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Non-intrusive assessment of radionuclides in enclosed pipes and vessels

Traci Renee Glew
University of Nevada, Las Vegas

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NONINTRUSIVE ASSESSMENT OF RADIONUCLIDES IN ENCLOSED PIPES AND VESSELS

by

Traci R. Glew

Bachelor of Science
University of Nevada, Las Vegas
1994

A thesis submitted in partial fulfillment of the requirements for the

Master of Science Degree
Department of Mechanical Engineering
Howard R. Hughes College of Engineering

Graduate College
University of Nevada, Las Vegas
December 1999

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The Thesis prepared by

TRACI R. GLEW

Entitled

RADIONUCLIDE ASSESSMENT IN PIPES & VESSELS

is approved in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

Examination Committee Chair

Dean of the Graduate College
ABSTRACT

Non-Intrusive Assessment of Radionuclides in Enclosed Pipes and Vessels

by

Traci R. Glew

Dr. William Culbreth, Examination Committee Chair
Associate Professor of Mechanical Engineering
University of Nevada, Las Vegas

The assessment and cleanup of various nuclear sites throughout the country has become an increasingly important issue. Methods for assessment of radioactive material within pipe and duct systems at these sites must be cost effective, efficient, and safe. Several tests were conducted at the University of Nevada, Las Vegas, using both steel and aluminum pipes with a Cesium 137 source placed inside. A Geiger-Muller pancake detector was used to measure gamma rays from several angular positions and at various axial distances along the outside of the pipe. A plot of the data showed excellent results despite the low efficiency of the detector. The data was run through an algorithm to determine the optimum predicted source strength and axial position. Results were again excellent and showed errors of as little as 28% off from the known value. Based on these results, it seems possible that contamination within pipes for more complicated geometries is possible with reasonably accurate predictions of the contaminant radioactivity and distribution within the pipe.
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ACKNOWLEDGMENTS

I would like to thank first and foremost my Committee Chair and Advisor, Dr. William Culbreth, for all his help and patience. I would also like to thank Dr. Vernon Hodge for his kindness in lending equipment, the Health Physics Department for lending theirs, the undergraduate students who assisted with this project, each of the members of my committee for their time, and the secretaries in the Mechanical Engineering office for advice, direction, and general support. Finally, I would like to thank my husband for all his support on the home front.
CHAPTER 1

INTRODUCTION

1.1 Review of Topic

Developing an efficient and cost effective means of assessing radioactive contamination in waste pipe and duct systems has become an important issue in site remediation. Currently, the designs being tested by various agencies involve intrusive methods which are, at times, the most logical means of determining the level of contamination in pipe systems. But the majority of these methods do not investigate the composition or species of radioactive contaminant. It may be more feasible in particular situations to examine the contamination from outside of the pipe or vessel. Most likely a site cleanup would involve a combination of several methods to be most effective.

The Department of Energy has funded several research grants at the University of Nevada, Las Vegas, to explore the most effective and efficient designs and methods for radionuclide assessment in pipes and vessels.

1.2 Review of Past Work

The U. S. Department of Energy has invested research dollars to design a system for pipe and duct inspection that would save money and provide a safe environment for technicians conducting assessments on pipes. Systems such as the Radiological Services,
Inc. Pipe Crawler® have actually been tested at Department of Energy facilities. A Large-Scale Demonstration Project (LSDP) was conducted at the Chicago Pile-5 (CP-5) Research Reactor located at Argonne National Laboratory-East (ANL-E) (DOE, 1998). The CP-5 is a heavy water moderated and cooled, highly-enriched, uranium-fueled thermal reactor designed to supply neutrons for research.

The Pipe Explorer™, designed by Science and Engineering Associates. Inc., was also tested, under the Department of Energy’s sponsorship, at the DOE FUSRAP site in April and May of 1995. During the 1950’s the site was home to a factory which produced material for uranium fuel elements for the reactors in Hanford, Washington, and the Savannah River Site in South Carolina. Waste from the extrusion process mixed with oil from machinery and contaminated the oil drain piping system.

Both of these have shown good results in screening the interior of piping systems. Several other companies have also worked on detection systems of which most are still in the design process. Each design, as described below, has certain benefits and limitations for each particular case. All are for use in interior or intrusive inspection of pipes.

1.2.1 Existing Methods Used at the Nevada Test Site

Current methods at the Nevada Test Site, (NTS), include various intrusive methods of which most involve Geiger-Muller counters which are manually deployed in short stretches of pipe. This exposes technicians to radiation that might be retained on the measurement device when it is withdrawn. None of these methods attempt to characterize the species of contaminant material inside the pipes. The current baseline method at the Nevada Test Site involves cutting the pipes into sections and analyzing
each by section before disposing of them. (DOE, 1998) This can potentially spread contaminant to the environment as well as to workers. In addition, the required work of digging up, cutting, and disposing of pipe sections is significantly more costly and time consuming than analyzing the pipe in place. For ductwork, similar methods are available as for the pipe systems.

1.2.2 Existing Methods Used in the Industry

Several companies have developed equipment which avoids using the NTS baseline approach of excavation and disposal. Each method has benefits and limitations which will be addressed. It is important to note that all of these methods require the intrusive application of detector equipment.

The Pipe Crawler® internal piping characterization system was developed for the U.S. Department of Energy and tested at the Chicago Pile 5 (CP-5) Research Reactor at Argonne National Laboratory in Argonne, Illinois. (DOE, 1998) It includes a family of manually advanced and wheeled instruments used for a variety of pipe sizes which are fitted with a Geiger-Muller instrument and operated from a remote location. This system can be used in pipes ranging from 2 inches to 18 inches and up to 200 feet in length. Detection instrument limitations only allow for partial detector coverage of the interior of the pipe. However, the goal of the Pipe Crawler® is to determine total radioactivity in a pipe and not to distinguish isotopic composition or position of the sediment within the pipe. It cannot be used in pipe systems containing standing water due to sensitive electronic parts. Pipes are also required to be free of any obstructions and to have two free ends for manually advancing the instruments.
The Pipe Explorer™ is a pipe characterization system developed by Science and Engineering Associates, Inc. This system makes use of a small detector attached to a tether and deployed using an airtight membrane and pressurized air to force it through the pipe. The detector is towed within the membrane as it deploys and is protected from moisture and contamination as measurement data is collected. It has been used to inspect pipes from 2 to 18 inch diameter and consisting of up to eight elbows. Problems with this method are that the membrane can potentially get snagged and tear, thereby exposing the equipment to contamination. It is limited to a surveying distance of 250 feet. There is limited control over counting intervals and time.

The Internal Duct Characterization System (IDCS) developed jointly by Idaho National Engineering and Environmental Laboratory, Inuktun Services, Ltd. and Automation Systems Associated, Ltd. is another robotic vehicle design with limitations similar to the Pipe Crawler®. It uses a tractor pulling system with modular housing and is operated from a computer control center. The vehicle can operate in pipe or duct ranging from 6 inch to 32-inch diameter.

1.3. EMAD Facility, Setup to Measure Flux in Pipe

The EMAD facility at the Nevada Test Site was used for the clean up and disassembly of nuclear rocket engines. An assessment of the pipes and ducts used to transfer contaminated waste fluid and air has never been completed and possible contamination may still exist in sections throughout the building. The pipes within the building are 3-inch diameter mild steel drainage pipes and are color coded according to the type of effluent passing through them. Radioactive waste was passed through a
completely independent system that ultimately leads out to a leach field over 800 feet behind the building. Most of the various pipe systems are exposed at least partially. Accesses to drains in some areas are located in “hot” rooms that may require appropriate safety dress to enter. Ducts are located outside of the facility. Those used for exhaust from “hot” areas of the building are also part of an independent system and pass through one of two filter towers. A plan of the facility has been checked and corrected where needed to design an efficient method of detecting radionuclides within the pipes and ducts. All fluid and air systems will be checked with particular emphasis on systems used for transporting nuclear fluid waste to leach field behind facility. Leach field pipe runs approximately 800 feet behind building, is buried up to 10 feet in soil, and is of 6-inch diameter. It is unknown what level of radioactivity is present in the leach field. The nuclear rocket test stands at the Nevada Test Site were used for intercontinental ballistic missiles in the 60’s. When the rocket was launched, the fuel was converted to spent fuel producing the different isotopes. These launch areas are also scheduled for assessment using methods similar to those which may be prescribed at the EMAD facility, though information about the site is still currently limited.

At the EMAD facility site, the plan is to insert a small autonomous robot equipped with a gamma detector inside the pipe at a convenient location along the stretch of pipe leading out to the leach field. At regular intervals a count will be taken and data will be locally stored till the robot is removed. Inside the building, the exterior pipe assessment method will be tested on pipes and ducts that are exposed and easily accessible.
1.4 Current Work

There is a need at the Nevada Test Site for technology to assist in land and facility remediation in pipes and ducts that potentially contain radioactive contaminants. Current methods are intrusive and pose a potential hazard to employees implementing them. The current work outlines an effort to design efficient, accurate and safe methods of analyzing radionuclides in enclosed pipes with the minimum human contact and spread of radionulides in the environment.

The proposed system utilized a scintillation gamma detector located on the outside of the pipe to measure gamma energies from deposits within the pipe. Based on these external gamma ray measurements, a mathematical technique was developed to infer the content of radiation inside the pipe. Potentially contaminated pipes located in DOE facilities at the Nevada Test Site are used as an example for demonstrating the detection model. Possible contaminants within the pipe sediment include isotopes of plutonium and uranium that are low energy gamma emitters. Cesium, strontium, cobalt, and other high energy gamma emitters may also be present. By moving the detector along the outside wall of the pipe, the geometry of the sediment within can be assessed using an algorithm to calculate the radioactivity and the configuration of the radioactive material.

1.4.1 Methodology

Previously there has not been a successful way of analyzing levels of contamination from the exterior of pipes and ducts due to gamma ray attenuation by the pipe wall. The number of gamma-ray counts detected on the outside of the container are
considerably decreased due to absorption or attenuation of the radioactive emissions by the container wall material. As a result, the radioactivity is greatly underestimated.

We have put together an experiment to show that, with a knowledge of the container material and the original uncontaminated fluid or gas within it, it is possible to determine what the radioactive source energy is as well as its axial position without opening or damaging the container itself. Each radionuclide emits one or more types of particles at very specific energies. Once the energy of the contaminant is established, it is possible to match the energy to its respective nuclide and thereby show which radionuclide(s) is present. In certain situations this can be a much safer and more inexpensive approach. To begin, it is important to have a basic understanding of the theory behind radiation detection when setting up the calculations to determine activity and position of the contaminant. This is discussed in chapter 2. Chapter 3 outlines briefly the mathematical theory behind radiation attenuation. The numerical method that was developed for this work is explained in chapter 4. Results of the experiments and comparison with the predicted source characteristics from the numerical model are discussed in chapter 5.
CHAPTER 2

RADIATION DETECTION METHODS

2.1 Sources of Radiation at the Nevada Test Site

Since the 1950’s the Nevada Test Site has been actively using radionuclides in testing of not only nuclear weapons, but also environmental studies, tracers in wells, and for industrial purposes. Many laboratory facilities were built in the 1960’s that used radionuclides in processing and experiments which required waste systems to remove contaminated effluent in the form of fluid or air from the buildings. Decommissioning of these facilities has required some form of testing for radioactivity levels in these systems and determination of the types of radionuclides present. The ideal method would need to be efficient, inexpensive, and be able to detect very low levels of radioactivity in round or rectangular pipes and ducts of various sizes, both small and large. In addition, it should be able to detect low level gamma radiation from both inside and outside a pipe or vessel with minimum intrusion and risk of human exposure. The data collected would then need to be processed and used to determine where hot spots are located, if any, and what types of nuclides are present.

2.1.1 The Actinides (U, Pu)

The U.S. Department of Energy is primarily concerned with those nuclides which
are possibly present at the EMAD facility and the nuclear rocket test stands located at the Nevada Test Site. The most prominent radionuclides are actinides resulting from the fission of $^{239}$Pu and $^{235}$U. The actinides include all the heavy elements with atomic numbers (Z values) of 89 to 103 at the bottom of the periodic chart. Table 1 shows a brief list of these actinides with their decay types and respective energies in MeV. The kinetic energy of gamma rays and subatomic particles are conventionally listed in millions of electron volts (MeV) where 1 MeV = $1.602 \times 10^{-19}$ J. Table 2 shows some additional nuclides which are frequently products of nuclear reactions.

Most pipe inspection methods are designed to detect isotopes emitting low level gamma rays since charged particle emissions, such as alpha and beta decay, are quickly absorbed or attenuated over very short distances in the pipe material and any surrounding medium.

