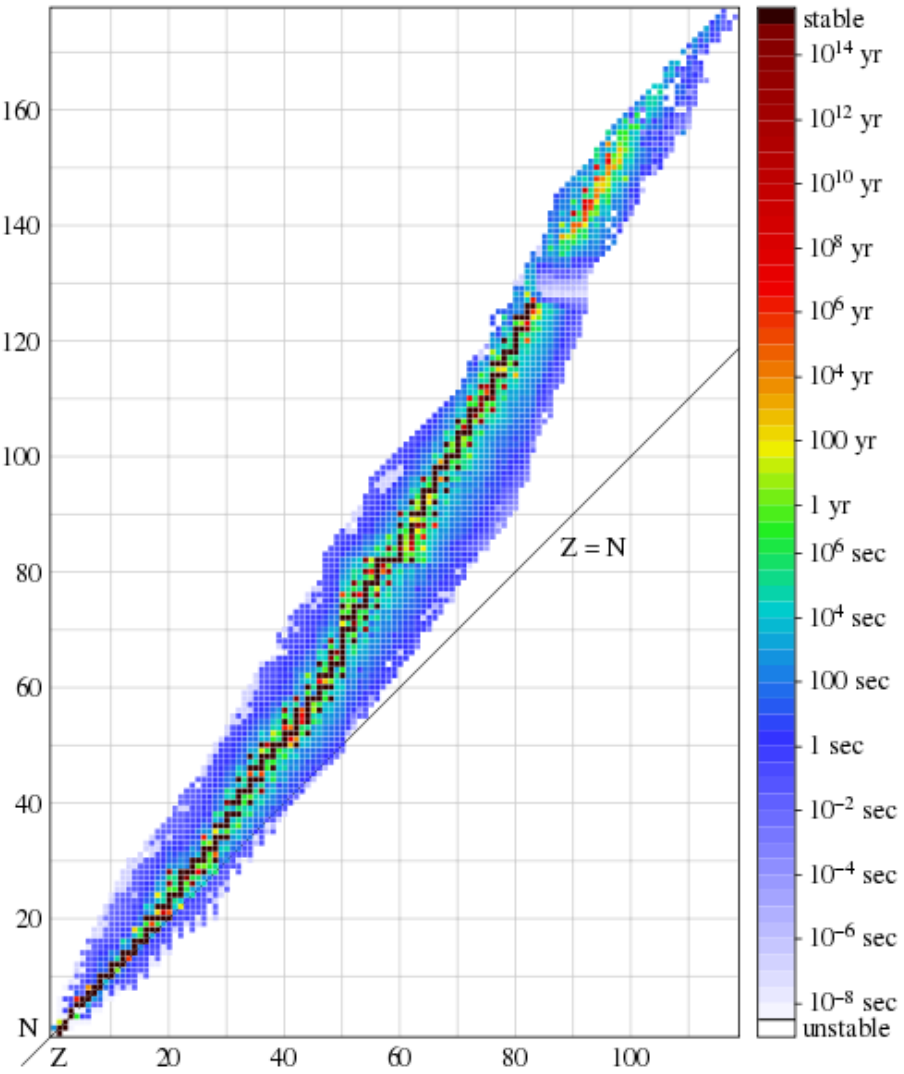

Figure 3: Table of Nuclides.[2]

and because it contains two protons, it is very susceptible to Coulombic forces. Its large positive charge allows it to be easily stopped by almost any type of barrier, including even a sheet of paper.

Beta radiation (β) is defined as the release of either an electron or positron from an atom. The former case is deemed beta minus decay (which leaves the atom with an additional positive charge), while the latter is called beta plus decay (which leaves the atom with an additional negative charge). Because beta radiation releases only a single subatomic particle, it is less susceptible to Coulombic forces and can penetrate heavier barriers than

Gamma radiation (γ) is electromagnetic radiation of relatively high energy. Gamma decay occurs when an atomic nucleus is in an excited energy state, and releases excess energy by emitting a photon. Similar to gamma radiation is the x-ray, which is identical to the gamma ray except for the methods by which each is produced. X-rays, unlike gamma

[2]This image courtesy of http://en.wikipedia.org/wiki/Isotope.

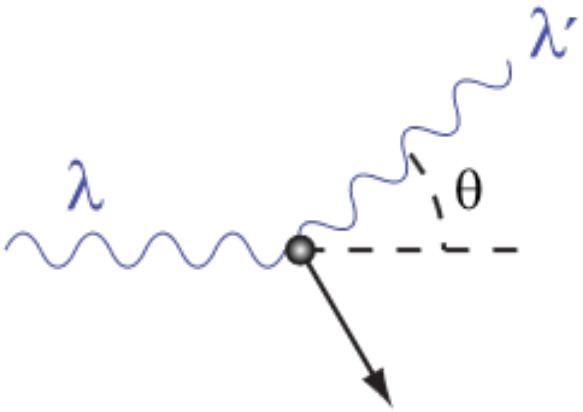

Figure 4: A photon with initial wavelength λ interacts with a particle and scatters at an angle θ with wavelength λ'.[3]

rays, are not produced by the decay of an atomic nucleus. Instead, x-rays are created either by colliding electrons with a material (which are called Bremsstrahlung) or by the de-excitation of orbital electrons [6].

Electron capture decay (ε) is the absorption of an electron by a nucleus, which then emits a neutrino. In this process, a proton is converted into a neutron, thus lowering the overall positive charge of the nucleus. Because the number of protons decreases by one, the atom is considered to be a new nuclide containing a lower ground state. To reach its new ground state, the atom will then release a photon (x-ray) and the absorbed electron is replaced. Additionally, the nucleus of the atom may also be left in an excited state, only to move to the ground state by releasing a photon (gamma ray).

2.2.2 Attenuation

When radiation interacts with matter, several occurrences are possible. Gamma radiation can, for example, be absorbed as energy by orbital electrons in the material. The process by which this occurs is simply called *absorption*. The energy from the absorption process can then lead to the ejection of electrons from the material, which is called the *photoelectric effect*. If it does not lead to the ejection of orbital electrons, then the electrons are often left in an excited state, from which they then decay by releasing a new photon. This process is called *coherent scattering*, which changes the direction of the photon's travel, but leaves the energy of the photon unchanged.

Alternatively, gamma radiation can have its trajectory and wavelength altered after colliding with another particle. This type of interaction is called *Compton scattering*. Figure 4 shows how a photon might scatter after interacting with a particle.

Compton scattering (referred to henceforth as simply "scattering") is an important concept in fields that study radiation, because it can often cause skewed measurements of radi-

[3]This image courtesy of http://en.wikipedia.org/wiki/Compton_scattering.

ation. The wavelength of a scattered photon is given by

$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta) \tag{2.1}$$

where λ is the initial wavelength of the photon, λ' is the wavelength that the photon scatters with, and θ is the angle of scattered photon with respect to its initial direction. Compton scatter is the main source of error in measuring incoming photons, because photons that might not have entered a photon detector with their initial trajectory can be scattered into the detector, thus altering the results.

Because of the many ways that radiation can interact with matter, beams of radiation can be blocked by materials that provide sufficient absorption and scattering effects. The loss of intensity of some radiation by either absorption or scattering as it passes through a material is called *attenuation*. Attenuation is dependent on the material that the radiation is passing through, the type of radiation, and the energy of the radiation. Oftentimes, the probability of some attenuation process occurring for a given system is called the attenuation *cross section* (σ) which has units of area. Cross sections are often extremely small, and are therefore expressed in units of *barns*, where 1 barn = 10^{-24} cm^2.

Since the attenuation cross section includes both absorption and scattering possibilities, it is often useful to look at the cross sections for absorption and scattering independently. The absorption cross section (σ_A) is a measure of the probability of an absorption process, and is given by

$$\sigma_A = \left(\frac{\mu_{en}}{\rho}\right)\frac{A}{N_A}$$

where A is the atomic mass of the material through which the radiation is traveling, and $\frac{\mu_{en}}{\rho}$ is a constant that is dependent on both the material and the energy of the radiation.

Similarly, the probability of radiation scattering off of the material as it passes through is called the scattering cross section (σ_S). Therefore, the total attenuation cross section can also be written as

$$\sigma = \sigma_A + \sigma_S. \tag{2.2}$$

2.2.3 Properties of Radioactive Nuclides

Radioactive decay is an important process that describes the release of energy by an atom through the emission of radiation. As mentioned in Section 2.1, nuclides can be classified as either stable (do not readily decay) or radioactive (readily decay). Radioactive nuclides have many properties that distinguish them from other nuclides, including half-life, activity (or decay rate), and the type of radiation emitted. These properties are especially useful to know for persons who wish to use radioactive materials for practical applications where radiation is required.

