Simulation of X-Ray Imaging Systems
For Luggage Inspection

by

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(ABSTRACT)

This thesis describes XL, an x-ray imaging simulator for luggage inspection. This software system runs on a workstation and models x-ray sources, x-ray detectors and objects between them. A simple graphical interface permits the user to specify simulation parameters and inputs. XL then uses Monte Carlo methods to simulate x-ray interaction with matter, including the photoelectric effect, coherent scattering, and incoherent scattering. Finally, XL can produce x-ray images which agree closely with experimental data obtained from a commercial luggage scanner. The simulator will be a valuable tool in the development of future x-ray scanners, particularly those designed to detect explosives in luggage.
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Chapter 1

Introduction

1.1 Motivation

Over the last ten years, the levels of international travel and commerce have increased dramatically. It is perhaps unavoidable that the illegal movement of such contraband items as firearms, drugs, and explosives have also increased. Because of this, much effort has been focused on the need to detect illegal substances, particularly those that may endanger the public. For airlines, the systematic inspection of all containers is now common for all international flights.

Since a plastic explosive first occurred in an airplane bombing causing severe damage on August 11, 1982, the detection of explosives has received particular attention [NOV92]. Small quantities of explosives are believed to have caused several recent fatal airline disasters [EIB92]. A reliable method for detecting explosives in airport luggage is urgently needed.

X-ray based detection systems have been extensively studied and are in use at most airports in the world. Most of these, however, gather transmission images that must be evaluated manually. Because plastic explosives can be in any shape, there is an urgent need for an automatic way to sense the presence of plastic explosives without relying on shape. Some x-ray sensing techniques show promise but need to be explored. No single x-ray method seems to be adequate, and multisensor methods are therefore needed.
This thesis describes XL, an X-ray simulator for Luggage, that has been developed at Virginia Tech. The motivation for creating this software simulation package comes from three needs. First, it allows investigators to simulate and compare various explosive detection methods. Second, specific parameters of the detection system can be determined from simulation after a basic design has been chosen. Third, the simulator can be used to test whether a physical system is functioning correctly, and whether results from the system are reasonable.

1.2 Background

In 1976, the Federal Aviation Administration (FAA) began a research and development program in explosives detection with the goal of establishing an operating environment that can preclude acts of terrorism. Since that time, several sensing methods have been suggested and studied, including thermal neutron analysis, nuclear magnetic resonance, and vapor detection. Because plastic explosives have become the preeminent threat in recent years, the FAA has directed much of its counter-terrorist efforts toward the development of detection techniques specifically for plastic explosives.

Plastic explosives are hard to detect because they have variable shape and low x-ray absorption characteristics. X-ray sensing is not a new technique, but its application to explosives detection is relatively new. As a part of the FAA's counter-terrorism thrust, Virginia Tech researchers are developing new x-ray sensing methods. In addition to the simulator described in this thesis, researchers at Virginia Tech are building a prototype
luggage scanning system and are developing multisensor fusion techniques. The XL simulator is an important component of this effort.

1.3 Objectives and Contributions of this Study

The major goal of this research is to develop a software system that can model the operation of an x-ray luggage scanning system. In particular, the software system must simulate the generation, transmission, and detection of x-rays and should produce x-ray images that match the outputs of a corresponding physical system with high accuracy. The major contributions of this research are as follows:

(1) The XL simulator is one of the first systems that can generate simulated x-ray images.

(2) XL predicts x-ray transmission and scattering by interfacing with MCNP, a software package that uses Monte Carlo techniques to simulate x-ray interaction with matter. (MCNP is described in Chapter 3.)

(3) XL has been developed to accommodate a large range of sensing geometries. A scanning system can be entered into a 3D drawing system, such as AutoCAD. XL converts this CAD description to the format required by MCNP.

(4) An x-ray source model has been developed for XL. Tungsten target x-ray spectra are generated by the model, which have a good agreement with published experimental data.
(5) A scintillation x-ray detector model is employed in XL, and its spectral response characteristic has been developed.

(6) The system has been employed to investigate several methods of explosives detection. Examples include dual-energy and dual-axis sensing, which are described in Chapter 6.

(7) The accuracy of the system has been tested by comparing simulated images with those from a physical x-ray scanner.

1.4 Outline of Thesis

This thesis describes the capabilities of the XL simulation package. Chapter 2 describes three basic transport phenomena of x-ray physics: the photoelectric effect, coherent scattering, and incoherent scattering. Chapter 3 introduces the MCNP simulation software. Chapter 4 presents the model that has been developed in this research for generating tungsten target x-ray source spectra. Chapter 5 presents the model of the x-ray scintillation detector that has been developed in this research. Chapter 6 discusses the complete simulation system, including its interface with AutoCAD and MCNP. An accuracy analysis of the XL simulator is also discussed in this chapter. Chapter 7 presents the simulation accuracy analysis. Example images produced by XL are also presented and compared with a physical scanning system. Chapter 8 presents a conclusion of the thesis.
Chapter 2

Review of X-Ray Physics

This chapter summarizes the ideas of x-ray physics that are needed to understand the XL simulator.

2.1 Introduction

A variety of physical processes are involved in the interaction of x-rays with matter [ATT68][JOS77]. On passing through matter, an x-ray beam undergoes attenuation; that is, its intensity decreases gradually by absorption and scattering. Absorption refers to the case in which an incident x-ray photon gives up all of its energy. In other words, the photon is fully absorbed and disappears during the interaction. Scattering refers to those x-ray photons that have undergone a change in direction after interaction with atoms of matter. Other photons are neither absorbed nor scattered; they simply pass through matter. This process is known as transmission. By measuring the transmitted, forward-scattered and back-scattered x-rays, and by knowing the number of photons and the intensity of a photon beam passing through a material with known thickness, the probability of photon removal along the path of a beam can be estimated. This information can be used to characterize material that lies in the path of the x-ray beam.

When an x-ray beam interacts with matter, four major processes of attenuation exist: (1) the photoelectric effect, (2) coherent scattering, (3) incoherent (or Compton)
scattering, and (4) pair production. The photoelectric effect corresponds to absorption and is one of the predominant interactions in the energy range of 1-100 keV. Coherent scattering and incoherent scattering contribute to a beam's attenuation by scattering the incident photons with and without energy change, respectively. Brief descriptions of the photoelectric effect, coherent scattering, and incoherent scattering will be given in the next section. Pair production can only occur at energy levels greater than 1.022 MeV. Because the energy range of x-rays commonly used for explosives detection is from approximately 1 keV to 150 keV, pair production will not be considered in this chapter.

2.2 X-Ray Interactions with Matter

2.2.1 The Photoelectric Effect

The photoelectric effect is the process by which an incident photon of energy \( E \) interacts with an orbital electron and ejects several fluorescent photons and an orbital electron. The electron must have binding energy \( e \) that is less than the energy of the incident photon. The incident photon is absorbed by the atom and loses all its energy. The atom responds by ejecting an electron, usually from the K or L shell, leaving a hole in that shell (see Figure 2.1) [JOS77]. Now the atom is ionized and is in an excited state. Generally, the inner electrons are the predominant contributors to the photoelectric effect. The energy of the incident photon ultimately results in freeing the electron from its shell and setting it in motion as a photoelectron. For low energy x-rays, the photoelectric effect is the dominant process.
The photoelectric effect is characterized by the photoelectric absorption coefficient, also known as the “cross-section.” This is defined to represent the effective cross-sectional area of an atom, and is related to the probability that an interaction will take place between an x-ray photon and an atom. The photoelectric cross-section $\sigma_{pe}$ in barn/atom ($10^{-24}$ cm$^2$/atom) can be approximated, in the x-ray energy range of several keV to hundreds of keV, by the relationship:

$$\sigma_{pe} \approx 10 \frac{Z^{4.5}}{E^3}$$  \hspace{1cm} (2.1)

where $Z$ is the atomic number of the target atom and $E$ is the photon energy in keV [HUB69]. The relationship indicates that $\sigma_{pe}$ increases as the atomic number $Z$ (or the effective atomic number $Z_{eff}$ for a compound) increases. On the other hand, it decreases as the x-ray photon energy increases.

![Diagram](image)

Figure 2.1. Photoelectric interaction with true absorption. (a) An incident photon loses all its energy on entering an atom, being absorbed in the process. (b) The atom responds by ejecting an inner shell electron, which becomes a photoelectron. The atom is now in an excited state. (c) An electron from a higher energy level fills the vacancy in the K-shell or L-shell, and emits a characteristic x-ray photon.
The photoelectric effect is of the utmost importance in distinguishing organic materials from inorganic materials. Generally, organic materials are low-Z materials, while inorganic materials are high-Z materials. The importance of the photoelectric effect is greater for the higher Z elements. The photoelectric effect contributes to a large difference in photoelectric absorption of these two kinds of materials. The photoelectric cross-sections of high-Z materials are higher and decrease much faster than those of low-Z materials (such as those encountered in explosives). This is a major factor in x-ray image formation.

2.2.2 Coherent Scattering

Coherent scattering (sometimes referred to as Thomson and Rayleigh scattering) occurs from strongly bound electrons, if a very low energy x-ray photon interacts with a strongly bound electron that may be set into vibration. It involves no energy loss, but result in the deflection of the incident x-ray photon from its original path, as shown in Figure 2.2 [JOS77]. The energy of photons determines the wavelength, following the relation \( E = \frac{hc}{\lambda} \), where \( \lambda \) is the wavelength, \( c \) is the velocity of light, and \( h \) is Planck’s constant. The incident photon has been scattered without undergoing any change in wavelength, frequency, or energy.

At low photon energies (less than 50 keV), coherent scattering represents the major contribution to x-ray scattering. As the energy of the photon increases, the coherent scattering becomes small and can be ignored.
2.2.3. Incoherent (Compton) Scattering

Incoherent (Compton) scattering is a process in which a photon interacts with a loosely bound electron that may be considered free and dislodged, and then the photon proceeds in a different direction, as shown in Figure 2.3 [JOS77]. The dislodged electron is called a Compton electron. Incoherent scattering involves both energy loss and the deflection of an x-ray photon path. Therefore, Compton scattering acquires a certain amount of kinetic energy that must be subtracted from the energy of the incident photon, in accordance with the law of conservation of energy. The wavelengths, frequency, or energy of scattered and incident x-rays are different. A scattered photon, in turn, performs in the same way as the incident photon interacts with matter.

At an energy range commonly used in explosives detection systems, scattering is dominated by the incoherent component. The incoherent scattering is not considerably affected by changes in the x-ray photon energy. Because the photoelectric effect decreases faster and is relatively small for organic materials, x-ray attenuation in organic materials (low-Z) is mainly governed by Compton scattering.
2.3. Discussion and Summary

If a beam of x-rays of initial intensity $I_0$ passes through a material of thickness $d$, the resulting intensity $I$ is calculated as [MCM92]

$$I = I_0 e^{-\sigma \rho d}$$

(2.2)

where $d$ is commonly given in cm, $\sigma$ is the total cross-section in cm$^2$/atom, and $I$ and $I_0$ are given in keV. ($\sigma$ is often given in barn/atom, where 1 barn = $10^{-24}$ cm$^2$.) For a given elemental substance, the number of atoms per unit volume, $n$, is calculated from

$$n = \frac{N_A \rho}{A}$$

(2.3)

where $N_A$ (6.02252×$10^{23}$ atom/mole) is Avogadro’s number, $A$ is the atomic weight in g/mole, $\rho$ is the density of the substance in g/cm$^3$, and $n$ is in atoms/cm$^3$.

The quantity $\sigma$ in Equation (2.2) is the total cross-section per atom which is the sum of three independent cross-sections

$$\sigma = \sigma_{\text{ne}} + \sigma_{\text{ca}} + \sigma_{\text{nca}}$$

(2.4)
where $\sigma_{pe}$ is the photoelectric cross-section, $\sigma_{cs}$ is the coherent scattering cross-section, and $\sigma_{ncs}$ is the incoherent scattering cross-section.

The total cross-section per atom $\sigma$, when multiplied by the number of atoms per unit volume of matter, is the linear attenuation coefficient $\mu$, which is per centimeter of travel in the matter. The function used to calculate the linear attenuation coefficient $\mu$ is as follows:

$$\mu \text{ [cm}^{-1}] = \sigma \left[ \frac{cm^2}{\text{atom}} \right] \times \rho \left[ \frac{g}{cm^3} \right] \times \frac{N_A}{A} \left[ \frac{\text{atom}}{g} \right] \tag{2.5}$$

The mass attenuation coefficient $\mu^* \text{[cm}^2/g]$ is the ratio of the linear attenuation coefficient and the density of the material, which can be represented by

$$\mu^* \text{ [cm}^2/g] = \frac{\mu \text{ [1/cm]}}{\rho \text{ [g/cm}^3]} \tag{2.6}$$

If the linear attenuation coefficient $\mu$ is used, the attenuation of photons in homogeneous matter can be defined by the exponential law

$$I = I_0 e^{-\mu d} \tag{2.7}$$

If the mass attenuation coefficient $\mu^*$ is used instead of $\mu$, Equation (2.7) is changed as follows:

$$I = I_0 e^{-\mu^* d} \tag{2.8}$$
It is clear from equations (2.2), (2.7) and (2.8) that the cross-section $\sigma$, the linear attenuation coefficient $\mu$, and the mass attenuation coefficient $\mu^*$ are different in conceptual terms.