Table 1 Common Actinides and Their Most Prominent Decay Types (Foster, 1983)

<table>
<thead>
<tr>
<th>$Z$</th>
<th>Isotope</th>
<th>Half-Life</th>
<th>Predominant decay type(s)</th>
<th>Energy(ies) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>$^{231}$Th</td>
<td>25.6 hours</td>
<td>$\beta^-, \gamma$ $\beta^-, \gamma$</td>
<td>0.308, 0.084 (44%) 0.094, 0.058, 0.026 (45%)</td>
</tr>
<tr>
<td>92</td>
<td>$^{233}$U</td>
<td>$1.62 \times 10^5$ years</td>
<td>$\alpha$</td>
<td>4.823</td>
</tr>
<tr>
<td>92</td>
<td>$^{234}$U</td>
<td>$2.48 \times 10^5$ years</td>
<td>$\alpha$, $\gamma$</td>
<td>4.67 (73%) 4.71, 0.068 (27%)</td>
</tr>
<tr>
<td>92</td>
<td>$^{235}$U</td>
<td>$7.1 \times 10^4$ years</td>
<td>$\alpha$</td>
<td>4.40 (83%)</td>
</tr>
<tr>
<td>92</td>
<td>$^{236}$U</td>
<td>$2.3 \times 10^4$ years</td>
<td>$\alpha$, $\gamma$</td>
<td>4.494, 0.049</td>
</tr>
<tr>
<td>92</td>
<td>$^{238}$U</td>
<td>$4.51 \times 10^9$ years</td>
<td>$\alpha$, $\gamma$</td>
<td>4.195 (77%) 4.18, 0.048 (23%)</td>
</tr>
<tr>
<td>92</td>
<td>$^{239}$U</td>
<td>23.5 minutes</td>
<td>$\beta^-, \gamma$</td>
<td>1.2, 0.73</td>
</tr>
<tr>
<td>93</td>
<td>$^{238}$Np</td>
<td>2.1 days</td>
<td>$\beta^-, \gamma$ $\beta^-, \gamma$</td>
<td>1.272, 0.044 (47%) 0.258, 1.03 (53%)</td>
</tr>
<tr>
<td>94</td>
<td>$^{239}$Pu</td>
<td>89.6 years</td>
<td>$\alpha$, $\gamma$</td>
<td>5.49 (72%) 5.45, 0.044 (28%)</td>
</tr>
<tr>
<td>94</td>
<td>$^{239}$Pu</td>
<td>24,360 years</td>
<td>$\alpha$, $\gamma$</td>
<td>5.155, 0.052</td>
</tr>
<tr>
<td>94</td>
<td>$^{240}$Pu</td>
<td>6760 years</td>
<td>$\alpha$, $\gamma$</td>
<td>5.168, 0.045</td>
</tr>
<tr>
<td>94</td>
<td>$^{241}$Pu</td>
<td>15 years</td>
<td>$\alpha$, $\gamma$</td>
<td>4.897, 0.149</td>
</tr>
<tr>
<td>94</td>
<td>$^{242}$Pu</td>
<td>$3.79 \times 10^3$ years</td>
<td>$\alpha$, $\gamma$</td>
<td>4.901, 0.045</td>
</tr>
<tr>
<td>95</td>
<td>$^{241}$Am</td>
<td>432 years</td>
<td>$\alpha$, $\gamma$</td>
<td>5.477, 0.060</td>
</tr>
</tbody>
</table>

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Table 2 Other Common Fission Products and Their Most Prominent Decay Types (Foster, 1983)

<table>
<thead>
<tr>
<th>Z</th>
<th>Isotope</th>
<th>Half-Life</th>
<th>Prominent decay type(s)</th>
<th>Energy(ies) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(^3)H</td>
<td>12.6 years</td>
<td>(\beta^-)</td>
<td>0.18</td>
</tr>
<tr>
<td>11</td>
<td>(^{22})Na</td>
<td>2.6 years</td>
<td>(\beta^+, \alpha)</td>
<td>0.54, 1.28</td>
</tr>
<tr>
<td>19</td>
<td>(^{40})K</td>
<td>1.2 x 10^9 years</td>
<td>(\beta^-), EC, (\gamma)</td>
<td>1.33 (89%), 1.46 (11%)</td>
</tr>
<tr>
<td>27</td>
<td>(^{55})Co</td>
<td>5.24 years</td>
<td>(\beta^-), (\gamma_1, \gamma_2)</td>
<td>0.30, 1.33, 1.17</td>
</tr>
<tr>
<td>38</td>
<td>(^{85})Sr</td>
<td>27.7 years</td>
<td>(\beta^-)</td>
<td>0.545</td>
</tr>
<tr>
<td>53</td>
<td>(^{121})I</td>
<td>8.08 days</td>
<td>(\beta^-, \gamma)</td>
<td>0.608, 0.364 (87.2%), 0.335, 0.638 (9.3%)</td>
</tr>
<tr>
<td>55</td>
<td>(^{137})Cs</td>
<td>30 years</td>
<td>(\beta^-, \gamma)</td>
<td>0.51, 0.66 (92%), 1.17 (8%)</td>
</tr>
<tr>
<td>43</td>
<td>(^{99})Tc</td>
<td>2.13 x 10^5 years</td>
<td>(\beta^-, \gamma)</td>
<td>0.293, 0.090</td>
</tr>
</tbody>
</table>

2.2 Radionuclide Detection Instrumentation

Radiation detection devices fall into one of five general categories:

- Gas-filled detectors
- Scintillation detectors
- Solid state or semiconductor devices
- Photographic processes
- Chemical processes

Of these types, those that are of interest for spectroscopy or the discrimination of individual isotopes in a single counting period, are scintillation detectors and semiconductor devices. For general detection without discrimination a Geiger counter is often used.

Geiger counters are a form of gas-filled particle counter and are most useful for general screening and safety purposes. The system consists of a 600V DC power source, a high ohm resistor, and a gas-filled counting chamber with two coaxial electrodes that...
are insulated from each other. Production of ions within the chamber when the instrument is exposed to radiation causes the gas, typically a noble gas, to become electrically conducting. This creates a voltage pulse from the ionic charge. The fact that the pulse size from a gas filled particle counter depends on the number of ions produced in the chamber makes it possible to use gas-filled particle counters for distinguishing between radiation types such as alpha, beta, or gammas. (NRRPT, 1998) Figure 1 shows the relationship between pulse height and voltage. In the Geiger region, the size of all pulses are the same regardless of the nature of the primary ionizing particle and the counter cannot distinguish among the types of radiation.

Figure 1  Relationship Between Voltage and Pulse Height. (NRRPT, 1998)

One of the most common devices used for radiation detection is the scintillation detector. Scintillation detectors are based on the changing of the kinetic energy of an
ionizing particle into a flash of light which is then viewed electronically by a photomultiplier tube whose output pulses may be amplified and counted. This method is used extensively for counting low-energy beta as well as gamma rays. These instruments have excellent detection efficiencies nearing 100%.

![Scintillation Detector Diagram](image)

**Figure 2 Scintillation Detector.**

The most common type of scintillation detector used for gamma detection is the sodium iodide crystal activated with thallium [NaI(Tl)] and optically coupled to a photomultiplier tube. Again, this is based on the conversion of the absorbed energy to light. The gamma rays passing through the crystal interact with the atoms in the crystal by photoelectric absorption, Compton scattering, and pair production. The resulting emission of light pulses strikes the photosensitive cathode of the photomultiplier tube which causes electrons to be ejected from the cathode. The electrons are accelerated to another electrode called a dynode which causes several more electrons to be emitted and thereby “multiplying” the photocurrent. The current pulse is then amplified and counted.

Detection instruments are often coupled with an energy discriminating device known as a spectrometer. These are used to differentiate the various isotopes in nuclear
spectroscopy by measuring the energy distribution of a source or sample. A spectrometer separates the output pulses from a detector, such as a scintillation detector or a semiconductor detector, according to the maximum voltage in each pulse. The most commonly used instrument is the multichannel analyzer which can distinguish between multiple isotopic energies in a single count. The resolution, or the ability of a detector to separate energy peaks that are close together, is a function of energy and improves with increased energy (NRRPT,1998) and is defined as:

\[
\text{Percentage resolution} = \frac{\Delta E}{E} \times 100\% \tag{2.1}
\]

\(\Delta E\) = energy spread

\(E\) = energy of photon

The semi-conductor detector acts as a solid state ionization chamber. The ionizing alpha, beta, or gamma rays interact with atoms in the sensitive volume of the detector to produce electrons by ionization. The most common type of semi-conducting materials used for these types of detectors are silicon and germanium. It’s advantages are high speed counting and very low resolving time, high energy resolution superior to NaI crystals (scintillation counters), and a low operating voltage of about 25 to 300V. (NRRPT,1998)

These detectors primarily function by exciting the primary electrons which in turn excite a cascade of secondary electrons in the process of dissipating its energy. The number of electrons collected by the detector is proportional to the energy of the primary electron and the energy of the incident photon. Impurities in the crystal can act as traps for secondary electrons and, as a result, lower the efficiency of the detector. It was previously necessary to compensate for the impurities by drifting lithium ions through the
detector material. But because the mobility of lithium within the crystal lattice is significant at room temperature, the instrument must be cryogenically cooled, typically to about \(-320^\circ\) F, to protect the crystal. They are also generally smaller than NaI crystals and, as a result, are less efficient. However, crystals produced with almost pure germanium, or high purity germanium (HPGe), do not need to be supercooled to prevent the migration of the impurity into other regions. Liquid nitrogen is used to minimize dark current and "electronic noise", but there is no risk of damage to the crystal if it warms up.

For the standard impure germanium detector, efficiencies are only in the vicinity of 20%. But with the newer HPGe detectors, efficiencies of 70 to 90% have been determined. The use of n-type HPGe detectors (with a thin p-type outer contact) makes possible sensitivities for low energy x-rays down to 3 keV. (NCRP, 1985) The GeLi and HPGe crystals are commonly used for high-energy gammas while SiLi is used for the low energy photons. The surface barrier form of the germanium or silicon detector is used for measuring alpha and beta radiation.

2.2.1 Resolving Time

When two or more particles enter the counter in rapid succession, the ionization from the first particle can paralyze the instrument and prevent it from responding to the following particles. In a Geiger counter, positive ions formed near the anode are attracted to the cathode. Because ions are heavier particles than electrons, the time it takes for them to travel to the cathode disables the instrument until the discharging process is complete. (Camber, 1987) This time is calculated as:
\[ t = \frac{(b^2 - a^2)p \ln \frac{b}{a}}{2V\mu} \text{ (seconds)} \] (2.2)

\( b = \text{radius of cathode, (m)} \)
\( a = \text{radius of anode, (m)} \)
\( p = \text{gas pressure in counter, (Pa)} \)
\( V = \text{potential difference across counter, (volts, V)} \)
\( \mu = \text{mobility of positive ions, (m/s)/(V/m)} \)

The time required to recharge the electrodes after a pulse is known as dead time and is principally applicable to detectors operated in the Geiger and proportional region. During this period the detector cannot count any new ionizing events because it is still responding to the previous event.

Recovery time is the time from the initial full sized pulse to the next full sized pulse and includes the period of dead time. This is the minimum period of time required for the instrument to detect a full signal.

The resolving time refers to the instrument itself and is the minimum time needed after detection of an ionizing particle before any additional particles can be detected by that particular instrument. The detected pulse needs to only be high enough for the detector to pick up the signal. For Geiger counters, this can be on the order of 100 μsec or more.
Resolving time can be found using the two-source method. The count rate of two sources measured individually should equal the rate of both measured together. In reality, the sum of the two sources counted singly will exceed the counts of the two sources measured together due to resolving time.

\[ \tau = \frac{R_1 + R_{1-2} - R_b}{R_{1-2} - R_1^2 - R_2^2} \]  \hspace{1cm} (2.3)

R_1 and R_2 are the count rate for source 1 and 2 individually, R_b is the background count rate, and R_{1-2} is the count rate measured with 1 and 2 together. The corrected count rate will then be:

\[ R = \frac{R_o}{1 - R_o \tau} \]  \hspace{1cm} (2.4)

Where R_o is the observed or measured count rate.
CHAPTER 3

THEORY OF RADIATION ATTENUATION

3.1 Fundamentals

Radiation results from the radioactive decay of the unstable nucleus of an atom as it attempts to reach a state of equilibrium. The definition of a stable nucleus is one which will not spontaneously transform into another isotope. The probability of a transformation occurring is described by the half-life of the atom or the time in which one half of a given number of unstable nuclei radioactively decay. An isotope decaying with a half-life of $10^{14}$ to $10^{19}$ years is at the measurable limit of half-life and so is considered stable. (Mladjenovic, 1973) Decay can be described by the relationship

$$-dN = N \lambda dt$$

or:

$$N = N_0 e^{-\lambda t}$$

Where $N$ is the number of non-disintegrated atoms, $N_0$ is the initial number of atoms, $\lambda$ is the decay constant for a particular element and $t$ is time. The half-life of an isotope is related to the decay constant by:

$$\lambda = \frac{\ln 2}{t_{1/2}}$$
Many radioactive substances form decay chains during the decay process. This chain can involve two or more isotopes known as daughter products and can occur almost instantaneously or over extremely long periods of time until a final stable element is formed. Radioactivity of a particular radioactive source at time $t$ is described as:

$$A = A_0 e^{-\lambda t}$$  

$A$ = actual activity.

$A_0$ = original activity.

$t$ = time elapsed since the measurement of the original activity.

$\lambda$ = decay constant for a particular isotope.

Equation 3.4 is known as the absolute activity. The measured radioactivity of a source is less than the actual radioactivity since the detector usually only detects a portion of the total radiation emitted from the source. The remainder of the radiation reacts with the air and surrounding materials as shielding. Radiation can be divided into two basic types: charged particle radiation and electromagnetic radiation. Charged particle decay includes electron release carrying a negative charge and known as $\beta$ decay. $\alpha$ decay can also occur which consists of the emission of a helium nucleus carrying two positive charges. Electromagnetic radiation includes gamma and $x$-rays presented as a beam of energy quanta or photons.

3.2 Attenuation Model

As previously described, radiation involves either charged particle radiation or electromagnetic radiation. Charged particles are referred to as directly ionizing particles which have sufficient kinetic energy to produce ionization by collision and include
electron, proton, and alpha decay. Uncharged particles, including neutrons, gamma rays, and x-rays, are indirectly ionizing particles which can liberate directly ionizing particles or initiate a nuclear transformation. When radiation interacts with matter, one of several things happens: The photon or particle of energy is either absorbed, reflected, or a combination of the two. To what degree these interactions take place depends on the type of radiation involved (i.e. alpha, beta, or gamma radiation), the energy of the emitted particle or photon, and the properties of the matter, also known as the absorber, it is interacting with.

