DEVELOPMENT OF AN ELECTRON BEAM IRRADIATION DESIGN FOR USE IN THE TREATMENT OF MUNICIPAL BIOSOLIDS AND WASTEWATER EFFLUENT

A Dissertation

by

ALEXIS DAWN LAZARINE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2008

Major Subject: Nuclear Engineering

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ABSTRACT

Development of an Electron Beam Irradiation

Design for Use in the Treatment of

Municipal Biosolids and Wastewater Effluent. (May 2008)

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The need for pathogen-free water supplies has spurred investigations into the use of ionizing radiation for the treatment of wastewater effluent and municipal biosolids. The objective of this research was to develop an electron-beam irradiation scenario to effectively eliminate microbial pathogens from municipal biosolids and wastewater effluent. The Monte Carlo N-Particle (MCNP5) radiation transport code was used to simulate the irradiation scenario.

Using MCNP5, dual electron-beam sources were modeled as planar surface sources above and below a stainless steel delivery trough containing either effluent water or one of two biosolids material compositions. A dose deposition analysis was performed to assess both the planar dose distribution and 25 depth-dose curves. In addition, a density perturbation study was performed to assess the variance in the dose deposition for different mass solids concentrations.

To validate the MCNP5 code for this type of application, a benchmark study was performed. Two municipal biosolids materials and water were irradiated in plastic bags on a conveyor belt using a 10-MeV electron accelerator with the exit window below the material. The experimental configuration was modeled with the MCNP5 radiation transport code. Simplified and detailed models were created and analyzed.

Lastly, an economic analysis was performed to assess whether this treatment method is a financially viable alternative to current wastewater treatment methods. Processing capacity was calculated for two accelerator specifications. These capacity rates in conjunction with the operating and capital costs per dry ton to irradiate the material were compared with existing data for electron beam processing of municipal biosolids. The cost breakdown was also compared with quoted costs for existing conventional methods.

The models developed showed that the use of 10MeV electron-beam technology for the treatment of wastewater effluent and municipal biosolids is effective and economically feasible. The benchmarking study illustrated the accuracy of Monte Carlo simulation for this type of application. The method development process was shown to be adaptable for various material compositions and irradiation configurations.

ACKNOWLEDGEMENTS

I would like to acknowledge the members of my committee for their guidance and critiques of this work. Thank you especially to Dr. John Ford for his endless support and to Dr. Suresh Pillai for conceiving of this project and allowing me to participate. Thank you to Mickey Speakmon and Joe Maxim of the National Center for Electron Beam Food Research for donating their time and efforts to setting up my benchmark experiment.

This material is based upon work supported under a National Science Foundation Graduate Research Fellowship. Thank you to the National Science Foundation for funding this research along with the majority of my graduate career. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author and do not necessarily reflect the views of the National Science Foundation.

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1 INTRODUCTION

1.1 Background

The treatment and disposal of municipal biosolids is considered a timely and critical environmental issue (Wang and Wang, 2007). Wastewater results from the use of water for human life-supporting applications and manufacturing processes (Stoll, 1996). Treatment of municipal wastewater is vital to preserving sanitary conditions and healthy populations across the world. Every year, an average person produces 70 m^3 of wastewater, 45 kg of feces, and 500 L of urine. A typical urban wastewater system consists of a sewer collection system, a treatment plant, and a receiving water body (Schutze, Butler, and Beck, 2002).

Municipal biosolids material is produced in several forms, and its characteristics vary considerably based upon the type of treatment used, the corresponding geographical area, and the commercial-industrial activity within the collecting area feeding the wastewater treatment plant (Harrington, 1978). The material composition of municipal biosolids is often characterized by nitrogen and phosphorus levels, carbon to nitrogen ratio, and metal concentrations (Yuncu, 2006).

Microorganisms and chemical contaminants present in municipal biosolids and

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This dissertation follows the style of Water Resource Management.

wastewater effluent can pose substantial health risks to the general public. Historically, outbreaks of typhoid and cholera have resulted from inadequate sewage handling and treatment. Improved sanitation methods have largely controlled the problem of waterborne diseases, but pathogen reduction remains a concern when developing a modern water treatment process. In addition, organic and inorganic compounds in wastewater are a concern with regard to long-term health problems (USDOE, 1983).

The water treatment techniques currently employed include physical, chemical and biological operations (United Nations, 2003). Physical operations include separation procedures such as screening, sedimentation, and granular-medium filtration (United Nations, 2003). Chemical operations including adsorption, disinfection, dechlorination (Chen, 1981), and chemical precipitation are also often used in typical wastewater treatment processes (United Nations, 2003). In addition, these plants also utilize biological methods such as biological nutrient removal (Daiger, 1993), aerobic digestion (Ramalho, 1983), and anaerobic digestion (Ramalho, 1983), among others (United Nations, 2003). While these methods, often used in accord, are effective at reducing the bioburden of municpal biosolids and effluent wastewater, ionizing radiation has attracted increasing interest because irradiation offers a fast, reliable method that tackles both the task of disinfection and the need for decomposition of organic toxins (Graino and Magnavacca, 2003).

Many municipalities would like to use these biosolids products in land applications. However, environmental concerns often prevent the use of these materials on public land. Re-using treated wastewater for land applications is contingent upon a treatment process that can reduce both the organic matter content and the pathogen load to acceptable levels in accordance with national regulations (Mattock, 1978).

Ionizing radiation technology, specifically electron beam irradiation, presents an effective and economically viable alternative to traditional wastewater treatment methods. This report analyzes the effectiveness of electron beam irradiation technology for treatment of municipal biosolids and wastewater effluent. Material dose deposition profiles were studied as well as density/solids concentration effects on the dose distributions. To conclude, a brief economic analysis was performed to attest to the economical viability of this study. While a specific case of irradiation geometry and material compositions was analyzed for this study, it is the opinion of the author that the methods used for this research can be applied in a straightforward manner to specific treatment plant scenarios.

1.2 Principles of Electron Radiation

1.2.1 Stopping Power and LET

Electrons traveling through matter lose their energy by exciting and ionizing atoms within the material. The average linear rate of energy loss of these electrons in a particular medium is referred to as “stopping power” and generally has units of MeV per cm. This quantity is also often referred to as the linear energy transfer (LET) of the particle with units generally expressed as keV per µm (Turner, 1995). Stopping power and LET are closely related to the dose imparted to the material by the electrons traveling through that material.

1.2.2 Range and Penetration

The distance that a charged particle travels before coming to rest is known as the "range" of the particle (Turner, 1995). The ranges of electrons in municipal biosolids and effluent water were of particular interest when designing the parameters for this study. Cleland, et al. utilized the one-dimensional ITS TIGER Monte Carlo code to calculate electron range values in water (Cleland, Lisanti, and Galloway, 2004). They compared their calculated results with the electron energy versus range equation given in ICRU Report 35 (ICRU, 1984a). This energy versus range equation is given in (1.1) below.

$$E_P = 0.22 + 1.98\,R_P + 0.0025\,(R_P)^2, \tag{1.1}$$

where,

E_P = electron energy in MeV and

R_P = practical range in g/cm^2.

Cleland, et al. calculated the range of 10-MeV electrons in water to be 4.922 cm (Cleland, Lisanti, and Galloway, 2004), which corresponded to an electron energy of

10.025 from the ICRU equation (ICRU, 1984a). This resulted in a less than 1% difference between the two methods. Therefore, the range for 10-MeV electrons in water was taken as approximately 5 cm for the purposes of this study.

1.2.3 Absorbed Dose

Absorbed dose is the primary quantity used in the field of dosimetry. It is defined s the energy absorbed per unit mass from any kind of ionizing radiation in any target. The SI unit of absorbed dose is the gray (Gy). One Gy represents one joule of energy deposited per kilogram of material.

1.3 Microorganisms of Interest

E. coli and *Streptococcus faecalis* were the typical indicator bacteria considered in wastewater treatment applications previously (Sundstrom and Klei, 1979). However, regulatory agencies around the world use levels of indicator microbes (such as fecal coliforms, aerobic spores, *Clostridium perfringens*, total culturable viruses) and specific pathogens (Salmonella spp., and Ascaris spp) as benchmarks. A multitude of disease-causing microorganisms are present in municipal biosolids and wastewater effluent. Table 1 lists important disease-causing organisms often found in municipal biosolids and effluent water and the corresponding disease(s) that each organism causes (Koltunski and Plumridge, 2007).

Table 1 Disease-causing organisms found in wastewater effluent and municipal biosolids (Koltunski and Plumridge, 2007).

Organism		**Disease Caused**
Bacteria	*Escherichia coli*	Gastroenteritis
	Leptospira	Leptospirosis
	Salmonella typhi	Typhoid fever
	Salmonella	Salmonellosis
	Shigella	Shigellosis (bacillary dysentery)
	Vibrio cholerae	Cholera
Protozoa	*Balantidium coli*	Balantidiasis
	Cryptosporidium parvum	Cryptosporidiosis
	Entamoeba histolytica	Amebiasis (amoebic dysentery)
	Giardia lamblia	Giardiasis
Helminths	*Ascaris lumbricoides*	Ascariasis
	T. solium	Taeniasis
	Trichuris trichiura	Trichuriasis
	Entoviruses	Gastroenteritis, heart anomalies, meningitis
	Hepatitis A virus	Infection hepatitis
	Norwalk agent	Gastroenteritis
	Rotavirus	Gastroenteritis

1.4 Decimal Reduction Dose

Decimal reduction dose (D_{10}) is usually employed to describe the radiation sensitivity of microorganisms (Wang and Wang, 2007). The D_{10} value represents the dose required to kill 90% of the microbial (pathogen) population, resulting in a one-log inactivation of that population. The D_{10} values for *Escherichia coli* and *Salmonella typhimurium* irradiated in buffer solution have been reported as 0.34 kGy and 0.30 kGy, respectively (Borrely et al., 1998).

1.5 Introduction to Monte Carlo Simulation

Monte Carlo as a general computational method estimates outcomes of stochastic processes by running many iterations of that process and averaging the outcomes together. The Monte Carlo simulation used for this study is the Monte Carlo N-Particle (MCNP) code. MCNP5 is a general-purpose Monte Carlo code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport. Some specific areas of application of MCNP5 include: radiation shielding, medical physics, radiation protection and dosimetry, nuclear criticality safety, and detector design and analysis (X-5 Monte Carlo Team, 2003). MCNP5 contains important standard features of MCNP such as powerful source options, geometry and output tally plotters, and flexible tally structure.

2 PROBLEM

The problem to be addressed by this research is to develop an electron beam irradiation design that can be used effectively to irradiate municipal wastewater effluent and municipal biosolids to destroy microorganisms. The irradiation process should inactivate pathogens and destroy chemical contaminants commonly found in wastewater materials to prescribed levels.

2.1 Treatment Goals

The goal of the proposed treatment process is material that can be land-applied without restrictions, resulting in a cost-effective and environmentally-sustainable end-use for the material (Zhou and Mavinic, 2003). The United States Environmental Protection Agency (USEPA) released the technical standards for the use and disposal of biosolids and introduced the criteria for Class-A biosolids in 1993 (USEPA, 2007). To be classified as Class-A material, municipal biosolids must be essentially pathogen-free and must meet metal concentration and vector attraction reduction requirements (Bastian, 1997). Upon meeting these requirements, the material can be land-applied without restrictions (Zhou and Mavinic, 2003).

Standards for pathogen-load reduction in biosolids intended for Class-A applications are as follows (USEPA, 2007). Either the density of fecal coliform in the biosolids shall be less than 1000 Most Probable Number per gram (MPN/g) of total solids (dry-weight basis) or the density of *Salmonella* sp. bacteria shall be less than three MPN per four grams of total solids (dry-weight basis). The density of enteric viruses shall be less than one Plaque-Forming Unit per four grams of total solids (dry weight basis). The density of viable helminth ova density shall be less than one per four grams of total solids (dry-weight basis).

2.2 Present Status of the Question

2.2.1 Co-60 Technology

The first biosolids irradiation plant was the Geiselbullach Treatment Plant, a pilot-scale Co-60 irradiation plant near Munich, Germany (Lessel, 1997). This plant was established in 1973, and it provided great momentum for the prospect of using ionizing radiation for environmental applications (McKeown et al. 1998; Graino and Magnavacca 1998). Almost 30 years later, a full-scale commercial plant has yet to be constructed, but many researchers have reviewed the value of ionizing radiation in the treatment of municipal biosolids.

Co-60 was also used as the source for a municipal wastewater treatment plant build by the Isotope Division of the Bhabha Atomic Research Center in collaboration with M.S. University of Baroda, Bujarat Water Supply and Sewerage Board, and Municipal Corporation of Baroda, India (Shah et al 2001). The Co-60 source for this facility had a maximum activity of 500,000 Ci, and the treatment capacity was 110 m^3/day (Shah et al 2001). The plant was commissioned in 1992 and has been in daily operation since that time implementing a target dose of 2 kGy (Shah et al 2001; Gautam et al 2005).

Sandia National Laboratories in Albuquerque, NM, USA, developed a pilot and demonstration plant to treat dewatered and compost municipal biosolids in 1979 (Lessel 1997). The Sandia plant employed a Cs-137 source with a maximum activity of 1,000,000 Ci. The capacity of the plant was 8 dry tons (about 50% solids) per day with a target dose of 10 kGy. The plant ceased operation due to unknown reasons.

Graino and Magnavacca (1998) explored a Co-60 facility design for municipal biosolids irradiation in Argentina. The irradiation plant in their design was intended for anaerobically-digested municipal biosolids with solids concentrations of 8-10% (Graino and Magnavacca 1998). The irradiation treatment process incorporated an irradiation tank with a recirculation system used to irradiate batches of 6.0 m^3 in 30-minute intervals. The Graino and Magnavacca research examined physicochemical changes induced by ionizing radiation such as diminishing viscosity, decrease in filtration specific resistance, and change in sedimentation velocity. They also explored chemical effects such as decomposition and evidence of a protection effect.

2.2.2 Electron Beam Technology

Electron beam technology has not been widely employed in biosolids treatment (Wang and Wang 2007). An electron accelerator was built to treat biosolids as a demonstration project at the Deer Land Wastewater Treatment Plant in Boston in 1976 (Lessel 1997). The project was designed and supervised by individuals from the Massachusetts Institute of Technology, and the plant capacity was reported to be 400 m^3/day (Lessel 1997). The study was performed in a laboratory and the researchers decommissioned the project in 1984, never scaling it up.

Another electron beam accelerator was built at a wastewater treatment plant in Virginia Key, Miami, Florida, during 1981-1983 (Lessel 1997). The accelerator employed at this facility operated at 75 kW utilizing a 50 mA current of 1.5 MeV electrons (Lessel 1997). The daily capacity was 645 m^3 with a target dose of 4 kGy (Lessel 1997).

McKeown et al. (1998) explored the viability of the IMPELA accelerator family for municipal biosolids irradiation. IMPELA is a family of electron linear accelerators first developed in 1988 at the Chalk River Nuclear Laboratories in Ontario, Canada (Lawrence et al 1988). The McKeown team of researchers considered the use of these accelerators for a detoxification process in which a dose of 800 kGy would be necessary to render tetrachlorodibenzo-*p*-dioxin (TCDD) inactive. While this target dose is much greater than the intended target dose for this municipal biosolids irradiation project, the economic and logistical considerations involved in the McKeown study were quite constructive for developing the methodology of this study.

There are other reports of the application of electron-beam accelerator technology in small-scale plants in Germany, Australia, and Japan (Lessel 1997), but these facilities were only operated for 2-4 years. No full-scale plant employing accelerators for biosolids processing has arisen (Wang and Wang 2007).

2.3 Problem Formulation

While the above studies presented useful information regarding the use of electron beam technology for irradiation of biosolids materials, a more detailed dosimetric model was needed to fully understand the nuances of an E-beam treatment process. The approach used in this study was novel because it utilized Monte Carlo simulation to evaluate the dose distribution throughout the entire volume of municipal biosolids subject to the electron beam at any given time.

The problem model included a rectangular parallelepiped of municipal biosolids material directly beneath the electron beam exit window. Although the municipal biosolids model included delivery on a continuous conveyor or flow through an open trough, only the volume of municipal biosolids directly below the exit window is of interest in the dosimetric model.

The key quantity of interest in this model is the ***volume rate*** of municipal biosolids processing. Since the end result of this project was to propose an economically feasible method for using ionizing radiation to process biosolids, this processing rate value was the basis for establishing a suitable model.

3 METHODS

The Monte Carlo N-Particle (MCNP5) radiation transport code was used in this study to model the problem geometries and source term and to simulate the radiation transport in the irradiation scenario.

3.1 Electron Beam Versus Isotopic Sources

Many researchers have examined the use of isotopic gamma-ray sources to irradiate municipal biosolids (Graino and Magnavacca 1998; Lessel 1997; Shah et al 2001). Electron beam technology has not been widely studied for this purpose. However, electron beams are extremely effective for this type of application for two important reasons. First, electron beam accelerators do not require the presence of radioactive material such as the Co-60 and Cs-137 often used in isotopic sources. Conducting an irradiation process without the presence of radioactive material assuages many public concerns regarding nuclear applications. Also, it is much easier to control the directionality of an electron beam. With an isotopic source, the directionality must be controlled using shielding. For these reasons, electron beam irradiation was selected for this study.

3.2 Geometry Specification

Models of the dose deposition in the biosolids and effluent water materials have been developed using the MCNP5 radiation transport code (X-5 Monte Carlo Team, 2003). For the models, only the portion of material directly under the electron beam exit window at any given time was taken into consideration. Therefore, the geometry was defined as a rectangular parallelepiped (rpp) of municipal biosolids or wastewater effluent surrounded on three sides by 2 cm stainless steel, representing the delivery trough. The electron beam was modeled as a rectangular surface source with the dimensions of the beam exit window.

