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Evaluating the Risk to Ostomy Patients Working With Uranium Using the ICRP Biokinetic Model for the Gastrointestinal Tract

Sara Taylor
University of Nevada, Las Vegas, sara.taylor116@yahoo.com

EVALUATING THE RISK TO OSTOMY PATIENTS WORKING WITH URANIUM USING THE ICRP BIOKINETIC MODEL FOR THE GASTROINTESTINAL TRACT

By

Sara Taylor

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School of Allied Health Sciences
Division of Health Sciences
The Graduate College

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Sara Taylor

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Master of Science - Health Physics
Department of Health Physics and Diagnostic Sciences

Gary Cerefice, Ph.D.
Examination Committee Chair

Kathryn Hausbeck Korgan, Ph.D.
Graduate College Interim Dean

Steen Madsen, Ph.D.
Examination Committee Member

Francis A. Cucinotta, Ph.D.
Examination Committee Member

Daniel Young, Ph.D.
Graduate College Faculty Representative

Abstract

The ICRP has published two biokinetic models providing a basis for radiation dose assessment due to radionuclides incorporated inside the gastrointestinal tract. These models are a sufficient tool to assess the committed dose equivalent for occupational exposures to workers assuming normal anatomy. The colostomy is becoming a more prevalent procedure. A colostomy permanently or temporarily bypasses a portion of colon to allow rest and healing. There are four different colostomies; ascending, transverse, descending and sigmoid and an ileostomy. As a patient's strength returns, they can return to normal daily activities, including returning to work. Therefore, as an ostomy patient returns to the workforce handling radioactive material, the potential for exposure to the radioactive material for these workers increases. The aim of this project is to determined whether or not an additional risk exists for these workers and if additional limitations should be placed on ostomy patients handling uranium. In order to determine if an additional risk exists two pathways are considered, ingestion and injection. Injection is a unique pathway for this work and is defined as radioactive material entering through the stoma. As part of the injection scenario as well as in the event contamination occurs, the dose per hou to the stoma was also determined. Using modified ICRP 30 gastrointestinal models and ICRP 100 HATM models to reflect the anatomy changes for each procedure, the committed dose equivalent (CDE) and committed effective dose equivalent (CEDE) was determined for each procedure. In addition, using the more limiting value between the CDE and CEDE annual limit, the annual limit on intake (ALI) was determined. Based on a decrease in CDE values within the alimentary tract for each procedure and the determination the ALIs were either equivalent or orders of magnitude greater than the current ICRP ALI values no additional risk exists. Finally, based on the dose per hour resulting from stoma contamination, the chemical hazards were determined to be of greater concern than the radiological. Therefore, no additional guidance is needed for ostomy patients working with uranium.

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Key Terms

Annual Limit on Intake

The activity of radionuclide, when taken alone, would irradiate a person to the limit set for occupational exposure [1].

Committed Dose Equivalent ($H_{T,50}$)

The total dose equivalent in an organ or tissue after intake of a radionuclide into the body, 50 years for adults and 70 years for children [1].

Committed Effective Dose Equivalent

The committed dose equivalent weighted by the appropriate tissue weighting factor [1].

Equivalent dose

The absorbed dose multiplied by the appropriate quality factor [1].

Effective dose

The equivalent dose multiplied by the appropriate tissue weighting factor for a specified tissue

Linear Energy Transfer

The amount of energy transferred by radiation to a medium per unit distance

Tissue Weighting Factors

The ratio of the stochastic risk arising from tissue T to the risk when the whole body is uniformly irradiated. Table 1 displays the tissue weighting factors from ICRP 26, ICRP 60, and ICRP 103 [2][3][4].

Table 1: Tissue weighting factors from ICRP 26, ICRP 60, and ICRP 103

Tissue or Organ	Tissue Weighting Factor		
	ICRP 26 (1977)	ICRP 60 (1990)	ICRP 103 (2007)
Bone Marrow (red)	0.12	0.12	0.12
Breast	0.15	0.05	0.12
Lung	0.12	0.12	0.12
Stomach	-	0.12	0.12
Colon	-	0.12	0.12
Gonads	0.25	0.20	0.08
Thyroid	0.03	0.05	0.04
Bladder	-	0.05	0.04
Liver	-	0.05	0.04
Esophagus	-	0.05	0.04
Bone Surface	0.03	0.01	0.01
Skin	-	0.01	0.01
Salivary Glands	-	-	0.01
Brain	-	-	0.01
Remainder	0.30	0.05	0.12

Quality Factor/Radiation Weighting Factor

The modifying factor, dependent on the collision stopping power for charged particles, that is used to determine equivalent dose from absorbed dose. This value is 20 for alpha particles and 1 for electrons [1].