Figure 4  Mass Stopping Power of Various Elements. (Data obtained from NIST, 1997)
3.2.1 Beta Particles

The required thickness of absorber decreases as the density of it increases. A universal curve of beta-ray range, (Camber, 1987), in units of density thickness vs. energy is:

\[ R = 412E^{1.265-0.0954\ln E} \]  

where:
- \( E \) = maximum beta-ray energy, (MeV)
- \( R \) = range, (mg/cm\(^2\))

Beta particles have the same mass as an electron and so are easily deflected during collisions. Their path is erratic through the absorbing media. The result of an inelastic collision with absorber atoms is either ionization and ion-pairs or Bremsstrahlung x-rays. Bremsstrahlung production increases with atomic number and for that reason, beta shields are made with material of the minimum practicable atomic number, (i.e. less than 13, such as aluminum). (Camber, 1987) The mass stopping power (figure 4) or the rate of energy loss for charged particles varies with interacting material and is defined as:

\[ \frac{S}{\rho} = \frac{dE}{dx \rho} \]  

where \( \rho \) is the density of the target material. The relative mass stopping power is used to compare, quantitatively, the energy absorption power of different media and is defined as:

\[ R_m = \frac{S_{\text{medium}}}{S_{\text{air}}} \]
Table 3 Common Beta Sources

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Predominant decay</th>
<th>Half-life</th>
<th>energy(ies) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3$H</td>
<td>β-</td>
<td>12.5 years</td>
<td>0.18</td>
</tr>
<tr>
<td>$^{14}$C</td>
<td>β-</td>
<td>5568 years</td>
<td>0.155</td>
</tr>
<tr>
<td>$^{32}$P</td>
<td>β-</td>
<td>14.3 days</td>
<td>1.707</td>
</tr>
<tr>
<td>$^{90}$Sr</td>
<td>β-</td>
<td>27.7 years</td>
<td>0.545</td>
</tr>
<tr>
<td>$^{90}$Y</td>
<td>β-</td>
<td>64.2 hours</td>
<td>2.26</td>
</tr>
</tbody>
</table>

3.2.2 Alpha Particles

Alpha rays are the least penetrating of the radiations, traveling only a few centimeters in air and only microns in tissue. Range is defined as either the mean range, or the range of the average alpha particle, and the extrapolated range, or the range extrapolated to zero particles in the absorption curve. The range of alpha particles in any medium, (Camber, 1987), is found from the relationship:

$$R_m\ (mg/cm^2) = 0.56 A^{\frac{1}{3}} R$$  \hspace{1cm} (3.7)

where:
- $R_m$ = range of alpha particle in air, (cm)
- $A$ = atomic number of the medium

The mechanism for energy loss of alpha particles is either electronic excitation or ionization, losing an average 35eV per ion pair it creates. The specific ionization of the alpha particle is very high and on the order of $10^4$ ion pairs per centimeter in air. The mass stopping power and the relative mass stopping power equations are the same as for the beta particle.
Table 4 Common Alpha Sources

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{210}\text{Po}$</td>
<td>138 days</td>
</tr>
<tr>
<td>$^{239}\text{Pu}$</td>
<td>24,410 years</td>
</tr>
<tr>
<td>$^{238}\text{Pu}$</td>
<td>89 years</td>
</tr>
<tr>
<td>$^{242}\text{Cm}$</td>
<td>162 days</td>
</tr>
<tr>
<td>$^{235}\text{U}$</td>
<td>$7.1 \times 10^8$ years</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>$4.51 \times 10^9$ years</td>
</tr>
<tr>
<td>$^{244}\text{Cm}$</td>
<td>18 years</td>
</tr>
</tbody>
</table>

3.2.3 Gamma Rays

The attenuation of gamma rays is qualitatively different than that of alpha or beta particles. While alpha and beta particles have a finite range and are eventually absorbed, gamma rays can only be reduced in intensity by increasingly thicker absorbers. The attenuation of gamma rays under "good geometry," with a well collimated, narrow beam of radiation, (NRRPT, 1998), is described using the relationship:

$$\frac{I}{I_0} = e^{-\mu t}$$  \hspace{1cm} (3.8)

$I_0 = \text{gamma ray intensity at zero absorber thickness}$

$t = \text{absorber thickness}$

$I = \text{gamma ray intensity transmitted through an absorber of thickness } t$

$\mu = \text{slope of the absorption curve = the attenuation coefficient}$

If $t$ is in centimeters, $\mu$ will be the linear attenuation coefficient, $\mu_i$ in (cm$^{-1}$).
If \( t \) is in \((g/cm^2)\), \( \mu \) will be the mass attenuation coefficient, \( \mu_m \) in \((cm^2/g)\).

The relationship between \( \mu \) and \( \mu_m \) is given by:

\[
\mu (cm^{-1}) = \mu_m (cm^2/g) \times \rho (g/cm^3)
\]  

\( \rho \) = density of the absorber

Gamma rays can interact with matter through either one or more of three major mechanisms: the photoelectric effect, the Compton effect, and pair production. The resulting reaction depends predominantly on the level of energy of the emitted gamma ray. Low energy gammas react chiefly through the photoelectric effect, medium energies are associated with the Compton effect, while high energies usually react through pair production. Table 5 shows some more common materials and the most probable reaction type given a gamma energy range.

<table>
<thead>
<tr>
<th>Material</th>
<th>Photoelectric effect</th>
<th>Compton effect</th>
<th>Pair production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>( E &lt; 20 \text{ keV} )</td>
<td>( 20 \text{ keV} &lt; E &lt; 23 \text{ MeV} )</td>
<td>( E &gt; 23 \text{ MeV} )</td>
</tr>
<tr>
<td>Al</td>
<td>( E &lt; 50 \text{ keV} )</td>
<td>( 50 \text{ keV} &lt; E &lt; 15 \text{ MeV} )</td>
<td>( E &gt; 15 \text{ MeV} )</td>
</tr>
<tr>
<td>Fe</td>
<td>( E &lt; 120 \text{ keV} )</td>
<td>( 120 \text{ keV} &lt; E &lt; 9.5 \text{ MeV} )</td>
<td>( E &gt; 9.5 \text{ MeV} )</td>
</tr>
<tr>
<td>Pb</td>
<td>( E &lt; 500 \text{ keV} )</td>
<td>( 500 \text{ keV} &lt; E &lt; 4.7 \text{ MeV} )</td>
<td>( E &gt; 4.7 \text{ MeV} )</td>
</tr>
</tbody>
</table>

**Photoelectric effect**

The photoelectric effect is the absorption of a gamma ray by an atom which results in an energy transfer from the incident gamma ray to an electron (usually in the K
The electron escapes with an energy equal to the difference between the gamma energy and the binding energy of the atom. The photoelectric effect is more pronounced in heavier substances, i.e., higher Z value, and when the gamma rays are of low energies. (Crouthamel, 1960)

The Compton effect

In this process of interaction with an electron, the gamma ray is scattered through an angle $\theta$ while transferring only part of its energy to the electron. This electron is considered free and at rest in comparison to the incident gamma ray. The relationship between the scatter angle and the energies, (Crouthamel, 1960), of the gamma ray before and after collision is obtained from the conservation of energy:

$$\alpha' = \frac{\alpha}{1 + \alpha (1 - \cos \theta)}.$$  \hspace{1cm} (3.10)

where

$\alpha = \text{energy of the incident gamma ray}$

$\alpha' = \text{energy of the scattered gamma ray}$

Figure 5  Photoelectric Effect.
The energy of the recoiled electron is:

\[ \alpha_e = \frac{\alpha^2 (1 - \cos \theta)}{1 + \alpha (1 - \cos \theta)} \]  

(3.11)

Forward scattering occurs when \( \theta \) is zero. The resulting scattered gamma ray energy is equal to the original gamma ray energy.

![Compton Effect Diagram]

**Figure 6** Compton Effect.

**Pair production**

Pair production occurs when a gamma ray produces an electron-positron pair. The pair ultimately is annihilated and produce of two or more 0.511 MeV photons. In order for pair production to occur, the minimum required incident gamma energy must be equal to the sum of the rest energies of the electron and positron pair. (NRRPT, 1998)

\[ 2m_e c^2 = 1.022 \text{MeV} \]  

(3.12)

As a result, pair production is the dominant reaction for most high energy gammas.
Table 6 Common Gamma Sources.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>(T_{1/2})</th>
<th>(E_{\text{max}(&gt;5%)}) MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{24}\text{Na})</td>
<td>15 hours</td>
<td>2.75</td>
</tr>
<tr>
<td>(^{72}\text{Ga})</td>
<td>14.3 hours</td>
<td>2.51</td>
</tr>
<tr>
<td>(^{140}\text{La})</td>
<td>40 hours</td>
<td>2.50</td>
</tr>
<tr>
<td>(^{110}\text{Ag})</td>
<td>270 days</td>
<td>1.52</td>
</tr>
<tr>
<td>(^{152}\text{Eu,}) (^{154}\text{Eu})</td>
<td>13.16 years</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>5.27 years</td>
<td>1.33</td>
</tr>
<tr>
<td>(^{60}\text{Co})</td>
<td>115 days</td>
<td>1.22</td>
</tr>
<tr>
<td>(^{187}\text{W})</td>
<td>24 hours</td>
<td>0.78</td>
</tr>
<tr>
<td>(^{192}\text{Ir})</td>
<td>74 days</td>
<td>0.6</td>
</tr>
<tr>
<td>(^{75}\text{Se})</td>
<td>121 days</td>
<td>0.4</td>
</tr>
<tr>
<td>(^{170}\text{Tu})</td>
<td>129 days</td>
<td>0.084</td>
</tr>
</tbody>
</table>

3.3 Shielding Calculations

Radiation can be attenuated by any material in its path whether it be solid, gas, or
liquid. The calculations involved in shielding of the different types of radiation can become highly complicated for even simple geometries and so the discussion following only covers the most important factors affecting detection through pipe walls. All other reactions that may take place are negligible or are assumed so for simplicity.

Some of the basic quantities used in measuring radiation for shielding purposes are the particle flux, and fluence. Particle fluence, \( \Phi \), is the number of particles, \( \Delta N \), which enter a sphere of cross section per unit time, \( a \), or:

\[
\Phi = \frac{dN}{da}
\]  

and the particle flux density is described as the fluence in time \( t \):

\[
\varphi = \frac{d\Phi}{dt}
\]  

These values are obtained using the output from a detector which typically measures in particles or disintegrations per unit time. As stated before, not all of the particles will reach the detector. Some will react with the surrounding material, including air, resulting in a lower count rate. The results of this shielding can be expressed as response curves or attenuation factors. They may also be expressed as the ratio of the total detector response to the uncollided particle's response or the buildup factor.

The buildup factor, \( B \), is a multiplicative factor used to correct scattering of photons to lower energy levels. It affects the actual count rate measured at some distance from the source and is defined as:

\[
B = \frac{\text{effect produced by all photons}}{\text{effect produced by primary photons}}
\]  

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There are several expressions for B depending on the nature of the recording instrument used for detection:

\[
\begin{align*}
\text{Gamma flux:} \quad B_N(r) &= \frac{\text{flux of } \gamma \text{ for all energies}}{\text{flux of primary } \gamma \text{ energies}} = \frac{\int N_a(r,E) dE}{\int N_0^a(r,E) dE} \quad (3.16) \\
\text{Energy flux:} \quad B_E(r) &= \frac{\text{energy carried by all } \gamma}{\text{energy carried by primary } \gamma} = \frac{\int I_a(r,E) dE}{\int I_0^a(r,E) dE} \quad (3.17) \\
\text{Energy absorption in a material:} \quad B_\lambda(r) &= \frac{\text{energy lost by all } \gamma}{\text{energy lost by primary } \gamma} = \frac{\int \mu_\lambda(E) I_a(r,E) dE}{\int \mu_\lambda(E) I_0^a(r,E) dE} \quad (3.18)
\end{align*}
\]

where:

- \( I \) = intensity for collided and uncollided, \( I_0 \), photons.
- \( r \) = radius of a spherical area considered.
- \( N \) = number of collided and uncollided, \( N_0 \), photons.
- \( E \) = energy of photons.
- \( \mu_\lambda \) = mass attenuation coefficient of material being considered.

However, the use of B as a multiplicative factor only applies to point sources. For distributed sources and other geometries the buildup factor can become quite complicated so is often approximated using the Taylor series:

\[
B = A_1 e^{\alpha_1 \mu_\lambda r} + (1 - A_1) e^{\alpha_2 \mu_\lambda r} \quad (3.19)
\]

where \( A_1, \alpha_1, \) and \( \alpha_2 \) are functions of \( E_0 \) for any given medium (Jaeger, 1968).
CHAPTER 4

DEVELOPMENT OF THE NUMERICAL METHOD

4.1 Overview

This chapter outlines in detail the mathematical procedures used to develop and algorithm for predicting source strength and axial position within a circular pipe based on external gamma ray measurements. A standard error between measured and predicted source strength and axial position must first be found. Next, the standard error can be optimized using the simplex method to find the value of source strength and axial placement. Point4.c is the algorithm developed to calculate source strength and axial position. (see Appendix II) This program and all of its components were developed on a PC platform using the C programming language.

4.2 Optimization Techniques

The Modified Simplex Method (MultiSimplex, 1998) was chosen because of its fast convergence, ease of use, and few required initial values to start. The goal of the Simplex method is to minimize a function of the form: \( f(x_1, x_2, \ldots, x_n) \). Figure 8 demonstrates the creation of “simplexes” or triads of \( f(x_1, x_2, \ldots, x_n) \) corresponding to different values of the independent variables \( x_i \).

Initially, \( k+1 \) values of the independent variable are chosen with \( k \) being the
number of unknown variables in the function. These are spread out evenly and form a k+1 polygon called a simplex. For two variables, three initial values are chosen which form a triangle. Each value is determined as either the best, next to worst, or worst. The worst value is then mirrored on the opposite side of a line drawn between the best and next to worst values, and forms a new triangle. The Basic Simplex Method continues this routine until the desired minimum or maximum is found. The Modified Simplex Method is a variation on this, in which the simplex can expand in the direction of a more favorable value or contract if a move was taken towards a less favorable value. This enables the simplex to accelerate towards an optimum solution more quickly than the Basic Simplex Method.