If the object is a chemical compound or a mixture, its mass attenuation coefficient can be approximately evaluated by the coefficients $\mu_i^*$ of the constituent elements according to their weighted fraction as shown in the following equation:

$$\mu^* = \sum_{i=1}^{m} W_i \mu_i^* \tag{2.9}$$

where $W_i$ is the weight fraction of the $i$th element and $m$ is the total number of elements in the object. Utilizing the relationships among cross-sections, linear attenuations and mass attenuations, the linear attenuation and the cross-section of a chemical compound or a mixture can also be calculated.

The cross-sections for Compton scattering do not vary much as a function of either the photon energy or the atomic number ($Z$) of the scattering materials. The photoelectric cross-section, on the other hand, is strongly dependent on both energy and $Z$. For a given elemental substance, $\sigma_{pe}$ and $\sigma_{ce}$ decrease as the x-ray photon energy ($E$) increases, but $\sigma_{nco}$ is not considerably affected by x-ray photon energy. The total effect of the three cross-sections is that $\sigma$ decreases as the energy of a photon increases. The photoelectric effect dominates for low photon energies. As the energy of the incident photon increases above 70 keV, the Compton effect becomes the predominant type of interaction.
Figure 2.4. Compton and photoelectric cross-sections as a function of photon energy for a typical low-Z material (carbon) and for an example of a high-Z material (iron) [MCM92].

At the energies commonly used in luggage inspection systems, x-rays are either absorbed or scattered by objects in the luggage. Figure 2.4 [MCM92] shows the total x-ray cross-section as a function of photon energy for carbon (a low-Z material) and iron (a high-Z material). For high-Z materials at a low energy range, $\sigma_{pe}$ decreases more rapidly, and is much higher than for low-Z materials. The photoelectric effect is more important for the higher Z materials. Inorganic (low-Z) materials exhibit the photoelectric effect at some low energy range, but as the photon energy increases, the probability of photoelectric interactions will decrease and is lower than the probability of scattering.
Chapter 3

MCNP

3.1 Overview of MCNP

XL relies heavily on MCNP (Monte Carlo N-Particle), a software package developed at Los Alamos National Laboratory and used to simulate neutron, photon and electron transport [LOS93]. For photons, MCNP takes into account the photoelectric effect, incoherent scattering and coherent scattering, etc., which exactly fit our simulation requirements. MCNP also simulates neutron and electron transport, which are not used by XL.

The Monte Carlo method is a numerical method of solving mathematical problems by the simulation of random variables [SOB94]. The method enables simulation by any process whose development is influenced by random factors, and it enables us to artificially construct a probabilistic model for many difficult problems.

For XL, all simulations of x-ray interaction with matter are performed using MCNP. This includes the generation of x-ray source spectra and x-ray detector responses.
3.2 MCNP Input File Format

3.2.1 Overview

The input to MCNP is an ASCII file containing command lines called "cards". The cards provide a description of the situation that is to be simulated. This includes the following:

(1) the geometry specification,
(2) the description of materials,
(3) the location and characteristics of the neutron, photon or electron source,
(4) the type of answers or tallies desired and
(5) any variance reduction techniques used to improve efficiency.

An MCNP input file includes cell cards, surface cards and data cards, as described in the following sections. The details of MCNP input requirements can be found in the MCNP manual [LOS93]. A brief introduction is given in this section. The format of an MCNP input file is shown in Figure 3.1, and an example is given in Appendix B.

The message block is optional and is used to supplement the MCNP execution line information. The problem title card is required and contains information describing the particular problem. Cell and surface cards define the simulation geometry. Data cards consist of mode cards, source specification cards, tally specification cards, materials specification cards, and problem cutoff cards. The details of these cards are described in the next section.
3.2.2 Cell Cards

A cell is a three-dimensional object of a user specified material that is bounded by surfaces. Each object is composed of a single homogeneous material. The format of cell cards is as follows:

\[ j \ m \ d \ geom \]

where \( j \) is a unique cell number, \( m \) is a material number, \( d \) is the density of the material, and \( geom \) is the specification of the geometry of the cell. The density \( d \), if positive, is interpreted as the atomic density in units of \( 10^{24} \) atoms/cm\(^3\). If negative, \( d \) is interpreted as the mass density in units of g/cm\(^3\). \( geom \) includes a list of signed surfaces that bound the
cell. The sign determines which side of the surface contains the cell. The surfaces are of the form \( f(X, Y, Z) = 0 \). A positive sign signifies that the cell contains points satisfying \( f(X, Y, Z) > 0 \), and a negative sign signifies that the cell contains points satisfying \( f(X, Y, Z) < 0 \). The details of how to define the sense of each surface can be found in MCNP manual [LOS93].

### 3.2.3. Surface Cards

Surface cards specify the parameters of surfaces that bound a cell. The format of surface cards is shown below:

\[
\text{j a list}
\]

where \( j \) is a unique surface number, \( a \) is an equation mnemonic from Table 3.1, and \( \text{list} \) is one to ten card entries from Table 3.1. MCNP uses the right-handed coordinate system shown in Figure 3.2.

![Figure 3.2. The right-handed coordinate system used in MCNP.](image)

Planes and spheres are only two kinds of surfaces used in XL. The surface types (plane and sphere), their equations, their mnemonics, and the order of the card entries are given in Table 3-1. Definition of MCNP surface cards for other kinds of surfaces can be found in [LOS93]. To specify a surface, select a surface type (mnemonic) and determine the coefficients (card entries) for the surface equation.
Table 3-1. MCNP surface cards. MCNP supports additional surface types, but only planes and spheres are used in XL.

<table>
<thead>
<tr>
<th>Mnemonic</th>
<th>Type</th>
<th>Description</th>
<th>Equation</th>
<th>Card Entries</th>
</tr>
</thead>
<tbody>
<tr>
<td>px</td>
<td>Plane</td>
<td>Normal to X axis</td>
<td>(X-D=0)</td>
<td>(D)</td>
</tr>
<tr>
<td>py</td>
<td>Plane</td>
<td>Normal to Y axis</td>
<td>(Y-D=0)</td>
<td>(D)</td>
</tr>
<tr>
<td>pz</td>
<td>Plane</td>
<td>Normal to Z axis</td>
<td>(Z-D=0)</td>
<td>(D)</td>
</tr>
<tr>
<td>so</td>
<td>Sphere</td>
<td>Centered at origin</td>
<td>(X^2+Y^2+Z^2-R^2=0)</td>
<td>(R)</td>
</tr>
<tr>
<td>sx</td>
<td>Sphere</td>
<td>Centered on X axis</td>
<td>((X-X_0)^2+Y^2+Z^2-R^2=0)</td>
<td>(X', R)</td>
</tr>
<tr>
<td>sy</td>
<td>Sphere</td>
<td>Centered on Y axis</td>
<td>(X^2+(Y-Y_0)^2+Z^2-R^2=0)</td>
<td>(Y', R)</td>
</tr>
<tr>
<td>sz</td>
<td>Sphere</td>
<td>Centered on Z axis</td>
<td>(X^2+Y^2+(Z-Z_0)^2-R^2=0)</td>
<td>(Z', R)</td>
</tr>
</tbody>
</table>

For example, a box is a cell that is composed of one cell card and six surface cards, each representing one bounding surface. Figure 3.3 shows a cell card and surface cards for a box bounded by planes: \(X=0\), \(X=5\) cm, \(Y=0\), \(Y=5\) cm, \(Z=0\), and \(Z=5\) cm. The cell card states that this is cell 1, it is composed of material type 16, and the material’s density is 2.7g/cm\(^3\). The six numbers that follow specify the surfaces that bound the cell. The sign determines which side of the surface contains the cell.

```
C  cell card
  1 16 -2.7 1 -2 3 -4 5 -6
```

```
C surface cards
  1 px 0
  2 px 5
  3 py 0
  4 py 5
  5 pz 0
  6 pz 5
```

Figure 3.3. The cell and surfaces cards for a box bounded by planes: \(X=0\), \(X=5\) cm, \(Y=0\), \(Y=5\) cm, \(Z=0\), and \(Z=5\) cm.
3.2.4 Data Cards

Data cards are the main parts of the MCNP input file. They specify the whole simulation model, except for geometry information. Data cards can include mode cards, source specification cards, tally specification cards, material specification cards, problem cutoff cards, etc. The problem cutoff card used in XL is MODE P, which means simulating photon transport only. Source specification cards define the source position, the initial x-ray photon direction, and an x-ray source spectrum.

Tally cards are used to specify what you want to learn from the Monte Carlo simulation. It can be the number of particles or the average energy of photons in MeV received over a surface. For example, the card *F1:p 500 specifies that MCNP should compute the average energy of all photons striking surface 500, and the card F1:p 500 specifies that MCNP should compute the number of photons striking surface 500. If surface 500 represents a plane, then MCNP would tally results for the entire plane. This plane could be segmented for separate tallies. In XL, a small detector is modeled by intersecting a plane with a sphere. For example, the cards, *F1:p 500 (representing a plane) and FS1 -506 (representing a sphere), specify that MCNP should compute the average energy of all photons striking surface 500 inside sphere 506 and outside sphere 506, separately. In XL, the average energy of photons is normally computed. An example of this is given in Appendix B.
The material specification gives a material number to be referenced by cell cards, the atomic number, the atomic mass and the weight fraction or the atomic fraction of each constituent (element) in the material. The format of material cards is shown below:

\[ Mm \ ZAID_1 \ fraction_1 \ ZAID_2 \ fraction_2 \ \ldots \ ZAID_n \ fraction_n \]

where \( m \) corresponds to the material number on the cell cards, \( ZAID_i \) \((i=1, \ldots, n)\) is in the format \( ZZZAAA \) where \( ZZZ \) is the atomic number and \( AAA \) is the atomic mass for constituent \( i \), \( fraction_i \) is the weight fraction if entered as a negative number, or the atomic fraction if entered as a positive number of constituent \( i \) in the material, and \( n \) is total number of constituents in the material. For example paper could be represented as

\[ M1 \ 1001 \ -0623 \ 6012 \ -4422 \ 8016 \ -4955 \]

This card signifies that material 1 consists of 6.23% H, 44.22% C, and 49.55% O, represented as weight fractions.

The history cutoff (NPS) card is one type of problem cutoff card used in XL. It terminates the Monte Carlo calculations after \( N \) histories have been computed.

### 3.3 Physics of MCNP

The physics of photon interactions in MCNP are described below. Electron and neutron interactions are not described, because XL is concerned only with photon interactions. The photon portion of MCNP comprises two main treatments [LOS93]: (1) the simple physics treatment and (2) the detailed physics treatment.
3.3.1 Simple Physics Treatment

This treatment is inadequate for high-Z nuclides or deep penetration problems. The physical processes treated are photoelectric effect, pair production, and Compton scattering on free electrons. Because this treatment is intended primarily for higher energy photons, the photoelectric effect is regarded as an absorption, Compton scattering is regarded to be on free electrons, and the highly forward coherent scattering is ignored. Thus the total cross section $\sigma$ is regarded as the sum of three components: photoelectric, pair production, and incoherent scattering.

In the energy range of interest to XL, the coherent scattering cannot be ignored. Therefore, MCNP's simple physics treatment is not suitable for this research.

3.3.2 Detailed Physics Treatment

The detailed physics treatment includes coherent scattering and photoelectric absorption. A photon cross-section library has been prepared by MCNP, incorporating all constants required by this treatment, for elements $Z=1, \ldots, 94$, in a form designed to expedite computation. The total photon cross section $\sigma$ is given by the sum of the photoelectric effect, pair production, and coherent and incoherent scattering components.

For XL, the energies of photons are from 1 keV to hundreds of keV. Within this energy range, x-ray interaction with matter involves three effects: photoelectric effect, incoherent scattering, and coherent scattering. The detailed physics treatment of MCNP is therefore used in XL.
3.4 MCNP Output

The output of MCNP is a long ASCII file. It includes a listing of the input file, a problem summary of particle creation and loss, any tallies, and any of the chosen output tables listed in the MCNP manual [LOS93]. In XL, the simulation results can be found in tallies of the MCNP output file. It will present the average energy of photons over a surface in the MCNP input file. An example of this is given in Appendix B.
Chapter 4

X-Ray Sources

This chapter describes an x-ray source model having a spectrum that can be used within the XL simulator.

4.1 Overview

X-ray radiation is produced whenever a beam of charged particles encounters any target material—solid, liquid, or gaseous [DYS90]. Electrons are generally used as the charged particles and are accelerated by a voltage ranging from a few hundred volts to many megavolts. When accelerated electrons hit a target, the kinetic energy of those electrons is converted to heat and x-rays. The radiation produced by the sudden retardation of a charged particle is known as "bremsstrahlung," which represents the predominant method of x-ray production in an x-ray tube.