1.0 Introduction

The ICRP has published several different biokinetic models providing a basis for radiation dose assessment due to radionuclides incorporated inside the human body. These models are sufficient tools to assess the committed dose equivalent for occupational exposures to workers assuming normal anatomy. A growing number of people have had a surgical procedure to remove either part of their intestine or bypass a portion of their intestine. More specifically, these procedures include four different colostomies, ascending, transverse, descending and sigmoid and an ileostomy. Surgery may be required for various reasons including infection of the abdomen, injury to the colon or rectum, partial or total blockage of the large bowel, or rectal or colon cancer. Furthermore, a colostomy may be temporary or permanent depending on the extent of injury or disease. As a patient's strength returns they can return to normal daily activities, including returning to work. In general, an ostomy patient is not limited in the job they can perform when they return [5]. Therefore, as an ostomy patient returning to the workforce handling radioactive material, the potential for exposure to the radioactive material for these workers increases.

The ICRP models for the GI tract assumes a pathway through unmodified organs and tissues and does not take procedures such as these into consideration. In addition, there is no guidance from the Nuclear Regulatory Commission (NRC) regarding restrictions on these workers, other than general guidance regarding open wound and potential injection risks. The NRC states intake through wounds and skin contamination must be evaluated and accounted for, when practical [1]. Therefore, it should be determined whether or not an additional risk exists for these workers, and if an increased risk does exist, what precautions need to be taken. This could include restrictions on the worker's potential exposure to radioactive material to the development of guidance in case of contamination of the stoma, including the evaluation of what actions may be necessary to limit dose to the stoma and intestine itself.

To examine the potential risk for a worker with an ostomy, biokinetic models will be modified to reflect the new anatomy and estimate the dose to a worker with an ostomy following exposure to uranium. To determine the internal dose for workers dealing with uranium who have undergone an operation on their GI tract, the ICRP 30 and ICRP 100 biokinetic models can be modified to reflect the anatomical changes made by each surgery. Using the modified models, the dose to each organ can be determined as well as the total effective dose. The modified models will be used to investigate two different pathways, ingestion and injection. Injection is a unique pathway proposed in this work for workers with an ostomy. Injection refers to the instantaneous injection of material through the stoma. While inhalation is also a pathway, it is not considered due to the small fraction of material transferred to the gastrointestinal tract from the inhalation pathway. By looking at the NRC reported annual limit of intake (ALI) for uranium, it can be determine whether or not a worker needs further limitations when working with uranium.

2.0 Background

2.1 Internal Dosimetry

Biokinetic models for internal exposure are used to determine the number of transformations occurring within an organ or tissue during a given period of time by determining the activity as a function of time in each source region. This time usually ranges from 50 years for adults and 70 years for children [2]. The model is used to calculate the number of transformations occurring in each region taking into account the energies and yields of all emissions. Knowing the number of decays occurring in each organ and the energy deposited, the committed dose equivalent in sievert can be calculated.

2.2 Dosimetry Principles

To evaluate the dose to target tissues, the committed equivalent dose, $\mathbf{H_T}$, is determined. The committed equivalent dose is determined by the number of nuclear transformations of a radionuclide within the source region, **S**, over a given period after intake of the radionuclide. In general, the period of time is 50 years for adults. In addition, $\mathbf{H_T}$ is determined by the energy absorbed per mass in the target tissue, which is modified by the radiation weighting. The radiation weighting factor is dependent upon the type of radiation emitted per nuclear transformation. The committed equivalent dose, $H_{T,}$ in the target tissue T can be expressed by Equation 1 [1].

$$H_T = cU_s SEE(T \leftarrow S) \quad (1)$$

Where $\mathbf{U_s}$ is the number of transformations of a radionuclide 50 years after intake, $SEE(T \leftarrow S)$ is the specific effective energy per nuclear transformation in region **S** for a radionuclide and **c** taken to be 1.6×10^{-13}, the number of joules in one MeV, assuming SEE is in MeV per unit mass [1].

For each radionuclide in the decay chain, the specific effective energy (SEE) at age **t** takes into account the contribution from each radiation emitted. This is also weighted by the appropriate radiation weighting factor. The SEE can be determined by the following equation [1]

$$SEE(T \leftarrow S)_i = \frac{\sum w_{R,i} Y_i E_i AF(T \leftarrow S, E_i, t) + w_{R,\beta} \int_0^\infty Y(E) EAF(T \leftarrow S, E_i, t) dE}{M_T(t)} \quad (2)$$

Where, $\mathbf{w_{r,I}}$ is the radiation weighting factor applicable to the *i*-th radiation, $\mathbf{Y_i}$ is the intensity of the radiation, $\mathbf{E_i}$ is the energy of the *i*-th discrete radiation emitted by the radionuclide per nuclear transformation, $\mathbf{M_T(t)}$ is the mass of the target tissue **T** at age **t**, $\boldsymbol{AF(T \leftarrow S, E_i, t)}$ is the absorbed fraction quantity representing the fraction of the energy emitted in **S** that is absorbed in **T** for an individual of age **t** and **Y(E) dE** denotes the number of electrons in the beta or positron spectrum with energy between **E** and **E + dE** [1].