3.2.1 Surfaces

Eleven surfaces were used to define the geometry of this problem. Six plane surfaces were used to delineate the sides of the voxels used in the lattice specification. A macrobody surface was defined in the problem to represent the rectangular parallelepiped of municipal biosolids/effluent material. Three more rectangular parallelepiped (rpp) macrobody surfaces were defined to represent the three sides of the stainless steel delivery trough. The last surface needed to complete the geometry specification of this problem was a sphere at the origin (so) used to define the scope of the radiation transport. The surface cards used to fully specify the geometry of this model are shown in Figure 1.

```
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0
```

Figure 1 Geometry surface card specification

3.2.2 Cells

Five cell cards were used to define the cell card portion for the MCNP5 simulation model. The municipal biosolids rectangular parallelepiped was defined to be inside the rpp macrobody surface created for that purpose. For this model, the FILL card was used on the definition of cell 1, indicating that this cell was filled with a lattice composed of the cell in universe 1. Cell 2 in the MCNP5 input was used to define the lattice in the problem. The stainless steel trough was defined in cell 3 as the union between the volumes contained in cells 14, 15, and 16. The surrounding air in the problem was defined in cell 4. The outside world was defined in cell 5. This portion of the geometry specification allowed a point of reference for the termination of particle tracks in the problem. The cell cards used to specify the geometry in this model are shown in Figure 2. Slices of the voxelized problem geometry taken from the MCNP5 geometry plotter are shown in Figures 3 and 4.

```
1  1 -0.9784 -12                FILL=1          $Sludge
2  1 -0.9784 -7 1 -8 3 -9 5 U=1 LAT=1           $Lattice element
3 4 -8.03   -14:-15:-16                         $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                     $Air
5 0          13                                 $Outside World
```

Figure 2 Geometry cell card specification

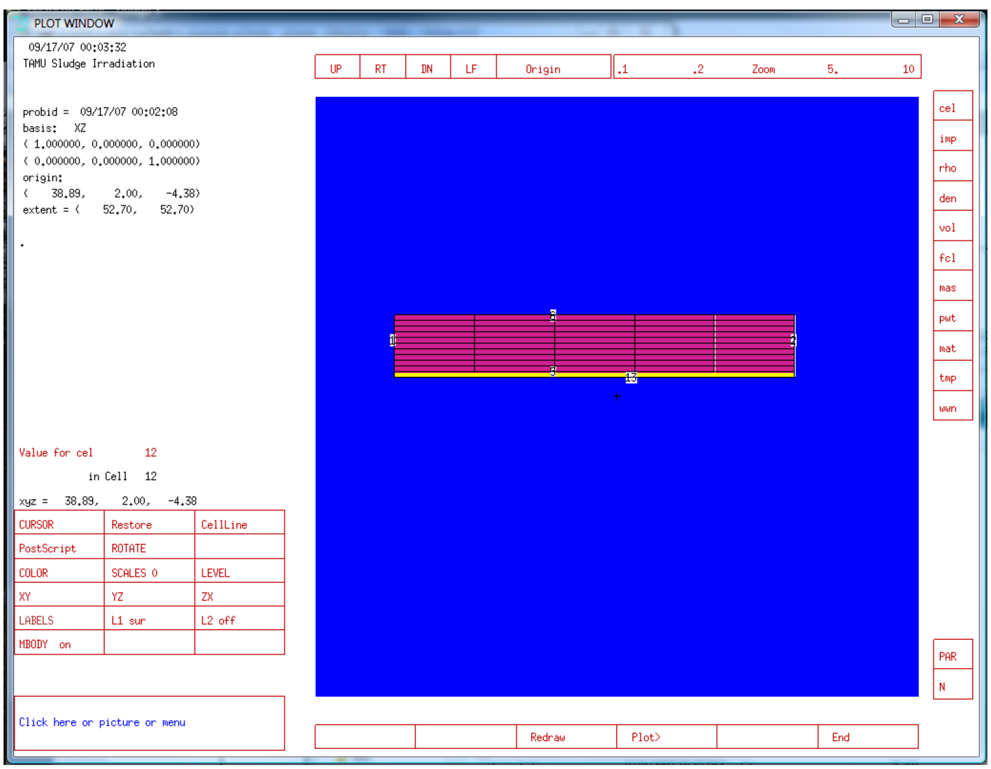

Figure 3 XZ slice of the voxelized problem geometry

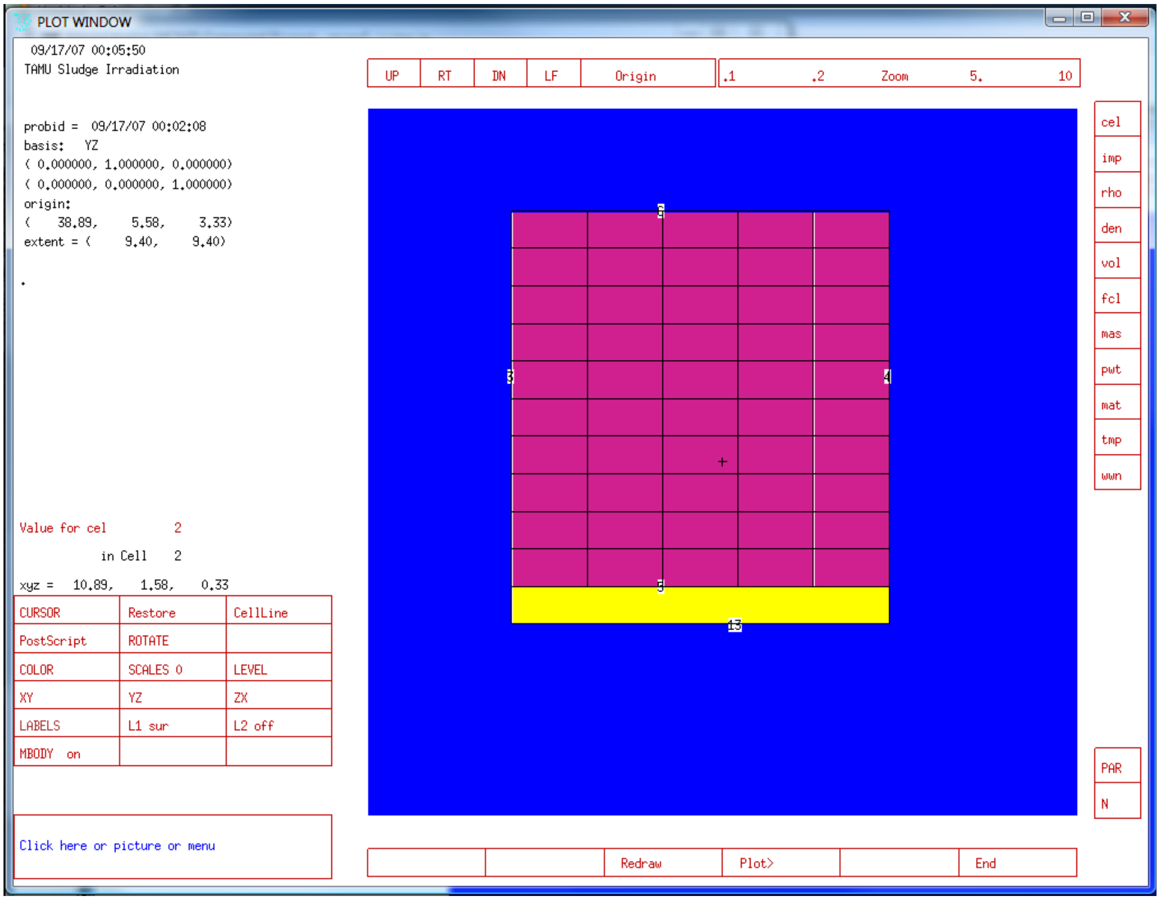

Figure 4 YZ slice of the voxelized problem geometry

3.2.3 Introduction to Lattice Geometries

The lattice geometry specification for the problem at hand not only formed the foundation for the analysis of dose-deposition values in the simulation but also reinforced the value of this type of approach over conventional dosimetry methods.

Because the lattice specification wais an integral part of this study, it is useful to describe the technique as it pertains to the MCNP5 coding of this problem.

Creation of a lattice in an MCNP5 input deck establishes a regular grid within the problem geometry. Each grid location is referred to as an individual "voxel" and is typically a single, homogenized material. Specifying "LAT=1" on the cell card means that the lattice is made of hexahedra, or solids with six faces. "LAT=2" specifies a lattice composed of hexagonal prisms, solids with 8 faces. After designing the lattice, the (0,0,0) element must be defined as well as the directions in which the three lattice indices will increase. Constraints for these choices are explained on page 3-29 of the MCNP5 manual (X-5 Monte Carlo Team 2003). The bounding surfaces of the (0,0,0) element should then be entered on the cell card with the "LAT" keyword in the right order. For a hexahedral lattice cell, such as the one used for the applications in this study, the surfaces should be listed such that the (1,0,0) element is beyond the first surface listed, the (-1,0,0) element is beyond the second surface listed, then the (0,1,0), (0,-1,0), (0,0,1), and (0,0,-1) lattice elements in that order, for a total of six surfaces. The listing of these surfaces fully defines the lattice arrangement to MCNP5.

The "FILL" card is perhaps the most useful portion of the lattice specification for the simulations created for this research. Non-zero entries on the "FILL" card indicate the numbers of the universes that fill the corresponding cell. When the filled cell is a lattice, the "FILL" specification can be a single entry or an array. With an array specification, the portion of the lattice covered by the "FILL" array is explicitly defined, and the rest of the lattice does not exist. For the single entry case on the "FILL" card, every element in the lattice is filled by the same universe. The single-entry definition has been used to define the municipal biosolids or effluent material that is segmented by a lattice grid. More options for filling array elements can be found on page 3-30 of the MCNP manual (X-5 Monte Carlo Team 2003).

Once the lattice has been created and all voxels in the problem have been categorized according to universe, tallying over particular materials or individual voxels becomes a straightforward process. This method becomes very useful for using the MCNP5 code to calculate the dose deposited in small grid elements of the material under study.

3.3 Materials

For the purposes of these simulations, effluent material has been modeled as pure water. For the municipal biosolids material, samples were taken from the Texas A&M University water treatment plant and from the College Station water treatment plant. The Texas A&M sample (TAMU) consists of an anaerobically-digested municipal biosolids. The College Station (ATAD) sample consists of autothermal thermophilic aerobically-digested municipal biosolids. The material compositions for the municipal biosolids samples can be defined using weight fraction compositions including the same sets of elements. The weight fractions were measured by the Texas A&M Soil Testing Laboratory. The material compositions for the TAMU and ATAD municipal biosolids are shown in Tables 2 and 3, respectively. The “ZAID” column in Table 2 is used to write the MCNP5 material card. The digits preceding the period in the ZAID definition represent the atomic number followed by the atomic weight of the isotope. For the values in Tables 2 and 3, the atomic weights were set to "000" to indicate that the naturally-occurring combination of isotopes is used for each element. This is often referred to as the "elemental description." When selecting electron transport tables within MCNP5, nuclides should be given as elemental descriptions (X-5 Monte Carlo Team 2003). The portion of the ZAID definition that follows the period represents the MCNP5 data library identifier followed by the class of data. The class of data is "electrons" represented by "e." The "03" data library is the most recent electron transport library packaged with MCNP5. Therefore, this cross-section library was used in the Monte Carlo simulation.

Table 2 TAMU municipal biosolids sample material composition

TAMU Sludge		**2.6% solids**
ZAID	**Element**	**Weight Fraction**
7000.03e	Nitrogen	0.1681
15000.03e	Phosphorus	0.0383
19000.03e	Potassium	0.0108
20000.03e	Calcium	0.0526
12000.03e	Magnesium	0.0046
11000.03e	Sodium	0.0339
30000.03e	Zinc	0.002385
26000.03e	Iron	0.00862
29000.03e	Copper	0.003477
25000.03e	Manganese	0.001907
6000.03e	Carbon	2.2753
1000.03e	Hydrogen	10.898
8000.03e	Oxygen	86.502

Table 3 ATAD municipal biosolids sample material composition

ATAD Sludge		**4.3% solids**
ZAID	**Element**	**Weight Fraction**
7000.03e	Nitrogen	0.191
15000.03e	Phosphorus	0.0751
19000.03e	Potassium	0.0227
20000.03e	Calcium	0.0852
12000.03e	Magnesium	0.0059
11000.03e	Sodium	0.0386
30000.03e	Zinc	0.002159
26000.03e	Iron	0.00751
29000.03e	Copper	0.00141
25000.03e	Manganese	0.003562
6000.03e	Carbon	3.8669
1000.03e	Hydrogen	10.708
8000.03e	Oxygen	84.992

A stainless steel trough and the air in the room was included in the model as well. Material composition for other materials used in the simulation can be found in the complete input files located in the Appendix to this document.

3.4 Source Definition

The beam exit window was modeled as the radiation source for this problem. The source particles were defined as 10-MeV electrons emitted from a planar source in one direction. Two beam exit windows were modeled to represent a dual-beam configuration—one beam above the material and one beam below the material. For the MCNP5 simulation, separate input files were created for each of the beam sources. The final results were then convolved to represent the combined presence of both beams. The top beam was placed 14 cm from the top surface of the material. The bottom beam was placed 14 cm from the bottom surface of the stainless steel trough. The general source definition (SDEF) cards used to define the top and bottom beam windows are shown in Figures 5 and 6, respectively.

```
SDEF  par=3 erg=10 x=d1 y=d2 z=20 dir=1 vec=0 0 -1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
```

Figure 5 SDEF card representing the top rectangular beam source

```
SDEF  par=3 erg=10 x=d1 y=d2 z=-14.2 dir=1 vec=0 0 1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
```

Figure 6 SDEF card representing the bottom rectangular beam source

3.5 Tallies and Miscellaneous Data Cards

3.5.1 Tallies

Energy deposition per source particle was tallied in each problem for this study. For each material (TAMU municipal biosolids, ATAD municipal biosolids, and effluent water), a comprehensive dose profile was created using *F8 lattice tallies. The *F8 tally is a pulse height tally with modified units of MeV per source particle. The pulse height tally records the energy deposited in a particular cell by each source particle and all secondary particles. For the pulse height tally in particular, microscopic events must be modeled much more realistically than for other tallies (X-5 Monte Carlo Team 2003).

The lattice tally format allows for simplified syntax to specify a tally for particular voxels in a lattice geometry. As specified in the geometry, each lattice element, or voxel, in this problem measures 14 cm x 2 cm x 1 cm. The problem employs 5 voxels in the length (X) dimension, 5 voxels in the width (Y) dimension, and 6 voxels in the depth (Z) dimension for a total of 150 voxels. The tally cards used to specify this lattice tally over 150 total voxels are shown in Figure 7. The FC card shown in the figure is a comment card used to describe the tally in the problem output file.

```
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:4 0:4 0:5])
```

Figure 7 Tally cards used to calculate energy deposited per source particle in each problem voxel.

After obtaining the *F8 tallies from the MCNP5 input file, a conversion equation is necessary to translate the MCNP5 results into calculations for dose rate in the material. The derivation for this conversion is shown in equations (1.2) and (1.3) below.

$$\frac{M\left(\frac{MeV}{e}\right)\cdot I\left(\frac{C}{s}\right)\cdot\frac{1e}{1.602e-19\,C}\cdot\frac{1.602e-13\,J}{MeV}}{m\,(kg)}\cdot\frac{1\,kGy}{1000\,Gy}=D\left(\frac{kGy}{s}\right), \tag{1.2}$$

$$D\left(\frac{kGy}{s}\right)=1000\cdot\frac{MI}{m}, \tag{1.3}$$

where,

M = *F8 tally result,

I = beam operating current, and

m = voxel mass.

3.5.2 Other Data Cards

The mode for this problem was set to "e p," instructing the MCNP code to track all electrons and secondary photons. A "random number generation" (RAND) card was used to increase the number of random numbers between source particles, or the "stride," to 1 million. Each calculation in this study simulated 150,000 to 10,000,000 particle histories to minimize statistical error to less than 5% for each tally. For the large lattice tallies, the "tally no print" (TALNP) card was used to prevent the tallies from printing in the output file, and the "print and dump cycle" (PRDMP) card was used to create a separate file containing the tally values, known as a MCTAL file. Writing to a MCTAL file often allows for easier post-processing of the data.

3.6 Density/Solids Model

MCNP5 was also used to study the effect of solids content on the dose distribution in the material. To study these effects, it was first necessary to find the density of the dewatered municipal biosolids. First, the density of the municipal biosolids samples (watered) was measured using conventional methods. To find the density of the solids, a simple formula was derived using the definition of density:

$$\rho = \frac{m}{V} = \frac{m_a + m_b}{V} = \frac{\rho_a V_a + \rho_b V_b}{V} = \frac{\rho_a V_a}{V} + \frac{\rho_b V_b}{V} \qquad (1.4)$$

$$\rho = \rho_a \omega_a + \rho_b \omega_b \tag{1.5}$$

In equations. (1.4) and (1.5), the subscripts “a” and “b” represent two species in a mixture. For the purposes of this model, subscript “a” represented water, and subscript “b” represented the soil solids. In equation (1.5), “ω” represents the solids volume fraction in each sample. This fraction was measured by centrifuging both municipal biosolids samples at a high speed (8000 rpm) and measuring the volume of the settled solids. The TAMU municipal biosolids sample was found to contain 25.5% solids by volume, and the ATAD municipal biosolids sample was found to contain 37% solids by volume. Using the measured sample densities, the densities for the TAMU and ATAD municipal biosolids solids were calculated to be 0.9153 g/cm^3 and 0.9108 g/cm^3, respectively. By increasing the theoretical solids volume concentrations, linear interpolation was used to calculate the corresponding mass concentrations. These calculations were performed for solids volume concentrations of 50%, 60%, 70%, 80%, and 90%. In order to quote the results in the form of percent solids by mass, a linear interpolation was performed using the sample volume and mass concentrations as the known values as represented by equation (1.6) below.

$$\frac{m_s}{v_s} = \frac{m_p}{v_p}, \tag{1.6}$$

where,

m_s = mass concentration of solids in municipal biosolids sample,

v_s = volume concentration of solids in municipal biosolids sample,

m_p = mass concentration of solids for perturbation (unknown), and

v_p = volume concentration of solids for perturbation.

Evaluating the effect of moisture content on the dose deposition in the municipal biosolids material was deemed valuable for several reasons. First, the moisture content of municipal biosolids will vary depending upon the wastewater processing plant. Evaluating the moisture and corresponding density effects serves to gauge the adaptability of the chosen methods for this study. In addition, particular treatment plants may choose to water or dewater the municipal biosolids to aid in transportability to or from the plant and/or to facilitate transport through the treatment process itself. For example, the municipal biosolids material may need to be dewatered in order to transport it via a conveyor system or watered in order to transport it via a gravity- or pump-fed trough system. Again, evaluation of these effects helps to determine whether changing the moisture content for logistical considerations will greatly affect the efficiency of the treatment process. Lastly, results from some studies have suggested that lowering the moisture content in municipal biosolids material can prevent regrowth of organisms when long-term storage is part of the treatment process (Yeager and Ward 1981). Yeager and Ward found that regrowth was prevented at moisture levels of less than 20% at an optimal temperature of 37°C. Given this assertion, it is important to also evaluate changes in the dose distribution at lower moisture levels in case a dewatering method is used to help prevent organism regrowth.