Though the type of radiation released by a decay process is important to know, another factor, called *half-life*, is equally important for understanding the qualities of a radioactive material. By definition, the half-life (τ) of a radioactive element is the amount of time it takes for a supply of that element to decay to half of its original amount. This number is often used in nuclear science because it is impossible to predict the decay of a single atom of an element. However, the probability that an atom will decay is constant over time, and

so one can accurately predict the half-life of a supply of a particular nuclide. Knowing an isotope's half-life is essential for determining the period of time over which a radioactive source will be emitting useful amounts of radiation.

The half-life of a nuclide can also be written as what is called the *decay constant* of that nuclide. The decay constant (λ) for a particular nuclide is defined as

$$\lambda = \frac{\ln 2}{\tau} \approx \frac{0.693}{\tau} \tag{2.3}$$

and has units of inverse time. This quantity is often used instead of the half-life, but only for the convenience of calculation.

Another property, called *activity*, describes the number of decays a particular source experiences per unit time. Activity is represented with the symbol A and is typically in units of Becquerels (Bq), which are equivalent to one decay per second. Another unit called the Curie (Ci), named after the famous physicist and chemist by the same name, is also often used. One Curie is equivalent to 3.7×10^{10} Becquerels. The activity of a source at a time t is modeled by a survival curve according to the initial activity A_0 of a radioactive source and the decay constant for that nuclide:

$$A(t) = A_0 e^{-\lambda\tau}. \tag{2.4}$$

Activity is useful for measuring the "output" of a radioactive source over time.

2.2.3.1 Cesium-137

Cesium-137 is a radioisotope of cesium ($Z = 55$), with a half-life of 30.07 years. Cs-137 decays by β^- decay to either a metastable isomer of barium (Ba-137m), or a stable state of Ba-137. About 95% of the time, Cs-137 will decay to Ba-137m, which then decays by emitting a gamma ray with an energy of 661.7 keV. The Ba-137m isomer has a half life of about 2.55 minutes, so this nuclide and the Cs-137 source are in secular equilibrium (i.e. they can be considered to have the same decay rate) [7]. Figure 5 shows the decay scheme of Cs-137.

Before one can fully understand the usefulness of measuring the output of a radioactive source such as Cs-137, one must know how radiation is used in different fields of study. One field that often uses radiation is the medical field, where medical physicists and radiologists use radiation for diagnoses and treatment. In the following sections, radiation's interaction with biological organisms and radiation's role in medicine will be discussed.

2.3 Radiation and Biology

To understand how radiation interacts with biological organisms such as humans, one must first understand the interaction of radiation with animal cells. Cells, which contain DNA-harboring nuclei, are said to be technically "dead" when they have experienced clonogenic death. The term clonogenic death simply describes the state of a cell where the cell has lost its ability to undergo mitosis. Though clonogenically dead cells have the ability to continue

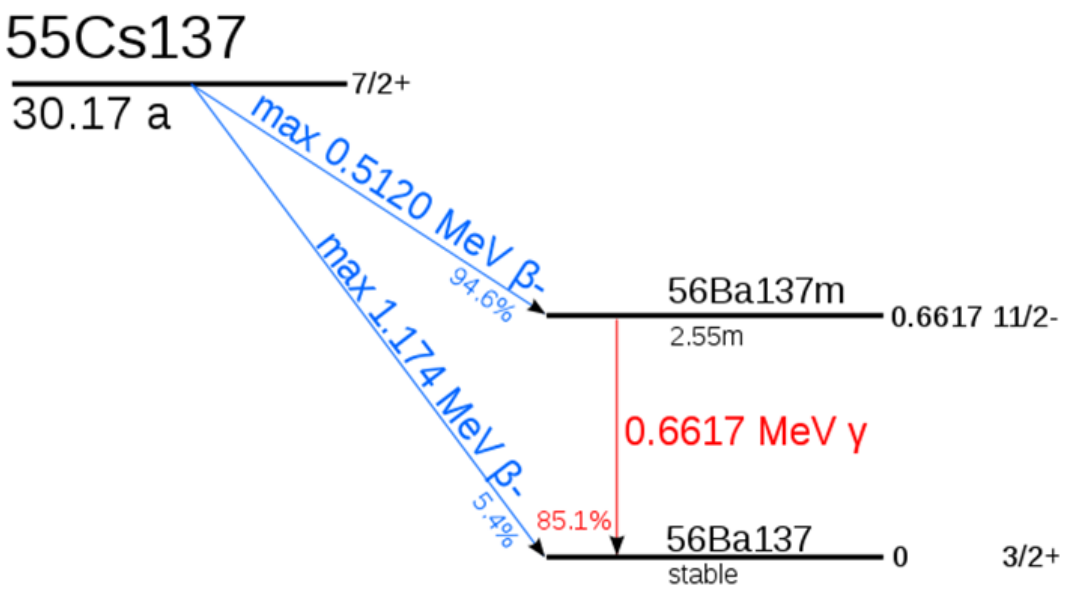

Figure 5: The decay scheme of Cs-137.[4]

living, their inability to reproduce makes them effectively useless for the functionality of a tissue.

It has been shown through a number of experiments that the most effective way to cause the clonogenic death of a cell is to damage its DNA. DNA's purpose in a cell is to store genetic information in the form of nucleotide combinations that will dictate the formation of proteins. Ionizing radiation is a type of radiation that is able to cause significant biological damage because of its ability to strip electrons from the atoms in DNA. When an electron is stripped from a molecule, the bond holding the molecule together is broken and the molecule falls apart. Ionizing radiation therefore has the ability to cause breaks in DNA strands.

Radiation can interact with biological organisms in two ways; it can either directly interact with a critical target and cause a biological effect, or it can interact with a non-critical target. The former case is called *direct action*. A photon hitting DNA to cause a strand break (and therefore damage to the cell) is an example of a direct action. The latter is called *indirect action*. Radiation can first interact with a non-critical target, which can then lead to a "hit" of the critical target. For example, photons may interact with the water molecules in a cell in such a way that creates highly-reactive atoms or molecules called free radicals. Free radicals are atoms or molecules that are lacking one electron to create a stable atom/molecule. When free radicals interact with the DNA of a cell, they extract electrons from the DNA. This causes DNA strand breaks and thus damage to the cell.

Ionizing radiation can cause the creation of free radicals by stripping electrons from water molecules in a cell. First, radiation will cause a water molecule to lose an electron, thus making $H_2O^+ + e^-$. From this stage, H_2O^+ can either split into a hydrogen atom and a free radical ($H^+ + OH\cdot$) or it can combine with another water molecule to create $OH\cdot + H_3O^+$. Additionally, the electron can then interact with water molecules or hydrogen atoms in the cell to create free radicals. Any of the free radicals created as a result of the

[4]This image courtesy of http://en.wikipedia.org/wiki/Caesium-137.

initial ionization that interact with a critical target will have caused an indirect action, and thus have damaged the cell to some degree.

The ability of ionizing radiation to cause clonogenic cell death makes it useful in medicine. For example, radiation can be used to treat cancer, which is caused by cells that divide rapidly and uncontrollably. Cancerous cells are abnormal, in that they can reproduce indefinitely, and can spread to many parts of the body and hinder normal body functionality. However, cancer cells can be killed if they are sufficiently irradiated. Radiation, therefore, can be used to slow or stop the growth of cancerous tissues or tumors, effectively treating the disease. In the following section, methods for treating cancer using radiation are described in detail.

2.3.1 Radiation Therapy

The discovery of the x-ray by Wilhelm Röntgen in 1895 marked the beginning of the use of radiation in medicine. Röntgen discovered that images of bone could be cast onto photographic plates and used for diagnostics [8]. Today, radiation is widely used in both medical diagnostics and the treatment of disease. The use of radiation in medicine is called radiation therapy. There are two main categories of radiation therapy: *external beam therapy* and *brachytherapy*.

Much like the name suggests, external beam therapy (EBT) describes any radiation therapy mechanism that relies upon beams of radiation that are introduced to a patient's target area from the exterior of his/her body. EBT can be used for many types of cancer including breast cancer, colorectal (bowel) cancer, head and neck cancer, lung cancer, prostate cancer, and brain tumors [9].