The x-ray tube is one type of generator and is used widely in x-ray scanning systems. X-ray tubes mainly consist of a solid metallic target used as an anode, a filament used as a cathode, and two circuits to heat the filament and drive electrons to the anode. An x-ray source is schematically shown in Figure 4.1. Tungsten is commonly used as a target material, because of its good heat conductivity and high melting point [MIC93].
Figure 4.1. X-ray tube geometry. Here $\alpha$ is the target angle, $d$ is the x-ray photon path length through the target, and $x$ is the depth of electron penetration.

An accurate knowledge of the x-ray spectrum is fundamental for x-ray image simulation. The earliest well-known theoretical model of thick target bremsstrahlung spectra was developed by Kramers [KRA23],

$$EN(E)dE = KZ(T - E)dE$$  (4.1)

where $E$ is the energy of x-ray photons produced, $N(E)dE$ is the number of x-ray photons produced with an energy between $E$ and $E + dE$ per incident electron, $K$ is a constant, $Z$ is the target atomic number, and $T$ is the electron's kinetic energy. The model is widely applied, because of its simplicity and general agreement with the experimental results. However, it does not consider the electron energy distribution and ignores the attenuation of photons in the target itself.

More recently, several semiexperimenntal models for generating x-ray spectra have been developed. Soole developed a model to simulate x-ray spectra that took into account energy reduction of electron within the target material [SOO72]. However, he did not show spectra calculated employing his theory. Birch and Marshall extended and
modified the work of Soole and published results which were in good agreement with measured spectra [BIR79]. The Birch and Marshall model is described in this chapter.

The purpose of this work is to develop an x-ray source that gives a spectrum that can be used in the simulator. Also included for comparison are spectra generated using experimental data obtained by Fewell, Shaping and Hawkins [FEW81].

4.2 Emission of Continuous X-Ray Spectrum and Characteristic X-Rays

X-ray source spectra are composed of "continuous" and "characteristic" components. A continuous x-ray spectrum is a distribution of radiation over many wavelengths, and is produced when electrons, or other high energy charged particles, lose energy by Coulomb interactions with the nuclei of the target material. In the case of high energy electrons hitting a target, such a high negative acceleration should produce a pulse of radiation [VAN93].

The continuous x-ray spectrum generated by electrons in an x-ray tube is characterized by a short-wavelength limit \( \lambda_{\text{min}} \) corresponding to the maximum energy of the exciting electrons,

\[
\lambda_{\text{min}} = \frac{hc}{eV_o}
\]  

(4.2)

where \( h \) is Planck's constant, \( c \) is the velocity of light, \( e \) is the electron charge, and \( V_o \) is the potential difference applied to the tube.
X-ray producing electrons may also have enough energy to produce ions by removing inner electrons from the atom, even down to the innermost or K-shell. Such an ion has a low-energy hole in its electronic structure, and this vacancy is promptly filled when one of its electrons in a higher energy state falls to this low-energy level. When an electron falls into a low-energy level, energy is released in the form of x-rays having particular wave-lengths which are characteristic of the target material. Therefore, x-rays generated by this mechanism are called characteristic x-rays. Characteristic x-rays are ignored in our source model.

4.3 Calculation of X-Ray Source Spectra

4.3.1 Basic Model

An electron with initial kinetic energy $T_o$ in keV impinging in a target material with atomic number $Z$, atomic mass $A$ in g/mole and density $\rho$ in g/cm$^3$, will produce $N(E)$ bremsstrahlung photons having energy between $E$ and $E+dE$, as given by [NAK93]

$$N(E)dE = \frac{N_A \rho}{A} \int_{E}^{T} \left[ 1 + \frac{T}{m_o c^2} \right] \frac{dE}{E} \left( \frac{1}{\rho} \frac{dT}{dx} \right)^{-1} dT$$  \hspace{1cm} (4.3)

where $N_A$ is Avogadro's number in atom/mole, $m_o c^2$ is the rest mass energy of the electron, $Q$ is described in [BIR79] as "x-ray energy intensity per unit energy interval per incident electron flux per atom expressed." The mass stopping power $dT/dx$ is given by

$$\left( \frac{1}{\rho} \frac{dT}{dx} \right) = A_{msp} + B_{msp} e^{-7T_{rep}}$$  \hspace{1cm} (4.4)
where $A_{msp}$, $B_{msp}$, and $C_{msp}$ are estimated using least-square techniques [TUC91] and $T$ is the kinetic energy of an electron in keV. Table 4.1 lists the parameters used with equation (4.4) to estimate the mass stopping power of tungsten.

<table>
<thead>
<tr>
<th>A_{msp} (keV m^2 kg^{-1})</th>
<th>B_{msp} (keV m^2 kg^{-1})</th>
<th>C_{msp} (keV^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>202.41</td>
<td>1036.1</td>
<td>0.04695</td>
</tr>
</tbody>
</table>

Table 4-1. Mass stopping power parameters for tungsten [TUC91].

There are several approaches to estimate $Q$. The Birch and Marshall [BIR79] model is one of them that fits well with the experimental spectra of [FEW81]. Because developing a model for $Q$ alone proved to be difficult, they developed a relation for $QT/Z^2$ as a function of $E/T$ that gives a good fit to experimental data. The model is as follows, and is plotted in Figure 4.2:

$$\frac{QT}{Z^2} = 0.503 - 0.94597u + 0.1553u^2 + 1.1632u^3 - 0.6818u^4,$$

where $u = \frac{E}{T}$.  

![Figure 4.2](image)

Figure 4.2. $QT/Z^2$ as a function of $E/T$, where $E$ in keV is the photon energy and $T$ in keV is the electron energy.
4.3.2 Refined Model

This is a refinement of the basic model given in Section 4.3.1. As an electron passes through the target, its energy is reduced at various depths into the target as x-rays are produced. The Thomson-Whiddington relation [TUC91] expresses the relationship between the average kinetic energy \( T \) and the distance \( x \) that electrons penetrate into the target as

\[
T_0^2 - T^2 = \rho x C
\]

(4.6)

where \( C \) is a Thomson-Whiddington constant given below, \( \rho \) is the density of the target material, \( T_0 \) is the initial kinetic energy of the incident electrons, and \( x \) is the depth that the electron penetrates the material. Thomson-Whiddington constants, tabulated by [BIR79] at several discrete energies, are employed in this work and are listed in Table 4.2.

Table 4-2. Thomson-Whiddington constants for different incident electron energies [BIR79].

<table>
<thead>
<tr>
<th>Electron Energy (( T )) (keV)</th>
<th>T-W constant (( C )) (keV²m²/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.54×10⁵</td>
</tr>
<tr>
<td>75</td>
<td>0.625×10⁵</td>
</tr>
<tr>
<td>100</td>
<td>0.7×10⁵</td>
</tr>
<tr>
<td>150</td>
<td>0.84×10⁵</td>
</tr>
<tr>
<td>200</td>
<td>1.0×10⁵</td>
</tr>
</tbody>
</table>

The x-ray photon path length through the target, \( d \), is a function of \( x \) and \( \alpha \), as illustrated in Figure 4.1. The distance \( d \) can be expressed as
\[ d = \frac{x}{\sin \alpha} \]  

(4.7)

Utilizing Equation (4.7), this expression becomes

\[ d = \frac{T_o^2 - T^2}{\rho C \sin \alpha} \]  

(4.8)

and the energy of a photon is therefore attenuated along this ray path (using Equation (2.7)) by a factor \( \exp(-\mu(E)d) \), where \( \mu(E) \) is the linear attenuation coefficient of a target for an x-ray photon of energy \( E \). For programming simplicity and interpolation accuracy, the tabulated mass attenuation coefficients of interest were individually fitted by Bevington [BEV69] utilizing least-square techniques:

\[ \frac{\mu(u)}{\rho \text{ [kg/m}^3\text{]}} = a_1 + a_2 u^{-1.6} + a_3 u^{-2.7} + a_4 u^{-3.5} + a_5 u^{-4.5} \]  

(4.9)

where \( u = E/(100 \text{ keV}) \). Listed in Table 4.3 are the parameters that are employed in conjunction with the above equation to compute the mass attenuation coefficients.

Table 4-3. Parametrization of the mass attenuation coefficients of tungsten from 20 keV to 200 keV, \( u = E/(100 \text{ keV}) \) [TUC91].

<table>
<thead>
<tr>
<th>Energy</th>
<th>( \frac{\mu(u)}{\rho} )</th>
<th>( a_1 ) (m(^2)/kg)</th>
<th>( a_2 ) (m(^2)/kg)</th>
<th>( a_3 ) (m(^2)/kg)</th>
<th>( a_4 ) (m(^2)/kg)</th>
<th>( a_5 ) (m(^2)/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E \leq 69.5 \text{ keV} )</td>
<td>( 2.394 \times 10^2 )</td>
<td>-1.461 \times 10^2</td>
<td>1.023 \times 10^1</td>
<td>-4.795 \times 10^3</td>
<td>1.318 \times 10^1</td>
<td></td>
</tr>
<tr>
<td>( E \geq 69.5 \text{ keV} )</td>
<td>4.31 \times 10^2</td>
<td>-3.636 \times 10^3</td>
<td>1.486 \times 10^6</td>
<td>-9.404 \times 10^1</td>
<td>2.184 \times 10^2</td>
<td></td>
</tr>
</tbody>
</table>

Taking into account target attenuation into Equation (4.3) gives

\[ N(E)dE = \frac{N_o \rho}{A} \int_E^{T_o} \left( \frac{T}{m_o c^2} \right) Q \frac{dE}{E} \left( \frac{1}{\rho} \frac{dT}{dx} \right)^{-1} \left\{ \exp \left( -\mu(E)(T_o^2 - T^2) / \rho C \sin \alpha \right) \right\} dT . \]  

(4.10)
Inserting Equations (4.4), (4.5) and (4.9) appropriately into Equation (4.10), one obtains

\[
N(E)dE = \frac{N_A D}{A} \int_0^T \left( 1 + \frac{T}{m_0 c^2} \right) \times \frac{Z^2}{T} \left( 0.503 - 0.94597 \left( \frac{E}{T} \right) + 0.1553 \left( \frac{E}{T} \right)^2 + 1.1632 \left( \frac{E}{T} \right)^3 - 0.6818 \left( \frac{E}{T} \right)^4 \right) \frac{dE}{E} \times \left( \frac{1}{A_{\text{wsp}} + B_{\text{wsp}} e^{-TC_{\text{wsp}}}} \right) \times \exp \left[ -\left( a_1 + a_2 \left( \frac{E}{100} \right)^{-1.6} + a_3 \left( \frac{E}{100} \right)^{-2.7} + a_4 \left( \frac{E}{100} \right)^{-3.5} + a_5 \left( \frac{E}{100} \right)^{-4.5} \left( \frac{T^2}{\rho C_\text{s} \sin \alpha} \right) \right] \right] dT.
\]

(4.11)

XL uses Equation (4.11) to estimate the number of photons at different energy levels. The step size \( dE \) and \( dT \) were chosen as 5 keV and 1 keV, respectively. \( C \) is linearly interpolated for different energy values.

### 4.4 X-Ray Source Simulation

Generally in x-ray tubes, an inherent filter is used to reduce the low energy x-ray photons that contribute very little to the x-ray penetration and scattering. Common filters include glass, oil, and aluminum. In order to simplify the simulation, the thickness of an equivalent aluminum filter is commonly used as the inherent filter, with a thickness depending on the type of x-ray tube.

XL simulates x-ray photons attenuated by the filter using MCNP. XL computes a composite source spectrum, which generates photons that have the energy distribution
calculated by Equation (4.11), a perfect detector, and a piece of aluminum that is between the source and the detector. The resulting x-ray spectrum of those photons that pass through the filter is used in subsequent luggage-scanning simulations. The flow chart of x-ray source simulation is shown in Figure 4.3.

Figure 4.3. Flow chart for x-ray source simulation.

As indicated in the figure, the incident electron energy and target angle are defined by users, and then the number of photons versus photon energy is calculated using Equation (4.11). An MCNP input file is developed using thickness of the aluminum filter and the result from Equation (4.11). After MCNP simulation, the number of photons versus photon energy after the aluminum filter can be found in MCNP output. Finally, the
x-ray source spectrum can be generated using the simulation result. The final source spectrum is later inserted into MCNP input files to simulate luggage scanning.

4.5 Results and Discussion

Figures 4.4, 4.5, and 4.6 show the comparison between spectra of XL and the spectra measured by [FEW81], for (a) a G.E. Maxray tube with a 10° target angle and a 2.8 mm Al filter, (b) a Petake x-ray tube with a 20° target angle and a 1.5 mm Al filter, and (c) an Eimac x-ray tube with a 12.5° target angle and a 1.2 mm Al filter for incident electron energies of 70 keV, 100 keV and 140 keV, respectively. Each spectrum was normalized by dividing by its maximum continuous-spectrum value. The energy intervals for the simulation data and the experimental data are 5 keV and 2 keV, respectively. As can be seen from these figures, the agreement between the simulated x-ray spectra and the experimental spectra is very good.