3.7 Verification Study

3.7.1 Experimental Configuration

To add validity to the use of the MCNP5 radiation transport code for the dose models in this study, a verification study was performed. For the verification study, 20-mL municipal biosolids and water samples were placed into 2” x 3” (5.08 cm x 7.62 cm) zippered storage bags using a 10-mL pipette. Alanine dosimeters were placed at the top left-hand corner, middle interior, and bottom right-hand corner of each bag. Five samples were prepared for each of the material samples, resulting in 15 bags and 45 dosimeters in all. Since alanine is easily damaged by moisture, each dosimeter was heat-sealed into a polyethylene bag. After the bags were loaded with dosimeters, they were taped to a 1/8”-thick (0.3175 cm) polyethylene board. Another polyethylene board was placed on top of the bags. This board was weighted down with bricks to keep the experimental configuration in place while in motion on the electron-beam conveyor. After irradiation, the dosimeter packets were unloaded from the material packets, and the alanine dosimeters were removed from their heat-sealed packaging. Each dosimeter was numbered, and the absorbed dose was read using a Bruker e-scan measuring device. Photographs documenting the experimental procedure are shown in Figures 8 through 14.

The prepared samples were irradiated at the National Center for Electron Beam Food Research located at Texas A&M University. One 10-MeV electron beam located approximately 8.5” (21.6 cm) below the sample box, shown in Figure 13, was used for the irradiation. For this benchmark, the approximate target dose was set by the facility staff at 2.5 kGy. This predicted target dose called for a conveyor speed of approximately 37 ft/min (18.8 cm/s). During the irradiation, the beam current was 1695 μA.

Figure 8 Dosimetry configuration for water samples

Figure 9 Dosimetry configuration for ATAD municipal biosolids samples

Figure 10 Dosimetry configuration for TAMU municipal biosolids samples.

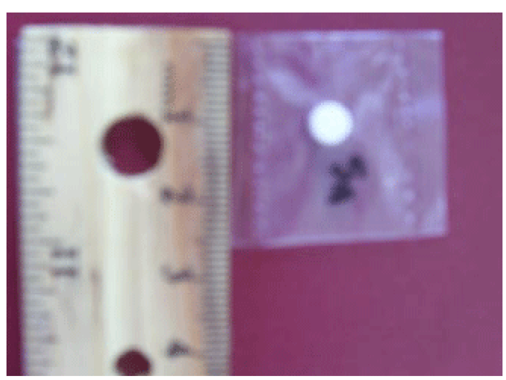

Figure 11   Dosimeter and heat-sealed polyethylene packaging

Figure 12 Dosimetry packets with polyethylene shielding

Figure 13 Dosimetry configuration in box before irradiation

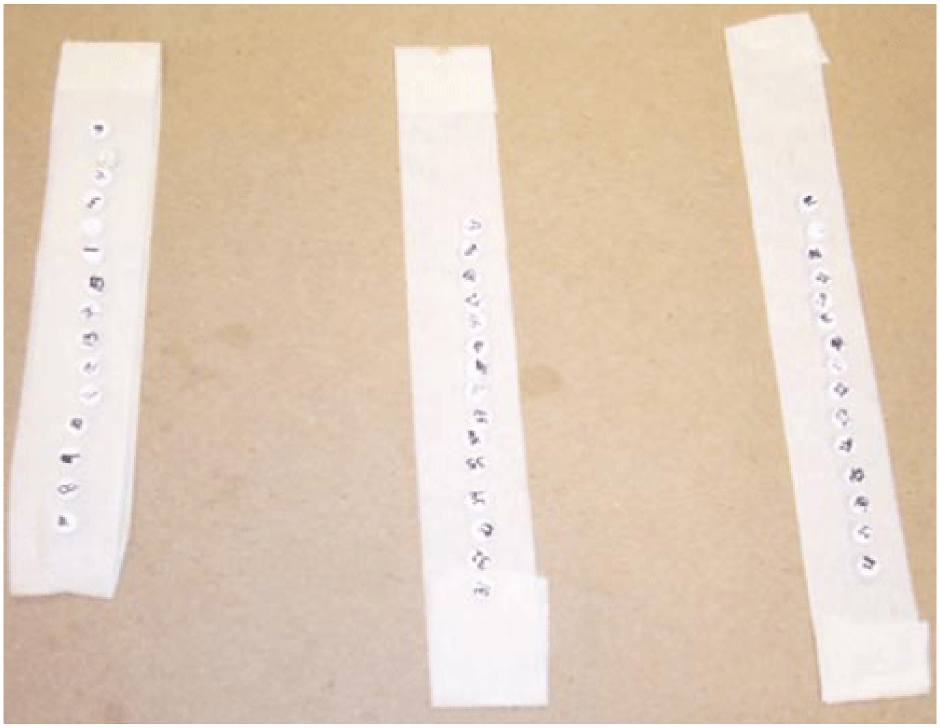

Figure 14 Numbered dosimeters removed from packets after irradiation

3.7.2 Monte Carlo Benchmark Model

For the benchmark verification study, two MCNP5 models were analyzed—a simplified version and a detailed version. For the simplified version, the dosimeter-loaded material packets were modeled along with the lower 10-MeV electron beam. For all models, the electron beam exit window was modeled with dimensions of 29”x4” (73.66 cm x 10.16 cm). The dosimeter packets themselves have not been modeled; only the material (ATAD municipal biosolids, TAMU municipal biosolids or water) and the alanine dosimeters have been included. As an example, the cell cards, surface cards, and data cards used for the simplified effluent water benchmark are shown in Figures 15, 16, and 17, respectively. The cell cards, surface cards, and data cards used for the detailed effluent water benchmark are shown in Figures 18, 19, and 20, respectively.

```
c ******************************
c              CELL CARDS
c ******************************
1 3 -1.0       -1 3
2 1 -1.42      -2
3 1 -1.42     -3
4 1 -1.42      -4
5 2 -0.0012  -5 1 2 4
6 0             5
```

Figure 15 MCNP5 cell cards for simplified water benchmark

```
c *****************************
c          SURFACE CARDS
c *****************************
1 rpp 0 7.62 0 5.08 0 0.516
2 rcc 2 3.08 0.516 0 0 .25 .25
3 rcc 3.81 2.54 0.133 0 0 .25 .25
4 rcc 5.62 2 0 0 0 -.25 .25
5 so  150
```

Figure 16 MCNP5 surface cards for simplified water benchmark

```
c ****************************
c                 DATA CARDS
c ****************************
mode e p
SDEF x=d1 y=d2 z=-21.59 erg=10 par=3 vec=0 0 1 dir=1
SI1 -33.02 40.64
SP1 0 1
SI2 -1.27 8.89
SP2 0 1
c Alanine
m1 6000.03e 3 1000.03e 7 14000.03e 1 8000.03e 2
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c Water
m3 1000.03e 2 8000.03e 1
IMP:e,p 1 1 1 1 1 0
*F8:p,e   2
*F18:p,e 3
*F28:p,e 4
nps 10000000
```

Figure 17 MCNP5 data cards for simplified water benchmark

```
c ******************************
c               CELL CARDS
c ******************************
1 3 -1.0       -1 3                  $ Target cell
2 1 -1.42      -2                    $ Top alanine dosimeter
3 1 -1.42     -3                     $ Middle alanine dosimeter
4 1 -1.42      -4                    $ Bottom alanine dosimeter
5 5 -0.93      -5                    $ Top layer of poly
6 5 -0.93      -6                    $ Bottom layer of poly
7 4 -0.689     -7                    $ Cardboard
8 2 -0.0012  -8 1 2 4 5 6 7          $ Air
9 0             8
```

Figure 18 MCNP5 cell cards for detailed water benchmark

```
c ****************************
c           SURFACE CARDS
c ****************************
1 rpp 0 7.62 0 5.08 0 0.516               $ Target material
2 rcc 2 3.08 0.516 0 0 .25 .25            $ Top alanine dosimeter
3 rcc 3.81 2.54 0.133 0 0 .25 .25         $ Middle alanine dosimeter
4 rcc 5.62 2 0 0 0 -.25 .25               $ Bottom alanine dosimeter
5 rpp 0 7.62 0 5.08 0.766 1.0835          $ Top layer of poly
6 rpp 0 7.62 0 5.08 -0.5675 -0.25         $ Bottom layer of poly
7 rpp 0 7.62 0 5.08 -0.885 -0.5675        $ Cardboard
8 so  150
```

Figure 19 MCNP5 surface cards for detailed water benchmark

```
c ****************************
c                 DATA CARDS
c ****************************
mode e p
SDEF x=d1 y=d2 z=-21.59 erg=10 par=3 vec=0 0 1 dir=1
SI1 -33.02 40.64
SP1 0 1
SI2 -1.27 8.89
SP2 0 1
c Alanine
m1 6000.03e 3 1000.03e 7 14000.03e 1 8000.03e 2
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c Water
m3 1000.03e 2 8000.03e 1
c  Cardboard
m4  6000.03e 6 1000.03e 10 8000.03e 5
c Polyethylene
m5 6000.03e 2 1000.03e 4
IMP:e,p 1 1 1 1 1 1 1 1 0
*F8:p,e   2
*F18:p,e 3
*F28:p,e 4
RAND stride=1000000
nps 10000000
```

Figure 20 MCNP5 data cards for detailed water benchmark

4 RESULTS AND DISCUSSION

Dose-deposition analyses were performed for the municipal biosolids and wastewater effluent irradiation configurations proposed. The data for these analyses were obtained using the MCNP5 radiation transport code. All MCNP5 input files are included in the Appendix to this document. The flexibility of MCNP5 input file construction served as an asset to this study. A single code could, therefore, be modified to accommodate differing materials, material densities, material thicknesses, and voxel sizes.

4.1 Dose Deposition Study

The MCNP5 code was first used to study the dose deposition in the municipal biosolids samples and in effluent water. Dose deposition was calculated in three-dimensional voxels across six X-Y slices and in 25 depth slices. The voxel dimensions were defined as 14 cm x 5 cm x 1 cm. Dose rates were calculated in each of the 150 problem voxels using *F8 lattice tallies in MCNP5. The MCNP5 code employs *F8 tallies to calculate the energy deposition per source particle in specified problem cells. All *F8 tally results were converted to dose rate using Eq. (1.3).

4.1.1 Depth-Dose Analysis

Depth-dose curves were created for the ATAD municipal biosolids, TAMU municipal biosolids, and wastewater effluent models. Curves at each (x,y) location for each material are shown in Figures 21 though 23.

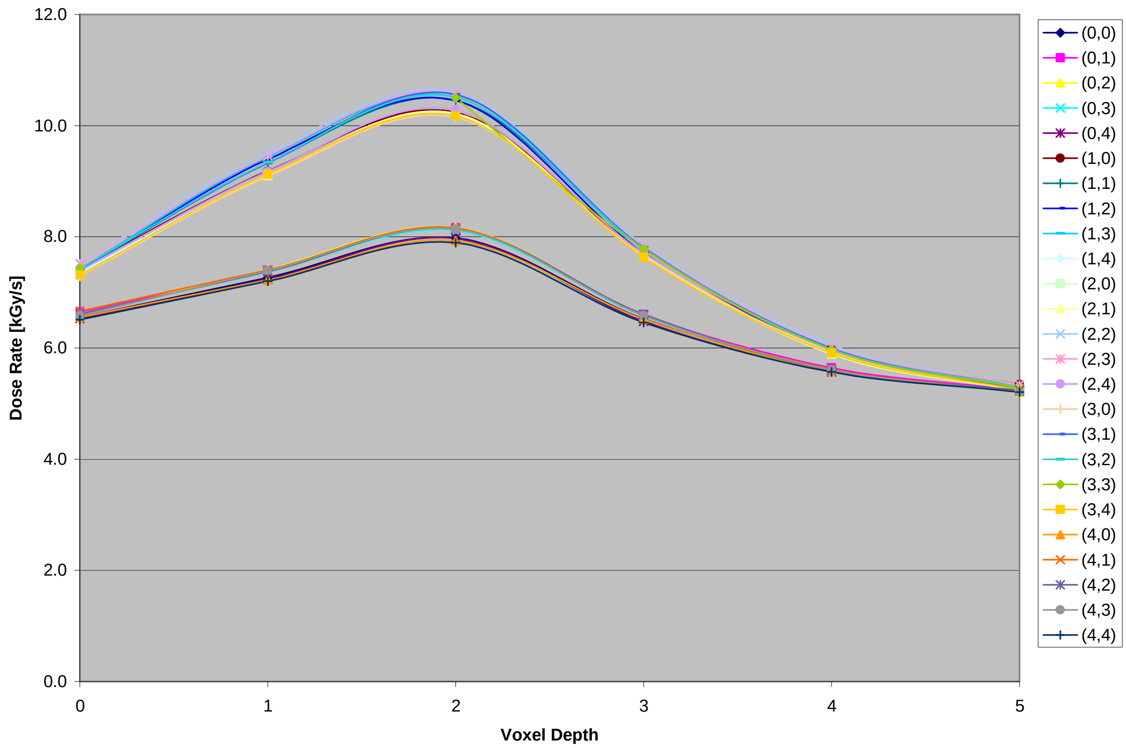

Figure 21 Depth-dose curves for all (x,y) positions in TAMU municipal biosolids material.

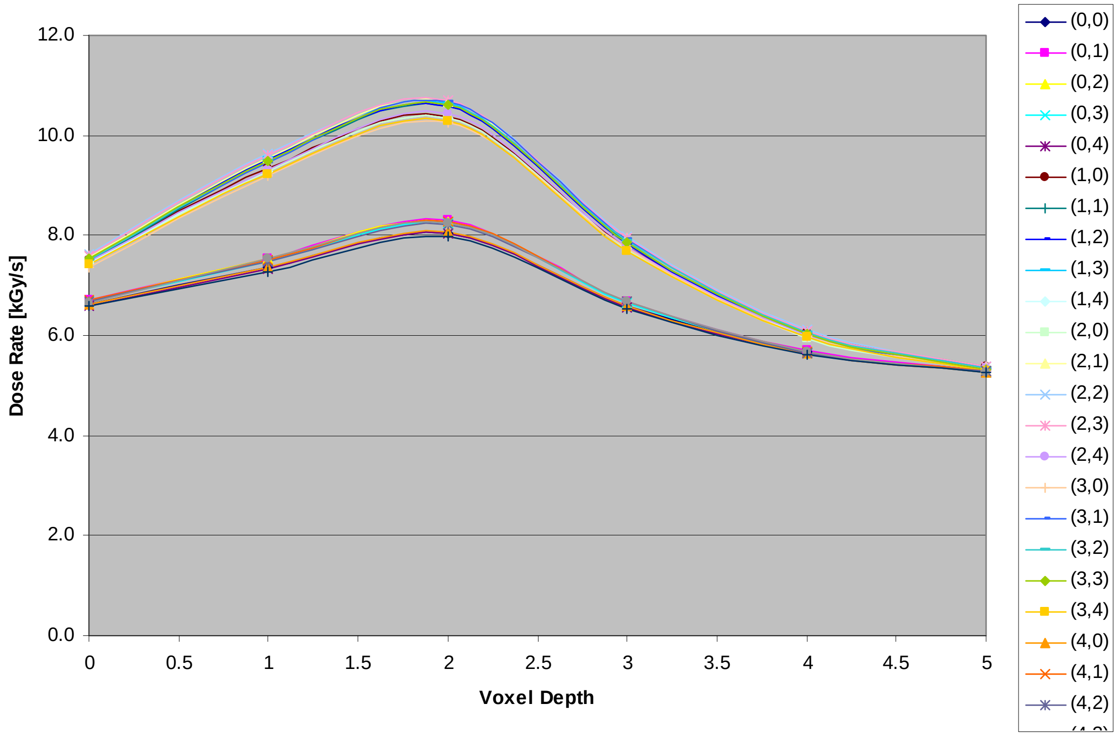

Figure 22 Depth-dose curves for all (x,y) positions in ATAD municipal biosolids material

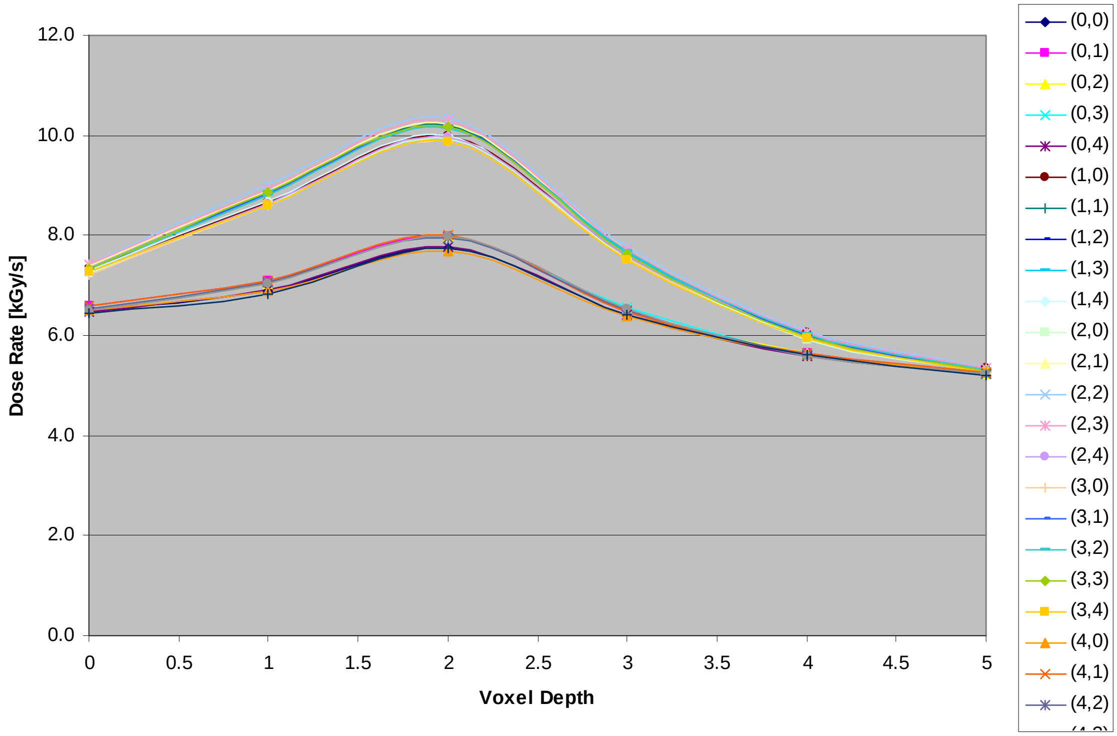

Figure 23 Depth-dose curves for all (x,y) positions in water

The trends in the depth-dose curves for the three materials studied were quite similar. The three materials all show clustering around two average curves. The placement of the curves depends upon the location of the (x,y) pair in the material. The bottom set of curves consists of the points on the two x-dimension borders, i.e. points (0,y) and (4,y). These points were surrounded by less bordering material and thus receive less in-scatter of particles. The points on the two y-dimension borders are not included on this lower curve most likely because the voxels are much shorter in the y-dimension than in the x-dimension. Because of the concentration of curves on any given plot, error bars were not added to the figures. In this case, relative error represents the statistical perturbations in the Monte Carlo simulations. The simulations have been constructed such that all relative errors are less than 5%.