Brachytherapy, unlike external beam therapy, treats tumors from the inside out, and so it is much different in planning and implementation than external treatment.

2.3.1.1 Brachytherapy

In brachytherapy, radioactive "seeds" are placed inside of a patient's target area (such as a tumor) for treatment. A seed is typically a radioactive source encased in a heavy metal, which contains daughter decay products and any alpha or beta particles that are released. In this way, tissues are only treated with gamma radiation that is released from the source. Figure 6 shows what a brachytherapy seed looks like in relation to a human finger. Figure 7 is a diagram showing the different internal and external components of a brachytherapy seed.

Elements used for brachytherapy seeds are picked according to several factors, such as their decay rate (activity), half-life and decay products. The decay rate and half-life of an element are important in determining how long the treatment should last as well as what dose the patient will receive. Decay products must also be considered when choosing a source type, because typically, only gamma radiation is able to provide effective treatment. If an element's decay series does not include the emission of gamma rays, it is considered a poor candidate for brachytherapy.

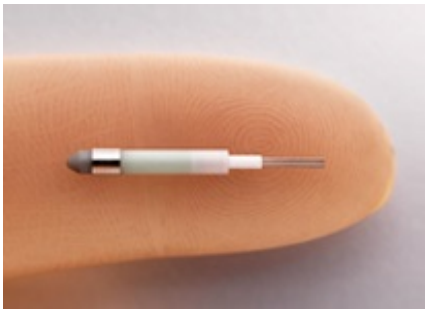

Figure 6: A brachytherapy seed shown on the tip of a person's finger for size comparison.[5]

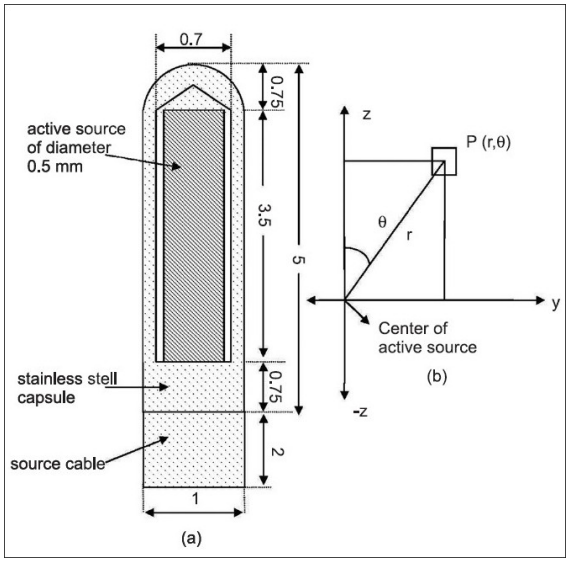

Figure 7: Diagram of the components of a brachytherapy seed.[6]

One of the first isotopes to be used in brachytherapy was radium-226. This nuclide was commonly used in brachytherapy sources because of its fitting properties. Firstly, the half-life of this isotope is 1622 years, so it is stable enough to be reasonably kept in storage and then used with a patient. The decay series for radium-226 has 11 steps that emit alpha, beta and gamma radiation, and the average energy for gamma radiation that is emitted is 0.8 MeV. This high energy proved to work well for treatment, but radium was eventually replaced due to previously unknown dangers posed to medical physicists by this isotope. For example, radium chemically acts like calcium, and so it can be hoarded by the body if it leaks from the source and comes into contact with a person. Such hoarding is incredibly dangerous for personnel who work with brachytherapy sources. Also, the high average energy of the gamma radiation proved to be unhealthy for medical personnel employing brachytherapy treatment.

Because of brachytherapy's history with radium, source activity is often defined in terms of what is called "radium equivalent", where 1 mg Ra-226 = 1 mCi. Sources typically have activities between 0.1 and 30 mg radium equivalent for what is called low dose rate (LDR) brachytherapy. With this type of source, treatment spans over a time interval of a few days. Alternatively, high dose rate (HDR) sources can have activities up to 1000 mg radium equivalent and must be removed after only minutes. Each source type has its advantages and disadvantages and can be used in situations where they are best suited to that individual's tumor.

Currently, elements such as iridium-192 and ytterbium-169 are being researched and used as LDR brachytherapy sources. Iridium is used in flexible tubes called ribbons that encase

[5]This image courtesy of http://www.xoftinc.com/products_hdrsource.html.

[6]This image courtesy of http://www.jmp.org.in/showbackissue.asp?issn=0971-6203;year=2010;volume=35;issue=1;month=January-March.

seeds. Ribbons are temporarily inserted into a patient by being threaded into a hollow needle that is implanted during surgery. This needle is called a trocar, and is removed from the patient's tumor following the implanting of the iridium ribbon. Temporarily leaving only the ribbon in a tumor will help to irradiate the tumor while providing a mostly painless implant for the patient to cope with. Once a ribbon has been placed, radiographs are taken to double-check the location of the sources and to calculate the absorbed dose to areas, a practice called dosimetry.

Other types of implants include intracavitary implants, where sources are placed within body cavities such as the vagina or uterus to treat tumors. Additionally, interstitial therapy uses needles that are pushed into tumors that can be accessed from the outside of the body. Both of these are considered brachytherapy, though they use different mechanisms for inserting radioactive sources into target sites. Both intracavitary and interstitial implants are short-term implants that must be removed after, at most, a few days. This type of treatment is called temporary insertion or temporary implant [8].

A technique called afterloading helps to reduce unnecessary radiation exposure by preparing a treatment site with an empty applicator. Dummy implants can be used to test the placement of radioactive sources by being implanted into the tumor where the radioactive source is marked to be implanted. Once a dummy implant has been set in place, two orthogonal radiographs are usually needed to ensure correct placement. Once placement is deemed accurate, radioactive sources can be placed in the patient's tumor instead of a dummy source.

Radioactive sources can be arranged to meet the needs of a patient's tumor. Treatment plans specify where implants will be placed, how long they will remain inside of the tumor, and the composition of the implant itself. Source type and amount can vary widely, as implants can be made of a single source, a plane of sources (called single plane implants), two planes of sources (called double plane implants) or more (called volume implants). Implants can also be permanent, where sources used have relatively short half-lives in order to deliver the proper dose in a short period of time. Sources such as Gold-198, Iodine-125 or Palladium-103 are used for permanent implants because they have the qualities needed for effective treatment [8].

2.3.2 Radiation Dosimetry

For many different scientific fields - including radiation therapy - it is useful for radiation to be measured and expressed in terms of the energy that is transferred to and absorbed by irradiated materials. The measurement of radiation for useful purposes is called radiation dosimetry. In this section, the concepts of exposure, absorbed dose, and kerma will be discussed.

Exposure is a term that is often used when trying to express the amount of radiation that something has interacted with. By definition, exposure (X) describes the amount of ionization that is created by electromagnetic radiation (gamma or x-rays) in air. Exposure has units of roentgen (R). The roentgen is defined such that

$$1 \text{ R} = 2.58 \times 10^{-4} \text{ C kg}^{-1}. \tag{2.5}$$

However, because exposure is only defined for photons in air, it is not useful for measuring the amount of radiation that is delivered to other materials. For this reason, absorbed dose

is primarily used to quantize radiation [10].

Absorbed dose (D) describes the amount of energy absorbed by a material per unit mass from any kind of ionizing radiation and for any material. Absorbed dose (often referred to as just "dose") is measured in J kg^{-1} or gray (Gy). The rad, another unit for absorbed dose, is related to gray according to the following:

$$1 \text{ J kg}^{-1} = 1 \text{ Gy} = 100 \text{ rad} \tag{2.6}$$

It is now important to note that the same dose of different types of radiation do not necessarily cause the same effect to biological organisms. For this reason, a constant called the *radiation weighting factor* (W_R) must be introduced to scale measured absorbed dose into what is called *equivalent dose*. Equivalent dose (H) is a weighted measure of the absorbed dose from a particular radiation, and is given by

$$H = D \cdot W_R. \tag{2.7}$$

Values for W_R are known for different types of radiation, and can be looked up in order to calculate equivalent dose [10].