Figure 8 shows an example of a simplex progression with two control variables using the modified simplex method. The following labels are used to distinguish the three trials: B = best value, Nw = next to worst value, and W = worst value. A line is drawn between B and Nw and the reflection R is made directly opposite of W. If R is a better value than B, expansion E is made beyond R. If E is a better value than R, then the new simplex will be the triangle formed by the previous values B and Nw, with the third new point being E. Otherwise R is retained as the new value. If R is not better than B, then either a positive or negative contraction is made to form the new simplex. In this way, the simplex may expand or contract depending on how favorable or unfavorable the response is.
Figure 8. Simplex Progressions with 2 Control Variables; B=best, Nw=next to worst, W=worst, R=reflection, E=expansion, C+=positive contraction, C-=negative contraction

Figure 9 shows a flow chart which demonstrates the procedure for each step of the simplex optimization procedure. The following values are used to calculate the expansion or contraction used in each step:

\[ R = C + W \quad (4.1 \text{ a}) \]
\[ E = R + W \quad (4.1 \text{ b}) \]
\[ C+ = \frac{1}{2} R + C \quad (4.1 \text{ c}) \]
\[ C- = \frac{1}{2} R - C \quad (4.1 \text{ d}) \]

where:

- \( B \) = previous result's best value
- \( Nw \) = previous result's next to worst value
- \( R \) = new test value
- \( E \) = expansion value
- \( W \) = worst value or rejected value
- \( C \) = centroid between \( B \) and \( Nw \)
C+ & C- = contraction value, either to the left or to the right of line B-Nw

The modified simplex method is excellent for processes which change over time and processes which require a new optimization with each new set of data. However, for some processes, the simplex method may converge on a single local minima or maxima and neglect the actual minimum or maximum values. This can be avoided by seeding several areas with initial values and performing the optimization procedure over various simplexes.

Figure 9. Modified Simplex Method Optimization Procedure. (MultiSimplex, 1997)
4.3 Combined Algorithm

A Cesium 137, \(^{137}\text{Cs}\), source was used to validate the combined algorithm. The original activity of the \(^{137}\text{Cs}\) source was labeled at 8 \(\mu\text{Ci}\) as of 05/09/91. With a half-life of 30.17 years, the current activity of the source was calculated to be 6.54 \(\mu\text{Ci}\) as of 02/12/99. An Eberline Instruments Model E-520 Geiger Counter was used to first verify instrument efficiency with the pancake directly over the \(^{137}\text{Cs}\) source button. The instrument returned a reading of 25,000 ±1000 counts/min on one side of the button which is roughly estimated at 833 gammas/sec total. This value compared to the known activity gives an instrument efficiency of 0.34%. The source was then placed in a 6-inch pipe while the detector was rotated along the outer surface of the pipe at 45° degree intervals and the activity recorded for each interval. This data was then input into the algorithm and used to determine a calculated source activity and geometry within the pipe and finally compared to the actual activity and geometry of the source.

4.4 Point Source Algorithm

4.4.1 Calculation of Attenuation Distance

The simplest case of detecting radiation from the exterior of an enclosed pipe would be from an isotropic point source. As shown in figures 10 and 11, the z-axis is assumed to be along the length of the pipe with the origin located directly above the source. Angle \(\theta\) is the angle of the detector measured from the top of the pipe measured counterclockwise. (see figure 10)
$R =$ radius of pipe

$\delta R =$ wall thickness of pipe

$r =$ distance from source to detector

$\theta =$ angle of detector measured from the origin at $y = 0$ and counterclockwise

The coordinates for the source and the detector, respectively, are:

$$[0, -R, 0] \quad (4.2)$$

$$[R \cos \theta, R \sin \theta, z_d] \quad (4.3)$$

Figure 10. Cross-section of Pipe with Point Source.

Figure 11. Axial View of Pipe with Point Source.
If the distance from the origin to the detector on the outer radius of the pipe is:

$$R' = R + 8R$$ (4.4)

located at an angle of $\theta$ degrees, then the vector from the source S to the detector is found using the equation of a 3D line:

$$x = tv + (1 - t)u$$ (4.5)

where $u$ and $v$ represent two known coordinate points along the line, $x$ represents any point along the line, and $t$ is:

$$t = \frac{x_1 - u_1}{v_1 - u_1} = \frac{x_2 - u_2}{v_2 - u_2} = \frac{x_3 - u_3}{v_3 - u_3}$$ (4.6)

Let $u$ and $v$ be equal to:

$$[u_1, u_2, u_3] = [0, -R, 0]$$ (4.7)

$$[v_1, v_2, v_3] = [R' \cos \theta_d, R' \sin \theta_d, z_d]$$ (4.8)

$$[x_1, x_2, x_3] = \text{point of intersection with inside pipe wall}$$ (4.9)

Using the two known coordinate values for the source and detector positions, this equation becomes:

$$t = \frac{x_1}{R' \cos \theta_d} = \frac{x_3 + R}{R' \sin \theta_d + R} = \frac{x_3}{z_d}$$ (4.10)

And, since the point of intersection with the inside pipe wall lies on the parameter of a circle, the equation for a circle can be used to find the $y$ coordinate of the point.

$$y = x_2 = \sqrt{x_1^2 - R^2}$$ (4.11)

Equation 4.10 then becomes:

$$t = \frac{x_1}{R' \cos \theta_d} = \frac{\sqrt{x_1^2 - R^2} + R}{R' \sin \theta_d + R} = \frac{x_3}{z_d}$$ (4.12)
Solving the first two terms of this equation gives the value for $x_1$ as:

\[
x_1 = \frac{1}{2(S^2 - 1)} \left( -2p \pm 2\sqrt{S^2p^2 + S^4R^2 - S^2R^2} \right) \quad (4.13)
\]

where:

\[
S = \frac{R'\cos\theta_d}{R'\sin\theta_d + R} \quad (4.14)
\]

\[
P = \frac{R(R'\cos\theta_d)}{R(R'\sin\theta_d + R)} \quad (4.15)
\]

These two values represent the $x$ component of the point of intersection with the inside pipe wall in both the positive and negative $y$ direction. Only one of these values represents where the detector actually sits, and a small routine within the 3D subroutine in Appendix II is constructed to test for which value this would be based on the distance from the source to the detector. The values for $x_2$ and $x_3$ are easily found by replacing $x_1$ into equation 4.10 and are:

\[
x_2 = \sqrt{x_1^2 - R^2} \quad (4.16)
\]

\[
x_3 = \frac{z_D x_1}{R'\cos\theta_d} \quad (4.17)
\]

where the point of intersection with the inside pipe wall is $[x_1, x_2, x_3]$. 

The distance between the intersection of $r$ with the inside wall to the intersection with the detector on the outside wall, $\Delta r$, is found to be:

\[
\Delta r_{r-i-o-D} = \sqrt{\left(\delta R\cos\theta\right)^2 + \left(\delta R\sin\theta\right)^2 + \left(z_D \left[ 1 - \frac{R\sin\theta + R}{R'\sin\theta + R} \right] \right)^2} \quad (4.18)
\]

Similarly, the distance from the source to the inner wall is found to be:
Once the position and distance of the detector relative to the source is calculated, the radiation flux at the detector can be determined.

4.4.2 Attenuation of Gamma Source Emissions

Two key assumptions are made: it is assumed that the radiation point source is isotropic with the same radiation emissions in all directions, and that backscatter is negligible through any fluid or material within the pipe and through the pipe walls to the detector. Therefore, the buildup factor, \( B \), is assumed to be 1 or unity. This greatly simplifies the calculations for this test case. The particle fluence is the number of particles detected per unit area per unit time, or, in the case of gamma radiation, \((\gamma's/cm^2s)\):

\[
\Phi = \frac{S_p e^{(-\gamma_s \cdot t_{\text{source}} - \gamma_s \cdot t_{\text{detector}})} }{4\pi r^2}
\]  

(4.20)

The detected count rate for the source is:

\[
D = \Phi A_D = \frac{\gamma's}{\text{second}}
\]  

(4.21)

with the detection factor being the ratio of count rate over source strength:

\[
\frac{D}{S_p} = \frac{\text{detector}(\gamma's/\text{sec})}{\text{source}(\gamma's/\text{sec})} = \frac{\Phi A_D}{S_p}
\]  

(4.22)

or

\[
\frac{D}{S_p} = \frac{\sum\gamma_s \Delta t}{4\pi r^2} B(\mu r)
\]  

(4.23)
To test the theory behind the attenuation of steel and aluminum pipes, the research team used a point source of $^{137}$Cs placed in a pipe and an Eberline Geiger Counter to measure the activity from the outside of the pipe at varying degree intervals, starting at 0° directly above the source. Instrumentation and source data are as follows:

- $^{137}$Cs source known activity: $6.54 \times 10^{-6}$ Ci = 241,980 (γ/s) as of 2/12/99
- Actual measured counts: 833 (γ/s)
- Detection Instrument: Geiger Counter, Model E-520, Eberline Instrument Corp.
- Instrument efficiency: 0.34%

4.5 Integration Methods

There are three possible geometries that are of concern when developing a technique to calculate radiation flux and configuration within a pipe: a thin layer of sediment collected on the bottom of the pipe, a point source, or an evenly distributed radioactive film covering the entire inside of the pipe. For a layer of sediment collected on the bottom, a preliminary program has been developed to calculate the source strength and a profile of the sediment within the pipe. Figures 12 and 13 show the geometry used to form the characteristic equations.
Figure 12. Pipe Cross-section

Figure 13. Pipe Axial Cross-section.
The particle fluence is described in equation 3.13 as the number of particles which enter a sphere of unit area:

\[
\Phi = \frac{dN}{da} \tag{4.24}
\]

or:

\[
\Phi = \frac{\sum_{\mu,\lambda} \cdot}{4\pi r^2} \tag{4.25}
\]

For a thin layer of sediment on the bottom of a pipe, the fluence is taken over a three dimensional area \((\phi, \theta, z)\), and can be described in a triple integral as:

\[
S_{d''''} = \frac{q''''}{4\pi} \int_{R_{min}}^{R} \int_{z=-\infty}^{z=\infty} \int_{\theta=0}^{\theta=2\pi} \frac{e^{-\mu_{\text{total}}(r(\phi,\theta,z)-l_{1}(\phi,\theta,z))-\mu_{\text{partial}}(l_{2}(\phi,\theta,z))}}{4\pi r(\phi,\theta,z)^2} R \, dR \, d\phi \, dz \tag{4.26}
\]

Where the lengths \(r, r', l_2\) as shown in figures 12 and 13 are:

\[
r'(\phi, \theta) = \sqrt{\left[R + \delta_2\right]^2 + R^2} - 2R(R + \delta_2)\cos(\phi - \theta) \tag{4.27}
\]

\[
r(\phi, \theta, z) = \sqrt{r'(\phi, \theta)^2 + z^2} \tag{4.28}
\]

\[
l_2(\phi, \theta, z) = \frac{2r'(\phi, \theta)\delta_2(R + \delta_2)}{(R + \delta_2)^2 + r'(\phi, \theta)^2 - R^2} \tag{4.29}
\]

As with the point source, once the fluence is calculated, the detection factor can be found from equations 4.222 and 4.23. The standard error is then calculated and passed to the simplex subroutine which can easily be modified for this source profile to find the optimum \(S_p\). In this case, the buildup factor is assumed to be unity as well. To solve the triple integral, the trapezoidal rule is implemented and included in a subroutine or header file which is called from the main program.
4.6 Program Organization

Included in Appendix II are the programs used to calculate the activity and axial position of a point source within a circular pipe. The files required for running the program are:

- **point4.c**  main program
- **setup.dat**  Setup file used for establishing program parameters, including optimization seed values and tolerance, material properties, and pipe geometry.
- **xxx.dat**  File containing the measured gamma-ray data. The name of this file is defined in *setup.dat*.
- **read.h**  File called in *point4* to read in the data file specified in *setup.dat*.
- **codes.h**  File called in *point4* to calculate attenuation distance.
- **simplex.h**  File called in *point4*, simplex optimization routine.
- **props.h**  File called in *point4*, calculates attenuation coefficients for materials specified in *setup.dat*.

Program *point4.c* serves as the main program for input and output and calls several subroutines to assist in calculations. It searches first for the *setup.dat* file which can be easily edited in any word processor to change the properties and optimization parameters as needed. It includes the name of the data file which contains the count data. *Read.h* is then called to read this data file and set up arrays for measured counts, detector angle, and axial position of detector. The vector positions and distances are calculated through the file *codes.h* which is described above in the 3D line calculations. The mass attenuation for various materials are calculated in *props.h* and currently include air, water, aluminum and iron. Once all the preliminary data is complete, program *point4*
calculated the standard deviation between a set of actual field data, $\gamma_{m}(\theta_{i}, z_{i})$ and the predicted detection measurement, $\gamma_{i}(\theta_{i}, z_{i})$.

$$SE = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (\gamma_{m}(\theta_{i}, z_{i}) - \gamma_{i}(\theta_{i}, z_{i}))^2}$$ (4.30)

The program then called the simplex subroutine, *simplex.h*, to optimize the standard error, (SE), by finding $S_{p}$ which minimizes $SE(S_{p})$. Finally, *point4* outputs the original parameters used in *setup.dat* and the optimum axial position and activity for the source.
CHAPTER 5

RESULTS

5.1 Point Source Tests

A contour plot of the data from the aluminum and steel pipes gives a rough estimation of where the source is located within the pipe using a Geiger counter for detection. Though the Geiger counter count efficiency is very low, (0.34% efficiency), the plots clearly show that a relatively low activity $^{137}$Cs gamma source can be detected through either aluminum or steel pipes of up to 6 inch diameter. Each test was conducted using an Eberline Instrument Corporation Model E-520 Geiger counter and a $^{137}$Cs source button with an original activity of 8 $\mu$Ci as of May 09, 1991. The half-life of $^{137}$Cs is $t_{1/2} = 30.17$ years. The coefficient $\lambda$ is calculated to be:

$$\lambda = \frac{0.693}{t_{1/2}} = 0.02297 \text{years}^{-1}$$  \hspace{1cm} (5.1)

The activity can then be calculated using the equation

$$A = A_0 e^{-\lambda t} = 6.54 \mu \text{Ci}$$  \hspace{1cm} (5.2)

where $A_0$ is the original activity, and $t$ is the time elapsed since the date given for the original activity. This value is related to counts per minute through:

$$6.54 \mu \text{Ci} \times \frac{10^{-6} \text{Ci}}{1 \mu \text{Ci}} \times \frac{3.7 \times 10^{10} \gamma}{1 \text{Ci}} = 241,980 \frac{\gamma}{\text{s}}$$  \hspace{1cm} (5.3)
The source was then measured with the pancake probe of the Geiger counter to be 25,000 counts/min. or 416.7 μs. This is the value measured from one side of the cesium source and if the source is assumed to be thin, the total activity for both sides of the source will be 833 μs. The efficiency of the detector can then be determined using the ratio of calculated counts to actual detected counts and is found to be 0.34%. The source was placed within the pipe and each pipe was marked from 0 to 315° on the outside with 0° directly above the source. Measurements were then taken at various recorded positions along the outside of the pipe as well as at various axial distances from the source. These values were then plotted on a surface chart according to angular detector position, axial distance from source, and counts detected. Figures 14-17 show a plot of the source detected from the outside of an aluminum and steel pipe with the parameters listed in Table 7.