For all curves, the maximum dose rate occurs at the z=2 voxel which extends from 2 to 3 cm from the top of the material rectangular parallelepiped. The minimum dose rate value occurs at the z=5 voxel which extends from 5 to 6 cm from the top of the material rectangular parallelepiped. The bottom of the material receives a smaller dose than the top of the material because some of the electrons scatter and lose energy in the stainless steel of the trough before entering the waste material. The lowest and highest maximum/minimum ratios are shown in Table 4.

Table 4 Lowest and highest maximum/minimum dose ratios for the municipal biosolids and water materials

Material	Lowest Ratio	Highest Ratio
TAMU	1.46	1.93
ATAD	1.52	1.99
Water	1.47	1.93

4.3 X-Y Dose Profile

MatLab plots were created using the MCNP5 data to visualize the dose profile across the X-Y slices of the problem geometry. Each slice extended 1-cm in the Z direction, corresponding to the voxel dimension in that direction. This method resulted in six X-Y slices. The mesh plots for each slice are shown in Figures 24 through 29, categorized by material. The color bars on each figure range from 5.2 kGy/s to 10.8 kGy/s. All color bar values have been set to this range to achieve consistency between the models.

Through examination of these slice figures, two trends are evident. First, all plots are nearly symmetric. It is assumed that any asymmetry is a result of the statistical fluctuation in the results. All 150 voxels were not examined to confirm this as fact, but visual symmetry suffices to confirm that the modeled results conform to the expectations of symmetry in the geometry. No geometrical nuances exist as explainable influences that might result in asymmetry in the dose results. Second, the values in any one plot become more uniform as the slices reach the bottom of the geometry.

In the following figures (24-29), one will notice that the three plots in each figure fall in the same regions on the color scale except in Figure 25. In Figure 25, the water dose distribution is just low enough to move the voxels down a notch on the color scale. The depth-dose values for the water sample take longer to reach a maximum. This trend is evident most prominently in the dose distribution values for slice 1 of the geometry.

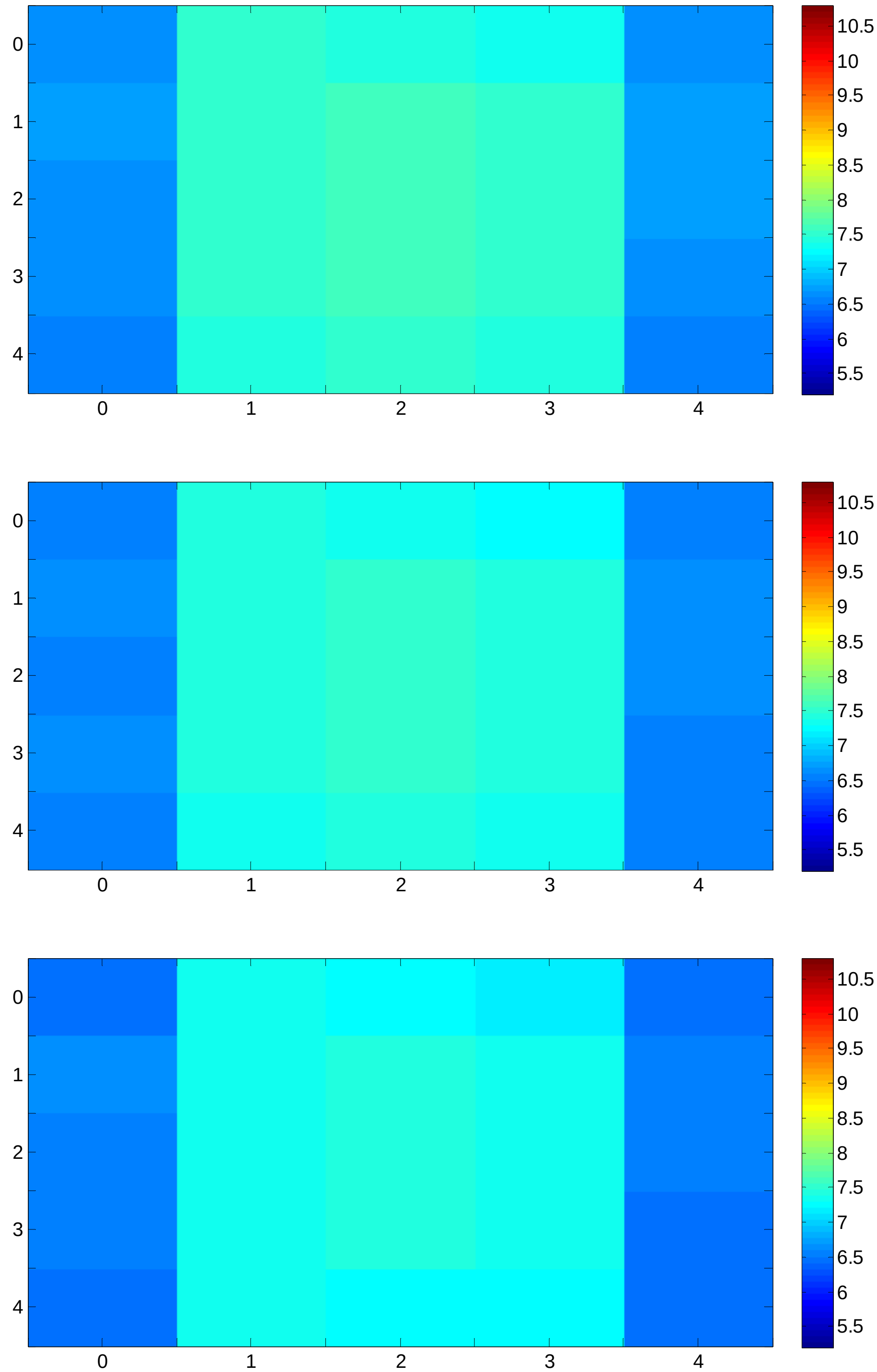

Figure 24 Slice 0 of the ATAD (top), TAMU (middle), and water (bottom) material dose deposition studies

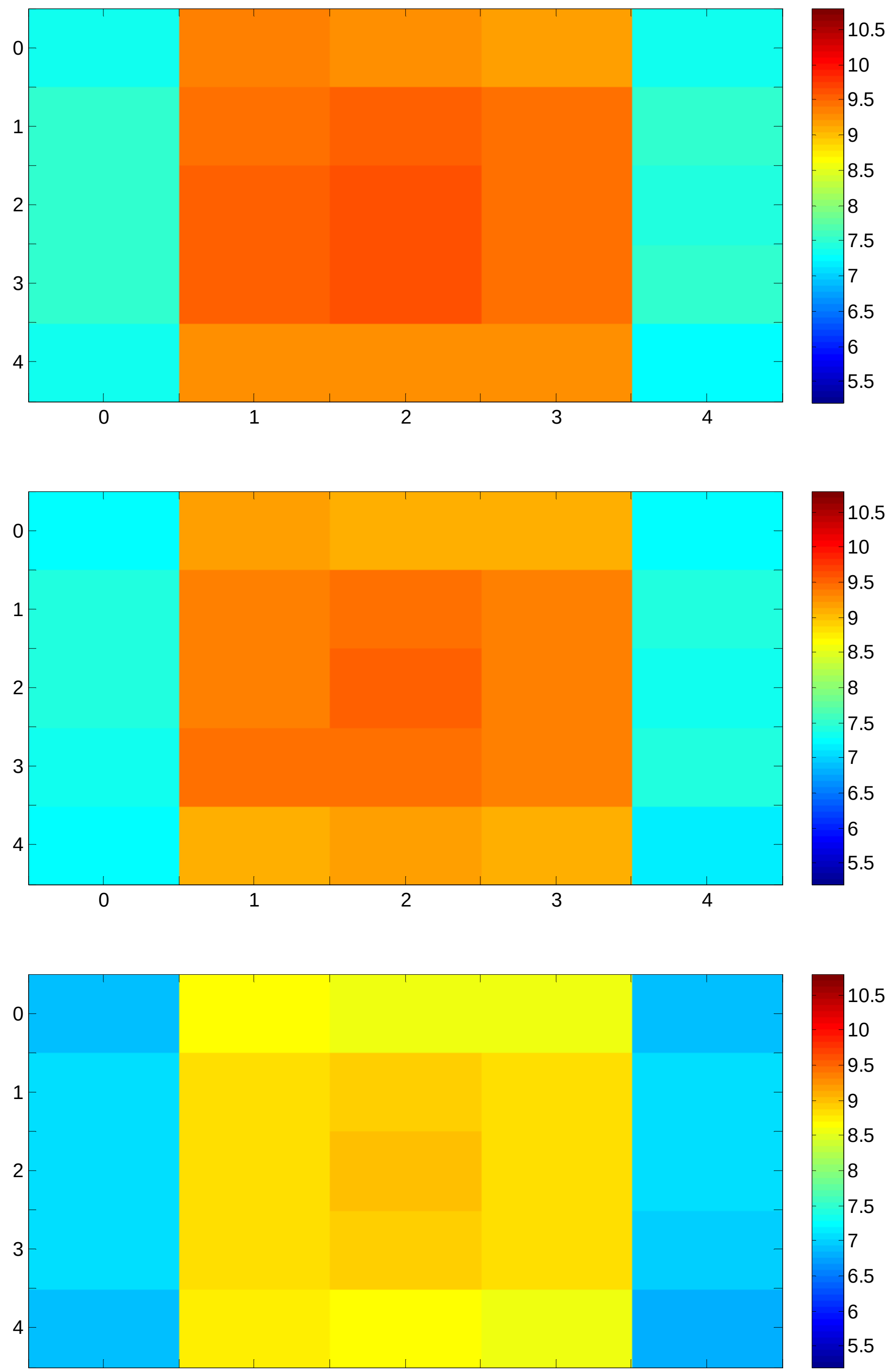

Figure 25 Slice 1 of the ATAD (top), TAMU (middle), and water (bottom) material dose deposition studies

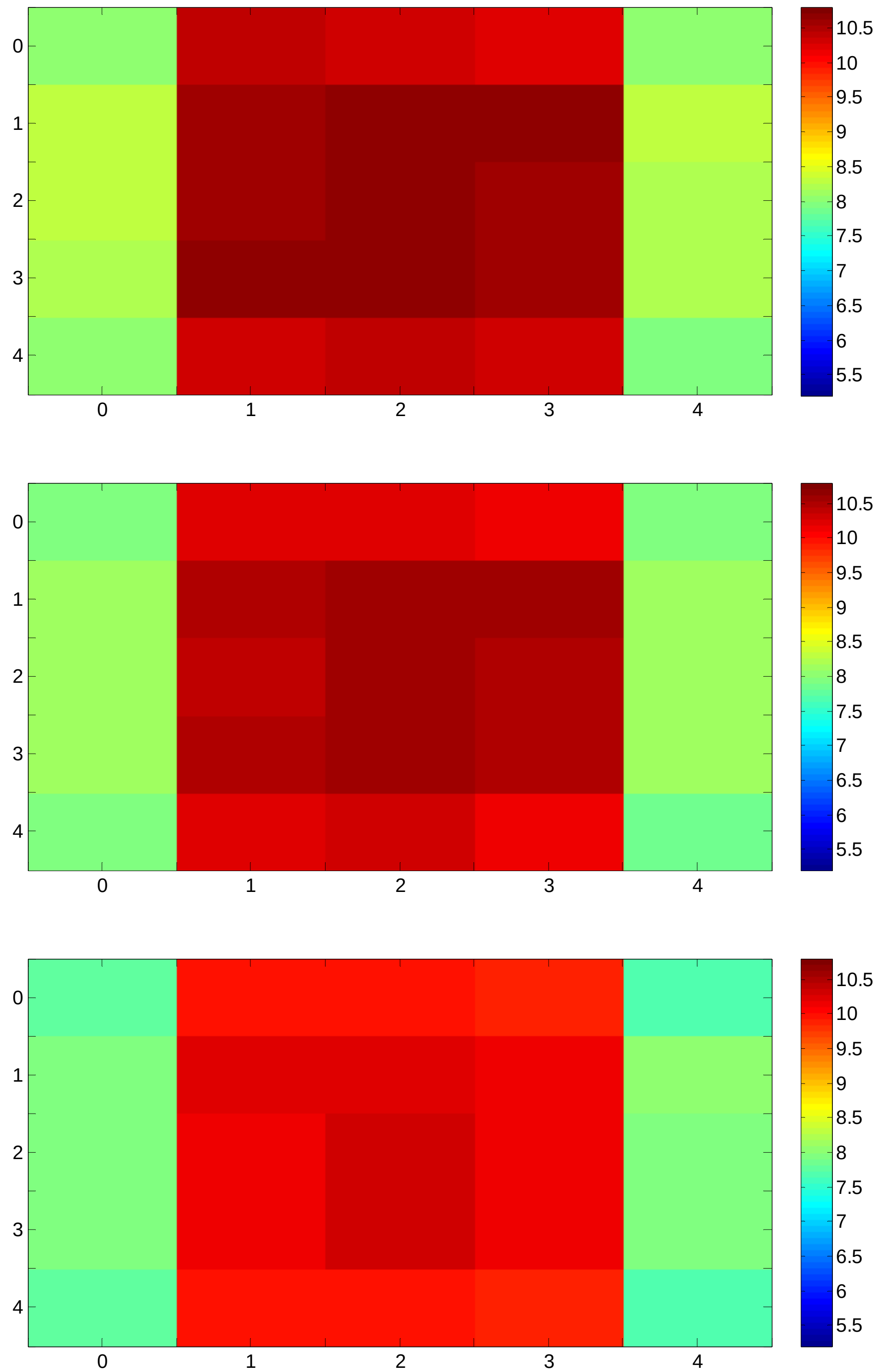

Figure 26 Slice 2 of the ATAD (top), TAMU (middle), and water (bottom) material dose deposition studies

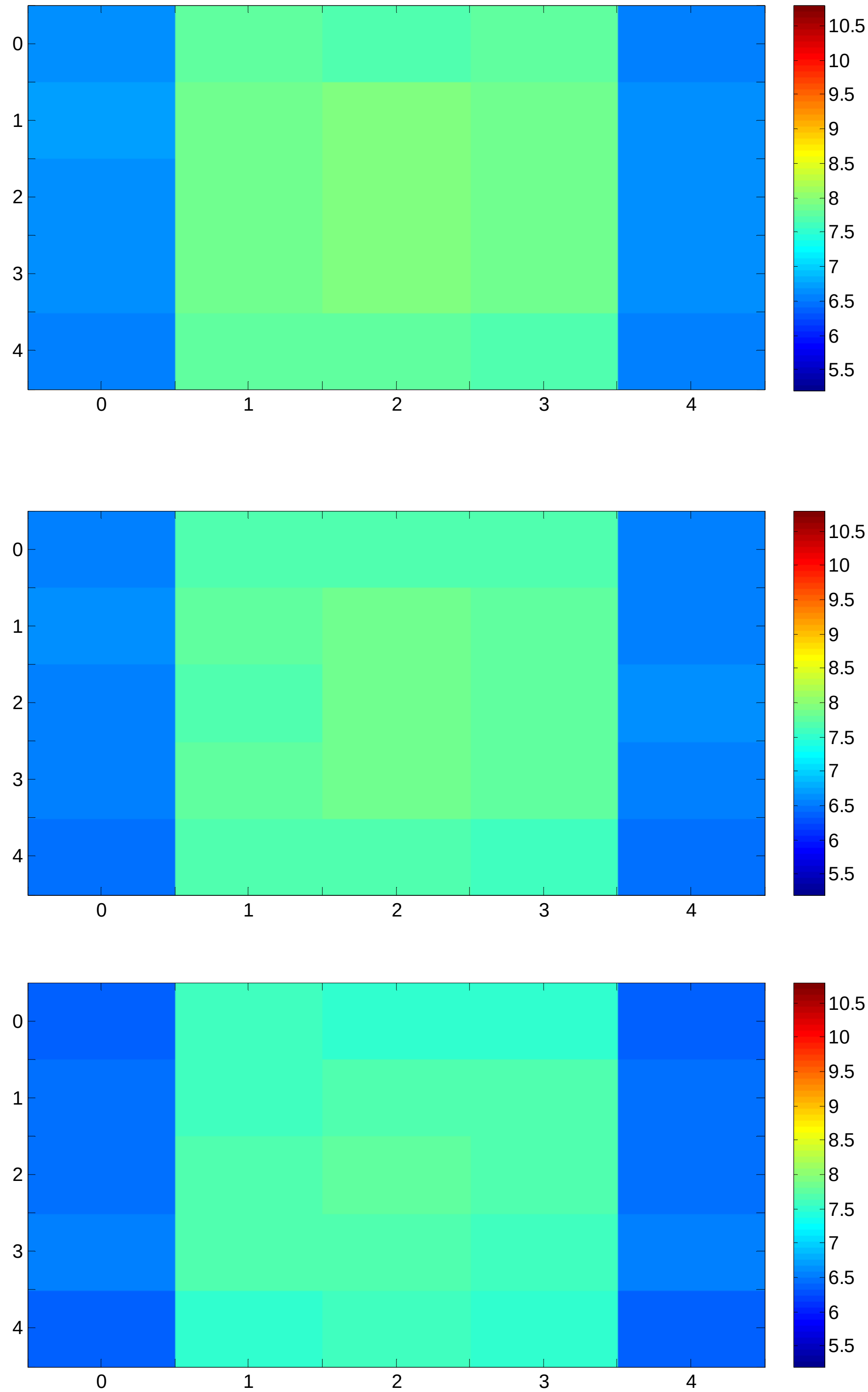

Figure 27 Slice 3 of the ATAD (top), TAMU (middle), and water (bottom) material dose deposition studies