Another quantity that is important to know is the *dose rate* for a specific source and material. The absorbed dose rate for some material that is being irradiated is given by

$$\dot{D} = \dot{\Psi}\frac{\mu_{en}}{\rho} \tag{2.8}$$

where $\dot{\Psi}$ is the energy fluence incident on some material (typically bodily tissues) and μ_{en}/ρ is the mass energy absorption coefficient of that material for a given photon energy. Energy fluence is a term that represents the instantaneous rate of energy flow per unit area per unit time. Additionally, energy fluence is dependent only on the source that is used to create the radiation. The mass energy absorption coefficient (μ_{en}/ρ) is a coefficient that is dependent only on the type of material that is being irradiated and energy of the photons with which the material is being irradiated. This coefficient is usually known for any given material for a large range of photon energies, so it does not have to be calculated in order to determine the absorbed dose rate of a source.

The absorbed dose rate is a desired quantity when calibrating a radiation therapy source. Because μ_{en}/ρ is a known quantity, $\dot{D}$ for the interaction of a particular source and irradiated material can be determined simply by calculating $\dot{\Psi}$ for the source.

Similar to absorbed dose is the concept of *kerma*. Kerma (K) measures the total kinetic energy of all charged particles liberated by uncharged radiation per unit mass of material. The difference between kerma and absorbed dose is simple, yet easily overlooked. Kerma measures ions that are created in a material by some radiation, and absorbed dose measures those ions that are absorbed back into the material from which they were created. Kerma and absorbed dose are not necessarily equal because ions that are created may have the ability to escape the material without being absorbed. Figure 8 shows the difference between kerma and absorbed dose.

Kerma and absorbed dose are equal for the case a "thin" sample is at *charged particle equilibrium* (CPE). CPE is achieved when the material being irradiated is thicker than the

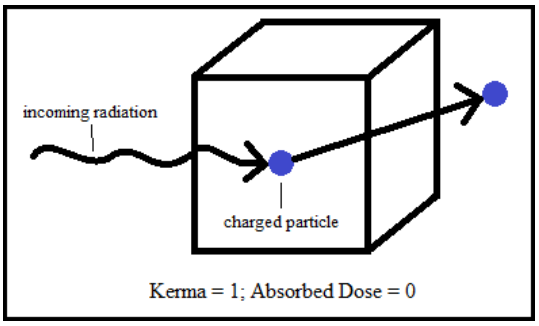

Figure **8.a**

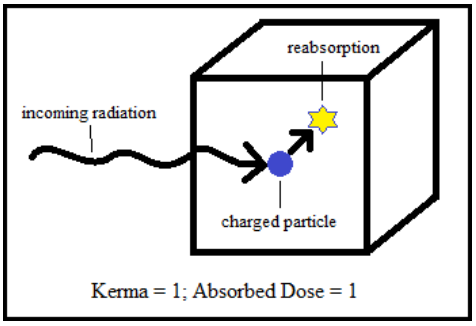

Figure **8.b**

Figure 8: Figure 8.a shows an ion that is created within a material by incoming radiation and contributes to kerma but not absorbed dose. Figure 8.b shows an ion that is created in the material and then absorbed by it, thereby contributing to both kerma and absorbed dose.

maximum penetration range of the most energetic electron that can be produced by the radiation within that material.

However, for a "thick" sample at CPE, there is a difference between the kerma and absorbed dose that is proportional to a quantity called *radiation yield* (g). Radiation yield is defined as the average fraction of an electron's energy that it releases as photons as it travels through a medium and slows to a stop. Typically, radiation yield is a very small quantity. For example, g for a 100 keV electron in water is 0.0007 [10]. In macroscopic samples, a state called *transient CPE* (TCPE) is achieved at distances greater than exactly CPE. Past exactly CPE, kerma and absorbed dose decrease at the same rate, but are not equal. Instead, they are separated by a quantity that is inversely proportional to $1 + g$.

Because kerma and absorbed dose are so similar, in most cases, one can say that these quantities are equivalent [11]. Therefore, one can indirectly measure the dose rate of a source by measuring the kerma rate. The kerma rate of a source is given by

$$\dot{K} = \dot{\Psi}\frac{\mu_{tr}}{\rho} \tag{2.9}$$

where μ_{tr}/ρ is the mass energy attenuation coefficient. The mass energy attenuation coefficient describes the amount of energy that is transferred to a specific material (but not necessarily absorbed) for a given photon energy. Like the mass energy absorption coefficient, μ_{tr}/ρ is a quantity that is known for specific materials and ranges of photon energies. This particular constant is called the mass energy transfer coefficient.

When radiation interacts with some material, it creates ion pairs. The creation of ion pairs can be measured by a device called an *ionization chamber*. A diagram of an ionization chamber can be seen in Fig. 9.

As one can see in Fig. 9, an ionization chamber consists mainly of two plates that are held at some potential difference in order to attract ions that are created in the chamber. When the ions collide with the plates, they generate a measurable current. These ion pairs are created when radiation interacts with the air inside of the chamber. However, at small enough potential differences, the electric field inside of the chamber is too weak to separate

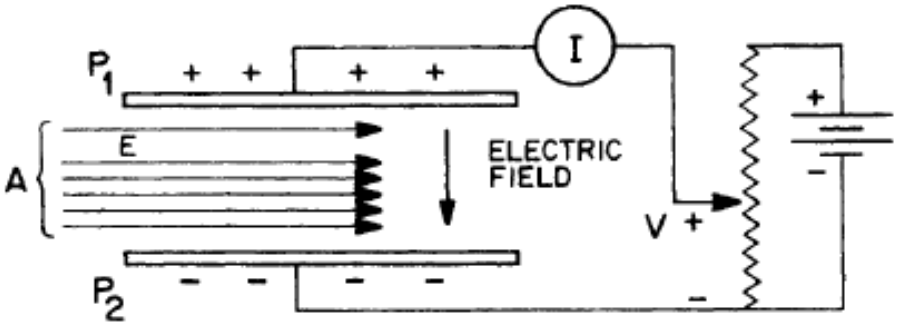

Figure 9: An ionization chamber with active area A is irradiated by a monoenergetic beam of particles that are fully stopped within the chamber. Plates P_1 and P_2 are a cathode and anode, respectively, with a potential difference V across them. The ion pairs created by the incoming beam create current I when they collide with the cathode.[7]

all of the pairs, so some ion pairs will recombine. At and above a potential difference V_0, the electric field in the chamber becomes strong enough to collect all of the ion pairs that are created. The current that is produced at the potential difference V_0 is called the saturation current, which is denoted by the symbol I_0.

In order for an ionization chamber to work correctly, it must operate under charged particle equilibrium. If the ionization chambers are not in CPE, then ions that are created by the incoming radiation may have enough energy to leave the detector and therefore not be measured. Additionally, there is an average amount of energy that is required for a particular type of radiation to produce an ion pair in a designated gas. This average energy is denoted by the symbol W, and has units of eV per ion pair.

To measure the charge created by some radioactive source using an ionization chamber, the device has to be placed such that it is uniformly irradiated by the source's radiation. This means that the source must be held some distance away from the ionization chamber and not directly next to it. Ionization chambers can be used to measure varying properties of radioactive sources. One such property is discussed in section 2.3.2.1.

2.3.2.1 Air Kerma Strength

Medical physicists need to know the absorbed dose rate of brachytherapy sources in tissue in order to create radiation treatment plans. However, it is difficult to directly measure the kerma or absorbed dose for sources in materials such as tissue. Instead, dosimetrists measure kerma and absorbed dose of radioactive sources in air, then translate their results for the desired materials. The ease of measurements in air allows for quick calibrations of sources before they are used.

As stated section 2.3.2, kerma and absorbed dose can be considered the same for materials at CPE. Therefore, to find the absorbed dose for a radioactive source in air, one can instead measure the kerma for that source. The kerma of a source in air is generally called *air kerma*. Air kerma is defined as the energy released per unit mass of a small volume of air when it is

[7]This image taken from Atoms, Radiation, and Radiation Protection by James E. Turner [10].

irradiated by an photon beam. However, kerma cannot be directly measured. Instead, one can measure the *air kerma strength* (S_k) of a source, which is the air kerma rate at a point along the transverse axis of the source in free space. Air kerma strength is defined as the product of the air kerma rate at a distance d, multiplied by the square of the distance d. The equation for air kerma strength is given by

$$S_k = \dot{K} d^2. \tag{2.10}$$

One can see that by measuring S_k at a known distance d, the kerma rate $\dot{K}$ (and therefore $\dot{D}$) of a source can be easily extrapolated. For this reason, air kerma strength is often used as a standard for calibration, where physicists can measure S_k for a source in air and compare it to known values that give certain dose rates. Air kerma strength measurement is discussed in greater detail in the next section.