<table>
<thead>
<tr>
<th>Table 7 Pipe Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Pipe wall thickness (in)</td>
</tr>
<tr>
<td>Inside diameter (in)</td>
</tr>
<tr>
<td>Outside diameter (in)</td>
</tr>
</tbody>
</table>

The first steel pipe test was conducted using 45° detector angle increments and -4 to +4 inch axial detector position with 2 inch increments. Radiation measurements were highest between 135° and 225° which represented the bottom 90° of the pipe where the
source was placed. These values resulted in a total of 40 data points. As seen in Figure 14, the source location corresponded to the peak of the gamma flux distribution which is roughly at $\theta = 180^\circ$ and $z = 0.0$ inches. From a visual inspection of the resulting plot, it is possible to get a reasonable estimate of the source's angular position, but its axial position is vague. This can be attributed to reading errors and misrecording the detector's position along the pipe. Since this was the first test completed, and therefore not as fine tuned as subsequent tests, data for this test was not as accurate.

![Figure 14 Contour Plot for Point Source in Steel Pipe, Test 1.](image)

The second test completed was that for the aluminum pipe. This test was done immediately following the first steel pipe test and the same method of reading and measurement was used. A total of 56 data points were taken at $45^\circ$ angular increments and at axial positions from +6 inches to -6 inches in 2 inch increments. The resulting
plot, (Figure 15), was somewhat rough which can also be attributed to human error in positioning and recording instrument data.

Figure 15 Contour Plot for Point Source in Aluminum Pipe.

Figure 16 shows the second steel pipe test. This test varied from the previous tests in that the pipe was more carefully measured and marked with instrument positions to decrease error and assure a greater accuracy in data readings. Readings were taken at 45° increments for the top section of pipe and increased to 22.5° increments for the bottom half near the source, and from 1 inch to 4 inches at 1 inch increments in the axial position for a total of 108 data points. The plot in Figure 16 is considerably smoother than the previously two plots. It shows a much improved estimate of the source’s angular position as well as its axial position. This is probably due to a combination of better testing technique and an increase in the number of data points used. Peak values are
constrained in a tighter range within 2 inches in the axial direction and between 135° and 225° near the source.

![Contour Plot for Point Source in Steel Pipe, Test 2.](image)

**Figure 16** Contour Plot for Point Source in Steel Pipe, Test 2.

The last test was conducted with the steel pipe completely filled with water and the source secured at the 180° position on the inside. Measurements were taken in the same manner as the second steel pipe test with tighter increments in the axial and angular positions near the source for a total of 108 data points. The results were very similar to the second steel pipe test and showed a greater accuracy of readings compared to the first two tests. (Figure 17) It appeared that the water was not a significant factor in attenuation of gamma rays. More likely, any error in source strength predictions might be attributed to a large resolving time in the Geiger-Muller detector used.
Figure 17 Contour Plot for Point Source in Steel Pipe, Filled with Water.

5.1.1 Sample Output

The program `point4.c` computed up to 10,000 iterations in less than a minute. The results could be viewed as a text file. Below is an example output for one test. Listed are the material within the pipe and its attenuation coefficient. In this case, the pipe was filled air. Part A. shows the parameters entered in the `setup.dat` file including the pipe geometry and material, the internal fluid, the radionuclide type and properties, detection instrument efficiency, and the name of the gamma ray measurements data file. In this case, an aluminum pipe with an inside diameter of 5.23 inches was used. The radionuclide being detected is $^{137}\text{Cs}$. The instrument used to detect the gamma rays has an efficiency of 0.034 and a detection area of 3.14 in$^2$. The data was located in the file `point.dat` and included 56 data sets or measurements.
Part B displays the output data including the optimum predicted source strength in gammas/second and as the radioactivity in curies, the optimum predicted axial position of the source in both meters and inches, the estimated mass of the source in kilograms, and the standard error in gammas/second. The tolerance and maximum number of iterations set in the setup.dat file are also listed.

Aluminum pipe results
a. Opening the setup file: setup.dat
Air: $\mu (\text{cm}^2/\text{g}) = 0.075563$
* * * * * * * * * * * * * * * * * * * * * * * * *
* POINT Results *
* * * * * * * * * * * * * * * * * * * * * * * * *

A. INPUT DATA
1. Pipe Wall Material: 
am. Linear Attenuation Coeff. (1/m): 19.688481 
b. Thickness (m): 0.003429 
   (in): 0.135000 
2. Pipe Internal Fluid: 
am. Linear Attenuation Coeff. (1/m): 0.009672 
3. Pipe Inside Diameter (m): 
   (in): 5.230000 
4. Radionuclide Type: 
am. Halflife (s): 9.4608e+08 
b. Gamma Ray Energy (MeV): 0.662000 
5. Filename, measured gamma: 
am. Number of data sets in file: 56 
6. Time and Date of Calculation: Mon Apr 19 14:10:01 1999 
7. Detector Properties: 
am. Efficiency (fraction): 0.034000 
b. Area (m^2) 
   (in^2): 0.002026 
   3.140000

B. OUTPUT DATA
1. Optimization Routine Output: 
am. Source Strength (gammas/s): 4996.5 
b. Source Axial Position (m): 0.005080 
   (in): 0.200000 
c. Number of iterations: 100 
d. Value of the SE (gammas/s): 75.3514 
e. Mass of Source (kg): 1.23335e-21 
f. Radioactivity of Source (Ci): 3.97178e-06
5.1.2 Gamma Source Strength

The first two tests converged very quickly in two iterations with a 39% error. These tests were the first set of tests done on the same day and used fewer data points (8 angles and 5-7 axial positions), and less accurate measurements. The second set of tests used the steel pipe, both dry and tilled with water. Measurements were taken at a total of twelve angles at each axial position, and at a total of 8 axial positions for each test. The increased number of measurements and greater attention to setting up the tests may have contributed to a lower error value of 28%. This is also reflected in Figures 14 and 15, which more clearly show the estimated position of the source from the last two tests.

Both results are excellent considering the extremely low counting efficiency, the resolution of the Geiger-Muller detector used, and the low energy $^{137}$Cs gamma source.

Table 8 Results for Point Source Tests.

<table>
<thead>
<tr>
<th>Source strength (γ/s)</th>
<th>Aluminum</th>
<th>Steel – test 1 (dry)</th>
<th>Steel – test 2 (dry)</th>
<th>Steel (filled w/ water)</th>
<th>Known $^{137}$Cs source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activity (μCi)</td>
<td>3.97</td>
<td>3.97</td>
<td>4.6984</td>
<td>4.68334</td>
<td>6.54</td>
</tr>
<tr>
<td>Axial Position (m)</td>
<td>0.00508</td>
<td>0.00508</td>
<td>-0.012093</td>
<td>-0.012115</td>
<td>0.0</td>
</tr>
<tr>
<td>Standard error (γ/s)</td>
<td>75.3514</td>
<td>36.9804</td>
<td>6.01788</td>
<td>6.87892</td>
<td>N/A</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>1.23335x10-21</td>
<td>1.23335x10-21</td>
<td>1.45899x10-21</td>
<td>1.45431x10-21</td>
<td>N/A</td>
</tr>
<tr>
<td>% error (as fraction)</td>
<td>0.3930</td>
<td>0.3930</td>
<td>0.2816</td>
<td>0.2839</td>
<td>N/A</td>
</tr>
</tbody>
</table>
5.1.3 Computation Time

The program was run several times with various optimization parameters for each data set. The number of iterations, tolerance, and seed values were varied to test convergence and computation time. Tests were run on a Pentium III 500 system using a GNU freeware C compiler. All tests run at a tolerance of 0.05 computed in less than one minute at 0 to 100,000 iterations.

5.2 Convergence

Four tests were done on steel and aluminum pipes. The program point4.c was used to calculate results for each test. To test for convergence, the number of iterations was varied with a set tolerance of 0.05 while maintaining a constant strength and axial position seed value of 5000 and 0.0 respectively. The results are listed in Table 9.

A plot of the results for convergence of axial position, activity, and standard error are shown in Figures 18, 19 and 20. Because the first two tests introduced significant errors in measuring technique which was later improved upon, only the last two tests are plotted for each parameter.

<table>
<thead>
<tr>
<th>Test</th>
<th># Data Points</th>
<th># Iterations to Convergence</th>
<th>Source Strength (y/s)</th>
<th>Axial position (m)</th>
<th>SE (y/s)</th>
<th>Activity (µCi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>56</td>
<td>2</td>
<td>4996.5</td>
<td>0.00508</td>
<td>75.3521</td>
<td>3.97178</td>
</tr>
<tr>
<td>Steel Test1</td>
<td>40</td>
<td>2</td>
<td>4996.5</td>
<td>0.00508</td>
<td>36.9804</td>
<td>3.97178</td>
</tr>
<tr>
<td>dry</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel Test2</td>
<td>108</td>
<td>96</td>
<td>5910.6</td>
<td>-0.012093</td>
<td>6.01788</td>
<td>4.69841</td>
</tr>
<tr>
<td>dry</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel filled</td>
<td>108</td>
<td>112</td>
<td>5891.6</td>
<td>-0.012115</td>
<td>6.87892</td>
<td>4.68331</td>
</tr>
<tr>
<td>w/ h2o</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 18 shows the progression of radioactivity to convergence. Both tests converged quickly to a steady value for activity in under 100 iterations. The test using a steel pipe filled with water took approximately 20 more iterations than the dry steel pipe test before converging on a steady value of roughly 4.7 μCi.

![Graph showing Activity vs. Number of Iterations](image)

Figure 18 Activity vs. Number of Iterations

Figure 19 shows the progression of the calculated value for standard error through the algorithm. Again the progression is similar for tests 3 and 4. A sharp drop in standard error occurred very early at approximately 10 iterations and only waivered slightly up to 100 iterations. Test 4 again took several more iterations to converge when compared to test 3 using the dry pipe.
Figure 19 Standard Error vs. Number of Iterations.

Figure 20 shows the progression of the axial position value through the algorithm. Values for both tests start between −0.002 and −0.003 inches, converging quickly within the first ten iterations. Test 3 drops slightly more than Test 4 in approximately 5 iterations, before stabilizing to an axial position value within ten thousandths of a meter from the Test 4 value at approximately 100 iterations.
The algorithm successfully predicted values for axial position within 0.25 inches and values for activity with as low as 28% error. Axial position converged very quickly with only minor fluctuations within 10 to 15 iterations while activity took between 50 and 70 iterations to converge. Several runs were made varying the seed values and tolerance with no effect on the final converged values in Table 9.
CHAPTER 6

CONCLUSIONS

6.1 Summary

As decommissioning of former nuclear sites increases, it is becoming vitally important that more efficient, safe, and cost effective methods be developed for determining contamination levels in pipes, ducts and vessels. The Nevada Test Site currently has several sites scheduled for decommissioning in the near future including the EMAD facility and its associated nuclear rocket launch sites. Due to the variety of situations and systems to be decommissioned, it is most likely a battery of solutions would be needed to aid in cleanup.

Here we have constructed a measurement scheme for a point source case of non-intrusive detection of radionuclides in round pipes. The method uses a gamma detector positioned at successive intervals along the outside of a pipe. The gamma counts per second, detector angle and detector axial position are recorded and fed into a C program which has taken into account the pipe geometry, material, and the waste or effluent material within the pipe to determine the effects of attenuation. An optimum source strength and axial position are found using the SIMPLEX method.
A point source case was ran through the program using a $^{137}$Cs source placed in aluminum and steel pipes. The counts were read at varying positions on the outside of the pipes using a Geiger or pancake counter. Considering the low detector efficiency and that backscattering was assumed negligible, the results were very good, coming within 28 to 30% of the known value. It is hoped that with better detection equipment the error can be significantly reduced and enable a high enough resolution to permit accurate determination of energy peaks and nuclide species.

6.2 Suggested Future Work

The test conducted with the point source has clearly proven that it is possible to determine an approximate axial position within about a radius of the source itself or 0.25 inches, and the approximate source strength to within about ±500 counts/second. The optimization will then be extended to look at three other cases:

1) A rectangular duct (HVAC) with a thin uniform film of radioactive material on the inside wall.

2) A round pipe with a thin uniform film of radioactive material.

3) A round pipe with sediment on the bottom.

Additional testing will include tests on additional pipe materials and sizes, as well as other nuclides using higher efficiency gamma detectors.
APPENDIX I

Computer Programs

POINT4.C

/*****************************/

***

* Program: POINT
*

* Purpose: Compute the optimal configuration of radionuclides
* within an enclosed circular pipe based on external
* measurements of the gamma ray flux distribution. The
* source is assumed to be a point source.
*
* Input: ASCII file containing measured values
* of Exterior Gamma Ray Flux as a function
* of detector placement angle and distance
* along the pipe. All data is set up through a file
* in ASCII format called SETUP.DAT.
*
* Output: Optimal values of:
* 1) gamma ray source strength
* 2) source position along pipe axis
*
* Author: WGC
* Date: 2/22/99
* Version: 1
*
* Outline: A. Define common variables.
* 1. Define the pipe geometry.
* 2. Define the geometry of the enclosed radionuclides.
* 3. Define the geometry of the gamma ray detector.
* 4. Define the attenuation coefficients for the pipe
*    wall and the pipe internal fluid.
* 5. Define material densities.
* 6. Define the radionuclide halflives.
* 7. Define the radionuclide and material atomic weights.
* 8. Define the fraction of decays that lead to the

57
production of gamma rays.