The largest difference between them is that the simulated x-ray spectra did not include the characteristic x-rays. Except for the characteristic x-rays, there is only a slight difference between spectra from simulations and spectra from experimental data. Two reasons may be responsible for these differences. First, the use of an aluminum equivalent instead of using the various components of the inherent filtration may have an impact on accuracy. The filtration in fact consists of glass, oil, aluminum, etc. Second, employing the Thomson-Whiddington relation (Equation 4.6) is an obvious simplification and does not take into account the electron energy distribution in a target material.
Some simulations have been done using MCNP to compare the source model developed in Section 4.4 with the source spectrum published by [FEW81]. Given a source spectrum to MCNP as a set of points, MCNP uses linear interpolation [LOS93]. This has been done for several objects having several thicknesses for several incident electron energies for the G.E. Maxray tube. The comparisons between them are shown in Tables 4-4, 4-5, and 4-6. In these tables, \( T_o \), the incident electron energy, is used in Equation (4.12) to determine the source spectrum. The second column \( (O_2) \) is the simulation output, given by MCNP as the average photon energy, for transmission from simulated x-ray source spectra without characteristic x-rays; the third column \( (O_3) \) is the simulation output, but from the experimental x-ray source spectrum with characteristic x-rays by [FEW81]; and the fourth column is relative error calculated as follows:

\[
\text{relative error} = \left| \frac{O_3 - O_s}{O_s} \right| \quad (4.12)
\]

The relative error is quite small. In these tables, it can be found that error usually decreases as the thickness of an object decreases or as the incident electron energy increases. Aluminum has the largest error, just under 10%, because of its large thickness, its high density, and its large cross section. Therefore, only very few photons can transmit through the object.
Figure 4.4. Comparison of bremsstrahlung spectra simulated by XL with the spectra measured by [FEW81], for an incident electron energy of 70 keV: (a) for a GE Maxray tube, (b) for a Pentak x-ray tube, and (c) for an Eimac x-ray tube.
Figure 4.5. Comparison of bremsstrahlung spectra simulated by XL with the spectra measured by [FEW81], for an incident electron energy of 100 keV: (a) for a GE Maxray tube, (b) for a Pentak x-ray tube, and (c) for an Eimac x-ray tube.
Figure 4.6. Comparison of bremsstrahlung spectra simulated by XL with the spectra measured by FSH [FEW81], for an incident electron energy of 140 keV: (a) for a GE Maxray tube, (b) for a Pentak x-ray tube, and (c) for an Eimac x-ray tube.
Table 4-4. Simulation results for TNT at several thicknesses and several energy levels.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Simulation(MeV)</th>
<th>Experiment(MeV)</th>
<th>Relative Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cm</td>
<td>2.496e-2</td>
<td>2.425e-2</td>
<td>0.0293</td>
</tr>
<tr>
<td>5 cm</td>
<td>5.469e-3</td>
<td>5.236e-3</td>
<td>0.0445</td>
</tr>
<tr>
<td>7 cm</td>
<td>2.649e-3</td>
<td>2.533e-3</td>
<td>0.0458</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Simulation(MeV)</th>
<th>Experiment(MeV)</th>
<th>Relative Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cm</td>
<td>3.325e-2</td>
<td>3.233e-2</td>
<td>0.0288</td>
</tr>
<tr>
<td>5 cm</td>
<td>8.803e-3</td>
<td>8.413e-3</td>
<td>0.0464</td>
</tr>
<tr>
<td>7 cm</td>
<td>4.599e-3</td>
<td>4.416e-3</td>
<td>0.0414</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Simulation(MeV)</th>
<th>Experiment(MeV)</th>
<th>Relative Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cm</td>
<td>4.134e-2</td>
<td>4.053e-2</td>
<td>0.0200</td>
</tr>
<tr>
<td>5 cm</td>
<td>1.223e-2</td>
<td>1.195e-2</td>
<td>0.0234</td>
</tr>
<tr>
<td>7 cm</td>
<td>6.749e-3</td>
<td>6.565e-3</td>
<td>0.0280</td>
</tr>
</tbody>
</table>

Table 4-5. Simulation results for aluminum at several thicknesses and several energy levels.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Simulation(MeV)</th>
<th>Experiment(MeV)</th>
<th>Relative Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cm</td>
<td>9.065e-3</td>
<td>8.634e-2</td>
<td>0.0499</td>
</tr>
<tr>
<td>5 cm</td>
<td>2.269e-4</td>
<td>2.191e-4</td>
<td>0.0356</td>
</tr>
<tr>
<td>7 cm</td>
<td>4.197e-5</td>
<td>4.096e-5</td>
<td>0.0247</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Simulation(MeV)</th>
<th>Experiment(MeV)</th>
<th>Relative Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cm</td>
<td>1.717e-2</td>
<td>1.650e-2</td>
<td>0.0406</td>
</tr>
<tr>
<td>5 cm</td>
<td>1.018e-3</td>
<td>9.355e-4</td>
<td>0.0882</td>
</tr>
<tr>
<td>7 cm</td>
<td>3.174e-4</td>
<td>2.895e-4</td>
<td>0.0963</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Simulation(MeV)</th>
<th>Experiment(MeV)</th>
<th>Relative Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cm</td>
<td>2.536e-2</td>
<td>2.474e-2</td>
<td>0.0251</td>
</tr>
<tr>
<td>5 cm</td>
<td>2.366e-3</td>
<td>2.250e-3</td>
<td>0.0516</td>
</tr>
<tr>
<td>7 cm</td>
<td>8.299e-4</td>
<td>7.746e-4</td>
<td>0.0714</td>
</tr>
</tbody>
</table>
Table 4-6. Simulation results for carbon at several thicknesses and several energy levels.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Simulation(MeV)</th>
<th>Experiment(MeV)</th>
<th>Relative Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cm</td>
<td>2.681e-2</td>
<td>2.612e-2</td>
<td>0.0264</td>
</tr>
<tr>
<td>5 cm</td>
<td>7.187e-3</td>
<td>6.920e-3</td>
<td>0.0386</td>
</tr>
<tr>
<td>7 cm</td>
<td>3.748e-3</td>
<td>3.592e-3</td>
<td>0.0434</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Simulation(MeV)</th>
<th>Experiment(MeV)</th>
<th>Relative Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cm</td>
<td>3.485e-2</td>
<td>3.396e-2</td>
<td>0.0262</td>
</tr>
<tr>
<td>5 cm</td>
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Chapter 5

X-Ray Detectors

5.1 Overview

Instruments used for the detection of uncharged radiation (γ-rays, x-rays, and neutrons) are based on producing secondary ionizing particles during their passage through matter [BIR60]. The various types of detection instruments differ in material within which the ionization is produced, and in the manner by which it is observed. For x-ray detectors, it is usual to distinguish between wavelength-dispersive detectors, which depend upon the diffraction of x-rays, and energy-dispersive detectors, in which electrical signals are proportional in magnitude to the incident photon energy. There are many types of x-ray detectors, such as phosphors, channel electron multipliers, silicon detectors, and scintillation detectors. This chapter will focus on scintillation detectors, which are energy-dispersive and are commonly used in x-ray scanning systems.

5.2 Scintillation Detectors

5.2.1 Structure of Scintillation Detectors

The operation of a scintillation detector depends on the luminescence of a crystal when excited by ionizing radiation. Photons are produced in the visible region and then are allowed to impinge on a photodiode. The photodiode converts the energy of visible photons to an electrical current, which is then sensed electronically.
Scintillators are usually classified as organic or inorganic. Inorganic scintillators are preferred for x-ray studies because of their high level of photoelectric absorption.

The structure of a scintillation detector is shown in Figure 5.1 [TAK90]. X-rays enter a scintillator material, and produce visible photons by luminescence. These visible photons pass through a film and are detected by a photodiode. The mirror-polish scintillator is normally surrounded by an optical light reflector to ensure maximum channeling of light to the photodiode. One face of the scintillator is covered with a transparent film that is in contact with the photodiode, in order to smooth remaining craters on the polished surface to ensure maximum transmission of light.

![Diagram of scintillation detector](image)

*Figure 5.1. Schematic illustration of the structure of an x-ray detector. An x-ray photon is converted to visible photons which are detected by a photodiode after several reflections on surfaces of the scintillator.*

5.2.2 **Processes Involved in X-Ray Detection and Measurement**

An x-ray photon impinges on the scintillator where it dissipates its energy in the ionization and excitation of the molecules. A fraction of this energy is converted into light photons that are radiated in all directions. These light photons have a main emission
wavelength region. Finally, the emitted light photons fall on the photodiode through the transparent film directly or after reflection from the surfaces of the scintillator in contact with the light reflectors.

The operation of the scintillation detector can be divided into four distinct, consecutive stages:

1. The absorption of the incident radiation by the scintillator.
2. The luminescent conversion of the energy dissipated in the scintillator, and the emission of light photons.
3. The collection of the emitted light photons to the photodiode.
4. The absorption of light photons at the photodiode.

The electrical output of the photodiode can be measured or even amplified to indicate the intensity of the incident x-ray photons.

5.3 Estimation of Output Signal

The total light energy fluence on the surface of photodiode as described by [TAK90] is

\[ W\left(E_p\right) = e \int A(E)X(E)p(E, E_p)f(E_p)kEdE \]  \hfill (5.1)

where \( W(E_p) \) is in units of [W], \( E_p \) [eV/photon] is the light-photon energy, \( e \) [coulomb] is electron charge, \( E \) [eV/x-ray photon] is the x-ray photon energy, \( A(E) \) is the x-ray photon absorbance of the scintillator, \( X(E) \) [x-ray photons/s] is the x-ray photon energy flow on the surface of the scintillator, \( p(E, E_p) \) is the light collection efficiency of the photodiode,
$f(E_p)$ is the normalized emission spectrum of the scintillator, and $k$ is the energy conversion efficiency of the scintillator. The photo current $I_s$ in mA is given by

$$I_s = \int W(E_p)q(E_p)dE_p$$

(5.2)

where $q(E_p)$ [mA/W] is the light to current conversion factor of the photodiode. The complete expression for the output signal is

$$I_s = e \int \int A(E)X(E)p(E, E_p)f(E_p)kEq(E_p)dEdE_p$$

(5.3)

$A(E)$ can be approximated by the attenuation coefficient of the scintillator material, and can be estimated by simulation. $X(E)$ can be also estimated by simulation.

The quantity $p(E, E_p)$ can be estimated by Monte Carlo simulation but is quite complicated. Values of $p$ depend on the refractive index and the transparent photon absorption length of the scintillator, and on the reflectance of the reflector and photodiode [FAN64]. If the geometry and the parameters of the detector are fixed, then $p$ should be can be approximated by using the mean value of $p(E, E_p)$.

The value $k$ is a constant if the components of the scintillator do not change.

The only remaining terms to consider are $f$ and $q$, which are functions of $E_p$ only. Using a bar to represent average value, Equation (5.3) can be rewritten as

$$I_s = e \bar{p} \bar{k} \int A(E)X(E)EdE \cdot \int f(E_p)q(E_p)dE_p$$

(5.4)

Because the scintillator material and photodiode are assumed to be fixed in XL, the term at the right may also be assumed to be constant. Furthermore, because relative photodiode
current is sufficient for XL simulations, XL computes only $\int A(E)X(E)EdE$, and all other terms are ignored.

5.4 X-Ray Detector Simulation Development and Results

A model has been constructed for the pseudo-dual-energy system, model MEX-6585, manufactured by TRICO Industry Inc. which is in our laboratory. In this system, there are two detectors: one is for detecting low energy x-ray photons, and the other is for detecting high energy x-ray photons. A thin sheet of copper is set between the two detectors in order to separate energy spectra of the two detectors. The whole detector element is like a sandwich of two detectors as shown in Figure 5.2. Detector 1, which first receives the radiation, tends to absorb the low-energy x-rays, while the detector 2, behind the first detector, tends to absorb the high-energy x-rays that penetrate the first detector and the copper between the two detectors. The highest light output per incident x-ray photon is given by inorganic crystals. Cesium iodide is used as the scintillator in the system, since it has good stopping powers and can be shaped for efficient optical coupling [CHE95]. The added impurity, thallium, helps cause cesium iodide crystals to emit photons in the visible range.

Figure 5.2. Side view of pseudo-dual-energy x-ray detector.
This detector model has been simulated using MCNP and using the method illustrated in Figure 5.3. Using a single energy source and a perfect detector, the CsI or copper are considered as an object and put between the source and the perfect detector individually.

![Diagram of monoenergetic x-ray source and perfect detector with 0.3mm or 4mm CsI, or 0.5mm Cu](image)

Figure 5.3. The model used to simulate the detector response of individual detectors or copper.