2.4 Air Kerma Strength Measurement

In order to create a brachytherapy treatment plan, medical physicists must first know about the dose rate of the brachytherapy source. This information is typically known by the manufacturer of the source. However, the dose rates of brachytherapy sources vary within a range given by the manufacturer. Typically, the activity of seeds can be divergent from the manufacturer's specifications by up to 7% or 2σ ($\pm$ 3.5% or 1σ). This range has an uncertainty of $\pm$ 4% or 2σ. This means that with the uncertainty, the total range allows for two seeds of the same batch to be separated in output by up to 11%. According to the American Association of Physicists in Medicine (AAPM), medical physicists are responsible for ensuring that the correct dose is delivered to patients needing brachytherapy treatments regardless of a seed's deviation from the manufacturer specifications. Therefore, because of the variation of the dose rates of individual seeds, physicists must perform calibrations in order to find the exact dose rate of each individual seed [3].

The AAPM states in their Task Group 40 report that "brachytherapy sources are assigned a 'calibration' by the manufacturer. It is not uncommon for an institution to accept the manufacturer's calibration. However, it is the responsibility of the institution to verify that this calibration is correct. The institution should compare the manufacturer's stated value with the institution's standard. If the two are within acceptable limits (see Table 1), either the manufacturer's or institution's value may be used" [12].

According to Table 1, a batch of brachytherapy seeds cannot have a mean measured output that has a deviation greater than 3% from the manufacturer's specifications. Additionally, individual seeds cannot exceed a 5% deviation from the mean.

Medical physicists need some measurement technique that allows them to quickly and accurately calibrate brachytherapy seeds according to the AAPM's standards. The AAPM recognizes air kerma strength measurement as a calibration method for photon sources (sources that decay by gamma emission). Typically, air kerma strength is expressed using the unit "U", where U = μGy m^2/h. Ideally, air kerma strength is a measurement of the kerma rate in a volume of air that is surrounded by a vacuum (i.e. there is no scattering of photons into the volume). As one can see from Eq. (2.10), air kerma strength is also proportional to the square of the distance between the source and the point of reference. With an ideal

Table 1: QA tests for brachytherapy sources. I, initial purchase; D, documented; and E, at every use.[8]

Type of source	Test	Frequency	Tolerance
Long half-life: calibration	Mean of batch	I	3%
	Deviation from mean	I	5%, D
	Calibration verification	E	Visual check
Short half-life: calibration	Mean of batch	E	3%
	Deviation from mean	E	5%
	Calibration verification	E	Visual check

measurement, the source of radiation is considered a point source.

One method of measuring air kerma strength is called the *seven-distance* measurement technique. This method allows medical physicists to quickly and easily measure the air kerma strength of brachytherapy sources, and is discussed in detail in the next section.

2.4.1 Seven-Distance Technique

The seven-distance measurement technique is a way of measuring the air kerma strength of a brachytherapy source. Using this technique, medical physicists are able to indirectly measure S_k using a direct measurement of the charge created by the radioactive source in a volume of air. This charge is directly measured using an ionization chamber. This technique was first developed in 1990 by Goetsch et. al. [13], and has since been reviewed by VanDamme et. al. [14]. This technique is also the current standard for measuring air kerma strength.

The raw charge reading that is collected using an ionization chamber is given by M_d in amps. However, scatter contributes a small, constant amount of additional photon interactions in the ionization chamber, which leads to excess charge as read by the electrometer. We call this component M_s. Therefore, the charge created by only the primary radiation (M_p) is such that

$$M_p = M_d - M_s. \tag{2.11}$$

Because we are only concerned with the charge created by the brachytherapy source, we must subtract contributions from scatter M_s from our raw reading M_d in order to obtain our corrected charge reading M_p. It is worth noting that this corrected charge reading can also be written as

$$M_p = M_d \cdot P_{tp} \cdot P_{elec} \cdot P_{ion} \cdot P_{kr} \cdot P_{attn} \cdot P_{scat}, \tag{2.12}$$

where each of the terms multiplied to the raw charge reading M_d is a correction factor. These terms correct for temperature and pressure, the electrometer's calibration coefficient, the chamber size, possible ion recombination within the chamber, photon scatter contributions, photon attenuation, and electron contamination of the beam, all respectively [14]. According to VanDamme et. al., the total uncertainty caused by the combination of these correction factors is 1.1%. However, VanDamme's is, to date, the only published estimate of the uncertainty in the seven-distance technique [4].

[8]This table was taken directly from AAPM Report No. 46 [12].

To calculate the air kerma strength using M_p, we use the formula

$$S_k = \frac{N_k \cdot M_p \cdot d^2}{\Delta t} \tag{2.13}$$

where N_k is a known value called the ionization chamber calibration factor, Δt is the time over which the measurement is taken (usually in hours), and d is the distance from the source at which the measurement is taken. We can treat the brachytherapy source as a point source because it is so small compared to the distance at which the measurement is taken. There will, however, be a small correction factor c that must be accounted for when calculating the distance between the source and the ionization chamber, such that

$$d = d_n + c. \tag{2.14}$$

where d_n is the distance measured in the laboratory between the ionization chamber and the brachytherapy source. This means that c is the correction that gives the true center-to-center source-chamber distance. We call this exact distance d. We can now introduce the factor f, which is defined as

$$f = M_p d^2 = (M_d - M_s)(d_n + c)^2. \tag{2.15}$$

This factor allows us to rewrite Eq. (2.13) for air kerma strength as

$$S_k = \frac{N_k \cdot f}{\Delta t}. \tag{2.16}$$

Our unknowns are f, M_s, and c for Eq. (2.15) and therefore also Eq. (2.16). This means that taking three measurements of charge M_d at different measured distances d_n will give three equations. This will allow us to solve for the three unknowns, among which is f. By determining f, we can then easily calculate the air kerma strength for the brachytherapy source using Eq. (2.16).

By taking more than three measurements (at more than three different distances), we will be able to obtain more accurate results. This averaging of several solutions to Eq. (2.15) allows us to minimize error and over-determine our result for S_k [13]. Therefore, seven measurements at intervals of 5 cm from the source (i.e. 10, 15, 20, 25, 30, 35, and 40 cm from the source to the ionization chamber) are typically taken to achieve sufficient accuracy. This technique is often called the seven-distance measurement technique because seven measurements are taken.

2.4.2 Gamma Spectroscopy

The seven-distance measurement technique is currently the accepted method for measuring air kerma strength. Recently, the use of gamma spectroscopy systems to calculate dosimetric quantities was partly described by Chen and Nath. In 2007, these researchers gave the background information needed to begin implementing gamma spectroscopy in the area of air kerma strength measurement [15].

Gamma spectroscopy can be used to measure air kerma strength indirectly, much like the seven-distance technique. However, instead of measuring charge created in air, the gamma spectroscopy technique uses a germanium detector to take a count of each photon energy

(E_γ) that it observes. Using simply a count of photons, one can then estimate the rate at which each photon energy is emitted by the source (A_γ) [4]. By combining this information, one is then able to calculate the air kerma strength of the source using the following formula:

$$S_k^{air} = \sum_\gamma \frac{A_\gamma}{4\pi} E_\gamma \left(\frac{\mu_{tr}}{\rho}\right)_\gamma^{air}. \tag{2.17}$$

Gamma spectroscopy does have advantages over the seven-distance technique, such as greater ease of use, fewer correction factors, and no contributions from external electron contamination [4]. Because of this, this technique is currently being researched and having uncertainty analysis performed to show its definitive effectiveness in measuring air kerma strength.

3 Methodology

The goal of this project was to build an apparatus that can accurately perform seven-distance measurements of the air kerma strengths of brachytherapy (or non-brachytherapy) sources. To build such an apparatus, I had to consider which materials to use and how to set up the device such that it is aligned to give measurements at the given seven distances. Once the apparatus was assembled, I then performed a preliminary test of the accuracy of seven-distance apparatus by measuring the air kerma strength of a Cs-137 source using both the seven-distance and gamma spectroscopy methods. In this section, I will describe the process by which I designed, constructed, and then used the seven-distance measurement apparatus. I will also describe how I was able to repeat this measurement using the gamma spectroscopy method.