9. Define the energy of emitted gamma rays from each radionuclide.

B. Read data from disk
   1. Read in the measured gamma ray distribution from disk.

C. Preliminary calculations
   1. Compute number densities.
   2. Compute the linear attenuation coefficients.

D. Optimization
   1. Compute the optimal values of the source strength in rems and the axial position on the bottom of the circular pipe. These are found based on the minimum standard error (SE) between the measured and predicted gamma flux distributions.
      a. Define a triad of 3 values of the SE to seed the simplex optimization routine. These values must define SE(gamma source strength, gamma source axial position).
      b. Seek the values of source strength and axial position that minimize SE:
         1) Compute the SE between predicted and actual gamma ray fluxes.
            a) Compute the expected gamma ray distribution based on source strength and source axial position.

E. Report Results
   1. Print out the optimal values of the source strength and the source axial position.
   2. Print out diagnostic information.
      a. Distribution of both predicted and measured fluxes at each detector position.

******************************************************************************
**********                         

#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <string.h>
#include <time.h>

******************************************************************************

* A. Define common variables.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
void Read_Input_Data();
double standard_error(double, double);
double predicted_gamma_countrate(double, double, double, double);

double pipe_inside_diameter;
double pipe_wall_thickness;
char pipe_wall_material[30];
char pipe_internal_fluid[30];
char radionuclide_source_type[30];
char data_filename[30];
int nitems;
double detector_efficiency, detector_area;
double Avagadros_Number = 6.023E26;
int maximum_iterations;
double optimization_tolerance;
double source_strength_seed_value;
double source_z_seed_value;
double source_strength_stepsize;
double source_z_stepsize;

double detector_countrate[1000], detector_angle[1000],
    detector_z[1000];

double halflife;
double gamma_energy;
double atomic_weight;

double density_water = 1000.0; /* (kg/m^3) */
double density_air = 1.28; /* (kg/m^3) */
double density_steel = 7.8E3; /* (kg/m^3) */
double density_aluminum = 2.7E3; /* (kg/m^3) */

double Gamma_Energy_Cs137 = 0.662; /* (MeV) */
double HalfLife_Cs137 = (30.*365.*24.*3600.); /* (s) */
double Atomic_Weight_Cs137 = 137.0; /* (amu) */

double mu_pipe_material; /* Linear attenuation coef. (m^-1) */
double mu_pipe_fluid; /* Linear attenuation coef. (m^-1) */
/* B. Include custom function modules. */

#include "props.h"
#include "read.h"
#include "codes.h"
#include "simplex.h"

main() {
    char filename[81];
    float Detector_CountRate, Detector_Angle, Detector_Z;
    double radioactivity, decay_constant, mass_source;
    int i;
    time_t current_time;

    SIMPLEX_INPUT optimize;
    SIMPLEX_OUTPUT answer;

    FILE *inputfile;

    /* C. Read in Data. This includes setup data
     * from the file SETUP.DAT and the measured
     * gamma ray flux distribution. */

    Read_Input_Data();

    /* D. Read from disk the values of the gamma ray
     * flux measured from the outside of the pipe. */
/* D.1 Report an error if the file cannot be found. */
if((inputfile = fopen(data_filename,"r")) == NULL)
{
    printf("Error opening file: %s\n",data_filename);
    exit(0);
}

/* D.2 Now, read in the data sets. They are organized as */
/* follows: */
/* COUNTRATE, ANGULAR POSITION, AXIAL POSITION */
/* COUNTRATE (gammas/s) */
/* ANGULAR POSITION (degrees), converted to (rad) */
/* in program below */
/* AXIAL POSITION (inches), converted to (m) below */

i = 0;
while(feof(inputfile) == 0) {
    fscanf(inputfile, "%f%f%f", &Detector_CountRate,
           &Detector_Angle, &Detector_Z);
    detector_countrate[i] = Detector_CountRate;
    detector_angle[i] = Detector_Angle * PI/180.0;
    detector_z[i] = Detector_Z * 0.0254;
    ++i;
}
nitems = i-1;

/* D.3 Print out the data sets and close the file. */
/* for(i=0; i<(nitems-I); ++i) {
    printf(" i, countrate, angle, z = %d, %f, %f, %f\n", 
           i, detector_countrate[i], detector_angle[i],
           detector_z[i]);
} */
printf("\n\n");
fclose(inputfile);

/**
 * E. Request User Input.
 */

/***************************************************/

/* E.1 Identify the point source radionuclide properties. */

if(strcmp(radionuclide_source_type, "Cs137") == 0) {
    gamma_energy = Gamma_Energy_Cs137;
    halflife = HalfLife_Cs137;
    atomic_weight = Atomic_Weight_Cs137;
}

/* E.2 Identify the properties of the pipe wall material. */

if(strcmp(pipe_wall_material, "aluminum") == 0) {
    mu_pipe_material = mass_attenuation_aluminum(gamma_energy) * density_aluminum;
}

if(strcmp(pipe_wall_material, "steel") == 0) {
    mu_pipe_material = mass_attenuation_iron(gamma_energy) * density_iron;
}

/* E.3 Identify the properties of the pipe internal fluid. */

if(strcmp(pipe_internal_fluid, "air") == 0) {
    mu_pipe_fluid = mass_attenuation_air(gamma_energy) * density_air;
}

if(strcmp(pipe_internal_fluid, "water") == 0) {
    mu_pipe_fluid = mass_attenuation_water(gamma_energy) * density_water;
}
F. Begin Calculations.

```c
optimize.x_seed = source_strength_seed_value;
optimize.y_seed = source_z_seed_value;
optimize.x_stepsize = source_strength_stepsize;
optimize.y_stepsize = source_z_stepsize;
optimize.tolerance = optimization_tolerance;
optimize.target_value = 0.0;
optimize.maximum_iterations = maximum_iterations;

answer = simplex(optimize);
```

/* Convert the source strength from (gammas/s) to (rems) and (kg). */

decay_constant = 0.693/halflife;

radioactivity = answer.x_optimal/(3.7e10 * detector_efficiency);
/* Radioactivity in (Curies). */

mass_source = atomic_weight * radioactivity / (decay_constant * Avagadros_Number);
/* Mass in (kg). */

G. Print Out the Results.

```c
printf("*************************
");
printf("* POINT Results *
");
printf("*************************
");
printf("A. INPUT DATA 
");
printf("1. Pipe Wall Material: %s
", pipe_wall_material);
printf(" a. Linear Attenuation Coeff. (1/m): %f
", mu_pipe_material);
printf(" b. Thickness (m): %f
", pipe_wall_thickness);
```

```
pipe_wall_thickness /= 0.0254;
```
printf(" 2. Pipe Internal Fluid: %s\n", pipe_internal_fluid);
printf("a. Linear Attenuation Coeff. (1/m): %f\n", mu_pipe_fluid);
printf(" 3. Pipe Inside Diameter (m): %f\n", pipe_inside_diameter);
printf("(in): %f\n", pipe_inside_diameter /= 0.0254);
printf(" 4. Radionuclide Type: %s\n", radionuclide_source_type);
printf("a. Half life (s): %g\n", half_life);
printf(" 5. Filename, measured gamma: %s\n", data_filename);
printf("a. Number of data sets in file: %d\n", nitems);

 time(&current_time); /* The current time. */
printf(" 6. Time and Date of Calculation: %s\n", ctime(&current_time));
printf(" 7. Detector Properties: \n\n");
printf("a. Efficiency (fraction): %f\n", detector_efficiency);
printf("b. Area (m^2): %f\n", detector_area);
 printf("(in^2): %f\n", detector_area /= (0.0254 * 0.0254));
 printf("\n\n");
printf("B. OUTPUT DATA \n\n");
printf(" 1. Optimization Routine Output: \n\n");
printf("a. Source Strength (gammas/s): %g\n", answer.x_optimal);
printf("b. Source Axial Position (m): %f\n", answer.y_optimal);
 printf("(in): %f\n", answer.y_optimal /= 0.0254);
 printf("c. Number of iterations: %d\n", answer.iterations);
 printf("d. Value of the SE (gammas/s): %g\n", answer.function);
 printf("e. Mass of Source (kg): %g\n", mass_source);
 printf("f. Radioactivity of Source (Ci): %g\n", radioactivity);
 printf("g. Tolerance in SE (gammas/s): %g\n", optimization_tolerance);
}

/*****************************/
*
* SUBROUTINES
*
/*****************************/

double user_function(double x, double y) {
This function is called by the optimization routine: SIMPLEX.

return(standard_error(x, y));

double predicted_gamma_countrate(double source_strength,
    double source_z,
    double detector_angle,
    double detector_z) {

double detector_countrate, r, fluence;

double source_angle;

/* A. Based on the position and strength of the source and the angular and axial position of the detector, compute the flux that would be measured by the detector. */

/* A.1  Compute the distance from the source to the inner wall intersection point, from the inner wall to the detector, and from the source to the detector. */

source_angle = 180.0 * (PI/180.0); /* bottom of pipe. */

distance = wall_intersection_point(detector_angle,
    detector_z, source_angle, source_z);

/* Predicted: source strength=%f, angle=%f, z=%f
  Predicted: detector angle = %f, z = %f
  Predicted: r(s-d) = %f, r(s-iw) = %f, r(iw-d) = %f*/
r = distance.source_to_detector;
fluence = source_strength * exp(-mu_pipe_fluid *
distance.source_to_innerwall - mu_pipe_material *
distance.innerwall_to_detector)/(4.0 * PI * r * r);

/* Fluence is measured in (gammas/m^2-s). */

detector_countrate = fluence * detector_area *
detector_efficiency;
/* printf("Predicted: r, fluence, countrate: %g, %g, %g\n",r, fluence,
detector_countrate);*/
return(detector_countrate);
}

double standard_error(double source_strength, double source_z) {
    int i;
    double sum, predicted_countrate, SE;

    /**************************************************************************
    * A. Compute the standard error between the measured and
    * predicted gamma ray measurements.
   **************************************************************************/
    for(i=0, sum=0.0; i<(nitems-1); ++i) {
        predicted_countrate = predicted_gamma_countrate(source_strength,
            source_z, detector_angle[i], detector_z[i]);
        /* printf("Standard_Error: i, predicted, actual countrate = %d, %g, %g\n",
            i, predicted_countrate, detector_countrate[i]);*/
        sum += pow((predicted_countrate - detector_countrate[i]),2.0);
    }
    SE = sqrt(sum/(nitems - 2));
    /* printf("Standard_Error: SE, nitems = %g, %d\n\n",SE, nitems);*/
    return(SE);
}
void Read_Input_Data() {

    int i_hyphen = 45;

    char input_file[30], input_line[80];
    char *useful_string;

    char *ptr, *header;
    char *position_of_node, *determine_position(int, int, int);

    FILE *fp;

    /* B. Read User Input. */
    /* I. Obtain data from the setup file: "setup.dat". */
    strcpy(input_file,"setup.dat");
    printf("a. Opening the setup file: %s\n",input_file);

    fp = fopen(input_file,"r");

    /* 2. Read the setup data from the setup file. */
    strcpy(input_line,"begin");

    while( strstr(input_line,"END") == NULL ) {

        fgets(input_line,80,fp);

        /* c. Search for each header defining a variable in the setup file. (e.g. A.1, B.1, etc.) */
        /* Note that the last hyphen in the string is used */
if(strlen(input_line) > 60) {

    if((input_line[4]==='A') && (input_line[6]==='1')) {
        ptr = strrchr(input_line,i_hyphen);
        if(ptr != NULL) { ++ptr; pipe_inside_diameter = atof(ptr); }
    }

        ptr = strrchr(input_line,i_hyphen);
        if(ptr != NULL) { ++ptr; pipe_wall_thickness = atof(ptr); }
    }

        ptr = strrchr(input_line,i_hyphen);
        if(ptr != NULL) {
            ++ptr;
            useful_string = ++ptr;
            strcpy(pipe_wall_material, useful_string);
            pipe_wall_material[strlen(pipe_wall_material)-1] = '0';
        }
    }

        ptr = strrchr(input_line,i_hyphen);
        if(ptr != NULL) {
            ++ptr;
            useful_string = ++ptr;
            strcpy(pipe_internal_fluid, useful_string);
            pipe_internal_fluid[strlen(pipe_internal_fluid)-1] = '0';
        }
    }

        ptr = strrchr(input_line,i_hyphen);
        if(ptr != NULL) {
            ++ptr;
            useful_string = ++ptr;
            strcpy(radionuclide_source_type, useful_string);
            radionuclide_source_type[strlen(radionuclide_source_type)-1] = '0';
        }
    }
}
if((input_line[4] == 'C') && (input_line[6] == '1')) {
    ptr = strchr(input_line, i_hyphen);
    if(ptr != NULL) {
        ++ptr;
        useful_string = ++ptr;
        strcpy(data_filename, useful_string);
        data_filename[strlen(data_filename) - 1] = '0';
    }
}

if((input_line[4] == 'D') && (input_line[6] == '1')) {
    ptr = strchr(input_line, i_hyphen);
    if(ptr != NULL) { ++ptr; detector_efficiency = atof(ptr); }
}

    ptr = strchr(input_line, i_hyphen);
    if(ptr != NULL) { ++ptr; detector_area = atof(ptr); }
}

    ptr = strchr(input_line, i_hyphen);
    if(ptr != NULL) { ++ptr; maximum_iterations = atoi(ptr); }
}

    ptr = strchr(input_line, i_hyphen);
    if(ptr != NULL) { ++ptr; optimization_tolerance = atof(ptr); }
}

    ptr = strchr(input_line, i_hyphen);
    if(ptr != NULL) { ++ptr; source_strength_seed_value = atof(ptr); }
}

    ptr = strchr(input_line, i_hyphen);
    if(ptr != NULL) { ++ptr; source_z_seed_value = atof(ptr); }
}

    ptr = strchr(input_line, i_hyphen);
    if(ptr != NULL) { ++ptr; source_strength_stepsize = atof(ptr); }
}
    ptr = strchr(input_line,i_hyphen);
    if(ptr != NULL) ++ptr; source_z_stepsize = atof(ptr); }
}