The absorbance of a material, $A(E)$, is defined as the percentage of the number of photons absorbed by CsI or Cu when each is used individually. The absorbance depends on the photon energy, because the attenuation coefficient of materials is a function of energy. By interpreting outputs of MCNP, the absorbance of materials can be estimated using the method shown in Figure 5.3. For example, suppose that 100,000 photons of energy 100 keV are generated by a single energy source, and MCNP predicts that only 40,000 photons are detected by the perfect detector after 0.3 mm CsI absorption. Then clearly about 60,000 photons are absorbed by the low energy detector and the absorbency coefficient of the low energy detector for photons of 100 keV should be estimated as 0.6. This process is repeated for Cu and for 4 mm CsI. Most low energy photons are absorbed by the first detector, and high energy photons will pass through the first detector. Some photons are absorbed by the copper. Even higher energy photons have a chance to
transmit through the copper and absorbed by the second detector. Only very few photons transmit through the second detector.

The response efficiency of the low energy detector is defined to be the percentage of photons absorbed by the detector. The response efficiency of the low energy detector \( R_L(E) \) is therefore equal to its absorbance \( A_L(E) \). The response efficiency of the copper sheet is defined as the percentage of photons absorbed by it after some photons have been absorbed by the first detector. The response efficiency of the high energy detector is the percentage of photons absorbed after some of them have already been absorbed by the scintillator of the low energy detector and by the copper. According to the definition, the response efficiency of the high energy detector \( R_H(E) \) is follows:

\[
R_H(E) = (1 - A_L(E))(1 - A_C(E))A_H(E)
\]

(5.5)

where \( A_C(E) \) and \( A_H(E) \) are the absorbance of copper and the high energy detector, respectively. Figures 5.4 and 5.5 show the sensitivities and spectral responses of the first and second detectors simulated by MCNP, respectively. The energy step size is chosen as 5 keV.

![Diagram](image.png)

**Figure 5.4.** The absorbance of the low energy detector \( A_L(E) \) and the high energy detector \( A_H(E) \).
Figure 5.5. The spectral response efficiencies of the detector components: low energy detector $R_L(E)$, high energy detector $R_H(E)$, and copper $R_C(E)$.

Figure 5.6. The mass attenuation coefficients of iodine and cesium.

It can be seen in Figures 5.4 and 5.5 that there is a wedge between 20 keV and 40 keV for the absorbance and for the response efficiency of the low energy detector. It is
probably because the mass attenuation coefficient of CsI has a sudden change between 20 keV and 40 keV. According to Equation (2.9), the mass attenuation coefficient of CsI can be calculated from the cross sections of Cs and I, which have a abrupt rises between 20 keV and 40 keV as shown in Figure 5.6. The mass attenuation coefficient of CsI and experimental data on actual detectors were not available.

Simulations were done by using the source model, which is described in Chapter 4, a perfect detector, and the whole detector package used as simulated objects located between the source and the perfect detector. The outputs of MCNP were the number of photons transmitted through the first detector, the copper, or the second detector, respectively, at different energy levels. Therefore, the energy was absorbed by the first detector, the copper, and the second detector can be determined. The upper curve of Figure 5.7 (a) shows the original spectrum that is the x-ray spectrum before the first detector; the solid curve represents the spectrum absorbed or detected by the first detector; and the lowest curve represents the spectrum after the first detector. The upper curve of Figure 5.7 (b) represents the spectrum before the copper; the solid curve represents the spectrum absorbed or detected by the copper; and the lowest curve represents the spectrum after the copper. The upper curve of Figure 5.7 (c) represents the spectrum before the second detector; the solid curve represents the spectrum absorbed or detected by the second detector; and the lowest curve represents the spectrum after the second detector.
Clearly, the total intensity of the low energy signal is much higher than the total intensity of the high energy signal. This phenomenon is in a good agreement with the experimental data from the physical system, as expected. This explains why in the lab system the high energy signal is amplified much more than the low energy signal.

Notice also that there is some overlap between these two detector responses. The purpose of adding copper between the two detectors is to decrease the amount of overlap, thereby separating the two detector response ranges. Increasing the thickness of copper can decrease the overlap. However, as the copper becomes thicker, more photons will be absorbed by the copper, and the intensity of the high energy signal will be decreased accordingly. This will affect the resolution of the high energy x-ray image and increase the relative noise level. Therefore, the proper thickness of copper is important. A simulator such as MCNP can be of considerable assistance in selecting the appropriate thickness for new x-ray scanning systems.

During simulation of luggage scanning, the high energy image and low energy images of a pseudo-dual-energy system are generated by XL multiplying the MCNP outputs for a perfect detector with the spectrum of the two detectors, respectively. Given a detector spectrum of response efficiency to MCNP as a set of points, MCNP uses linear interpolation [LOS93].
Figure 5.7. Spectra before, after, and absorbed by the detector components. (a) Low energy detector (0.3 mm CsI). (b) Filter (0.5 mm Copper). (c) High energy detector (4 mm CsI).
Chapter 6

The XL Simulation Package

6.1 Overview

Now that x-ray source and detector models have been refined, the complete simulation package can be developed. The primary goal of the XL simulator is to provide the capability to specify the parameters for the simulation and to synthesize realistic x-ray images with high accuracy. Objects to be simulated can be specified using AutoCAD. XL interprets the resulting drawing in Data Exchange Format (DXF), and performs the following major steps: 1) creates an MCNP input file; 2) simulates x-ray scanning and x-ray interaction with matter using MCNP; and 3) generates simulated x-ray images. The outline of the simulation package is shown in Figure 6.1.

![Diagram]

Figure 6.1. Major processing steps in the XL simulator.
6.2 Simulation Geometry

In a physical system, luggage passes through a tunnel as illustrated in Figure 6.2. For transmission detectors, an x-ray point source is on one side of the tunnel, and an array of detectors is on the other side. Typically, a fan-shaped plane of x-rays travels from the source to the detector array. Many luggage scanners utilize detectors that are arranged in an "L" shape as shown in the figure. The point source is at the origin of the right-handed Cartesian coordinate system, as shown in the figure, and the detectors lie in the Y-Z plane. A 2D image is generated when the luggage bag passes through the tunnel in the X or -X direction as the scanner acquires image data column by column. Each pixel value of the resulting image depends on the detected intensity of x-rays.

Figure 6.2. The geometry of an x-ray luggage scan system. As luggage passes through the tunnel, a 2D image is formed. The source is at the origin of a right-handed Cartesian coordinate system.
For simulation using XL, objects are first generated in AutoCAD at an arbitrary location. XL places the objects inside the tunnel before simulating the scanning process. The two vertical surfaces of the tunnel are assumed to lie at \( Y = -75 \text{ cm} \) and \( Y = -140 \text{ cm} \), and the two horizontal surfaces of the tunnel are assumed to lie at \( Z = 0 \) and \( Z = 85 \text{ cm} \), respectively. To implement scanning, XL moves the detector and the x-ray source instead of the luggage because this is simpler to implement. Only one detector is considered during an MCNP simulation, and several MCNP simulations must be performed to construct one x-ray image. The luggage bag is not be simulated by XL, because it will much complicate the simulator if intersecting objects are considered. More explanation of the simulation process are given in the following sections.

6.3 Simulation Assumptions

There are three fundamental assumptions that have been made for reasons of computational efficiency.

First, the shape of each object must be rectangular, and the surfaces of each object must be orthogonal to the \( X \), \( Y \), or \( Z \) axis of the scanner. There are three reasons for making this simplification. First, it simplifies the C program that is used to convert the Data Exchange Format (DXF) file from AutoCAD to the input format needed by MCNP. Second, this condition reduces MCNP running time considerably. Third, the total number of MCNP runs can be reduced when generating an output image.
The second assumption is that a maximum of seven objects can be scanned, and no object can be inside another. This assumption has been made to simplify the C conversion program \texttt{dxf2mcnp}. In order to perform any simulation, MCNP requires that objects be within "containers," and only seven objects are permitted in one container. If more than seven objects must be specified, the container would need to be divided into several sub-containers, each containing at most seven objects. MCNP also requires that objects be non-intersecting and each object must be made of homogeneous material.

Third, characteristic x-rays are ignored in the x-ray source model. The reason is that the simulation of the characteristic x-rays is quite complicated, and the proportion of characteristic x-rays to the continuous x-rays is small.

6.4 MCNP Input File Development

6.4.1 Overview

As described in Chapter 3, a MCNP interface is quite complicated. Because of this, the \texttt{dxf2mcnp} program was developed to convert a drawing represented in a DXF file to the input format needed by MCNP. This is used by XL to produce x-ray images. This section will concentrate on converting information from DXF form to the format needed by MCNP.

The AutoCAD drawing describes rectangular objects that represent luggage contents. Development of the input file requires four steps:
(1) Objects are generated in AutoCAD by the user. A description of the objects is exported as a DXF file by AutoCAD.

(2) The program `dxfs2mcnp` is used to convert the DXF file to a file that will be used as input to MCNP. This can be invoked by XL.

(3) The source spectrum is generated by the source simulation package according to the initial electron energy, the target angle, and the inherent filter, all of which are specified to XL by the user.

(4) The results of the source simulation are added to the MCNP input file.

6.4.2 Generating Objects in AutoCAD

AutoCAD is a powerful CAD and drafting software package. Four reasons were considered in choosing AutoCAD as a tool to generate luggage for the simulator:

(1) 2D or 3D objects are quick and easy to create in AutoCAD.

(2) Any AutoCAD drawing can be exported to a DXF file, which contains all the information needed to reconstruct a drawing.

(3) AutoCAD has the "layer" feature, which can be used to identify attributes for each object.

(4) Objects can be redrawn from different viewpoints, and the object can be rotated easily. The material types and layer names that are currently supported by XL are give in `layer` listed in Appendix C.
The details of how to generate a drawing in AutoCAD can be found in the menu of AutoCAD. Additional rules that users must follow when developing AutoCAD drawings for the XL simulator are as follows:

1. The surface of each object should be parallel to $X$, $Y$, or $Z$ axis.
2. All objects should be 3D entities.
3. The $Y$-$Z$ cross-section of the objects should be no larger than the size of the tunnel. Currently, the default cross-section of the tunnel is $65 \times 85$ cm$^2$.
4. A separate AutoCAD layer should be defined for each material type that is to be simulated. Objects should be placed on the appropriate layers.
5. A maximum of seven objects should be defined, and no objects should intersect.

Figure 6.3 is a AutoCAD drawing that contains three objects which will be scanned by XL to illustrate several scan methods. The left one is aluminum, the middle small cube is TNT, and the right one is paper. Figure 6.4 shows the same objects from a different viewpoint. Figure 6.5 shows the same objects after a clockwise rotation of 90° about an axis that is parallel to the $X$-axis. Figure 6.6 shows the flipped objects from the viewpoint as in Figure 6.3. The AutoCAD layer names are 'ALUMINUM', 'TNT', and 'PAPER' for the three objects, respectively.
Figure 6.3. An AutoCAD drawing with three objects: aluminum, TNT, and paper (from left to right).

Figure 6.4. The same three objects as in Figure 6.3 from a different viewpoint. The $X$ and $Z$ axes are shown in the figure, and the $Y$-axis is normal to the paper.
Figure 6.5. The same three objects as those in Figure 6.3 rotated $90^\circ$ clockwise about an axis parallel to the $X$-axis.

Figure 6.6. The same three objects as those in Figure 6.5 seen from the same viewpoint as that of Figure 6.4.
6.4.3 Generating the MCNP Input File from a AutoCAD Description

dxf2mcnp converts an AutoCAD drawing from the Data Exchange Format (DXF) to an MCNP input file. It is a modification of dxfint [ZAL95].

Objects developed in AutoCAD can be exported into a DXF file, which can be read by dxf2mcnp. A DXF file is a comprehensive ASCII description of the drawing. A DXF file is quite long, generally over 2000 lines, among which only a few are useful for the purposes of the conversion of the software.

dxfint can convert object geometry information to the cell, surface and material cards of MCNP input file. For use with XL, two modifications were made to dxfint. First, the location of the created objects can be arbitrary if they satisfy all the rules described in this section; the program dxf2mcnp moves objects to a position inside the tunnel as follows:

$$(X_{new}, Y_{new}, Z_{new}) = (X, Y, Z) - (0, 75 + Y_{max}, Z_{min})$$

(6.1)

where $(X, Y, Z)$ represents the original object coordinates, $(X_{new}, Y_{new}, Z_{new})$ is the new object coordinates, $Y_{max}$ is largest $Y$ value of the object, and $Z_{min}$ is smallest $Z$ value of the object. All units are in centimeters. Second, the data cards of the MCNP input file are rewritten to add a source spectrum and a detector response spectrum, and to make the cell, surface, and data cards compatible.

A block diagram of the main functions of the dxf2mcnp software is shown in Figure 6.7.
Figure 6.7. Flow chart of main functions in dxf2mcnp.

The *main* function opens the appropriate files to read and write, reads and stores the DXF file information in a linked list, records information from users, and then calls the appropriate sub-functions.

The first sub-function is called *rec_ent*. It reads a DXF file, picks useful information such as entity, determines the shape of each object, and stores the information in a linked list. The detailed steps and sub-functions of this function could be found in the DXFINIT Programmer’s Guide [ZAL95]. No modifications were made in this part.