3.1 Design and Construction of Seven-Distance Apparatus

In order to build an apparatus to take accurate seven-distance air kerma strength measurements, I had to consider possible events that could alter my data. These include:

- photon scattering off of the materials used
- inaccurate determination of the distances that the source was moved by
- and the incorrect alignment of the source and ionization chamber.

To address these possible issues, I had to carefully select the materials used to build the apparatus. I also had to design the structure of the apparatus around these potential problems.

3.1.1 Material Selection

To determine which materials to use for the apparatus, I had to determine the way in which I wanted the gamma ray photons to travel from the cesium-137 source to the ionization chamber. To obtain uniform results, I decided to attempt to allow the photons to travel

only through air (and air-like substances) from the source to the ionization chamber. As discussed in section 2.2.2, attenuation effects (absorption and scattering) are dependent on the type of radiation, the energy of the radiation, and the material that the radiation is passing through. Therefore, by allowing the radiation to travel only through air, we can be sure that all attenuation effects that occur between the source and ionization chamber will occur uniformly with equal probability. Consequently, the attenuation error (M_s) is kept constant and is therefore more easily calculated using the seven-distance technique.

Additionally, I decided to attempt to minimize scattering of the photons off of surrounding materials, which in turn minimizes the collection of photons that originate from outside of the uniform radiation field by the ionization chamber. Figure 10 shows how scattered photons are able to alter the readings of the ionization chamber.

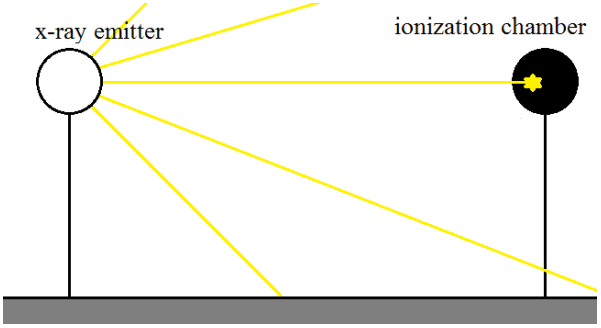

Figure **10.a**

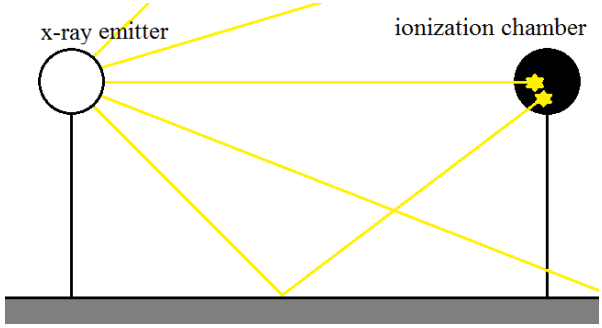

Figure **10.b**

Figure 10: Figure 10.a shows the ideal photon emission scenario, where photons (yellow) that are not emitted in the direction of the ionization chamber are not scattered or collected. Figure 10.b shows the effects of scattering. When photons are not absorbed by the environment, they can scatter and enter into the ionization chamber. Because these photons are not originally directed toward the ionization chamber, they alter the expected results.

To decide on the materials to use to achieve the two above conditions, I had to analyze the absorption, scattering and attenuation cross sections of all possible materials with the gamma ray photon energy that is released by cesium-137. Specifically, I was concerned with the interactions between the photons released by Cs-137 and steel, aluminum, and air. Steel is an alloy consisting mainly of iron with small amounts of other elements [16]. Therefore, elemental iron was used in place of steel when determining its cross section with 661.7 keV photons. For aluminum alloys, elemental aluminum was also used. Air is defined here as a mixture of 21% oxygen, 78% nitrogen, and 1% argon [17].

The National Institute of Standards and Technology (NIST) provides a tool for calculating the photon cross sections for different materials [18]. As stated in section 2.2.3.1, Cs-137 releases gamma rays with the energy 661.7 keV. Table 2 gives the numerical results of a search of cross sections using NIST's database, as well as the average interactions per centimeter of that photon energy in iron, aluminum, and air. Additionally, this table gives the average number of interactions that a photon will experience with a given material. This is calculated by multiplying the cross section by the density of the material.

The average number of interactions per unit length tells us how a photon of 661.7 keV interacts with the given material. As one can see, these photons interact easily with iron,

Table 2: Cross sections of aluminum, iron and air with 662 keV photons.[9]

Material	Total Attenuation Cross Section (cm^2/g)	Density (g/cm^3)	Average Interactions Per Unit Length (cm^{-1})
Aluminum	7.47E-02	2.700	2.02E-01
Iron	7.35E-02	7.874	5.79E-01
Air	7.72E-02	0.0001275	9.84E-05

thus suggesting attenuation effects if the photons come into contact with the material. The same photons interact less than half as much with aluminum. Finally, these photons interact far less with air than either of the previously mentioned materials. Using this information, I decided to use aluminum supports in my apparatus as opposed to steel. Additionally, I ensured that all of the material between the Cs-137 source and the ionization chamber were air-equivalent.

3.1.2 Ionization Chamber

The type of ionization chamber that was used for this project was a farmer-type Exradin A12 ionization chamber made by Standard Imaging. Figure 11 shows a picture of the ionization chamber. One can see that the tip of the ionization chamber is marked for alignment. Figure 12 shows the tip of the ionization chamber, which is the end containing a small volume of air. This is this part of the device that acts as the actual "chamber", where ion pairs are both created and measured. Each ionization chamber is calibrated before it is used. This

Figure 11: Picture of Exradin A12 ionization chamber [19].

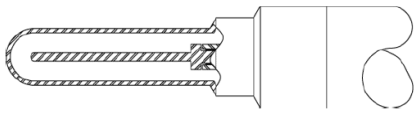

Figure 12: Schematic of the active region of the Exradin A12 ionization chamber [19].

calibration yields what is called the ionization chamber calibration factor, denoted by N_k. The ionization chamber used for this project was calibrated at the University of Wisconsin Accredited Dosimetry Calibration Laboratory, and was found to have a calibration factor $N_k = 4.772 \times 10^7$ Gy/C. Additionally, its efficiency was determined to be 0.9992. The plastic used for the casing of the ionization chamber is C552 Shonka air-equivalent plastic, meaning that it has the same ionization properties as air [19]. More information about the ionization chamber used in this project can be found in Appendix A.

[9]This information taken from NIST's Physical Reference Data database [18].

The ionization chamber was connected to an electrometer, which displayed the charge collected by the ionization chamber. To determine time intervals (Δt) for Eq. 2.16, a timer that is built into the electrometer was used. This timer has a range of 0-600 seconds, works in 15 second increments, and has a resolution of 1 second. [20].

3.1.3 Structure of the Apparatus

In order to address possible issues with inaccuracy in determining the distances between the source and ionization chamber, I used an adjustable metal track to move the ionization chamber in relation to the Cs-137 source. This track was secured to the table to prevent it from moving. To secure the ionization chamber to the track, I attached a threaded aluminum rod to the movable plate on the track and secured the ionization chamber to the rod.

The source was also suspended above the table using an aluminum threaded rod that was threaded directly into the table, with a clamp secured to the top to hold the source in place. All of the equipment was held at some distance above the table in order to reduce the measurement of scattering from the metal track and metal surface of the table.

Finally, I used a laser (also held above the table by an aluminum threaded rod) to ensure that the ionization chamber was correctly aligned with the source, and moved only in the transverse plane of the source as the platform on the track was moved.

A picture of the completed apparatus is presented in Fig. 13.