/*
 * C. Convert values from English units to SI units.
 *
 *********************************************/

pipe_inside_diameter *= 0.0254;
pipe_wall_thickness *= 0.0254;
detector_area *= (0.0254 * 0.0254);
source_z_seed_value *= 0.0254;
source_z_stepsize *= 0.0254;

fclose(fp);
typedef struct DISTANCE {
    double source_to_detector;
    double source_to_innerwall;
    double innerwall_to_detector;
} DISTANCE;

typedef struct POINT3D {
    double x, y, z;
} POINT3D;

DISTANCE wall_intersection_point(double detector_angle,
                                  double detector_z, double source_angle, double source_z) {

    double R = pipe_inside_diameter/2.0;
    double Ro = pipe_inside_diameter/2.0 + pipe_wall_thickness;
    double A, B, C, gamma;

    Function: POINT3D
    Purpose: Calculate the point where a 3D line emanating from a source position to the detector intersects the inside wall of a circular pipe.
    Input:  a) source angular position and axial (z) position.
            b) detector angular position and axial (z) position.
    Output: x, y, z positions of the wall intersection point.
    Author:  W. Culbreth
    Date:  4/7/99
    Version: 1.0
double x_source, y_source, z_source;
double x_detector, y_detector, z_detector;
double x_innerwall, y_innerwall, z_innerwall;
double distance_source_to_detector;
double distance_innerwall_to_detector;
double distance_source_to_innerwall;

DISTANCE wall;

/*****************************************************************************/
* A. Compute the necessary constants, A, B, C, and gamma.
* Assume that the negative root is the actual intersection point. (Remember, a line connecting the source and the detector will intersect the inner pipe wall at TWO points. We want the solution that occurs BETWEEN the source and the detector).
* */
A = R*R + Ro*Ro - 2.0*R*Ro*(cos(detector_angle)*
   cos(source_angle) + sin(detector_angle)*sin(source_angle));
B = -2.0*Ro*(Ro - R*(cos(detector_angle)*cos(source_angle) -
   sin(detector_angle)*sin(source_angle)));
C = Ro*Ro - R*R;
gamma = (-B - pow((B*B - 4.0*A*C),0.5))/(2.0*A);

/*****************************************************************************/
* B. Compute the position of the intersection point on the pipe inner wall.
* */

x_innerwall = Ro*cos(detector_angle) - gamma*(
    Ro*cos(detector_angle) - R*cos(source_angle));

y_innerwall = Ro*sin(detector_angle) - gamma*(
    Ro*sin(detector_angle) - R*sin(source_angle));

z_innerwall = gamma*source_z + (1.0 - gamma)*detector_z;

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C. Compute the cartesian position of the source and the detector. Follow by computing the distances from source to inner wall and source to detector.

```c
x_source = R*cos(source_angle);
y_source = R*sin(source_angle);
z_source = source_z;

x_detector = Ro*cos(detector_angle);
y_detector = Ro*sin(detector_angle);
z_detector = detector_z;
```

```c
distance_source_to_detector = pow((
    pow((x_detector - x_source),2.0) +
    pow((y_detector - y_source),2.0) +
    pow((z_detector - z_source),2.0)),0.5);

distance_source_to_innerwall = pow((
    pow((x_innerwall - x_source),2.0) +
    pow((y_innerwall - y_source),2.0) +
    pow((z_innerwall - z_source),2.0)),0.5);

distance_innerwall_to_detector = pow((
    pow((x_detector - x_innerwall),2.0) +
    pow((y_detector - y_innerwall),2.0) +
    pow((z_detector - z_innerwall),2.0)),0.5);
```

D. If the distance between the source and the detector is SMALLER than the distance between the inner wall and the source, use the other root of the quadratic equation for gamma.

```c
/* if(distance_source_to_detector < distance_source_to_innerwall) {

    gamma = (-B + pow((B^2 - 4.0*A*C),0.5))/(2.0*A);

    x_innerwall = Ro*cos(detector_angle) - gamma*(
```
\[ R_o \cos(\text{detector\_angle}) - R \cos(\text{source\_angle}); \]

\[ y_{\text{innerwall}} = R_o \sin(\text{detector\_angle}) - \gamma \left( R_o \sin(\text{detector\_angle}) - R \sin(\text{source\_angle}) \right); \]

\[ z_{\text{innerwall}} = \gamma \text{source\_z} + (1.0 - \gamma) \text{detector\_z}; \]

E. Return the appropriate wall intersection point to the calling routine.

wall.source_to_detector = distance_source_to_detector;
wall.source_to_innerwall = distance_source_to_innerwall;
wall.innerwall_to_detector = distance_innerwall_to_detector;

return(wall);
double mass_attenuation_air(double);
double mass_attenuation_water(double);
double mass_attenuation_aluminum(double);
double mass_attenuation_iron(double);

double mass_attenuation_air(double energy) { 

/*************************************************************************/

*  
*  Subroutine: mass_attenuation_air
*  
*  Purpose: Compute the mass attenuation coefficient for gamma
*  rays in air. Interpolation of tabulated data is
*  used in the analysis.
*  
*  Input:    gamma ray energy (MeV).
*  
*  Output:   mass attenuation coefficient
*            (m^2/kg).
*  
*  Author:   wgc
*  Date:     3/11/99
*  Version:  1
*  Source:   Shultis, J. K., and Faw, R. E., Radiation Shielding,
*  
*************************************************************************/

double mu[]={4.897, 1.482, 0.6904, 0.3076, 0.2202, 0.1889, 0.1582, 0.1489, 0.1332, 0.122, 0.1061, 0.09514, 0.08689, 0.0804, 0.07065, 0.06353, 0.05684, 0.05172, 0.04446, 0.0358, 0.03079, 0.02751, 0.02522, 0.0225, 0.02045, 0.0181, 0.01705, 0.01628, 0.0161, 0.01614, 0.01625, 0.01654, 0.01683 };

double E[]={ 0.01, 0.015, 0.02, 0.03, 0.04, 0.05, 0.06, 0.08, 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1, 1.25, 1.5, 2, 3, 4, 5, 6, 8, 10, 15, 20, 30, 40, 50,
int i, nitems = 34;
double value;

value = mu[0]; i = 0;
while(( energy > E[i]) && (i < nitems-2)) { ++i; }

value = mu[i] + (mu[i+1]-mu[i])*(energy-E[i])/(E[i+1]-E[i]);
printf("Air: \mu(cm^2/g) = \%fn",value);
return(value/10.0);

double mass_attenuation_water(double energy) {

/* Subroutine: mass_attenuation_water */
/* Purpose: Compute the mass attenuation coefficient for gamma */
/* rays in water. Interpolation of tabulated data is */
/* used in the analysis. */
/* Input: gamma ray energy (MeV). */
/* Output: mass attenuation coefficient */
/* (m^2/kg). */
/* Author: wgc */
/* Date: 3/11/99 */
/* Version: 1 */
/* Source: Shultis, J. K., and Faw, R. E., Radiation Shielding, */
/* Prentice Hall PTR, 1996, table C.7, page 464. */
*
**************************************************************************/

double mu[]={5.098, 1.539, 0.7211, 0.3286, 0.2395,
0.2076, 0.1920, 0.1755, 0.1654, 0.1481,
0.1356, 0.1180, 0.1058, 0.09664, 0.08940,
0.07857, 0.07066, 0.06320, 0.05751, 0.04940,
0.03968, 0.03402, 0.03031, 0.02770, 0.02429,
double E[] = { 0.01, 0.015, 0.02, 0.03, 0.04, 0.05, 0.06, 0.08, 
0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1, 1.25, 
1.5, 2, 3, 4, 5, 6, 8, 10, 15, 20, 30, 40, 50, 
60, 80, 100 };

int i, nitems = 34;
double value;

value = mu[0]; i = 0;
while(( energy > E[i]) && (i < nitems-2)) { ++i; }

value = mu[i] + (mu[i+1]-mu[i])*(energy-E[i])/(E[i+1]-E[i]);

return(value/10.0);
}

double mass_attenuation_aluminum(double energy) {

/*********************
 * Subroutine: mass_attenuation_aluminum
 * Purpose: Compute the mass attenuation coefficient for gamma rays in aluminum. Interpolation of tabulated data is used in the analysis.
 * Input: gamma ray energy (MeV).
 * Output: mass attenuation coefficient (m^2/kg).
 * Author: wgc
 * Date: 3/11/99
 * Version: 1
 *******************/

double mu[]={25.68, 7.641, 3.237, 1.019, 0.4999,
0.3214, 0.2440, 0.1817, 0.1572, 0.1317,
0.1188, 0.1026, 0.09187, 0.08388, 0.07762,
0.06818, 0.06131, 0.05486, 0.05000, 0.04320,
0.03539, 0.03105, 0.02836, 0.02655, 0.02437,
0.02318, 0.02195, 0.02168, 0.02196, 0.02251,
0.02306, 0.02358, 0.02447, 0.02517};

double E[]={ 0.01, 0.015, 0.02, 0.03, 0.04, 0.05, 0.06, 0.08,
0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1, 1.25,
1.5, 2, 3, 4, 5, 6, 8, 10, 15, 20, 30, 40, 50,
60, 80, 100 };;

int i, nitems = 34;
double value;

value = mu[0];  i = 0;
while(( energy > E[i]) && (i < nitems-2)) { ++i; }

value = mu[i] + (mu[i+1]-mu[i])*(energy-E[i])/(E[i+1]-E[i]);

return(value/10.0);
}

double mass_attenuation_iron(double energy) {

/*******************************************************************************/
/*
 * Subroutine: mass_attenuation_iron
 * 
 * Purpose: Compute the mass attenuation coefficient for gamma
 * rays in iron. Interpolation of tabulated data is
 * used in the analysis.
 * 
 * Input: gamma ray energy (MeV).
 * 
 * Output: mass attenuation coefficient
 * (m^2/kg).
 * 
 * Author: wgc
 * Date: 3/11/99
/*******************************************************************************/
double mu[]={169.4, 56.33, 25.16, 7.891, 3.450,
    1.833, 1.113, 0.5391, 0.3340, 0.1786,
    0.1357, 0.1051, 0.09131, 0.08241, 0.07583,
    0.06631, 0.05951, 0.05322, 0.04863, 0.04254,
    0.03616, 0.03309, 0.03144, 0.03056, 0.02991,
    0.02994, 0.03092, 0.03223, 0.03469, 0.03666,
    0.03828, 0.03961, 0.04172, 0.04329};

double E[]={ 0.01, 0.015, 0.02, 0.03, 0.04, 0.05, 0.06, 0.08,
    0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1, 1.25,
    1.5, 2, 3, 4.5, 6, 8, 10, 15, 20, 30, 40, 50,
    60, 80, 100 };

int i, nitems = 34;
double value;

value = mu[0]; i = 0;
while(( energy > E[i]) && (i < nitems-2)) { ++i; }

value = mu[i] + (mu[i+1]-mu[i])*(energy-E[i])/(E[i+1]-E[i]);
printf("Iron: mu= %f\n",value);
return(value/10.0);
typedef struct POINT {
    double x, y, f;
    int i;
} POINT;

typedef struct SIMPLEX_INPUT {
    double x_seed, y_seed;
    double x_stepsize, y_stepsize;
    double tolerance, target_value;
    int maximum_iterations;
    double (*f)(double);
} SIMPLEX_INPUT;

typedef struct SIMPLEX_OUTPUT {
    double x_optimal, y_optimal;
    double function;
    int iterations;
} SIMPLEX_OUTPUT;

SIMPLEX_OUTPUT simplex(SIMPLEX_INPUT Input) {

/*************************************************************/
/*
* SIMPLEX: Compute the optimal values of x and y based on
* the given seed values, x_seed and y_seed. The
* routine used is the simplex optimization routine.
* The range of x and y are given by globally-defined values of (x_min,y_min) and (x_max,
* y_max). Tolerance must also be defined globally.
*
* Global: \( x_{\text{min}}, x_{\text{max}}, y_{\text{min}}, y_{\text{max}}, \) tolerance,
* function(double \( x, y \)).
* Return: optimal value of \( x \), optimal value of \( y \),
* number of iterations to converge.
*
*******************************************************************************/

double x[4], y[4], f[4];
double old_best_f_value, deviation;
double x_offset, y_offset;
double x_seed, y_seed;
POINT W, N, B, P, R, E, Cw, Cr;
SIMPLEX_OUTPUT Output;
int i, i_counter;
extern double user_function();
char junk[10];

/*****************************************************************************/
* A. Define 3 points surrounding the seed value.
* \( x \) and \( y \) range represent the domain boundaries of
* the problem
*****************************************************************************/

x_offset = Input.x_stepsize;
y_offset = Input.y_stepsize;
x_seed = Input.x_seed;
y_seed = Input.y_seed;

/*****************************************************************************/
* B. Create the next two points of the simplex based on
* the coordinates of the initial seed point.
*****************************************************************************/

x[1] = x_seed; y[1] = y_seed + y_offset;
x[2] = x_seed - x_offset; y[2] = Input.y_seed - y_offset;
x[3] = x_seed + x_offset; y[3] = y_seed - y_offset;

/*****************************************************************************/
* C. Solve the function for each of the three points.
*****************************************************************************/

/*printf("Simplex: x(1), x(2), x(3): \%f, \%f, \%f\n",x[1],x[2],x[3]);
printf(" y(1), y(2), y(3): \%f, \%f, \%f\n",y[1],y[2],y[3]);*/

f[1] = fabs(user_function(x[1], y[1]) - Input.target_value);
f[2] = fabs(user_function(x[2], y[2]) - Input.target_value);
f[3] = fabs(user_function(x[3], y[3]) - Input.target_value);
/*printf("simplex: 1: x,y,f=%f, %f, %f\n",x[1],y[1],f[1]);
printf("simplex: 2: x,y,f=%f, %f, %f\n",x[2],y[2],f[2]);
printf("simplex: 3: x,y,f=%f, %f, %f\n",x[3],y[3],f[3]);*/