The *source* function simulates the spectrum of an x-ray source. The initial voltage of the x-ray source, the thickness of the inherent filter and the target angle are specified by the user. The *source* function is called at the beginning of the simulation. The x-ray source simulation result is saved in a file called *sim_source* that will be used in the *data_card* function. The *source* function will be recalled only if the parameters of the x-ray source are changed by the user. Therefore, the source spectrum will be simulated again only if the parameters of the x-ray source are changed.
Make_mcnp is the main function for creating an MCNP input file. Surface_cell is a sub-function of make_mcnp that produces the surface cards and cell cards at the same time by calling the functions print_planes and add2cell. In surface_cell, scan system geometry has been added, such as x-ray source and x-ray detector geometry.

When both the surface cards and the cell cards have been created, the data_card function is called to add the data card information after the surface cards. The data_card function for dxf2mcnp has been almost completely rewritten. The energy of source particles has a probability distribution. The data cards include the SI and SP cards when the energy variable is given by a probability distribution. SI gives bin boundaries for a histogram distribution and SP defines bin probabilities for distribution on the SI card that is the simulation result of a source function.

Tally cards are also defined in the function data_card according to the simulation requirements. These specify that MCNP should compute the energy of photons or the number of photons received by a surface.

The number of photons the x-ray source will generate, NPS, is also defined in the function data_card. NPS is specified by users. The typical values of NPS are 10,000, 100,000, and higher.

Material cards are defined in layer. Layer is similar to a data base that contains the information about materials’ names, densities, the atomic numbers, the atomic masses, and the weight fraction of the constituents in the material. The layer name in the AutoCAD
drawing should be identical to the material’s name in layer. The layer function can be found in Appendix C.

*Combine files* is used to put the cell cards, the surface cards and the data cards together.

Figure 6.7 compares the AutoCAD drawing of Figure 6.3 with a portion of the corresponding output of *dx2mncp*.

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</table>

Figure 6.8. An example of portion of a DXF file (left) and the corresponding output from *dx2mncp* (right). These describe objects in Figure 6.3. The complete MCNP input file can be found in Appendix B.
6.5 Simulation Processes

6.5.1 Overview

After the MCNP input file has been created, the simulation can begin.

In a physical system, x-rays are transmitted radially from a source to a set of detectors. To perform one MCNP simulation for each image pixel would be computationally prohibitive for implementation, because of the large number of pixels. We refer to this ideal simulation case as "point scanning".

To reduce computation time to a reasonable level, XL provides two approaches to generate x-ray transmission images: "parallel scan" and "radial scan". Parallel scan is the case that all x-ray paths are parallel to the Y-axis. This allows XL to divide objects into a small number of 3D sections, so that each resulting section requires only one MCNP run.

Radial scan is the case that x-ray paths have the correct angles with respect to the Y-axis. However, objects are divided into several 3D sections by the surfaces that are normal to the X-axis. XL computes only one image column for each resulting section.

Figure 6.9 illustrates the three approaches using two overlapping objects. The left side of Figure 6.9 shows "point scan", one scan per pixel. The center of Figure 6.9 shows "radial scan", in which objects are divided by surfaces normal to the X-axis, one column scan per rectangle. The right side of Figure 6.9 shows "parallel scan", in which the objects are divided by surfaces normal to the X-axis and surfaces normal to the Z-axis, one scan per small surface. In this section, implementations of "parallel scan" and "radial scan" will be described.
Figure 6.9. An image is a 2D array of pixels. Two overlapping objects scanned by three approaches: (a) point scan, one scan per small rectangle (pixel) □ ; (b) radial scan, one scan per rectangle □→ ; (c) parallel scan, one scan per rectangle □□.

6.5.2 Parallel Scan Implementation

The parallel scan is the case in which x-ray paths are parallel to the Y-axis, as shown in Figure 6.10. The source and detector are moved to several locations for separate MCNP simulation runs. The x-ray source is at \((X, 0, Z)\) and the x-ray detector is at \((X, -140, Z)\), in units of centimeters. The values \(X\) and \(Z\), for determining the center point of each section, will be explained in this section.

Figure 6.10. Parallel scan simulation model.

The parallel scan implementation can be separated into the following six steps:

First, XL reads an MCNP input file that contains the luggage geometry, the identity, density of each object, the source, and the detector information.

Second, XL finds all the surfaces normal to the \(X\)-axis and to the \(Z\)-axis from the surface cards of the MCNP input file. XL orders them from small to large coordinate
values for $X$-axis and $Z$-axis separately. These surfaces subdivide the luggage objects into small boxes, each with two surfaces normal to each of the $X$, $Y$, and $Z$ axes, as shown in Figure 6.11.

![Diagram](image)

**Figure 6.11.** Surfaces normal to the $X$-axis and the $Z$-axis subdivide the luggage objects into small sections. The values $x_0, x_1, ..., x_m$ determine planes that are normal to the $X$-axis, and the values $z_0, z_1, ..., z_n$ determine planes that are normal to the $Z$-axis. Each section will be scanned only once.

Last, the $x$ and $z$ coordinates of the center point of each section are calculated, as follows:

$$X = \frac{x_i + x_{i+1}}{2}, \quad Z = \frac{z_j + z_{j+1}}{2}, \quad i = 0, 1, ..., n-1, \quad j = 0, 1, ..., m-1$$  \hspace{1cm} (6.2)$$

where the values $x_0, x_1, ..., x_m$ determine planes that are normal to the $X$-axis, and the values $z_0, z_1, ..., z_n$ determine planes that are normal to the $Z$-axis. Figure 6.12 shows an example for two overlapping objects.

![Diagram](image)

**Figure 6.12.** Two overlapping objects are shown. An asterisk (*) represents the center point of each section. Nine separate MCNP simulations are performed for the objects.
Third, XL moves the source and the detector to a position so that no objects are between them. The simulation output of this geometry determines the maximum intensity $I_{\text{max}}$ and corresponds to pixel value 255, the largest 8-bit pixel value, because x-rays are neither absorbed nor scattered.

Fourth, for each center point, XL runs MCNP one time. The source and detector are moved to $(X, 0, Z)$ and $(X, 140, Z)$, respectively. The values of $X$ and $Z$ are given by Equation (6.1). After the MCNP input file is modified, XL invokes MCNP using a "system" call.

Fifth, XL locates the simulation results in the MCNP output file. The MCNP output file is quite long, about 500 lines, but only a few lines after the line, "tally for photons", are useful for our simulation. A function $mcnpda$ was developed to search the MCNP output file and find the simulation results. Once the simulation result is saved, XL goes back to step 4 until all center points are scanned by the simulator.

Finally, sixth, convert the simulation results to relative pixel values as follows:

$$p = \frac{255I}{I_{\text{max}}}$$

(6.3)

where $p$ is the resulting pixel value, $I_{\text{max}}$ is the maximum x-ray intensity, and $I$ is the intensity after the x-rays have traversed the objects. The pixel value is 255 if an x-ray does not traverse any object. On the other hand, the pixel value is 0 if the object between the x-ray source and the detector is so thick that no x-rays can penetrate it.
Every image point corresponding to the same section has the same pixel value as that of the center point. In this way, a binary image array can be developed.

The program parallel has been developed to implement the parallel scan steps. It provides an MCNP input file, implements the MCNP simulation, employs the x-ray scan, interprets the output of MCNP, converts the output of MCNP to a pixel value, and writes the pixel values to a 2D image array.

6.5.3 Radial Scan Implementation

Radial scan is when the x-ray source only moves along the X-axis during scanning, so that the x-ray paths are not parallel to the Y-axis. Figure 6.13 below shows the radial scan model, which assumes an L-shaped array of detectors. Implementation of the radial scan is almost same as that of the parallel scan. The biggest difference is the scan approach.

![L-Shaped Detector Array](image)

Figure 6.13. The radial scan model.

The first step is the same as that of the parallel scan. XL reads an MCNP input file that contains the luggage geometry, the identity, density of each object, the source information, and the detector information.
Second, XL searches the MCNP input file to find all surfaces normal to the X-axis only. The luggage is divided into several columns, as shown in Figure 6.14.

![Figure 6.14. Objects are divided into several columns by surfaces normal to the X-axis. The values $x_0, x_1, x_2, \ldots, x_m$ determine planes that are normal the X-axis](image)

Scan lines are chosen as follows,

$$x_s = \frac{x_i + x_{i+1}}{2}, \quad i = 0, 1, \ldots, m - 1$$  \hspace{1cm} (6.4)

where $x_s$ is the $x$ coordinate of the scan line, and the values $x_0, x_1, \ldots, x_m$ determine planes that are normal to the X-axis. The x-ray source is at $(x_s, 0, 0)$. Figure 6.15 shows the scan lines for two overlapped objects.

![Figure 6.15. X-ray scans three lines for two overlapping objects using the radial scan method. Vertical dashed lines (\ldots) represent x-ray scan lines.](image)

The third step is the same as that of the parallel scan. XL moves the source and the detector to a position where no objects are between them. The simulation output of this
geometry is maximum and corresponds to pixel value 255, the largest 8-bit pixel value, because x-rays neither absorbed nor scattered.

Fourth, XL fixes the position of the source, then only moves the position of the detector. For each column, XL scans along the central line of each column. The x-ray source is at \((x_s, 0, 0)\), where \(x_s\) is the \(x\) coordinate of the scan line as given in Equation (6.3). The location of the detector is described by

\[
(X, Y, Z) = \begin{cases} 
(x_s, -140+k\Delta y, 85), & \text{for } k=1, \ldots, 190 \\
(x_s, -140, l\Delta z), & \text{for } l=1, \ldots, 320
\end{cases}
\]  

(6.5)

where \(\Delta y\) and \(\Delta z\) are the detector spacings 3.3 mm and 2.6 mm of the x-ray detector in the horizontal or vertical directions, respectively, which approximates the TRICO system described in section 5.4.

The fifth step is almost the same as that of the parallel scan. Go back to step 4 until all columns are scanned, instead of until all center points of the areas are scanned.

Sixth, the points with same \(z\) coordinate in the same column have the same pixel value. A raw image array can be developed according to the idea.

The software \textit{radial} has been developed to implement the radial scan steps.

6.6 Simulation Results and Discussion

In XL, if parallel scan is used, the number of scans is equal to the number of sub-areas; if radial scan is used, the number of scans is the number of scan lines multiplied by the number of scan points on each line. Figure 6.16 shows an example that explains the differences between the two approaches. A piece of luggage contains two overlapping
objects. The luggage can be divided into nine areas (1, 2, 3, 4, 5, 6, 7, 8, 9), or three columns (I, II, III) as shown in figure. If the size of the image of the two objects is 200×200 pixels, for example, it would require 40,000 MCNP simulations for point scan, 600 MCNP simulations for the radial scan, and 9 MCNP simulations for the parallel scan. On average, this might take several days, several hours, and several minutes, respectively, on a DEC Alpha workstation. Point scan, not supported by XL, is the slowest but the most accurate and allows arbitrary shapes of the objects in the luggage, because it scans one time for every pixel in an image. Parallel scan and radial scan are easier to process than point scan, but require the surfaces of the objects to be parallel to either the X, Y, or Z axis. Parallel scan is the fastest approach but least accurate. Radial scan is fast and accurate for our simulation requirement. By comparison with parallel scan, radial scan is closer to the implementation of the real world system, because it can simulate the x-ray going into the object from the front surface and coming out from the top surface; it can give a little bit of 3-D information of the simulated object. However, the radial scan takes a longer time than the parallel scan.

![Diagram of overlapping objects](image)

**Figure 6.16** Two overlapping objects. This would require 9 MCNP simulations for parallel scan, and 3 scan lines for radial scan.
The three objects shown in Figure 6.3 have been scanned by XL using both parallel scan and radial scan. To show the versatility of XL, two orthogonal scans have been made, in which the two transmission paths are perpendicular. Two dual-axis scans are implemented by rotating the objects to be simulated in AutoCAD instead of changing the locations of the x-ray source and the x-ray detector. This has been done because objects are easy to rotate in AutoCAD. The dual-axis scan geometry is shown in Figure 6.17 for the parallel scans. Figure 6.18 and Figure 6.19 show the dual-energy and dual-axis images that are obtained. The dual-axis scan geometry is shown in Figure 6.20 for corresponding radial scans. Figure 6.21 and Figure 6.22 show the dual-energy and dual-axis images. In the two figures, it can be seen that the gray level is increasing on the top of the images. This phenomenon is because x-rays transmit into objects from the front surface and come out from the top surface. This causes the length of x-ray paths inside the objects to be shorter than normal.
Figure 6.17. The dual-axis system geometry for parallel scanning. The object is rotated instead of changing the direction of x-ray path.

Figure 6.18. Simulated high energy dual-axis images using the parallel scan method. Their scan geometries are shown in Figure 6.17.

Figure 6.19. Simulated low energy dual-axis images using the parallel scan method. Their scan geometries are shown in Figure 6.17.
Figure 6.20. Dual-axis system geometries for radial scanning. The object is rotated instead of moving the source and the detector.

Figure 6.21. Simulated high energy dual-axis images using radial scan. Their scan geometries are shown in Figure 6.20.