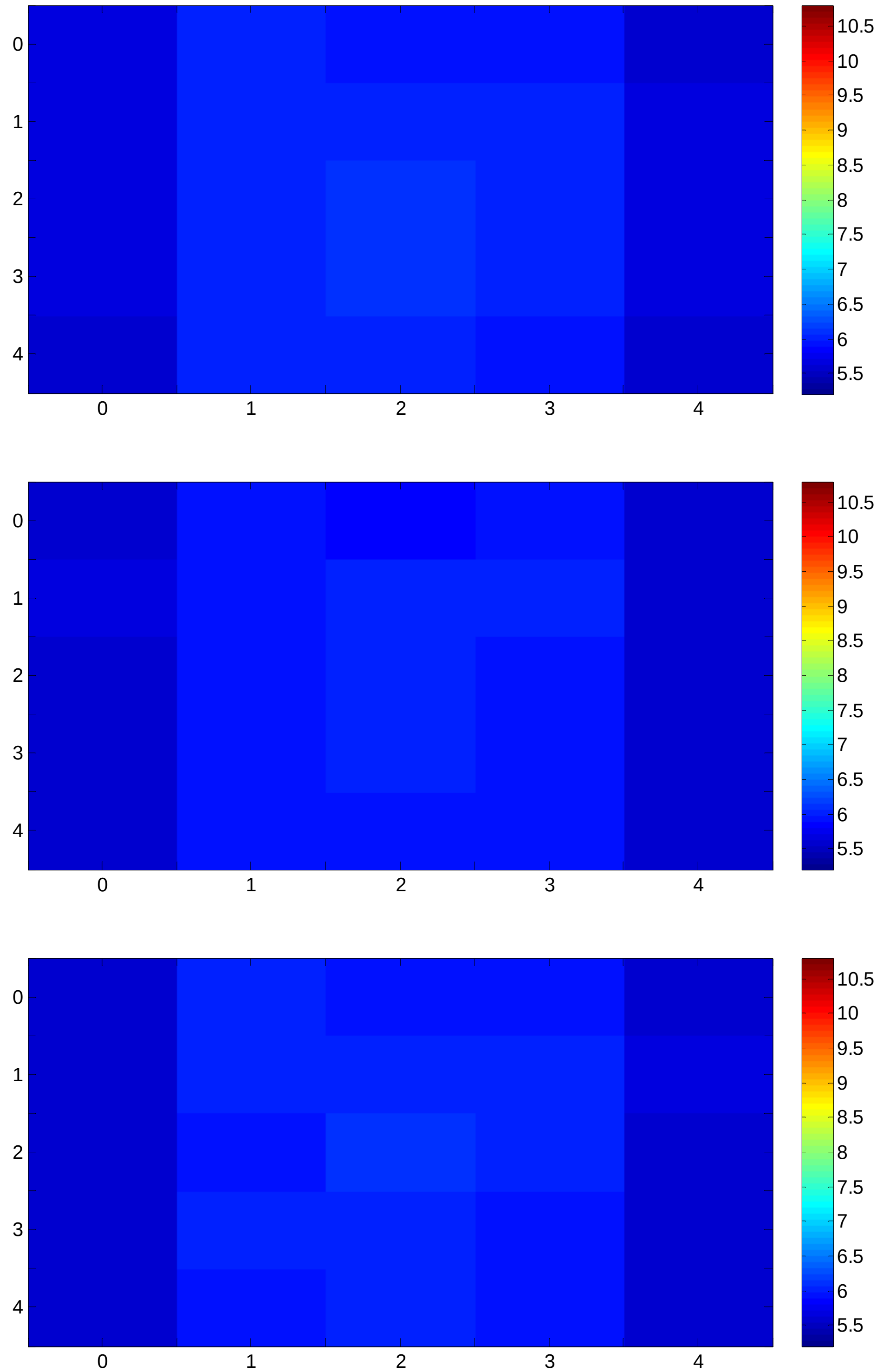

Figure 28 Slice 4 of the ATAD (top), TAMU (middle), and water (bottom) material dose deposition studies

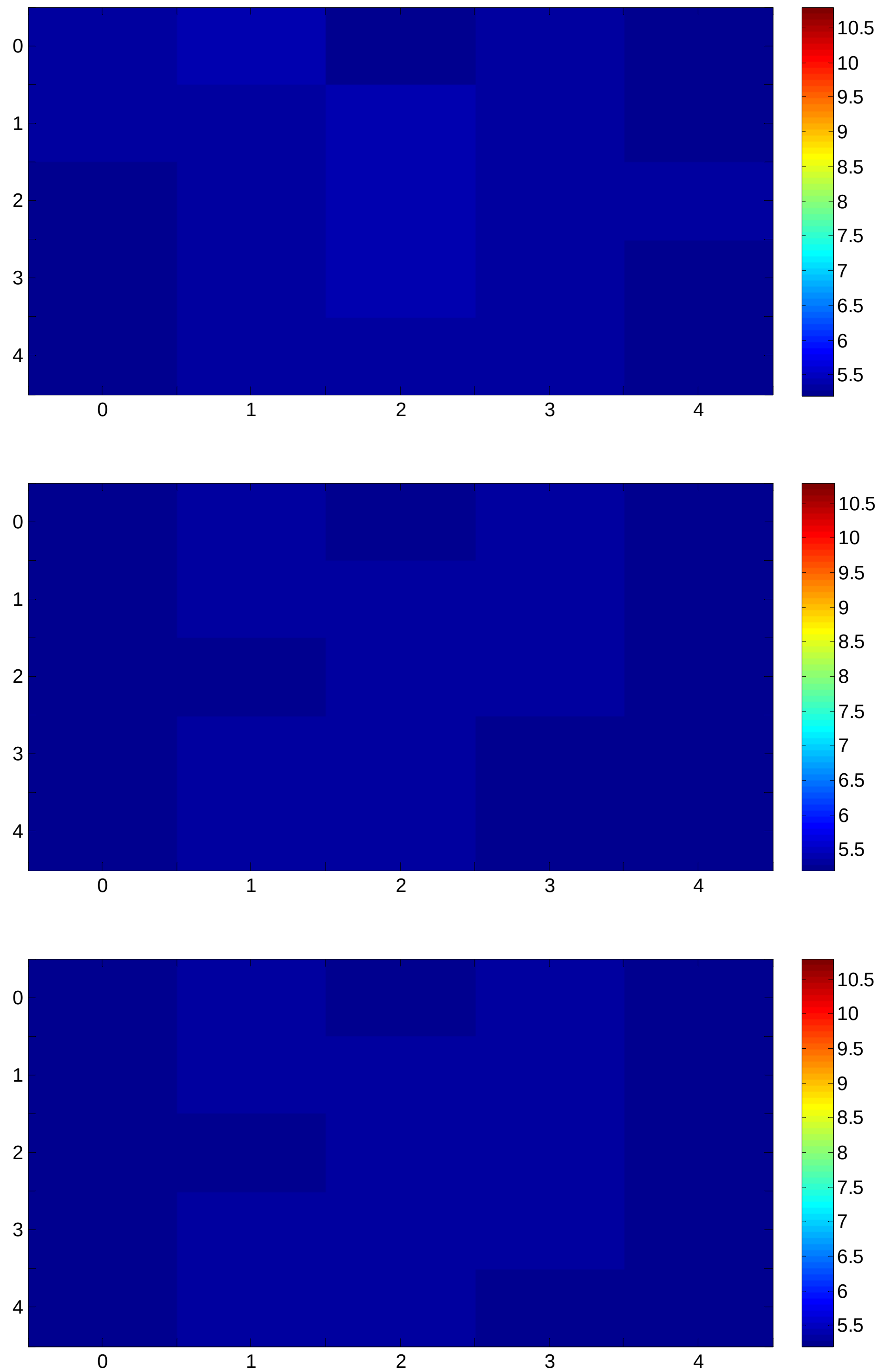

Figure 29 Slice 5 of the ATAD (top), TAMU (middle), and water (bottom) material dose deposition studies

4.4 Density Study

To analyze the adaptability of this study for applications with other material compositions, a density perturbation study was performed for the TAMU and ATAD municipal biosolids samples used for this project. The density calculations were performed as described in Section 3.5. The depth-dose curves for mass concentrations of 4.30%, 5.81%, 6.97%, 8.14%, 9.30%, and 10.46% in ATAD municipal biosolids are shown in Figure 30.

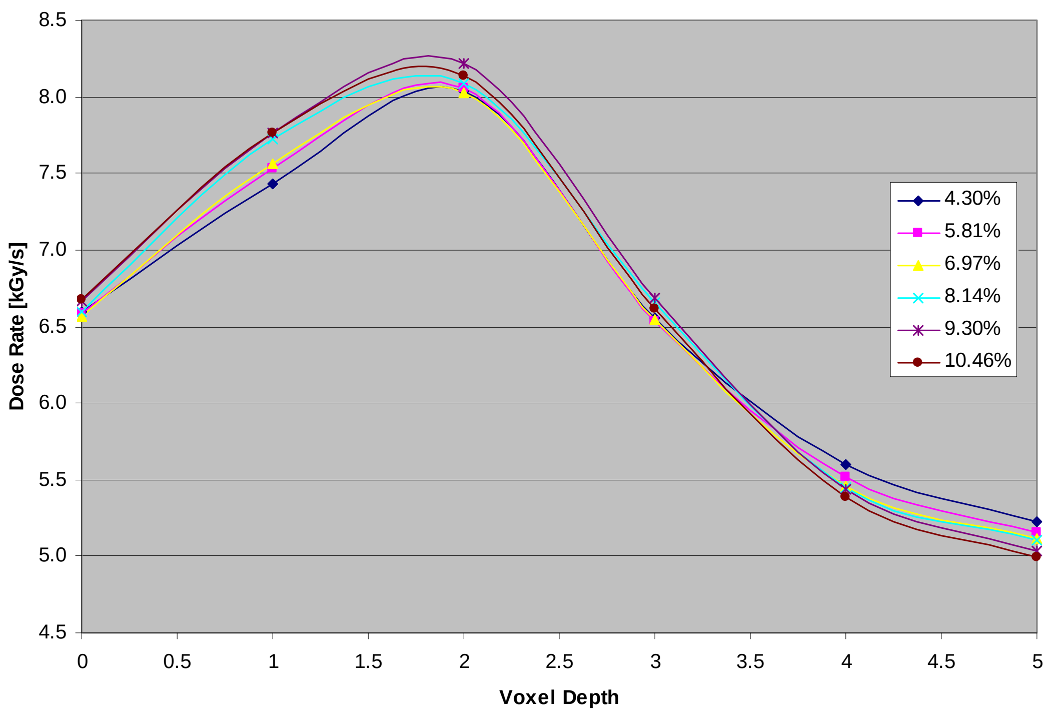

Figure 30 Depth-dose curves for perturbation of mass solids concentration in ATAD municipal biosolids

The depth-dose curves for mass concentrations of 2.60%, 5.10%, 6.12%, 7.14%, 8.16%, and 9.18% in TAMU municipal biosolids are shown in Figure 31.

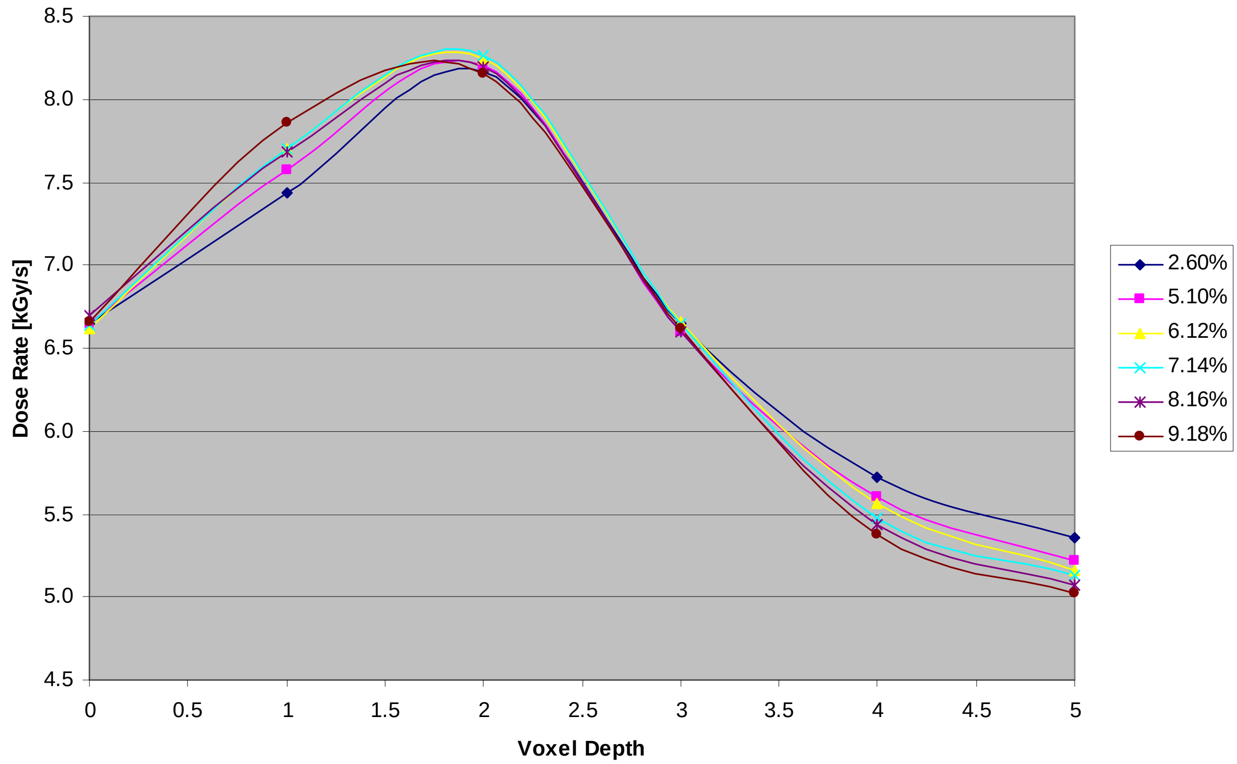

Figure 31 Depth-dose curves for perturbation of mass solids concentrations in TAMU municipal biosolids

The depth-dose curve variations in Figures 27 and 28 show the same trend. As mass concentration increases, the dose rate values increase in the area before the pivot point and decrease in the area after the pivot point. These examples show that the types of atoms in a material have more bearing on the dose rate result than the concentration of those atoms. Since the dry municipal biosolids material has a specific gravity less than 1, an increase in solids concentration lowers the overall density of the mixture. However, increased electron scatter in the municipal biosolids material raises the depth-dose curve as the solids concentration increases.

4.5 Benchmark Study

A benchmark study was performed to validate the use of MCNP5 software for studying wastewater municipal biosolids and wastewater effluent irradiation. Two MCNP5 models were constructed for the study. The first model (simplified) included only the material and dosimeters in the packets placed above the electron beam window. The second model (detailed) included the material packets, electron beam exit window, polycarbonate plates, and the bottom of the cardboard box. For the purpose of the models, the material packets were modeled individually, and the experimental values were averaged for each set of material packets.

As in the previous MCNP5 models, *F8 tallies were employed in the problem to record the simulated energy deposition in units of MeV/source particle. To convert these values to overall dose deposited in each dosimeter, Eq. (1.3) was used to first calculate the dose rate in each dosimeter. This dose rate was multiplied by the time it took for the sample to pass over the beam exit window, 0.54 seconds in this case.

Figure 32 shows the top-to-bottom depth-dose curves for the dosimeter placements in the experiment, simplified model, and detailed model. Table 5 shows the dose deposition values and the fractional difference between the models and the experimental values. Since the goal of this exercise was to benchmark the Monte Carlo code, the experimental values were taken as the "true" values for the fractional difference calculation.

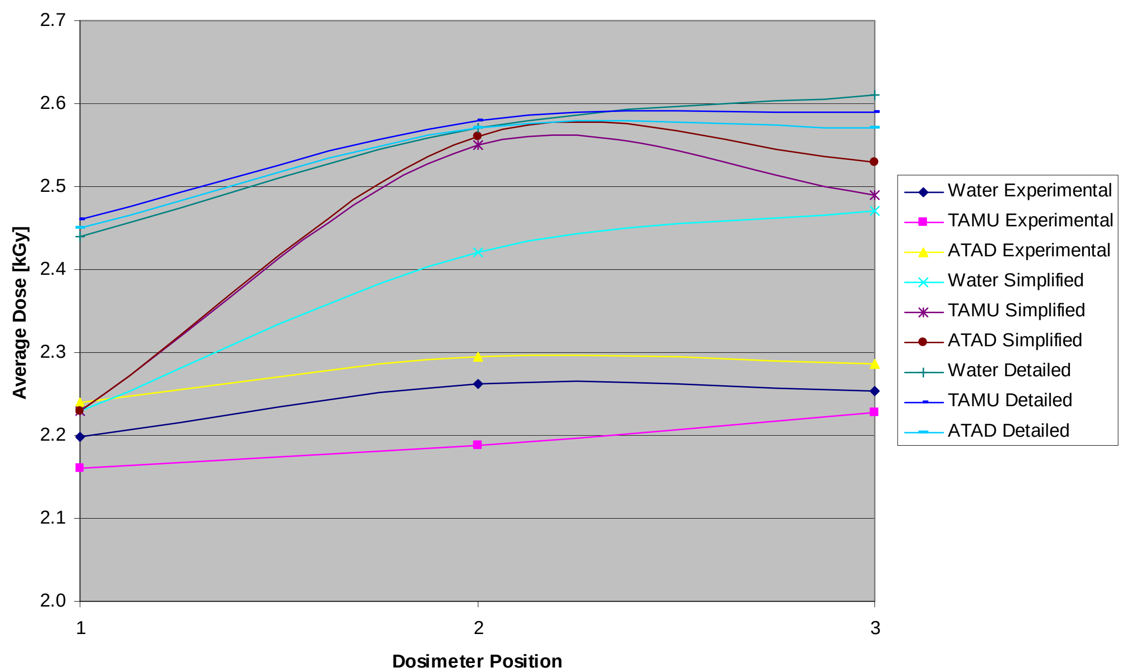

Figure 32 Top-to-bottom dosimeter dose values for the experimental, simplified model, and detailed model benchmark study values

Table 5 Dose deposition values by alanine dosimeter position for the experimental, simplified Monte Carlo, and detailed Monte Carlo results along with corresponding relative errors (RE)

		Experimental	Simplified Monte Carlo			Detailed Monte Carlo		
Material	Position	Dose [kGy]	Dose [kGy]	RE	Difference	Dose [kGy]	RE	Difference
Water	3	2.25	2.47	0.0222	0.096	2.61	0.0215	0.158
Water	2	2.26	2.42	0.0227	0.070	2.57	0.0214	0.136
Water	1	2.20	2.23	0.0234	0.015	2.44	0.0228	0.110
TAMU	3	2.23	2.49	0.0219	0.118	2.59	0.0214	0.162
TAMU	2	2.19	2.55	0.0220	0.165	2.58	0.0219	0.179
TAMU	1	2.16	2.23	0.0234	0.032	2.46	0.0228	0.139
ATAD	3	2.29	2.53	0.0218	0.107	2.57	0.0215	0.124
ATAD	2	2.30	2.56	0.0219	0.115	2.57	0.0219	0.120
ATAD	1	2.24	2.23	0.0234	0.004	2.45	0.0228	0.094

In Figure 32, the result curves cluster according to type (experimental, simplified, or detailed) rather than by material. This is to be expected since the material compositions differ less than the actual result methodologies. Table 5 shows that difference between the simplified Monte Carlo values and the experimental values varies from 0.4% to 16.5%. The difference between the detailed Monte Carlo values and the experimental values varies from 9.4% to 17.9%. These difference values do not take into account the statistical relative errors that are also given in Table 5. It is the opinion of the author that these difference values indicate excellent correlation between the experimental measurements and the modeled dose deposition calculations. In turn, these values show convincing evidence that Monte Carlo simulation is a useful tool for analyzing dose deposition in the wastewater materials considered for this study.