D. Identify the coordinates of the points as:
* B (best), N (Next-to-Worst), and W (Worst)
* in terms of the function(x,y).

i_counter = 0;

do {
    W.i = 1; W.x = x[1]; W.y = y[1]; W.f = f[1];
    B.i = 1; B.x = x[1]; B.y = y[1]; B.f = f[1];
    N.i = 1; N.x = x[1]; N.y = y[1]; N.f = f[1];
}

E. Relabel the values depending on whether they are
* better or worse than the initialized value above.

for(i=2; i<=3; ++i) {
    if (f[i] > W.f) {
        W.i = i; W.x = x[i]; W.y = y[i]; W.f = f[i];
    }
    if (f[i] < B.f) {
        B.i = i; B.x = x[i]; B.y = y[i]; B.f = f[i];
    }
}

for(i=1; i<=3; ++i) {
    if((i != W.i) && (i != B.i)) {
        N.i = i; N.x = x[i]; N.y = y[i]; N.f = f[i];
    }
}

/*printf("simplex,NW: N.i, W.i, B.i =%d, %d, %d\n",N.i, W.i, B.i);*/

/*printf("simplex: B.i, B.x, B.y, B.f = %d, %f, %f\n",B.i,B.x,B.y,B.f);
printf("simplex: N.i, N.x, N.y, N.f = %d, %f, %f\n",N.i,N.x,N.y,N.f);
printf("simplex: W.i, W.x, W.y, W.f = %d, %f, %f\n",W.i,W.x,W.y,W.f);*/
E.1 Now, compute the points R, E, Cw, and Cr. The point P lies midway between B and N.

\[
P.x = 0.5 \times (B.x + N.x); \quad P.y = 0.5 \times (B.y + N.y);
\]

\[
R.x = P.x + (P.x - W.x);
R.y = P.y + (P.y - W.y);
\]

\[
R.f = \text{fabs(user\_function}(R.x, R.y) - \text{Input.target\_value});
\]

/*printf("simplex: P.x, P.y = %f, %f\n",P.x,P.y);
printf("simplex: R.x, R.y, R.f = %f, %f, %f\n",R.x, R.y, R.f);*/

E.2 Determine which expression is to define the new point of the simplex. Is R.f greater than B.f? If true, than make expansion E.

\[
\text{if}(R.f < B.f) \{
\]

\[
E.x = P.x + 2.0 \times (P.x - W.x);
E.y = P.y + 2.0 \times (P.y - W.y);
\]

\[
E.f = \text{fabs(user\_function}(E.x, E.y) - \text{Input.target\_value});
\]

\[
\text{if}(E.f < R.f) \{
\quad W.x = E.x; \quad W.y = E.y; \quad W.i = E.i; \quad W.f = E.f;
\}
\]

\[
\text{if}(E.f >= R.f) \{
\quad W.x = R.x; \quad W.y = R.y; \quad W.i = R.i; \quad W.f = R.f;
\}
\]

/*printf("simplex: E.x, E.y, E.f = %f, %f, %f\n",E.x, E.y, E.f);*/

E.3 If R.f is not greater than B.f but is greater than W.f, then create contraction C+. If R.f is less than W.f, create contraction C-.

\[
\text{if}(R.f >= B.f) \{
\]

/*printf("simplex: E.x, E.y, E.f = %f, %f, %f\n",E.x, E.y, E.f);*/
if(R.f < N.f) {
    W.x = R.x; W.y = R.y; W.i = R.i; W.f = R.f;
}

if(R.f >= N.f) {
    if(R.f < W.f) {
        Cr.x = P.x + .5*(P.x - W.x);
        Cr.y = P.y + .5*(P.y - W.y);
        Cr.f = fabs(user_function(Cr.x, Cr.y) - Input.target_value);
        W.x = Cr.x; W.y = Cr.y; W.i = Cr.i; W.f = Cr.f;
        /*printf("simplex: Cr.x, Cr.y, Cr.f = %f, %f, %f\n", Cr.x, Cr.y, Cr.f);*/
    }
    if(R.f >= W.f) {
        Cw.x = P.x - .5*(P.x - W.x);
        Cw.y = P.y - .5*(P.y - W.y);
        Cw.f = fabs(user_function(Cw.x, Cw.y) - Input.target_value);
        W.x = Cw.x; W.y = Cw.y; W.i = Cw.i; W.f = Cw.f;
        /*printf("simplex: Cw.x, Cw.y, Cw.f = %f, %f, %f\n", Cw.x, Cw.y, Cw.f);*/
    }
}


/*printf("simplex: x_optimal, y_optimal = %f, %f\n", B.x, B.y);
printf("simplex: x_offset, y_offset = %f, %f\n", x_offset, y_offset);*/

declaration = fabs(B.f - Input.target_value);

/*printf("simplex: i_counter, deviation, tolerance = %d, %f, %f\n", i_counter, deviation, Input.tolerance);
printf("\n");*/
++i_counter;

/* scanf("%s" junk); */

} while((deviation > Input.tolerance) &&
    (i_counter < Input.maximum_iterations));
Output.x_optimal = B.x; Output.y_optimal = B.y;
Output.function = B.f;
Output.iterations = i_counter;

return(Output);
}
SETUP.DAT

Setup File
for the Program POINT

A. PIPE GEOMETRY AND PROPERTIES

A.1 Pipe Inside Diameter (in) ------------------------ 8.19
A.2 Pipe Wall Thickness (in) ------------------------- 0.250
A.3 Pipe Wall Material ------------------------------- steel
    (Choices are: aluminum, steel)
A.4 Pipe Internal Fluid ------------------------------- air
    (Choices are: air, water)

B. RADIONUCLIDE POINT SOURCE

B.1 Point Source Type ------------------------------- Cs137
    (Choices are: Cs137)

C. MEASURED GAMMA RAY DISTRIBUTION

C.1 Name of Data File -------------------------------- steel.dat

D. DETECTOR PROPERTIES

D.1 Detector Efficiency (fraction) ------------------ 0.034
D.2 Detector Area (in^2) ---------------------------- 3.14

E. OPTIMIZATION ROUTINE PARAMETERS

E.1 Maximum Number of Iterations (100000) ------------- 2
E.2 Tolerance in the Standard Deviation (gammas/s) ---- 0.05
E.3 Source Strength Seed Value (gammas/s) --------- 5000
E.4 Source Axial Position Seed Value (in) ---------- 0.0
E.5 Source Strength Step Size (gammas/s) ---------- 1.0
E.6 Source Axial Position Step Size (in) ---------- 0.1

END
## APPENDIX II

Tabulated Measured Data

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<th>axial position (m)</th>
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Cs-137 source; 8 µCi as of 05/09/91

6.54 µCi = 241,980 gamma/sec as of 02/12/99

Al pipe wall thickness = 0.135 inches

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Steel pipe
wall thick. = 0.25 inches
ID = 8.19 inches
OD = 8.63 inches
source located 18 inches from end of pipe

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**STEEL PIPE FILLED WITH AIR, TEST 2**

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Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
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| 1  | 90    | 0.01 | 2   | 1    | 0.333333 |
| 1  | 112.5 | 0.1  | 2   | 0.5  | 4   |
| 1  | 135   | 0.1  | 3   | 1    | 6   |
| 1  | 157.5 | 0.1  | 6   | 2    | 12  |
| 1  | 180   | 1    | 3   | 0.5  | 47  |
| 1  | 202.5 | 0.1  | 5   | 1    | 10  |
| 1  | 225   | 0.1  | 3   | 1    | 6   |
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| 1  | 270   | 0.1  | 2   | 0.5  | 4   |
| 1  | 315   | 0.1  | 1   | 0.5  | 2   |
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| 0  | 90    | 0.01 | 2   | 1    | 0.333333 |
| 0  | 112.5 | 0.1  | 2   | 1    | 4   |
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APPENDIX III

Tabulated Computer Results

ALUMINUM PIPE RESULTS
a. Opening the setup file:  setup.dat
Air:  \( \mu (\text{cm}^2/\text{g}) = 0.075563 \)

* POINT Results *

A. INPUT DATA

1. Pipe Wall Material:  aluminum
   a. Linear Attenuation Coeff. (1/m):  19.688481
   b. Thickness (m):  0.003429
      (in):  0.135000

2. Pipe Internal Fluid:  air
   a. Linear Attenuation Coeff. (1/m):  0.009672

3. Pipe Inside Diameter (m):  0.132842
   (in):  5.230000

4. Radionuclide Type:  Cs137
   a. Halflife (s):  9.4608e+08
   b. Gamma Ray Energy (MeV):  0.662000

5. Filename, measured gamma:  point.dat
   a. Number of data sets in file:  56

6. Time and Date of Calculation:  Mon Apr 19 14:10:01 1999

7. Detector Properties:
   a. Efficiency (fraction):  0.034000
   b. Area (m^2):  0.002026
      (in^2):  3.140000

B. OUTPUT DATA

1. Optimization Routine Output:
   a. Source Strength (gammas/s):  4996.5
   b. Source Axial Position (m):
      0.005080
      (in):  0.200000
   c. Number of iterations:  100
   d. Value of the SE (gammas/s):  75.3514
   e. Mass of Source (kg):  1.23335e-21
   f. Radioactivity of Source (Ci):  3.97178e-06
   g. Tolerance in SE (gammas/s):  0.05
STEEL PIPE, TEST 1 RESULTS

a. Opening the setup file: setup.dat
Iron: \( \mu = 0.071002 \)
Air: \( \mu (\text{cm}^2/\text{g}) = 0.075563 \)

* POINT Results *

A. INPUT DATA
1. Pipe Wall Material: steel
   a. Linear Attenuation Coeff. (1/m): 55.381560
   b. Thickness (m): 0.006350
      (in): 0.250000
2. Pipe Internal Fluid: air
   a. Linear Attenuation Coeff. (1/m): 0.009672
3. Pipe Inside Diameter (m): 0.208026
   (in): 8.190000
4. Radionuclide Type: Cs137
   a. Halflife (s): 9.4608e+08
   b. Gamma Ray Energy (MeV): 0.662000
5. Filename, measured gamma: steel.dat
   a. Number of data sets in file: 40
6. Time and Date of Calculation: Mon Apr 19 14:28:45 1999
7. Detector Properties:
   a. Efficiency (fraction): 0.034000
   b. Area (m^2): 0.002026
      (in^2): 3.140000

B. OUTPUT DATA
1. Optimization Routine Output:
   a. Source Strength (gammas/s): 4996.5
   b. Source Axial Position (m): 0.005080
      (in): 0.200000
   c. Number of iterations: 100
   d. Value of the SE (gammas/s): 36.9804
   e. Mass of Source (kg): 1.23335e-21
   f. Radioactivity of Source (Ci): 3.97178e-06
   g. Tolerance in SE (gammas/s): 0.05

STEEL PIPE, TEST 2 RESULTS

a. Opening the setup file: setup.dat
Iron: \( \mu = 0.071002 \)
Air: \( \mu (\text{cm}^2/\text{g}) = 0.075563 \)

* POINT Results *

A. INPUT DATA
1. Pipe Wall Material: steel
   a. Linear Attenuation Coeff. (1/m): 55.381560
   b. Thickness (m): 0.006350
      (in): 0.250000
2. Pipe Internal Fluid: air
   a. Linear Attenuation Coeff. (1/m): 0.009672
3. Pipe Inside Diameter (m): \(0.208026\) (in): \(8.190000\)

4. Radionuclide Type: Cs137
   a. Halflife (s): \(9.4608e+08\)
   b. Gamma Ray Energy (MeV): \(0.662000\)

5. Filename, measured gamma: sdry.dat
   a. Number of data sets in file: 108

6. Time and Date of Calculation: Mon Apr 19 13:44:20 1999

7. Detector Properties:
   a. Efficiency (fraction): \(0.034000\)
   b. Area (m^2): \(0.002026\)
       (in^2): \(3.140000\)

B. OUTPUT DATA
1. Optimization Routine Output:
   a. Source Strength (gammas/s): \(5910.59\)
   b. Source Axial Position (m): \(-0.012093\)
       (in): \(-0.476091\)
   c. Number of iterations: 100
   d. Value of the SE (gammas/s): \(6.01788\)
   e. Mass of Source (kg): \(1.45899e-21\)
   f. Radioactivity of Source (Ci): \(4.6984e-06\)
   g. Tolerance in SE (gammas/s): \(0.05\)

STEEL PIPE, FILLED WITH WATER, RESULTS
a. Opening the setup file: setup.dat
Iron: \(\mu = 0.071002\)

* POINT Results *

A. INPUT DATA
1. Pipe Wall Material: steel
   a. Linear Attenuation Coeff. (1/m): \(55.381560\)
   b. Thickness (m): \(0.006350\)
       (in): \(0.250000\)

2. Pipe Internal Fluid: water
   a. Linear Attenuation Coeff. (1/m): \(8.402790\)

3. Pipe Inside Diameter (m): \(0.208026\)
   (in): \(8.190000\)

4. Radionuclide Type: Cs137
   a. Halflife (s): \(9.4608e+08\)
   b. Gamma Ray Energy (MeV): \(0.662000\)

5. Filename, measured gamma: sh2o.dat
   a. Number of data sets in file: 108

6. Time and Date of Calculation: Mon Apr 19 14:13:36 1999

7. Detector Properties:
   a. Efficiency (fraction): \(0.034000\)
   b. Area (m^2): \(0.002026\)
       (in^2): \(3.140000\)

B. OUTPUT DATA
1. Optimization Routine Output:
   a. Source Strength (gammas/s): \(5891.64\)
   b. Source Axial Position (m): \(-0.012115\)
(in): -0.476975

- Number of iterations: 100
- Value of the SE (gammas/s): 6.87892
- Mass of Source (kg): 1.45431e-21
- Radioactivity of Source (Ci): 4.68334e-06
- Tolerance in SE (gammas/s): 0.05
REFERENCES


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Publications:

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Committee Member, Dr. Mauer, Ph. D.
Committee Member, Dr. Vernon Hodge, Ph. D.
Graduate Faculty Representative, Dr. Penny Amy