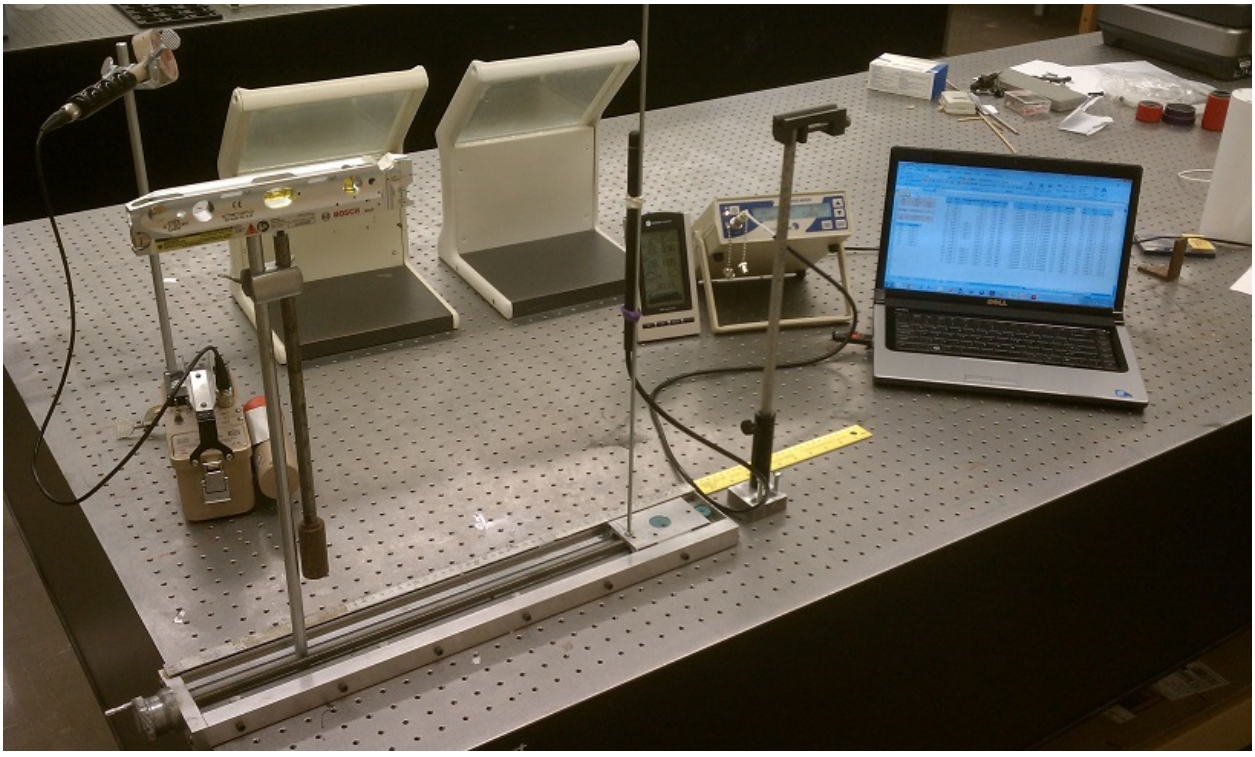

Figure 13: A picture of the completed seven-distance apparatus.

3.2 Experimental Procedure

Once the setup of the seven-distance measurement apparatus was complete, I proceeded in taking measurements with both the seven-distance apparatus as well as the gamma spectroscopy system. In the following section, I will describe the exact processes by which I was able to measure the air kerma strength of the Cs-137 source using these techniques.

3.2.1 Seven-Distance Technique

For the seven-distance measurement technique, I simply had to move the cesium-137 source away from the ionization chamber at intervals of 1.5 cm. Specifically, the source was positioned at approximately 18, 19.5, 21, 22.5, 24, 25.5, and 27 cm away from the ionization chamber. These distances differ from the distances typically used (10-40 cm in 5 cm intervals), because of restrictions due to the length of the track used to move the ionization chamber. Additionally, keeping the furthest distance from the source less than 30 cm helps to reduce the amount of attenuation that occurs between the source and the ionization chamber due to interactions in the air. Smaller intervals were picked such that the source was also kept at least 15 cm from the source, thus retaining our ability to approximate it as a point source.

At each distance, the electrometer measured the charge collected by the ionization chamber over a time interval of exactly 60 seconds. Additionally, a measurement of the background charge reading was taken at each distance and subtracted from the measured charge due to the source. Each measurement was also corrected for the temperature and pressure of the room, since the air inside of the ionization chamber is calibrated at standard temperature and pressure (20° C and 1 atm). These measurements were repeated three times at each distance and averaged to obtain an accurate result. Using these charge measurements, I was then able to set up a system of seven equations and solve for M_s and c, which are constant throughout the entire process and at each distance.

With all unknowns solved for, I was then able to calculate the air kerma strength of the source for each of the measurements of charge that were taken using Eq. 2.13. To find the final measurement of air kerma strength, I simply averaged the values for all of the distances, and took the standard deviation for all of the points. After this was complete, I then repeated the measurement using the gamma spectroscopy technique.

3.2.2 Gamma Spectroscopy Technique

For this measurement, I used the gamma spectroscopy technique as described in section 2.4.2. The gamma spectroscopy system that we used for this project consisted of a lead cylinder with walls on the order of a few inches thick. This lead cylinder houses a germanium detector, which is located at the bottom of the cylinder. The lead walls of the cylinder prevent scatter from the room from entering the germanium detector, and is lined with copper to absorb any fluorescence from the lead shielding. The detector itself was cooled by liquid nitrogen to reduce noise in the measurements.

The top of the cylinder opens as two lead doors swing to the sides of the cylinder. To make a measurement of the Cs-137 source, because it is relatively high-dose-rate, it had to be suspended about 30 cm above the opening on the top of the cylinder using a set of

aluminum rods and clamps. By keeping the source at a distance away from the detector, we were able to minimize noise in our measurement.

A picture of the gamma spectroscopy system that was used for this project is presented in Fig. 14. With the setup complete, we were then able to calculate the air kerma strength of the Cs-137 source using Eq. 2.17. We were able to calculate the standard deviation in our measurements by propagating the uncertainties in the efficiency of the detector, the estimate of μ_{tr}/ρ, and the counts of photon energy seen by the detector [21].

Figure 14: A picture of the gamma spectroscopy system used for this project. One can see the lead cylinder that houses the germanium detector sitting on a table above the container of liquid nitrogen to cool the system. The lead doors on the top of the cylinder are swung open, and the source is suspended above the opening on the top of the detector using a pair of metal rods.

4 Results

In this section, I will discuss the results of the seven-distance measurement technique, the results of the gamma spectroscopy technique, and how these two sets of results compare. Table 3 shows the different constants that were used in determining the air kerma strength of the cesium-137 source in both the seven-distance measurement and gamma spectroscopy techniques. The activity of the source was determined by the software used while taking measurements using the gamma spectroscopy technique. The constant μ_{tr}/ρ was looked up using NIST's database [18]. The average background reading while using the ionization chamber (denoted by Average Bg. in Table 3) was directly measured using the ionization chamber.

Table 3: Constants used in the detemination of S_k using the seven-distance and gamma spectroscopy techniques.

Activity (mCi)	Δt (seconds)	μ_{tr}/ρ (cm^2/g)	N_k (Gy/C)	Average Bg. (C)
17.08	60	2.93E-02	4.772 $\times 10^7$	-1.083E-13

Using the seven-distance method, I measured charge readings generated by the Cs-137 source at seven distances. Three, one-minute measurements were taken for each distance from the source. Using Maple, I was able to set up a system of equations to solve for M_s and c, which were -4.74E-14 C and -1.224 cm respectively. Using these constants, I was then able to determine the exact distances d, charge measurements M_p, and air kerma strengths S_k.The results of these calculations are presented in Fig. 4.

To obtain the air kerma strength of the source, I simply averaged the values of S_k calculated over all of the distances. The result of this average gives $S_k^{Cs-137} = 53.97 \pm 2.32$ cGy cm^2 h^{-1}. The gamma spectroscopy system gives the air kerma strength of the source per unit of activity, so for comparison purposes, I can also write the quantity found using the seven-distance measurement technique as $S_k/A = 3.16 \pm 0.13$ cGy cm^2 h^{-1} mCi^{-1} by dividing the original measurement by the activity of the source.

Table 5 gives the results obtained using the gamma spectroscopy method. With the uncertainty in measurement, the air kerma strength per unit activity found using the gamma spectroscopy system is $S_k/A = 3.29 \pm 0.13$ cGy cm^2 h^{-1} mCi^{-1}. However, it is worth mentioning that there was a recorded dead time of about 73% using this method. Dead time simply describes the amount of time that is spent calculating the data, and thus not recording incoming photons. Thus, the uncertainty in this measurement is likely higher.

A comparison of the results using the seven-distance measurement and gamma spectroscopy techniques is presented in table 6. In section **??**, I will discuss what these results mean in terms of the validity of the seven-distance apparatus that I built for measuring the air kerma strength of other sources.