5 ECONOMIC ANALYSIS

Economic viability of a wastewater treatment plant is most easily analyzed by first determining the throughput rate of the treatment process. The lowest dose rate across all materials for all voxel units in the study was 5.2 kGy/s. By using the lowest dose-rate values for each material and a target dose of 15 kGy, it has been determined that each voxel of material should be exposed to the electron beam for 2.88 seconds. Throughput rates have been calculated for an electron beam configuration similar to that of the National Center for Electron Beam Food Research (NCEBFR) at Texas A&M University. The Texas A&M facility utilizes two 18-kW accelerators operating at approximately 2 mA current. Using the samples from the College Station and Texas A&M University wastewater treatment plants as examples, i.e., mass concentrations of 2.6% for TAMU and 4.3% for ATAD, the mass flow rate of material under the beam window will be 1.5 kg of dry ATAD municipal biosolids in 2.88 seconds and 1.05 kg of dry TAMU municipal biosolids in 2.88 seconds. These values result in throughput rates of 11,250 dry tons of ATAD municipal biosolids per year and 7,875 dry tons of TAMU municipal biosolids per year. These calculations assume 20 hours of operation per day for 300 days per year at 2 mA current. This plant can also process $3.15\text{x}10^7$ L/y of effluent water.

Throughput rates have also been computed for an accelerator system similar to the IMPELA specifications of 50-kW power and 100-mA operating current. Eq. (1.3) stipulates that the dose rate imparted by the electron beam system is directly scaled by the operating current. Therefore, the throughput values are directly scaled as well. The throughput capacities for the 2-mA and 100-mA accelerator cases are shown in Table 6 in units of dry tons/year and m^3/day.

Table 6 Throughput capacity rates for the 2-mA and 100-mA accelerator cases

	Capacity (dry tons/year)		**Capacity (m^3/day)**	
	TAMU	ATAD	TAMU	ATAD
I=2 mA, P=18 kW	7,875	11,250	28.63	38.78
I=100 mA, P=50 kW	393,750	562,600	1332	1927

To calculate the capital cost per dry ton, it was assumed that a dual-beam facility would cost on the order of $15 million (personal communication from I-Ax Technologies). The amortization of this value over 10 years at 7% interest with a 20% ($3 million) down payment would result in monthly payments of $139,330. With the throughput rates calculated above, the capital cost for ATAD municipal biosolids processing will be $258 per dry ton with the NCEBFR electron beam specifications and $5.16 per dry ton with the IMPELA electron beam specifications. The capital cost for TAMU municipal biosolids processing will be $369 per dry ton with the NCEBRF specifications and $7.37 with the IMPELA specifications. The capital cost for processing the effluent water will be $0.092/L with the NCEBRF specifications and $0.00184 with the IMPELA specifications.

To evaluate the operating cost per dry ton, factors of electricity, labor, administration, and miscellaneous items were considered. Two 18-kW accelerators operating 6000 hours per year will consume 216,000 kW-h of electricity. At $0.10/kW-h, yearly electricity costs for the beam configuration will be $21,600. Electricity for the facility was expected to cost approximately $30,000 per year. For maintenance of the facility, $200,000 per year was budgeted. An average salary of $50,000 per year per employee for 20 employees will cost $1 million per year. In addition, $150,000 has been budgeted for administrative costs and $100,000 has been budgeted for miscellaneous expenses. These expenses result in a total yearly operating cost of $1.502 million. The given throughput rates result in operating costs of $232/dry ton for ATAD municipal biosolids, $331/dry ton for TAMU municipal biosolids, and $0.083/L of effluent water. The economic breakdown for the facility operating costs is shown in Table 7.

Table 7 Assumed facility operating costs

Item	**Cost per Year**
Electricity	$51,600
Maintenance	$200,000
Labor	$1,000,000
Administration	$150,000
Miscellaneous	$100,000
Total Operating Costs	$1,501,600

Operating costs were determined for the NCEBFR and IMPELA accelerator specifications. Since the IMPELA operates at 50 kW with a current of 100 mA, the increased current increases the dose rate in the material by 50 times, allowing 50 times the material processing capacity provided by the 2 mA accelerators. However, the electricity operating cost for the accelerators increases by 2.8 times as a result of the increased power. Therefore, the operating costs in this case will total $1.54 million as opposed to $1.50 million for the 2 mA case. The operating cost per dry ton per year for the ATAD and TAMU municipal biosolids processed under NCEBFR conditions will equal $232 and $378, respectively. These operating costs are drastically reduced when the IMPELA specifications are considered. The operating cost per dry ton per year under IMPELA specifications for the ATAD and TAMU municipal biosolids processing will equal $4.75 and $6.79, respectively. These figures assume that the accelerator exit window can be fabricated with the same dimensions for both the 2 mA and 100 mA cases. These values compare favorably with the IMPELA concept studied by McKeown et al (1998). The IMPELA study calculated the capital cost for an $8 million facility at $444 per dry ton and the operating cost at $378/dry ton (McKeown et al., 1998). Given that these values represent an imparted dose of 800 kGy, the IMPELA system can be expected to cost approximately $8.33 in capital costs per dry ton and $7.08 in operating costs per dry ton to achieve a 15 kGy target dose. The operating and capital costs for processing TAMU and ATAD municipal biosolidss with the 2-mA and 100-mA accelerators as designed for this research are given in Table 8.

Table 8 Operating and capital costs for processing TAMU and ATAD municipal biosolids with 2-mA and 100-mA accelerator systems

	Operating Cost ($/dry ton)		**Capital Cost ($/dry ton)**	
	TAMU	ATAD	TAMU	ATAD
I=2 mA, P=18 kW	378	232	369	258
I=100 mA, P=50 kW	6.79	4.75	7.37	5.16

An economic viability study for this irradiation design would be incomplete without a comparison with other traditional wastewater treatment methodologies. Table 9 gives the cost per dry ton for incineration, thermophilic aerobic digestion, co-composting, thermophilic anaerobic digestion, thermophilic alkaline treatment, and heat drying. While the cost estimates for processing with the 2-mA accelerator system are not competitive with these methods directly, it is important to remember that the methods in Table 9 are often used in tandem. However, the 100-mA irradiation scenario is much less expensive than any conventional method taken individually. The McKeown et al. (1998) study showed that 100-mA accelerators can be effectively employed for this purpose, supporting a claim that electron beam irradiation is far more cost effective than conventional wastewater treatment methods. It is not necessary to take into account the cost of anaerobic and aerobic pre-treatment of the ATAD and TAMU municipal biosolidss, respectively, since the 15-kGy target dose is expected to function as an independent treatment step with no additional pretreatment needed.

Table 9 Cost of conventional wastewater treatment technologies

Method	Cost ($/dry ton)
Incineration	250
Thermophilic Aerobic Digestion	180
Co-composting	150
Thermophilic Anaerobic Digestion	110
Thermophilic Alkaline Treatment	85
Heat Drying	85

6 CONCLUSIONS

This study concludes that utilizing electron beam technology for the processing of wastewater municipal biosolids and effluent is technologically and economically feasible. The MCNP5 software was shown to produce accurate results for dose deposition values within the materials studied. Given the validity of the software simulation, the flexibility of this approach further reinforced its merit in this type of application. The throughput rates calculated for this process are higher than those in the IMPELA (McKeown et al., 1998) study, and the capital and operation costs per dry ton were lower. The costs are also competitive with conventional wastewater treatment processes.

The purpose of this study was not only to analyze the data for the specific processing configuration described but also to serve as a guide for developing a similar analysis for a facility with different specifics. Specifications for geometry, electron energy, beam exit window locations, and material compositions can all be changed in the included MCNP5 input files to adapt the simulation to new conditions. In addition, individual values in the conversion equations developed throughout this report can be altered to reflect the specific conditions of other electron beam treatment facility scenarios.

7 FUTURE WORK

In the future, analysis of a wider variety of municipal biosolids samples would help to form a more complete picture of the adaptability of this study to other regions of the country and world. It would be particularly helpful to utilize samples from cities with a distinctive industry presence that might contribute different compounds to a biosolids mixture. The TAMU and ATAD municipal biosolids materials studied in this research did not show appreciably different depth-dose profiles. However, these materials were taken from a specific region of the United States. Other regions may produce municipal biosolids with very different material compositions from the samples studied in this research. The effects resulting from more diverse material samples should be studied.

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APPENDIX

A-1 Dose Analysis Models

```
TAMU Municipal biosolids Irradiation - Beam on Bottom
c ***************************************
c          Cell Cards
c ***************************************
1  1 -0.9784 -12          FILL=1            $Municipal biosolids
2  1 -0.9784 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                        $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                 $Air
5 0        13                                       $Outside World

c ***************************************
c         Surface Cards
c ***************************************
1  px  0
2  px  70
3  py  0
4  py  10
5  pz  0
6  pz  6
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c ***************************************
c          Material Cards
c ***************************************
c
c  TAMU Municipal biosolids
m1    7000.03e -0.1681
     15000.03e -0.0383
     19000.03e -0.0108
     20000.03e -0.0526
     12000.03e -0.0046
     11000.03e -0.0339
```

```
    30000.03e -0.002385
    26000.03e -0.008620
    29000.03e -0.003477
    25000.03e -0.001907
     6000.03e -2.2753
     1000.03e -10.9
     8000.03e -86.5
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
     15000 -0.045 16000 -0.03 26000 -68.595
c
c ******************************************
c        SOURCE DEFINITION
c ******************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=-14.2 dir=1 vec=0 0 1
SI1 0 70
SP1 0 1
SI2 0 10
```

```
TAMU Municipal biosolids Irradiation - Beam on Top
c ***************************************
c          Cell Cards
c ***************************************
1  1 -0.9784 -12          FILL=1            $Municipal biosolids
2  1 -0.9784 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                     $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                 $Air
5 0         13                              $Outside World

c ***************************************
c          Surface Cards
c ***************************************
1  px  0
2  px  70
3  py  0
4  py  10
5  pz  0
6  pz  6
```

```
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c ****************************************
c          Material Cards
c ****************************************
c
c  TAMU Sludge
m1    7000.03e -0.1681
     15000.03e -0.0383
     19000.03e -0.0108
     20000.03e -0.0526
     12000.03e -0.0046
     11000.03e -0.0339
     30000.03e -0.002385
     26000.03e -0.008620
     29000.03e -0.003477
     25000.03e -0.001907
      6000.03e -2.2753
      1000.03e -10.9
      8000.03e -86.5
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c ******************************************
c        SOURCE DEFINITION
c ******************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=20 dir=1 vec=0 0 -1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
```

```
c
c ****************************************
c          TALLY CARDS
c ****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:4 0:4 0:5])
FC18 Total Deposition
*F18:p,e 2
c
c ****************************************
c     OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
talnp          $tally no print
prdmp 2j 1     $get data via MCTAL file
nps 1e6
print
```

```
c *************************************
c          Surface Cards
c *************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c *************************************
c          Material Cards
c *************************************
c
c  ATAD Sludge
m1    7000.03e -0.191
```

```
     15000.03e -0.0751
     19000.03e -0.0227
     20000.03e -0.0852
     12000.03e -0.0059
     11000.03e -0.0386
     30000.03e -0.002159
     26000.03e -0.00751
     29000.03e -0.00141
     25000.03e -0.003562
      6000.03e -3.8669
      1000.03e -10.708
      8000.03e -84.992
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c ****************************************
c         SOURCE DEFINITION
c ****************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=-14.2 dir=1 vec=0 0 1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ****************************************
c           TALLY CARDS
c ****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ****************************************
c     OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
talnp          $tally no print
prdmp 2j 1     $get data via MCTAL file
```

```
nps 1e6
print
```

```
ATAD Sludge Irradiation - Beam on Top
c **************************************
c          Cell Cards
c **************************************
1  1 -0.967 -12          FILL=1            $Sludge
2  1 -0.967 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                    $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16               $Air
5 0        13                              $Outside World

c **************************************
c         Surface Cards
c **************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c **************************************
c          Material Cards
c **************************************
c
c  ATAD Sludge
m1    7000.03e -0.191
      15000.03e -0.0751
      19000.03e -0.0227
      20000.03e -0.0852
      12000.03e -0.0059
      11000.03e -0.0386
      30000.03e -0.002159
      26000.03e -0.00751
      29000.03e -0.00141
```

```
    25000.03e -0.003562
     6000.03e -3.8669
     1000.03e -10.708
     8000.03e -84.992
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
     15000 -0.045 16000 -0.03 26000 -68.595
c
c ****************************************
c        SOURCE DEFINITION
c ****************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=20 dir=1 vec=0 0 -1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ****************************************
c           TALLY CARDS
c ****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ****************************************
c     OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
talnp          $tally no print
prdmp 2j 1     $get data via MCTAL file
nps 1e6
print
```

```
Effluent Water Irradiation - Beam on Bottom
c ************************************
c           Cell Cards
```

```
c *************************************
1  1 -1.0 -12           FILL=1              $Sludge
2  1 -1.0 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                        $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                $Air
5 0         13                                          $Outside World

c *************************************
c          Surface Cards
c *************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c *************************************
c           Material Cards
c *************************************
c
c  Water
m1    1000.03e 2 8000.03e 1
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
     15000 -0.045 16000 -0.03 26000 -68.595
c
c ****************************************
c         SOURCE DEFINITION
c ****************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=-14.2 dir=1 vec=0 0 1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
```

```
c
c *****************************************
c           TALLY CARDS
c *****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:4 0:4 0:5])
FC18 Total Deposition
*F18:p,e 2
c
c *****************************************
c     OTHER DATA CARDS
c *****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
talnp          $tally no print
prdmp 2j 1     $get data via MCTAL file
nps 1e6
print
```

```
Effluent Water Irradiation - Beam on Top
c **************************************
c           Cell Cards
c **************************************
1  1 -1.0 -12           FILL=1             $Sludge
2  1 -1.0 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                     $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                 $Air
5 0         13                              $Outside World

c **************************************
c          Surface Cards
c **************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
```

```
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c **************************************
c           Material Cards
c **************************************
c
c  Water
m1    1000.03e 2 8000.03e 1
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
     15000 -0.045 16000 -0.03 26000 -68.595
c
c *****************************************
c         SOURCE DEFINITION
c *****************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=20 dir=1 vec=0 0 -1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c *****************************************
c           TALLY CARDS
c *****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:4 0:4 0:5])
FC18 Total Deposition
*F18:p,e 2
c
c *****************************************
c     OTHER DATA CARDS
c *****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
talnp           $tally no print
prdmp 2j 1      $get data via MCTAL file
```

```
nps 1e6
print
```

A-2 Benchmark Models

Simplified Water Model

```
Benchmark test problem
c ******************************
c                 CELL CARDS
c ******************************
1 3 -1.0       -1 3       $Material inside bag
2 1 -1.42      -2         $Alanine dosimeter
3 1 -1.42     -3          $Alanine dosimeter
4 1 -1.42      -4         $Alanine dosimeter
5 2 -0.0012  -5 1 2 4  $Air
6 0              5          $Outside world

c *****************************
c            SURFACE CARDS
c *****************************
1 rpp 0 7.62 0 5.08 0 0.516
2 rcc 2 3.08 0.516 0 0 .25 .25
3 rcc 3.81 2.54 0.133 0 0 .25 .25
4 rcc 5.62 2 0 0 0 -.25 .25
5 so  150

c ****************************
c                    DATA CARDS
c ****************************
mode e p
SDEF x=d1 y=d2 z=-21.59 erg=10 par=3 vec=0 0 1 dir=1
SI1 -33.02 40.64
SP1 0 1
SI2 -1.27 8.89
SP2 0 1
c Alanine
m1 6000.03e 3 1000.03e 7 14000.03e 1 8000.03e 2
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c Water
m3 1000.03e 2 8000.03e 1
```

```
IMP:e,p 1 1 1 1 1 0
*F8:p,e   2
*F18:p,e 3
*F28:p,e 4
nps 10000000
```