Figure 6.22. Simulated low energy dual-axis images using radial scan. Their scan geometries are shown in Figure 6.20.
6.5 Window Interface Development

A simple user interface has been developed using X-windows and Motif. The main purpose is to simplify the process of using XL.

The interface window is shown in Figure 6.23. It enables users to enter simulation parameters, to select one of the simulation functions, to open a text file, and to browse through its contents. The window displays a menubar with several pull-down menus, a text display area, and a scrollbar.

The interface program, invoked by typing "XL", consists of a main function and several subroutines. This main function takes care of the standard steps of initializing the Motif toolkit, realizing the windows, and initiating the event handing loop. For developing the window interface, the main window, the menu bar, the text area and the scrollbar are created, and then individual pull-down menus are implemented. Second, an action routine for the menubar is developed, which maps each pull-down menu on pressing any mouse button. Each pull-down menu displays a number of buttons and calls on some routines when the user presses any mouse button inside one of the buttons.

Five buttons, "File," "Source," "Convert," "Sim Parameter," and "Simulation," are displayed on the menubar. If any one of the five buttons is pressed, a pull-down menu with a list of options is displayed. More details about the interface can be found in Appendix A.
Figure 6.23. The XL interface window.
Chapter 7

Simulation Accuracy Analysis

7.1 Overview

Monte Carlo results represent an average of the contributions from many histories sampled during the course of the simulation [LOS93]. The concept of precision is different from that of accuracy. As illustrated in Figure 7.1 [LOS93], precision is the uncertainty in $x$ caused by the Monte Carlo process. Accuracy is a measure of how close the expected value of $x$, $E(x)$, is to the true physical quantity being estimated. MCNP can give the precision of the simulation result but does not give any information about accuracy. It is important to know the accuracy of the simulation results. MCNP gives good agreement with experiments [HEN93] [OLS93] [RED94].

![Diagram of precision and accuracy](image)

Figure 7.1. Illustration of precision and accuracy. $S_x$ is the variance of $x$.

7.2 Comparison of Simulation Results with Published Data

Some simulations have been done to analyze the accuracy of the simulator. A single energy source is used, and two objects were chosen. Of the objects chosen, aluminum (Al) is a typical inorganic element, while carbon (C) is a typical organic element. Both objects have been simulated at several thicknesses when the energy level is fixed, and
at several energy levels when the thickness is fixed. The mass attenuation coefficient $\mu^*$ is calculated as follows:

$$\mu^* = \frac{\ln \frac{I}{I_0}}{\rho d}$$  \hspace{1cm} (7.1)

where $I_0$ is the initial energy, $I$ is the received energy at the detector, $\rho$ is the density of the object, and $d$ is the thickness of the object. Tables 7-1, 7-2, and 7-3 show the simulated transmission results (average energy of photons) for carbon from MCNP. In order, the tables show 1) the received photon intensity $I$, 2) the mass attenuation coefficients calculated from $I$ using Equation (7.1), and 3) the relative errors of the mass attenuation coefficient compared with the published experimental mass attenuation coefficients [MCM92] for carbon. Tables 7-4, 7-5, and 7-6 show corresponding results for aluminum.

It can be seen from the tables that the mass attenuation coefficient of these simulated objects is almost independent of object thickness but depends on the energy and the atomic number $Z$. The simulation results are in good agreement with the published experimental data. This shows that the simulation model is quite accurate.
Table 7-1. Simulated transmission results (in keV) for carbon using a monochromatic x-ray source, at several energies and several thicknesses.

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</table>

Table 7-2. Mass attenuation coefficients (in cm²/g) calculated from the simulation results (in Table 7-1) for carbon, at several energies and several thicknesses.

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<th>20</th>
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Table 7-3. Average relative errors compared with published experimental mass attenuation coefficients [MCM92] for carbon.

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<th>Energy (keV)</th>
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</tbody>
</table>
Table 7-4. Simulated transmission results (in keV) for aluminum using a monochromatic x-ray source, at several energies and several thicknesses.*

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>6.8</td>
<td>1.55</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>30.6</td>
<td>18.8</td>
<td>11.5</td>
<td>7.1</td>
<td>4.375</td>
</tr>
<tr>
<td>60</td>
<td>41.46</td>
<td>28.57</td>
<td>19.65</td>
<td>13.55</td>
<td>9.39</td>
</tr>
<tr>
<td>80</td>
<td>60.9</td>
<td>46.4</td>
<td>35.4</td>
<td>26.9</td>
<td>20.6</td>
</tr>
<tr>
<td>100</td>
<td>79.5</td>
<td>63.04</td>
<td>50.2</td>
<td>39.8</td>
<td>31.56</td>
</tr>
<tr>
<td>150</td>
<td>124.5</td>
<td>103.3</td>
<td>85.7</td>
<td>71.2</td>
<td>59.1</td>
</tr>
</tbody>
</table>

Table 7-5. Mass attenuation coefficients (in cm$^2$/g) in calculated from the simulation results (in Table 7-4) for aluminum, at several energies and several thicknesses.*

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1.0986</td>
<td>1.0966</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.3635</td>
<td>0.3620</td>
<td>0.3626</td>
<td>0.3612</td>
<td>0.3606</td>
</tr>
<tr>
<td>60</td>
<td>0.2754</td>
<td>0.2750</td>
<td>0.2754</td>
<td>0.2753</td>
<td>0.2746</td>
</tr>
<tr>
<td>80</td>
<td>0.2019</td>
<td>0.2016</td>
<td>0.2012</td>
<td>0.2014</td>
<td>0.2011</td>
</tr>
<tr>
<td>100</td>
<td>0.1698</td>
<td>0.1708</td>
<td>0.1700</td>
<td>0.1705</td>
<td>0.1707</td>
</tr>
<tr>
<td>150</td>
<td>0.1379</td>
<td>0.1381</td>
<td>0.1381</td>
<td>0.1379</td>
<td>0.1379</td>
</tr>
</tbody>
</table>

Table 7-6. Average relative errors compared with published experimental mass attenuation coefficients [MCM92] for aluminum.*

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>Average error</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.75%</td>
<td>0.94%</td>
<td></td>
<td></td>
<td></td>
<td>0.85%</td>
</tr>
<tr>
<td>50</td>
<td>1.16%</td>
<td>1.55%</td>
<td>1.38%</td>
<td>1.77%</td>
<td>1.92%</td>
<td>1.56%</td>
</tr>
<tr>
<td>60</td>
<td>1.55%</td>
<td>1.68%</td>
<td>1.53%</td>
<td>1.56%</td>
<td>1.84%</td>
<td>1.63%</td>
</tr>
<tr>
<td>80</td>
<td>0.78%</td>
<td>0.93%</td>
<td>1.15%</td>
<td>1.03%</td>
<td>1.16%</td>
<td>1.01%</td>
</tr>
<tr>
<td>100</td>
<td>1.27%</td>
<td>0.72%</td>
<td>1.14%</td>
<td>0.88%</td>
<td>0.74%</td>
<td>0.95%</td>
</tr>
<tr>
<td>150</td>
<td>0.63%</td>
<td>0.52%</td>
<td>0.49%</td>
<td>0.66%</td>
<td>0.66%</td>
<td>0.59%</td>
</tr>
</tbody>
</table>

* Some cells are blank because only a negligible number of x-rays penetrate the material in these cases.
7.3 Comparison of XL Outputs with Outputs from a Commercial System

The XL simulator has also been tested by comparing its outputs with a commercial pseudo-dual-energy system, the MEX-6585, manufactured by TRICO Industries Inc. in China. Comparisons have been performed by using a plastic step wedge and an aluminum step wedge. The plastic step wedge is made of polyethylene, whose chemical formula and density are \((\text{CH}_2-\text{CH}_2)_{n}\) and 0.94 g/cm\(^3\). Figure 7.2 shows the geometry of the scanning wedges. The step thicknesses of the aluminum step wedge are 2.59 mm, 5.08 mm, 7.11 mm, 10.14 mm, 11.89 mm, 13.92 mm, 15.24 mm, and 20.32 mm. The step thicknesses of the plastic step wedge are 10.16 mm, 15.24 mm, 20.32 mm, 50.8 mm, 101.6 mm, 152.4 mm, 187 mm, and 250 mm. The x-ray source has a 32° target angle, a 5 mm aluminum filter, and a 140 keV initial energy. The simulated spectra of the x-ray source is shown in Figure 7.3. The detector is composed of a low energy detector (0.3 mm CsI), a 0.5 mm copper plate, and a high energy detector (4 mm CsI), as described in Chapter 5.

The low energy images and the high energy images of the plastic wedge and the aluminum wedge are compared in Figures 7.4 to 7.7. These images were obtained using the source spectrum shown in Figure 7.3 (a). The simulated aluminum wedge images using the radial scan are not significantly different from those obtained using the parallel scan, because the thickness of the aluminum wedge is quite small. Both of them are close to the experimental images. However, the simulated plastic wedge images using the radial scan have a lot differences from those using the parallel scan and are closer to the images of the commercial system. As a result, it is found that the parallel scan is suitable for
generating images of thin objects; on the other hand, the radial scan is reasonable for generating images of very thick objects.

Figure 7.2. The geometry for scanning two step wedges: (a) an aluminum wedge, (b) a plastic wedge.
Figure 7.8 and Figure 7.9 show the simulated results and outputs of the commercial system, the error and the relative error versus the thickness of each step of the plastic and aluminum wedges, respectively. The error is the absolute value of the output from TRICO abstracted from the XL simulation output, and the relative error is the error divided by the output from TRICO. The outputs generated by the XL are in good agreement with the outputs of the commercial system.

High energy outputs have better agreement than low energy outputs and the relative error increases as the thickness of the objects increases. If we change the number of photons from 0.1 million, to 1 million, to 10 million, the simulated outputs do not show much difference, no more than 1 pixel value’s difference. It can be concluded that the simulation outputs are reasonably precise. Several reasons corresponding to the difference between the simulation outputs and the experimental data are listed below:

(1) The x-ray source simulation does not model characteristic x-rays.

(2) The output signal may not be completely linear with respect to the x-ray photon energy absorbed by the scintillator.

(3) The thickness of the stepwedges are not known with perfect accuracy.

(4) The output from the real world system has some noise.

Another simulation for the aluminum wedge has been done using the spectrum shown in Figure 7.3 (b). This spectrum was obtained by inserting the experimental characteristic x-rays data [MCM92] to the simulated continuous x-ray spectrum. Figure 7.10 shows the comparison of simulation results with the experimental outputs.
Comparing Figure 7.9 and Figure 7.10, it is found that the error of low energy results has significantly decreased, while the error of high energy results has increased slightly. It can be concluded that the characteristic x-rays affect the low energy output much more than the high energy output, because the energy of the characteristic x-rays is around 70 keV when the initial energy of the x-ray source is 140 keV. Note in Figures 7.8 to 7.10 that there should be two points for each step of the step wedges. However, only one point will be present on the graphs if two points are overlapping.
Figure 7.3. Spectra simulated by XL for a 32° target angle, a 5 mm aluminum filter, and a 140 keV incident electron energy: (a) continuous x-rays, (b) continuous x-rays with added characteristic x-rays.
Figure 7.4. Comparison of low energy images of a commercial pseudo-dual-energy system with those of XL for a plastic wedge: (a) the image from the commercial system, (b) the image by radial scan simulation, and (c) the image by the parallel scan simulation.
Figure 7.5. Comparison of high energy images of a commercial pseudo-dual-energy system with those of XL for a plastic wedge: (a) the image from the commercial system, (b) the image by radial scan simulation, and (c) the image by the parallel scan simulation.
Figure 7.6. Comparison of low energy images of a commercial pseudo-dual-energy system with those of XL for an aluminum wedge: (a) the image from the commercial system, (b) the image by radial scan simulation, and (c) the image by parallel scan simulation.
Figure 7.7. Comparison of high energy images of a commercial pseudo-dual-energy system with those of XL for an aluminum wedge: (a) the image from the commercial system, (b) the image by radial scan simulation, and (c) the image by parallel scan simulation.
Figure 7.8. Comparison of the XL output (without characteristic x-rays in the source model) with the experimental data of the commercial pseudo-dual-energy system for the plastic wedge. Notice that points for low and high energy overlap at some thicknesses.
Figure 7.9. Comparison of the XL output (without characteristic x-rays in source model) with the experimental data of the commercial pseudo-dual-energy system for the aluminum wedge. Notice that points for low and high energy overlap at some thicknesses.
Figure 7.10. Comparison of the XL (with characteristic x-rays in the source model) with the experimental data of the commercial pseudo-dual-energy system for the aluminum wedge. Notice that points for low and high energy overlap at some thicknesses.
Chapter 8

Conclusion

This thesis has described a simulation package, known as XL, that can be used to simulate dual-energy and dual-axis x-ray scanning systems. This software system simulates x-ray sources, detectors, and the interaction of x-ray photons with matter. It can produce realistic x-ray images for simple objects with high accuracy.