Table 4: Numerical results obtained using the seven-distance apparatus.

d (cm)	M_p (C)	f (C cm^2)	S_k (cGy cm^2 h^{-1})
16.77569737	-6.74E-13	-1.9E-10	54.33297157
16.77569737	-6.64E-13	-1.9E-10	53.52719831
16.77569737	-6.94E-13	-2E-10	55.94451809
18.27569737	-5.84E-13	-2E-10	55.87693057
18.27569737	-5.74E-13	-1.9E-10	54.92061858
18.27569737	-5.94E-13	-2E-10	56.83324256
19.77569737	-5.04E-13	-2E-10	56.46779832
19.77569737	-4.94E-13	-1.9E-10	55.3480632
19.77569737	-4.64E-13	-1.8E-10	51.98885784
21.27569737	-4.14E-13	-1.9E-10	53.69453334
21.27569737	-4.14E-13	-1.9E-10	53.69453334
21.27569737	-4.24E-13	-1.9E-10	54.99057599
22.77569737	-3.54E-13	-1.8E-10	52.62127253
22.77569737	-3.84E-13	-2E-10	57.07697627
22.77569737	-3.64E-13	-1.9E-10	54.10650711
24.27569737	-3.34E-13	-2E-10	56.406135
24.27569737	-3.04E-13	-1.8E-10	51.34420226
24.27569737	-2.94E-13	-1.7E-10	49.65689135
25.77569737	-2.54E-13	-1.7E-10	48.37401388
25.77569737	-2.84E-13	-1.9E-10	54.0808288
25.77569737	-2.74E-13	-1.8E-10	52.17855716

Table 5: Results given by the gamma spectroscopy system.

Energy (keV)	Decay Rate (dps)	μ_{tr}/ρ (cm^2/g)	Kerma Rate at 1 cm (cGy cm^2 hr^{-1})	S_k/A (cGy cm^2 h^{-1} mCi^{-1})
661.7	6.320E+08	2.93E-02	5.62E+01	3.29

Table 6: Seven-Distance vs. Gamma Spectroscopy

Method	S_k (cGy cm^2 hr^{-1} mCi^{-1})	Percent Difference (%)
Seven-Distance	3.16 ± 0.13	4.028
Gamma Spect.	3.29 ± 0.13	

5 Conclusions

The data in section 4 shows that the seven-distance apparatus that was built for this project is fully operational, and can now be used to measure the air kerma strength of brachytherapy sources. The measurements taken with this technique coincide well with the measurements taken using the gamma spectroscopy technique. With this apparatus, WPI now has the ability to measure the air kerma strength of sources using the current accepted standard.

5.1 S_k Measurements for University Research

The seven-distance apparatus that was built for this project will allow for the measurement of the air kerma strength of sources that will be used for research at the university. Specifically, this apparatus provides WPI with the ability to begin brachytherapy research to aid in the development of new brachytherapy seed types and treatment planning methods. WPI's radiation laboratory hopes to use this apparatus to begin measuring the output of ytterbium-169 brachytherapy sources, in order to develop them for use in medical staples. This source type currently lacks dosimetric data, and so WPI's seven-distance apparatus will allow the university to research this data and provide it to manufacturers and medical physicists alike. Additionally, the radiation laboratory at WPI would like to use this apparatus to begin researching enclosure styles for brachytherapy sources. All of this research is now possible as a result of this project.

5.2 S_k Measurements for Other Institutions

WPI's new seven-distance apparatus will also allow for the measurement of the air kerma strength of sources on behalf of other institutions and/or manufacturers who require calibration services. The ability to measure air kerma strength is a relatively unique ability, as not many institutions have apparatuses that can measure air kerma strength. Therefore, with this apparatus now built and tested to be functional, those institutions that lack the ability to measure air kerma strength can rely on WPI's radiation laboratory to make these measurements on their behalf. Institutions that would rely on WPI's radiation laboratory include other universities, clinical laboratories and manufacturers of brachytherapy sources.

5.3 Development of Other S_k Measurement Techniques

Lastly, the seven-distance apparatus will allow for detailed research into the viability of other air kerma strength measurement methods, such as the gamma spectroscopy technique. As previously mentioned. the gamma spectroscopy technique is not a currently accepted method for measuring the air kerma strength of brachytherapy sources. This is because detailed information regarding the uncertainty in taking measurements using this technique has not previously been published. With an operational seven-distance apparatus, WPI's radiation laboratory will perform detailed analysis of both the seven-distance technique (which has also not been fully researched) and the gamma spectroscopy technique. If viable, the gamma spectroscopy technique could replace the seven-distance method as the standard for measuring air kerma strength.

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Appendices

A Ionization Chamber Specifications

The next three pages of this appendix give the specifications of the ionization chamber used for this project. This information was taken directly from http://www.standardimaging.com/print_product.php?id=83 [19].

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Exradin A12 Ion Chamber

92700

UNCOMPROMISING **QUALITY**

For absolute dosimetry calibrations in water, air, or other phantom material

DESIGNED FOR ABSOLUTE DOSIMETRY CALIBRATION

Exradin Farmer-type Chambers are specifically designed for absolute dosimetry calibrations in water, air, or other phantom material. The Model A12 is completely characterized in TG 51 and TRS 398.

FAST, PRECISE MEASUREMENTS

Its waterproof construction and two piece removable stem makes it ideal for use in water phantoms. The chamber vents through a flexible tube that surrounds the triaxial cable, ensuring the collecting volume is in pressure equilibrium with the surroundings. The design assures there are no stem or voltage soakage effects, providing precise and reliable measurements.

DURABLE CONSTRUCTION, BUILT TO LAST

Farmer-type Chambers are constructed of rugged C552 Shonka air-equivalent plastic, providing excellent conductivity and years of reliable use. Rigorous one meter drop test proves ruggedness and reliability.

Model A12 Exradin Farmer-type Chamber

Features and Benefits

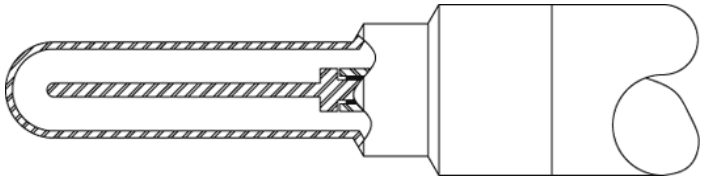
- Proven guard design yields stable, precise measurements and minimizes settling time by creating uniform field lines

- Shell, collector, and guard are made of durable, long lasting Shonka conductive plastic
- Use of homogeneous material throughout the chamber minimizes perturbation of the beam due to the presence of the chamber and optimizes measurements
- Axially symmetric design of the chamber provides an uniform, isotropic response
- Inherent waterproof construction eliminates need for additional protective coverings
- Two separate stem pieces of 5.1 cm and 12.7 cm can be coupled together for ease of use
- A matching 2.8 mm thick ^{60}Co build-up cap of C552 Shonka air-equivalent plastic is provided for air calibrations and measurements
- Additional build-up caps of Delrin and brass are available
- Ionization collection efficiency is 99.9% or better
- Collecting volume is 0.64 cc

Specifications

REF Number	92700
Collecting Volume	0.64 cm^3
Nominal Calibration Factor	5 R/nC
Centroid of Collecting Volume	12.9 mm from tip of chamber
Collector Diameter	1.0 mm
Outside Diameter of Shell Collecting Volume	7.1 mm
Wall Thickness	0.5 mm
Shell, Collector, and Guard Material	Shonka air-equivalent plastic C552
Included ^{60}Co Buildup Cap	Wall thickness of 2.8 mm; contructed of C552
Venting	Vented to the ambient via the flexible vent tube surrounding the triaxial cable
Stem	1.3 cm OD black phenolic, two-piece with 5.1 and 12.7 cm segments
Nominal Collection Efficiency	1.000

Maximum Polarizing Potential	1000 V
Nominal Inherent Leakage Currents	10^{-15} A
Low-Noise Triaxial Cable	50 ohms, 29 pF/ft, 1.5 m long
Signal Connector	Triaxial BNC plug (2-Lug, male pin); others available upon request
High Voltage Connector	Integral with triaxial connector (shell of chamber is common with connector body)
Waterproof	Yes
Product Standards	CE_{0413}, Designed to meet IEC 60601-1, IEC 60731



Model A12 Schematic

Publications

AAPM's TG-51 Protocol for Clinical Reference Dosimetry of High-Energy Photon and Electron Beams
P. Almond, P. Biggs, B. Coursey, W. Hanson, M. Huq, R. Nath, and D. Rogers
Medical Physics 26(9), 1847 (1999)
View Abstract

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View Abstract

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L. Buckley and D. Rogers
Medical Physics 33(2), 455 (2006)
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