Simplified TAMU Sludge Model

```
Benchmark test problem
c *******************************
c                 CELL CARDS
c *******************************
1 4 -0.9784       -1 3      $Material inside bag
2 1 -1.42      -2           $Alanine dosimeter
3 1 -1.42     -3            $Alanine dosimeter
4 1 -1.42      -4           $Alanine dosimeter
5 2 -0.0012  -5 1 2 4       $Air
6 0              5          $Outside world

c ******************************
c            SURFACE CARDS
c ******************************
1 rpp 0 7.62 0 5.08 0 0.516
2 rcc 2 3.08 0.516 0 0 .25 .25
3 rcc 3.81 2.54 0.133 0 0 .25 .25
4 rcc 5.62 2 0 0 0 -.25 .25
5 so  150

c *****************************
c                   DATA CARDS
c *****************************
mode e p
SDEF x=d1 y=d2 z=-21.59 erg=10 par=3 vec=0 0 1 dir=1
SI1 -33.02 40.64
SP1 0 1
SI2 -1.27 8.89
SP2 0 1
c Alanine
m1 6000.03e 3 1000.03e 7 14000.03e 1 8000.03e 2
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c Water
m3 1000.03e 2 8000.03e 1
```

```
c  TAMU Sludge
m4    7000.03e -0.1681
     15000.03e -0.0383
     19000.03e -0.0108
     20000.03e -0.0526
     12000.03e -0.0046
     11000.03e -0.0339
     30000.03e -0.002385
     26000.03e -0.008620
     29000.03e -0.003477
     25000.03e -0.001907
      6000.03e -2.2753
      1000.03e -10.9
      8000.03e -86.5
IMP:e,p 1 1 1 1 1 0
*F8:p,e   2
*F18:p,e 3
*F28:p,e 4
nps 10000000
```

Simplified ATAD Sludge Model

```
Benchmark test problem
c ******************************
c                 CELL CARDS
c ******************************
1 4 -0.967       -1 3       $Material inside bag
2 1 -1.42      -2           $Alanine dosimeter
3 1 -1.42     -3            $Alanine dosimeter
4 1 -1.42      -4           $Alanine dosimeter
5 2 -0.0012  -5 1 2 4     $Air
6 0              5          $Outside world

c *****************************
c            SURFACE CARDS
c *****************************
1 rpp 0 7.62 0 5.08 0 0.516
2 rcc 2 3.08 0.516 0 0 .25 .25
3 rcc 3.81 2.54 0.133 0 0 .25 .25
4 rcc 5.62 2 0 0 0 -.25 .25
5 so  150

c ****************************
```

```
c                    DATA CARDS
c *****************************
mode e p
SDEF x=d1 y=d2 z=-21.59 erg=10 par=3 vec=0 0 1 dir=1
SI1 -33.02 40.64
SP1 0 1
SI2 -1.27 8.89
SP2 0 1
c Alanine
m1 6000.03e 3 1000.03e 7 14000.03e 1 8000.03e 2
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c Water
m3 1000.03e 2 8000.03e 1
c  ATAD Sludge
m4 7000.03e -0.191
     15000.03e -0.0751
     19000.03e -0.0227
     20000.03e -0.0852
     12000.03e -0.0059
     11000.03e -0.0386
     30000.03e -0.002159
     26000.03e -0.00751
     29000.03e -0.00141
     25000.03e -0.003562
      6000.03e -3.8669
      1000.03e -10.708
      8000.03e -84.992
IMP:e,p 1 1 1 1 1 0
*F8:p,e   2
*F18:p,e 3
*F28:p,e 4
nps 10000000
```

Detailed Water Model

```
Benchmark test problem
c ******************************
c                 CELL CARDS
c ******************************
1 3 -1.0       -1 3                    $ Target cell
2 1 -1.42      -2                      $ Top alanine dosimeter
```

```
3 1 -1.42     -3                        $ Middle alanine dosimeter
4 1 -1.42      -4                       $ Bottom alanine dosimeter
5 5 -0.93      -5                       $ Top layer of poly
6 5 -0.93      -6                       $ Bottom layer of poly
7 4 -0.689    -7                        $ Cardboard
8 2 -0.0012  -8 1 2 4 5 6 7             $ Air
9 0              8

c *****************************
c           SURFACE CARDS
c *****************************
1 rpp 0 7.62 0 5.08 0 0.516                  $ Target material
2 rcc 2 3.08 0.516 0 0 .25 .25               $ Top alanine dosimeter
3 rcc 3.81 2.54 0.133 0 0 .25 .25            $ Middle alanine dosimeter
4 rcc 5.62 2 0 0 0 -.25 .25                  $ Bottom alanine dosimeter
5 rpp 0 7.62 0 5.08 0.766 1.0835             $ Top layer of poly
6 rpp 0 7.62 0 5.08 -0.5675 -0.25            $ Bottom layer of poly
7 rpp 0 7.62 0 5.08 -0.885 -0.5675           $ Cardboard
8 so  150

c ****************************
c                  DATA CARDS
c ****************************
mode e p
SDEF x=d1 y=d2 z=-21.59 erg=10 par=3 vec=0 0 1 dir=1
SI1 -33.02 40.64
SP1 0 1
SI2 -1.27 8.89
SP2 0 1
c Alanine
m1 6000.03e 3 1000.03e 7 14000.03e 1 8000.03e 2
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c Water
m3 1000.03e 2 8000.03e 1
c  Cardboard
m4  6000.03e 6 1000.03e 10 8000.03e 5
c Polyethylene
m5 6000.03e 2 1000.03e 4
IMP:e,p 1 1 1 1 1 1 1 1 0
*F8:p,e   2
*F18:p,e 3
*F28:p,e 4
RAND stride=1000000
```

```
nps 10000000
```

Detailed TAMU Sludge Model

```
Benchmark test problem
c *****************************
c              CELL CARDS
c *****************************
1 3 -1.0      -1 3                    $ Target cell
2 1 -1.42     -2                      $ Top alanine dosimeter
3 1 -1.42    -3                       $ Middle alanine dosimeter
4 1 -1.42     -4                      $ Bottom alanine dosimeter
5 5 -0.93     -5                      $ Top layer of poly
6 5 -0.93     -6                      $ Bottom layer of poly
7 4 -0.689    -7                      $ Cardboard
8 2 -0.0012  -8 1 2 4 5 6 7           $ Air
9 0           8

c ****************************
c          SURFACE CARDS
c ****************************
1 rpp 0 7.62 0 5.08 0 0.516              $ Target material
2 rcc 2 3.08 0.516 0 0 .25 .25           $ Top alanine dosimeter
3 rcc 3.81 2.54 0.133 0 0 .25 .25        $ Middle alanine dosimeter
4 rcc 5.62 2 0 0 0 -.25 .25              $ Bottom alanine dosimeter
5 rpp 0 7.62 0 5.08 0.766 1.0835         $ Top layer of poly
6 rpp 0 7.62 0 5.08 -0.5675 -0.25        $ Bottom layer of poly
7 rpp 0 7.62 0 5.08 -0.885 -0.5675       $ Cardboard
8 so  150

c ***************************
c               DATA CARDS
c ***************************
mode e p
SDEF x=d1 y=d2 z=-21.59 erg=10 par=3 vec=0 0 1 dir=1
SI1 -33.02 40.64
SP1 0 1
SI2 -1.27 8.89
SP2 0 1
c Alanine
m1 6000.03e 3 1000.03e 7 14000.03e 1 8000.03e 2
c Air [Metzger et al., 1993]
```

```
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c  TAMU Sludge
m3   7000.03e -0.1681
     15000.03e -0.0383
     19000.03e -0.0108
     20000.03e -0.0526
     12000.03e -0.0046
     11000.03e -0.0339
     30000.03e -0.002385
     26000.03e -0.008620
     29000.03e -0.003477
     25000.03e -0.001907
      6000.03e -2.2753
      1000.03e -10.9
      8000.03e -86.5
c  Cardboard
m4  6000.03e 6 1000.03e 10 8000.03e 5
c Polyethylene
m5 6000.03e 2 1000.03e 4
IMP:e,p 1 1 1 1 1 1 1 1 0
*F8:p,e   2
*F18:p,e 3
*F28:p,e 4
RAND stride=1000000
nps 10000000
```

Detailed ATAD Sludge Model

```
Benchmark test problem
c ******************************
c               CELL CARDS
c ******************************
1 3 -1.0       -1 3                   $ Target cell
2 1 -1.42      -2                     $ Top alanine dosimeter
3 1 -1.42     -3                      $ Middle alanine dosimeter
4 1 -1.42      -4                     $ Bottom alanine dosimeter
5 5 -0.93      -5                     $ Top layer of poly
6 5 -0.93      -6                     $ Bottom layer of poly
7 4 -0.689     -7                     $ Cardboard
8 2 -0.0012  -8 1 2 4 5 6 7           $ Air
9 0            8
```

```
c ******************************
c          SURFACE CARDS
c ******************************
1 rpp 0 7.62 0 5.08 0 0.516                $ Target material
2 rcc 2 3.08 0.516 0 0 .25 .25             $ Top alanine dosimeter
3 rcc 3.81 2.54 0.133 0 0 .25 .25          $ Middle alanine dosimeter
4 rcc 5.62 2 0 0 0 -.25 .25                $ Bottom alanine dosimeter
5 rpp 0 7.62 0 5.08 0.766 1.0835           $ Top layer of poly
6 rpp 0 7.62 0 5.08 -0.5675 -0.25          $ Bottom layer of poly
7 rpp 0 7.62 0 5.08 -0.885 -0.5675        $ Cardboard
8 so  150

c *****************************
c                DATA CARDS
c *****************************
mode e p
SDEF x=d1 y=d2 z=-21.59 erg=10 par=3 vec=0 0 1 dir=1
SI1 -33.02 40.64
SP1 0 1
SI2 -1.27 8.89
SP2 0 1
c Alanine
m1 6000.03e 3 1000.03e 7 14000.03e 1 8000.03e 2
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c  ATAD Sludge
m3 7000.03e -0.191
     15000.03e -0.0751
     19000.03e -0.0227
     20000.03e -0.0852
     12000.03e -0.0059
     11000.03e -0.0386
     30000.03e -0.002159
     26000.03e -0.00751
     29000.03e -0.00141
     25000.03e -0.003562
      6000.03e -3.8669
      1000.03e -10.708
      8000.03e -84.992
c  Cardboard
m4  6000.03e 6 1000.03e 10 8000.03e 5
c Polyethylene
m5 6000.03e 2 1000.03e 4
IMP:e,p 1 1 1 1 1 1 1 1 0
```

```
*F8:p,e   2
*F18:p,e 3
*F28:p,e 4
RAND stride=1000000
nps 10000000
```