A major motivation for developing XL was to model luggage inspection systems and to test explosives detection techniques. Using AutoCAD, the user can specify the three-dimensional geometry of an x-ray scanner. The simulator then generates images that are a close approximation to those that would be produced by a corresponding physical luggage scanner.

XL relies heavily on MCNP, a software package that uses Monte Carlo techniques to simulate x-ray interaction with matter. XL converts an AutoCAD DXF file to the format needed by MCNP, and then invokes MCNP repeatedly and interprets the results.

The x-ray source model was developed by combining MCNP with the semiexperimental model reported by Birch and Marshall [BIR79]. The simulated tungsten x-ray source spectra have a good agreement with the published experimental data for different target angles, inherent filters of different thicknesses, and a wide range of x-ray tube potentials.
The x-ray scintillation detector was studied and is modeled by XL. In order to simulate a dual-energy scanner, the detector model includes low energy and high energy detectors separated by a piece of copper. The sensitivity spectra of the low and high energy detectors agreed with predicted responses.

The complete software system can generate images that are in close agreement with images produced by a physical scanning system. Two simulation approaches, parallel scan and radial scan, have been implemented and compared. The parallel scan approach is the most efficient for generating x-ray transmission images, but the radial scan approach is closer to the real world scanning system.

The system has been tested by comparing its output with a commercial pseudo-dual-energy luggage scanning system. Images of aluminum and plastic wedges have been generated by XL and compared with those from the physical system. The maximum relative error of XL was 7%, and the average relative error was less than 3% in this evaluation.

It is expected that this simulator will be helpful in the development of future prototype luggage inspection systems.
Bibliography


Appendix A: XL User's Guide

This appendix describes XL and explains how to use it. XL is a software system that can generate simulated x-ray transmission images using 3-D geometry drawings in AutoCAD. Its main functions are converting a DXF file exported from AutoCAD to the input format file needed by MCNP, simulating x-ray source spectra, and generating dual-energy transmission images with simulated low and high energy detectors using the parallel scan or the radial scan. There are two ways to use these functions: one way is using the command line; the other way is using a window interface. XL is actually a set of programs: source.exe, dxf2mcnp, parallelh, parallel, radialh, and radial. XL runs on a DEC Alpha system.

Command Line Parameters for the XL Functions

USAGE NOTES:
Parameters in brackets (<...>) and in italics are required arguments. Items in bold are executable files.

source.exe
Simulate x-ray source spectrum according to the size of the target angle, the thickness of the target aluminum filter, and the energy of the initial electrons.

USAGE:
source.exe <angle> <filter> <energy> <change>

angle is the target angle in degree,
filter is the target aluminum filter in centimeter,
energy is the initial electron energy in keV,
change is an integer; if it is "1" that means the parameters of the x-ray source are changed, and if it is "0" that means the parameters of the x-ray source are not changed.

OUTPUT:
The simulated x-ray source spectrum is saved in file "source_sim".

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NOTE:
"source" is a MCNP file used in the x-ray source simulation.

dxf2mcnp
Convert DXF file to the input format needed by MCNP with simulated x-ray source spectrum.
USAGE:
dxf2mcnp <angle> <filter> <energy> <change> <dxfile> <nps> <MCNP_file>
INPUT:
dxf2mcnp is the executable file.
angle is the target angle in degree.
filter is the target aluminum filter in centimeter.
energy is the initial electron energy in keV.
change is an integer, if it is “1” that means the parameters of the x-ray source are changed, and if it is “0” that means the parameters of the x-ray source are not changed.
dxfile is the DXF file name.
nps is the number of photons to be simulated.
MCNP_file is the MCNP input file name.
OUTPUT:
The simulation x-ray source spectrum is saved in file “source_sim”.
The MCNP input file converted from DXF file is saved in the file that is specified by the parameter MCNP_file.

parallelh, parallelL, radialh, radialL
parallelh is to simulate the high energy image of the pseudo-dual-energy system using the parallel scan.
parallelL is to simulate the low energy image of the pseudo-dual-energy system using the parallel scan.
radialh is to simulate the high energy image of the pseudo-dual-energy system using the radial scan.
radialL is to simulate the low energy image of the pseudo-dual-energy system using the parallel scan.
USAGE:
parallelh <MCNP_file> <image_file> <magnification>
parallelL <MCNP_file> <image_file> <magnification>
radiall <MCNP_file> <image_file> <magnification>
radiall <MCNP_file> <image_file> <magnification>
MCNP_file is the MCNP input file name.
image_file is the file name of the output raw image.
magnification is the multiplier by which the output image will be magnified.
OUTPUT:
The numbers of rows and columns of the output image.

Window Interface for XL

The window interface for XL was developed by using X-window and Motif. It consists of a main window, a menu bar, a text area, and a scroll bar mainly. The outline of the interface is shown below:

The outline of the window interface for XL.

Where:
"File" submenu is used to open a file by pressing Open, to scroll through it, or to exit from the window interface by pressing Exit.
"Source" submenu is used to enter source parameters: target angle in degree by pressing Target Angle, the thickness of the aluminum filter in centimeter by pressing Target Filter, the x-ray tube voltage in keV by pressing Energy, and to invoke the source simulation function by pressing Source Simulation.
"Convert" submenu is used to specify an exported DXF file by pressing Specify input file (DXF), to specify a converted MCNP input file name by pressing Specify output file (MCNP), to select the convert function that converts the exported AutoCAD DXF file to the MCNP input file by pressing Convert, and to specify the number of photons (NPS) that the x-ray source will generate by pressing Number of photons.
"Sim Parameter" submenu is used to specify a MCNP input file name by pressing Specify input file (MCNP), to name output image file name by pressing

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Specify output file (image), and to declare the magnification time of the output image by pressing Magnification.

"Simulation" submenu can be used to select one of four simulation functions: parallelh, parallelh, radialh, and radiah by pressing any one of the four buttons: Parallel Scan(high energy), Parallel Scan(low energy), Radial Scan(high energy), and Radial Scan(low energy). Parallel Scan(high energy), Radial Scan(high energy) generate high energy images by the parallel scan and the radial scan, respectively. On the other hand, Parallel Scan(low energy) and Radial Scan(low energy) develop low energy images by the parallel scan and the radial scan, respectively.

Items in bold and in ("...") are buttons on the menubar. If any one of them is pressed, a pull down menu with a list of buttons is displayed. Items in bold and in italics are buttons on a pull down menu.

The software program is XL.c. On the DEC system running X11R6, the following command line compiles and links the program:
cc XL.c -o XL -lx11 -lx -lxmu -lxm

Note that in order to use parallelh, parallelh, radialh, and radiah, the cards of an MCNP input file should in capital letters, except the cards for the geometry of the tunnel of the x-ray system.
Appendix B: An MCNP Input File

This appendix contains an example MCNP input file. The cell and surface cards describe three rectangular objects: TNT, aluminum, and paper, as shown in Figure 6.3. The x-ray source spectrum is described in two cards, SI1 and SP1, for an x-ray source of 140 keV initial electron energy, 32° target angle, and a 5 mm aluminum filter. The location and direction of the source are given on the data card beginning with SDEF. The detector is described in two cards, "500 pi -140" and "506 s 5 -140 5 0.1", which specify the detector as a circle centered on (5 cm, -140 cm, 5 cm) with 0.1 cm radius on surface Y=-140. The tally is specified by ")F1:p 500 and FS1 -506", which means MCNP will output the average energy of photons (in me) inside and outside circle 506 separately on surface 500. This MCNP input file can be used to create the high energy or low energy images of the three objects using parallel scan or radial scan. For further details of MCNP, please refer to the MCNP manual [LOS93].

MCNP input file:

DXF to MCNP Conversion
  c  NOTE: All values in parentheses must be specified!
  c  beginning of cell cards
  1  1 -1 630000 1 -2 -3 4 5 -6                      $ TNT cell
  2  2 -0.696500 7 -8 -9 10 11 -12                  $ Paper cell
  3  3 -2.700000 13 -14 -15 16 17 -18                $ Aluminum cell
  4  0  500 -501 -502 503 -504 505 #1 #2 #3
  5  0  -500:501:502:-503:504:-505
  c  end of cell cards
beginning of surface cards

POLYLINE Layer: TNT
1 PY  -83.000000
2 PY  -81.000000
3 PX   20.000000
4 PX   18.000000
5 PZ    5.000000
6 PZ    7.000000

POLYLINE Layer: PAPER
7 PY  -80.000000
8 PY  -75.000000
9 PX   32.000000
10 PX   12.000000
11 PZ    0.000000
12 PZ   10.000000

POLYLINE Layer: ALUMINUM
13 PY  -85.000000
14 PY  -84.000000
15 PX   15.000000
16 PX    0.000000
17 PZ    0.000000
18 PZ   10.000000
500 py  -140
501 py  1000
502 px  1000
503 px  -1000
504 pz   85
505 pz  -1000
506 s  5  -140 5 0.1

end of surface cards

beginning of data cards

mode p
IMP:p 1 1 1 1 0
SDEF ERG=D1 POS=5.00 0.00 5.00 VEC=0.00 -1.00 0.00 PAR=2 DIR 1 ARA 1
S11 A 0.000 0.005 0.010 0.015 0.020 0.025 &
   0.030 0.035 0.040 0.045 0.050 0.055 &
   0.060 0.065 0.070 0.075 0.080 0.085 &
   0.090 0.095 0.100 0.105 0.110 0.115 &
   0.120 0.125 0.130 0.135 0.140
SP1 0.000000 0.000000 0.000000 0.000000 0.000279 0.002098 &
   0.005093 0.006914 0.007694 0.007730 0.007302 0.006658 &
   0.005941 0.005180 0.004012 0.003551 0.003211 0.002830 &
0.002482 0.002142 0.001935 0.001637 0.001392 0.001033 &
0.000781 0.000599 0.000394 0.000182 0.000009
M1 1001 -.022 6012 -.37 7014 -.185 8016 -.423 $ TNT
M2 1001 -.0623 6012 -.4422 8016 -.4955 $ PAPER
M3 130001 $ ALUMINUM
*F1:p  500
FS1 -506
NPS 1000000
PRINT 160

end of data cards

If the upper file is used as an input to MCNP, several output lines useful for the simulation are as follows:
surface  500
segment:  -506
           2.81442E-02 0.0013
surface  500
segment:  506
           6.97883E-03 0.0030

This means the average photon energy inside and outside circle 506 on surface 500 are 0.0281442 MeV with 0.0013 relative error, and 0.0069788 MeV with 0.0030 relative error, respectively.
Appendix C: The *Layer* Function

This appendix presents the *layer* function file. *Layer* contains information about materials' names, densities in g/cm³, the atomic numbers, the atomic masses, and the weight fraction of the constituents in the materials. In order to make the link between AutoCAD and XL for the material types, the layer name in the AutoCAD drawing should be identical to the material's name in *layer*, which is further described in Section 6.4.3.

```c
#ifndef LAYER_C_
define LAYER_C_

#define NUM_MATERIALS 10
typedef struct
{
   char *name;
   float density;
   char *ZAID;
} layer_def;

layer_def layer[NUM_MATERIALS];

void define_layers()
{
   layer[0].name = " C4";
   layer[0].density = -1.653;
   layer[0].ZAID = "1001 -0.0359 6012 -0.2186 7014 -.3443 8016 -.4021";
   layer[1].name = "NITRO";
   layer[1].density = -1.6;
   layer[1].ZAID = "1001 -.022 6012 -.159 7014 -.185 8016 -.634";
   layer[2].name = "TNT";
   layer[2].density = -1.63;
   layer[2].ZAID = "1001 -.022 6012 -.37 7014 -.185 8016 -.423";
```

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layer[3].name = "COTTON";
layer[3].density = -.15;
layer[3].ZAI D = "1001 .06 6012 .48 8016 .46";
layer[4].name = "EGDN";
layer[4].density = -1.48;
layer[4].ZAI D = "1001 .024 6012 .22 7014 .171 8016 .585";
layer[5].name = "WOOL";
layer[5].density = -.134;
layer[5].ZAI D = "1001 .053 6012 .4202 7014 .2455 8016 .2813";
layer[6].name = "WATER";
layer[6].density = -1;
layer[6].ZAI D = "1001 .1110 8016 .8890";
layer[7].name = "HEROIN";
layer[7].density = -.9993;
layer[7].ZAI D = "1001 .063 6012 .6824 7014 .0379 8016 .2167";
layer[8].name = "ALUMINUM";
layer[8].density = -2.7;
layer[8].ZAI D = "13000 1";
layer[9].name = "PAPER";
layer[9].density = -.06965;
layer[9].ZAI D = "1001 -0.0623 6012 -0.4422 8016 -0.4955";
}

# endif
Vita

Ms. Wei Xie was born in Hubei, China on April 16, 1968. She obtained her Bachelor of Science degree from Tsinghua University, Beijing, P. R. of China, in Materials Science and Engineering (with Ceramics Major) in July, 1991. In 1993, she joined Virginia Polytechnic Institute and State University as a Master of Science student in Electrical Engineering. During her Master's program, her areas of study included computers and communications.

Signed,

[Signature]

Wei Xie