A-3 Density Study Models

```
ATAD Sludge Irradiation - Beam on Top, 4.3% Solids
c ***************************************
c           Cell Cards
c ***************************************
1  1 -0.967 -12           FILL=1             $Sludge
2  1 -0.967 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                      $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                  $Air
5 0         13                               $Outside World

c ***************************************
c          Surface Cards
c ***************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c ***************************************
c           Material Cards
c ***************************************
c
c  ATAD Sludge
m1    7000.03e -0.191
     15000.03e -0.0751
     19000.03e -0.0227
     20000.03e -0.0852
```

```
    12000.03e -0.0059
    11000.03e -0.0386
    30000.03e -0.002159
    26000.03e -0.00751
    29000.03e -0.00141
    25000.03e -0.003562
     6000.03e -3.8669
     1000.03e -10.708
     8000.03e -84.992
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
     15000 -0.045 16000 -0.03 26000 -68.595
c
c ****************************************
c         SOURCE DEFINITION
c ****************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=20 dir=1 vec=0 0 -1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ****************************************
c           TALLY CARDS
c ****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ****************************************
c     OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
talnp          $tally no print
prdmp 2j 1     $get data via MCTAL file
nps 1e6
print
```

```
ATAD Sludge Irradiation - Beam on Bottom, 4.3% Solids
c **************************************
c           Cell Cards
c **************************************
1  1 -0.967 -12          FILL=1            $Sludge
2  1 -0.967 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                     $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16              $Air
5 0         13                              $Outside World

c **************************************
c         Surface Cards
c **************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c **************************************
c          Material Cards
c **************************************
c
c  ATAD Sludge
m1    7000.03e -0.191
    15000.03e -0.0751
    19000.03e -0.0227
    20000.03e -0.0852
    12000.03e -0.0059
    11000.03e -0.0386
    30000.03e -0.002159
    26000.03e -0.00751
    29000.03e -0.00141
    25000.03e -0.003562
```

```
     6000.03e -3.8669
     1000.03e -10.708
     8000.03e -84.992
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
     15000 -0.045 16000 -0.03 26000 -68.595
c
c ****************************************
c          SOURCE DEFINITION
c ****************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=-14.2 dir=1 vec=0 0 1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ****************************************
c            TALLY CARDS
c ****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ****************************************
c      OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
talnp           $tally no print
prdmp 2j 1      $get data via MCTAL file
nps 1e6
print
```

```
ATAD Sludge Irradiation - Beam on Top, 5.81% Solids
c *************************************
c          Cell Cards
c *************************************
1  1 -0.9554 -12          FILL=1            $Sludge
2  1 -0.9554 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                     $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                 $Air
5 0         13                              $Outside World

c *************************************
c         Surface Cards
c *************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c *************************************
c          Material Cards
c *************************************
c
c  ATAD Sludge
m1    7000.03e -0.2579
     15000.03e -0.1014
     19000.03e -0.0306
     20000.03e -0.1150
     12000.03e -0.0080
     11000.03e -0.0521
     30000.03e -0.00291
     26000.03e -0.01014
     29000.03e -0.00190
     25000.03e -0.00481
      6000.03e -5.22032
      1000.03e -10.540
      8000.03e -83.655
c
```

```
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c ****************************************
c         SOURCE DEFINITION
c ****************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=20 dir=1 vec=0 0 -1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ****************************************
c           TALLY CARDS
c ****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ****************************************
c     OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
talnp          $tally no print
prdmp 2j 1     $get data via MCTAL file
nps 1e6
print
```

```
ATAD Sludge Irradiation - Beam on Bottom, 5.81% Solids
c ***********************************
c           Cell Cards
c ***********************************
1  1 -0.9554 -12           FILL=1              $Sludge
2  1 -0.9554 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                        $Stainless Steel Trough
```

```
4 2 -0.0012 -13 12 14 15 16                 $Air
5 0         13                              $Outside World

c *************************************
c          Surface Cards
c *************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c *************************************
c          Material Cards
c *************************************
c
c  ATAD Sludge
m1    7000.03e -0.2579
     15000.03e -0.1014
     19000.03e -0.0306
     20000.03e -0.1150
     12000.03e -0.0080
     11000.03e -0.0521
     30000.03e -0.00291
     26000.03e -0.01014
     29000.03e -0.00190
     25000.03e -0.00481
      6000.03e -5.22032
      1000.03e -10.540
      8000.03e -83.655
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c ****************************************
```

```
c        SOURCE DEFINITION
c ****************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=-14.2 dir=1 vec=0 0 1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ****************************************
c          TALLY CARDS
c ****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ****************************************
c     OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
talnp          $tally no print
prdmp 2j 1     $get data via MCTAL file
nps 1e6
print
```

```
ATAD Sludge Irradiation - Beam on Top, 6.9% Solids
c *************************************
c          Cell Cards
c *************************************
1  1 -0.9465 -12          FILL=1            $Sludge
2  1 -0.9465 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                     $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                 $Air
5 0        13                               $Outside World

c *************************************
c         Surface Cards
c *************************************
1  px  0
3  py  0
```

```
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c **************************************
c           Material Cards
c **************************************
c
c  ATAD Sludge
m1    7000.03e -0.3094
     15000.03e -0.1217
     19000.03e -0.0368
     20000.03e -0.1380
     12000.03e -0.0096
     11000.03e -0.0625
     30000.03e -0.00350
     26000.03e -0.01217
     29000.03e -0.00228
     25000.03e -0.00577
      6000.03e -6.26438
      1000.03e -10.410
      8000.03e -82.624
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c *****************************************
c         SOURCE DEFINITION
c *****************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=20 dir=1 vec=0 0 -1
SI1 0 70
SP1 0 1
SI2 0 10
```

```
SP2 0 1
c
c ****************************************
c           TALLY CARDS
c ****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ****************************************
c     OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
nps 1e6
print
```

```
ATAD Sludge Irradiation - Beam on Bottom, 6.97% Solids
c *************************************
c           Cell Cards
c *************************************
1  1 -0.9465 -12           FILL=1              $Sludge
2  1 -0.9465 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                      $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                  $Air
5 0         13                               $Outside World

c *************************************
c         Surface Cards
c *************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0
```

```
c *************************************
c          Material Cards
c *************************************
c
c  ATAD Sludge
m1    7000.03e -0.3094
     15000.03e -0.1217
     19000.03e -0.0368
     20000.03e -0.1380
     12000.03e -0.0096
     11000.03e -0.0625
     30000.03e -0.00350
     26000.03e -0.01217
     29000.03e -0.00228
     25000.03e -0.00577
      6000.03e -6.26438
      1000.03e -10.410
      8000.03e -82.624
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c *****************************************
c        SOURCE DEFINITION
c *****************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=-14.2 dir=1 vec=0 0 1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c *****************************************
c          TALLY CARDS
c *****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c *****************************************
```

```
c     OTHER DATA CARDS
c ******************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
nps 1e6
print
```

```
ATAD Sludge Irradiation - Beam on Top, 8.14% Solids
c **************************************
c           Cell Cards
c **************************************
1  1 -0.9376 -12           FILL=1              $Sludge
2  1 -0.9376 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                        $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                    $Air
5 0         13                                 $Outside World

c **************************************
c          Surface Cards
c **************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c **************************************
c           Material Cards
c **************************************
c
c  ATAD Sludge
m1    7000.03e -0.3610
    15000.03e -0.1419
    19000.03e -0.0429
    20000.03e -0.1610
```

```
     12000.03e -0.0112
     11000.03e -0.0730
     30000.03e -0.00408
     26000.03e -0.01419
     29000.03e -0.00266
     25000.03e -0.00673
      6000.03e -7.30844
      1000.03e -10.280
      8000.03e -81.593
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c ****************************************
c         SOURCE DEFINITION
c ****************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=20 dir=1 vec=0 0 -1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ****************************************
c            TALLY CARDS
c ****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ****************************************
c     OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
nps 150000
print
```

```
ATAD Sludge Irradiation - Beam on Bottom, 8.14% Solids
c **************************************
c           Cell Cards
c **************************************
1  1 -0.9376 -12          FILL=1             $Sludge
2  1 -0.9376 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                      $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                 $Air
5 0        13                                $Outside World

c **************************************
c          Surface Cards
c **************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c **************************************
c           Material Cards
c **************************************
c
c  ATAD Sludge
m1    7000.03e -0.3610
     15000.03e -0.1419
     19000.03e -0.0429
     20000.03e -0.1610
     12000.03e -0.0112
     11000.03e -0.0730
     30000.03e -0.00408
     26000.03e -0.01419
     29000.03e -0.00266
     25000.03e -0.00673
      6000.03e -7.30844
      1000.03e -10.280
      8000.03e -81.593
c
```

```
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c ****************************************
c         SOURCE DEFINITION
c ****************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=-14.2 dir=1 vec=0 0 1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ****************************************
c           TALLY CARDS
c ****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ****************************************
c      OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
nps 1e6
print
```

```
ATAD Sludge Irradiation - Beam on Top, 9.30% Solids
c *************************************
c           Cell Cards
c *************************************
1  1 -0.9286 -12           FILL=1             $Sludge
2  1 -0.9286 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                       $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                   $Air
5 0         13                                $Outside World
```

```
c **************************************
c          Surface Cards
c **************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c **************************************
c          Material Cards
c **************************************
c
c  ATAD Sludge
m1    7000.03e -0.4126
     15000.03e -0.1622
     19000.03e -0.0490
     20000.03e -0.1840
     12000.03e -0.0127
     11000.03e -0.0834
     30000.03e -0.00466
     26000.03e -0.01622
     29000.03e -0.00305
     25000.03e -0.00769
      6000.03e -8.35250
      1000.03e -10.150
      8000.03e -80.562
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c ***************************************
c         SOURCE DEFINITION
c ***************************************
```

```
c
SDEF  par=3 erg=10 x=d1 y=d2 z=20 dir=1 vec=0 0 -1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ****************************************
c            TALLY CARDS
c ****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ****************************************
c      OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
nps 150000
```

```
ATAD Sludge Irradiation - Beam on Bottom, 9.30% Solids
c ***************************************
c          Cell Cards
c ***************************************
1  1 -0.9286 -12          FILL=1           $Sludge
2  1 -0.9286 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                    $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                $Air
5 0         13                             $Outside World

c ***************************************
c          Surface Cards
c ***************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c ***************************************
c          Material Cards
c ***************************************
c
c  ATAD Sludge
m1    7000.03e -0.4126
     15000.03e -0.1622
     19000.03e -0.0490
     20000.03e -0.1840
     12000.03e -0.0127
     11000.03e -0.0834
     30000.03e -0.00466
     26000.03e -0.01622
     29000.03e -0.00305
     25000.03e -0.00769
      6000.03e -8.35250
      1000.03e -10.150
      8000.03e -80.562
c
```

```
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c ****************************************
c         SOURCE DEFINITION
c ****************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=-14.2 dir=1 vec=0 0 1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ****************************************
c           TALLY CARDS
c ****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ****************************************
c     OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
nps 150000
```

```
ATAD Sludge Irradiation - Beam on Top, 10.46% Solids
c *************************************
c           Cell Cards
c *************************************
1  1 -0.9197 -12          FILL=1              $Sludge
2  1 -0.9197 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                       $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                   $Air
5 0         13                                $Outside World

c *************************************
```

```
c          Surface Cards
c *************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c *************************************
c          Material Cards
c *************************************
c
c  ATAD Sludge
m1    7000.03e -0.4641
     15000.03e -0.1825
     19000.03e -0.0552
     20000.03e -0.2070
     12000.03e -0.0143
     11000.03e -0.0938
     30000.03e -0.00525
     26000.03e -0.01825
     29000.03e -0.00343
     25000.03e -0.00866
      6000.03e -9.39657
      1000.03e -10.020
      8000.03e -79.531
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c ****************************************
c         SOURCE DEFINITION
c ****************************************
c
```

```
SDEF  par=3 erg=10 x=d1 y=d2 z=20 dir=1 vec=0 0 -1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ****************************************
c          TALLY CARDS
c ****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ****************************************
c     OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
nps 150000
```

```
ATAD Sludge Irradiation - Beam on Bottom, 10.46% Solids
c *************************************
c          Cell Cards
c *************************************
1  1 -0.9197 -12           FILL=1              $Sludge
2  1 -0.9197 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                      $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                $Air
5 0         13                               $Outside World

c *************************************
c         Surface Cards
c *************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
```

```
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c ***************************************
c          Material Cards
c ***************************************
c
c  ATAD Sludge
m1    7000.03e -0.4641
     15000.03e -0.1825
     19000.03e -0.0552
     20000.03e -0.2070
     12000.03e -0.0143
     11000.03e -0.0938
     30000.03e -0.00525
     26000.03e -0.01825
     29000.03e -0.00343
     25000.03e -0.00866
      6000.03e -9.39657
      1000.03e -10.020
      8000.03e -79.531
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c ******************************************
c         SOURCE DEFINITION
c ******************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=-14.2 dir=1 vec=0 0 1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ******************************************
c           TALLY CARDS
c ******************************************
c
FC8 Depth-Dose Tally
```

```
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ****************************************
c     OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
nps 150000
```

```
TAMU Sludge Irradiation - Beam on Top, 2.6% Solids
c *************************************
c          Cell Cards
c *************************************
1  1 -0.9784 -12          FILL=1            $Sludge
2  1 -0.9784 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                     $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                 $Air
5 0         13                              $Outside World

c *************************************
c         Surface Cards
c *************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c *************************************
c          Material Cards
c *************************************
c
c  TAMU Sludge
m1    7000.03e -0.1681
     15000.03e -0.0383
     19000.03e -0.0108
     20000.03e -0.0526
```

```
    12000.03e -0.0046
    11000.03e -0.0339
    30000.03e -0.002385
    26000.03e -0.00862
    29000.03e -0.003477
    25000.03e -0.001907
     6000.03e -2.2753
     1000.03e -10.898
     8000.03e -86.502
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
     15000 -0.045 16000 -0.03 26000 -68.595
c
c ****************************************
c         SOURCE DEFINITION
c ****************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=20 dir=1 vec=0 0 -1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ****************************************
c           TALLY CARDS
c ****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ****************************************
c     OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
nps 150000
```

```
TAMU Sludge Irradiation - Beam on Bottom, 2.6% Solids
c **************************************
c          Cell Cards
c **************************************
1  1 -0.9784 -12          FILL=1             $Sludge
2  1 -0.9784 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                       $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                 $Air
5 0         13                                $Outside World

c **************************************
c         Surface Cards
c **************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c **************************************
c          Material Cards
c **************************************
c
c  TAMU Sludge
m1    7000.03e -0.1681
     15000.03e -0.0383
     19000.03e -0.0108
     20000.03e -0.0526
     12000.03e -0.0046
     11000.03e -0.0339
     30000.03e -0.002385
     26000.03e -0.00862
     29000.03e -0.003477
     25000.03e -0.001907
      6000.03e -2.2753
      1000.03e -10.898
      8000.03e -86.502
c
```

```
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c ****************************************
c         SOURCE DEFINITION
c ****************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=-14.2 dir=1 vec=0 0 1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ****************************************
c           TALLY CARDS
c ****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ****************************************
c     OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
nps 150000
```

```
TAMU Sludge Irradiation - Beam on Top, 5.10% Solids
c *************************************
c           Cell Cards
c *************************************
1  1 -0.9577 -12          FILL=1             $Sludge
2  1 -0.9577 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                     $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                 $Air
5 0         13                              $Outside World

c *************************************
```

```
c          Surface Cards
c **************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c **************************************
c           Material Cards
c **************************************
c
c  TAMU Sludge
m1    7000.03e -0.3295
     15000.03e -0.0751
     19000.03e -0.0212
     20000.03e -0.1031
     12000.03e -0.0090
     11000.03e -0.0664
     30000.03e -0.00467
     26000.03e -0.01690
     29000.03e -0.00681
     25000.03e -0.00374
      6000.03e -4.45959
      1000.03e -10.619
      8000.03e -84.285
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c *****************************************
c         SOURCE DEFINITION
c *****************************************
c
```

```
SDEF  par=3 erg=10 x=d1 y=d2 z=20 dir=1 vec=0 0 -1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c *****************************************
c           TALLY CARDS
c *****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c *****************************************
c     OTHER DATA CARDS
c *****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
nps 150000
```

```
TAMU Sludge Irradiation - Beam on Bottom, 5.10% Solids
c **************************************
c           Cell Cards
c **************************************
1  1 -0.9577 -12           FILL=1              $Sludge
2  1 -0.9577 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                        $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                    $Air
5 0         13                                 $Outside World

c **************************************
c         Surface Cards
c **************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0
```

```
c ****************************************
c          Material Cards
c ****************************************
c
c  TAMU Sludge
m1    7000.03e -0.3295
     15000.03e -0.0751
     19000.03e -0.0212
     20000.03e -0.1031
     12000.03e -0.0090
     11000.03e -0.0664
     30000.03e -0.00467
     26000.03e -0.01690
     29000.03e -0.00681
     25000.03e -0.00374
      6000.03e -4.45959
      1000.03e -10.619
      8000.03e -84.285
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c ******************************************
c         SOURCE DEFINITION
c ******************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=-14.2 dir=1 vec=0 0 1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ******************************************
c           TALLY CARDS
c ******************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ******************************************
```

```
c     OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
nps 150000
```

```
TAMU Sludge Irradiation - Beam on Top, 6.12% Solids
c *************************************
c           Cell Cards
c *************************************
1  1 -0.9492 -12           FILL=1              $Sludge
2  1 -0.9492 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                        $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                $Air
5 0         13                                  $Outside World

c *************************************
c         Surface Cards
c *************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c *************************************
c          Material Cards
c *************************************
c
c  TAMU Sludge
m1    7000.03e -0.3950
    15000.03e -0.0900
    19000.03e -0.0254
    20000.03e -0.1236
```

```
    12000.03e -0.0108
    11000.03e -0.0797
    30000.03e -0.00560
    26000.03e -0.02026
    29000.03e -0.00817
    25000.03e -0.00448
     6000.03e -5.34696
     1000.03e -10.505
     8000.03e -83.385
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
     15000 -0.045 16000 -0.03 26000 -68.595
c
c ******************************************
c         SOURCE DEFINITION
c ******************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=20 dir=1 vec=0 0 -1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ******************************************
c           TALLY CARDS
c ******************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ******************************************
c     OTHER DATA CARDS
c ******************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
nps 150000
```

```
TAMU Sludge Irradiation - Beam on Bottom, 6.12% Solids
c **************************************
c            Cell Cards
c **************************************
1  1 -0.9492 -12           FILL=1            $Sludge
2  1 -0.9492 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                      $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                  $Air
5 0         13                               $Outside World

c **************************************
c          Surface Cards
c **************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c **************************************
c           Material Cards
c **************************************
c
c  TAMU Sludge
m1    7000.03e -0.3950
     15000.03e -0.0900
     19000.03e -0.0254
     20000.03e -0.1236
     12000.03e -0.0108
     11000.03e -0.0797
     30000.03e -0.00560
     26000.03e -0.02026
     29000.03e -0.00817
     25000.03e -0.00448
      6000.03e -5.34696
      1000.03e -10.505
      8000.03e -83.385
c
```

```
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c ******************************************
c         SOURCE DEFINITION
c ******************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=-14.2 dir=1 vec=0 0 1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ******************************************
c           TALLY CARDS
c ******************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ******************************************
c     OTHER DATA CARDS
c ******************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
nps 150000
```

```
TAMU Sludge Irradiation - Beam on Top, 7.14% Solids
c ***************************************
c           Cell Cards
c ***************************************
1  1 -0.9407 -12           FILL=1              $Sludge
2  1 -0.9407 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                       $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16               $Air
5 0         13                                $Outside World

c ***************************************
c         Surface Cards
c ***************************************
1  px  0
```

```
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c ****************************************
c          Material Cards
c ****************************************
c
c  TAMU Sludge
m1    7000.03e -0.4623
     15000.03e -0.1053
     19000.03e -0.0297
     20000.03e -0.1447
     12000.03e -0.0127
     11000.03e -0.0932
     30000.03e -0.00656
     26000.03e -0.02371
     29000.03e -0.00956
     25000.03e -0.00524
      6000.03e -6.25708
      1000.03e -10.389
      8000.03e -82.461
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c ******************************************
c         SOURCE DEFINITION
c ******************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=20 dir=1 vec=0 0 -1
SI1 0 70
SP1 0 1
```

```
SI2 0 10
SP2 0 1
c
c ****************************************
c           TALLY CARDS
c ****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ****************************************
c     OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
nps 150000
```

```
TAMU Sludge Irradiation - Beam on Bottom, 7.14% Solids
c *************************************
c           Cell Cards
c *************************************
1  1 -0.9407 -12           FILL=1             $Sludge
2  1 -0.9407 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                       $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                $Air
5 0        13                                      $Outside World

c *************************************
c          Surface Cards
c *************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
```

```
16 rpp 0 70 0 10 -0.2 0

c ***************************************
c          Material Cards
c ***************************************
c
c  TAMU Sludge
m1    7000.03e -0.4623
     15000.03e -0.1053
     19000.03e -0.0297
     20000.03e -0.1447
     12000.03e -0.0127
     11000.03e -0.0932
     30000.03e -0.00656
     26000.03e -0.02371
     29000.03e -0.00956
     25000.03e -0.00524
      6000.03e -6.25708
      1000.03e -10.389
      8000.03e -82.461
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c ******************************************
c        SOURCE DEFINITION
c ******************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=-14.2 dir=1 vec=0 0 1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ******************************************
c          TALLY CARDS
c ******************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
```

```
c ****************************************
c     OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
nps 150000
```

```
TAMU Sludge Irradiation - Beam on Top, 8.16% Solids
c *************************************
c           Cell Cards
c *************************************
1  1 -0.9322 -12           FILL=1             $Sludge
2  1 -0.9322 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                       $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                 $Air
5 0          13                               $Outside World

c *************************************
c          Surface Cards
c *************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c *************************************
c           Material Cards
c *************************************
c
c  TAMU Sludge
m1    7000.03e -0.5278
    15000.03e -0.1203
    19000.03e -0.0339
```

```
     20000.03e -0.1652
     12000.03e -0.0144
     11000.03e -0.1064
     30000.03e -0.00749
     26000.03e -0.02707
     29000.03e -0.01092
     25000.03e -0.00599
      6000.03e -7.14444
      1000.03e -10.275
      8000.03e -81.561
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c ******************************************
c         SOURCE DEFINITION
c ******************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=20 dir=1 vec=0 0 -1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ******************************************
c           TALLY CARDS
c ******************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ******************************************
c     OTHER DATA CARDS
c ******************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
nps 150000
```

```
TAMU Sludge Irradiation - Beam on Bottom, 8.16% Solids
c ***************************************
c         Cell Cards
c ***************************************
1  1 -0.9322 -12           FILL=1              $Sludge
2  1 -0.9322 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                      $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                 $Air
5 0         13                               $Outside World

c ***************************************
c        Surface Cards
c ***************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c ***************************************
c         Material Cards
c ***************************************
c
c  TAMU Sludge
m1    7000.03e -0.5278
     15000.03e -0.1203
     19000.03e -0.0339
     20000.03e -0.1652
     12000.03e -0.0144
     11000.03e -0.1064
     30000.03e -0.00749
     26000.03e -0.02707
     29000.03e -0.01092
     25000.03e -0.00599
      6000.03e -7.14444
      1000.03e -10.275
      8000.03e -81.561
```

```
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c ****************************************
c         SOURCE DEFINITION
c ****************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=-14.2 dir=1 vec=0 0 1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ****************************************
c           TALLY CARDS
c ****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ****************************************
c     OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
nps 150000
```

```
TAMU Sludge Irradiation - Beam on Top, 9.18% Solids
c ************************************
c           Cell Cards
c ************************************
1  1 -0.9238 -12           FILL=1              $Sludge
2  1 -0.9238 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                     $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                 $Air
5 0         13                              $Outside World
```

```
c **************************************
c          Surface Cards
c **************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c **************************************
c          Material Cards
c **************************************
c
c  TAMU Sludge
m1    7000.03e -0.5934
     15000.03e -0.1352
     19000.03e -0.0381
     20000.03e -0.1857
     12000.03e -0.0162
     11000.03e -0.1197
     30000.03e -0.00842
     26000.03e -0.03043
     29000.03e -0.01227
     25000.03e -0.00673
      6000.03e -8.03181
      1000.03e -10.162
      8000.03e -80.660
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c *****************************************
c         SOURCE DEFINITION
c *****************************************
```

```
c
SDEF  par=3 erg=10 x=d1 y=d2 z=20 dir=1 vec=0 0 -1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ****************************************
c           TALLY CARDS
c ****************************************
c
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ****************************************
c     OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
nps 150000
```

```
TAMU Sludge Irradiation - Beam on Bottom, 9.18% Solids
c *************************************
c           Cell Cards
c *************************************
1  1 -0.9238 -12           FILL=1              $Sludge
2  1 -0.9238 -7 1 -8 3 -9 5 U=1 LAT=1  $Lattice element
3 4 -8.03   -14:-15:-16                        $Stainless Steel Trough
4 2 -0.0012 -13 12 14 15 16                $Air
5 0         13                                 $Outside World

c *************************************
c          Surface Cards
c *************************************
1  px  0
3  py  0
5  pz  0
7  px  14
8  py  2
9  pz  1
12 rpp 0 70 0 10 0 6
```

```
13 so  150
14 rpp -0.2 0 0 10 -0.2 6
15 rpp 70 70.2 0 10 -0.2 6
16 rpp 0 70 0 10 -0.2 0

c ***************************************
c          Material Cards
c ***************************************
c
c  TAMU Sludge
m1    7000.03e -0.5934
     15000.03e -0.1352
     19000.03e -0.0381
     20000.03e -0.1857
     12000.03e -0.0162
     11000.03e -0.1197
     30000.03e -0.00842
     26000.03e -0.03043
     29000.03e -0.01227
     25000.03e -0.00673
      6000.03e -8.03181
      1000.03e -10.162
      8000.03e -80.660
c
c Air [Metzger et al., 1993]
m2  7014 -.752  7015 -.003  8016 -.232 18000 -.013
c Stainless Steel - SS T-304
m4    6000.03e -0.08 25000.03e -2.0 24000 -19.0 28000 -9.25 14000 -1.0
      15000 -0.045 16000 -0.03 26000 -68.595
c
c ******************************************
c        SOURCE DEFINITION
c ******************************************
c
SDEF  par=3 erg=10 x=d1 y=d2 z=-14.2 dir=1 vec=0 0 1
SI1 0 70
SP1 0 1
SI2 0 10
SP2 0 1
c
c ******************************************
c          TALLY CARDS
c ******************************************
c
```

```
FC8 Depth-Dose Tally
*F8:p,e  (2<2[0:0 0:0 0:5])
c
c ****************************************
c     OTHER DATA CARDS
c ****************************************
MODE  e p
IMP:e,p 1 1 1 1 0
RAND stride=1000000
nps 150000
```

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