Each biokinetic model consists of multiple compartments corresponding to an individual organ. The translocation from consecutive compartments is governed by first order kinetics. The solution gives the time dependent distribution of the radionuclide and its daughter, if applicable. If $\mathbf{A_{i,j}(t)}$ is the activity of the radionuclide ***i*** in compartment ***j*** at time, the number of nuclear transformations in a compartment is governed by the following first order differential equation [1].

$$\frac{dA_{i,j}(t)}{dt} = \sum_{\substack{k=1 \\ j \neq k}}^{M} A_{i,j} \lambda_{i,k,j} - A_{i,j} [\sum_{\substack{k=1 \\ j \neq k}}^{M} \lambda_{i,k,j} + \lambda_i^p] \sum_{k=1}^{i-1} A_{k,j} \beta_{k,i} \lambda_i^p \quad (3)$$

Where:

M is the number of compartments describing the kinetics

$\boldsymbol{\lambda_{i,k,j}}$ is the fractional transfer rate, of chain member ***i*** from compartment ***j*** (donor compartment) to compartment ***k*** (receiving compartment).

$\boldsymbol{\lambda_i^p}$ is the decay constant of chain member ***i*** and

$\boldsymbol{\beta_{k,i}}$ is the fraction of decays of chain member ***k*** forming member ***i*.**

For example, using equation 3, the first compartment of the ICRP 30 gastrointestinal tract model, the stomach, the first order differential equation is given by equation 4 [1].

$$\frac{d}{dt}q_{ST} = -\lambda_{ST}q_{ST}(t) - \lambda_R q_{ST}(t) + I(t) \quad (4)$$

Where

I(t) is the rate of ingestion of a radionuclide

$\boldsymbol{\lambda_{ST}}$ is the transfer coefficient of the stomach

$\boldsymbol{\lambda_R}$ is the decay constant of the radionuclide

2.3 Annual Limit on Intake

The current occupational exposure for ionizing radiation limit by the NRC is expressed as a total effective dose equivalent equal to 0.05 Sv or the committed equivalent dose to any organ other than the eye being equal to 0.5 Sv [6]. ICRP 60 updated recommendation to an intake of a radionuclide that would lead to a total effective dose of 0.02 Sv per year averaged over five years with the addition that the effective dose does not exceed 50 mSv in a year [2]. In the event skin contamination occurs, 10CFR20.1201 limits shallow dose to the skin to 0.5 Sv to the skin of the whole body or to the skin of an extremity. The shallow dose must be averaged over the 10 cm^2 receiving the highest exposure [6]**.** The annual dose limit applies to the sum of the effective doses from external radiation and the committed effective dose from intakes of radionuclides occurring within the one-year period [1]. In occupational exposure, doses are commonly received from external and internal sources. For external exposures, individually monitoring is typically performed by measuring individual dose equivalents using personal dosimeters. On the other hand, for internal exposures, committed effective dose values are determined from bioassay samples or in the workplace. Internal exposure can also be described through the use of

dosimetric models for long periods of time. Calculated ALI are based solely on radiation dose and does not take into account the chemical effects [1].

2.4 Skin Dose Calculation

The NRC utilizes VARSKIN code, a tool used to assess doses from skin contamination. Varskin performs a five-dimensional integration of the source volume and the target area [7]. The mathematical kernel used calculate the dose by the code is

$$B(r) = \frac{kE_{\beta}YF_{\beta}\left(\frac{r_1}{X_{99}}\right)}{\pi\rho r^2 X_{99}} \quad (5)$$

Where:

r is the distance between the source point and the dose point

k is a unit conversion constant

E_{β} is the average beta energy

Y is the beta yield per disintegration

$F_{\beta}(r_1/X_{99})$ is the scaled absorbed dose distribution

r_1 is the modified path length between a source point and the dose point

ρ is the density of the material

2.5 ICRP Publication 30 Dosimetric Model for the Gastrointestinal Tract

The dosimetric model for the gastrointestinal tract provides an important tool for the determination of internal dose to a worker after ingestion of a radionuclide [1]. The model employs the same general method used to calculate **$H_{50,T}$.** The methods used to calculate the number of transformations in the source organ, **U_S**, and **H_{50}** are discussed. The gastrointestinal model breaks the system into separate sections and these sections are treated as separate target tissues. ICRP 30 breaks the colon into the

upper large intestine (ULI) and the lower large intestine (LLI). The ULI refers to the ascending and transverse colon and the LLI includes the descending, sigmoid colon, and rectrum. Figure 1 displays the different components that make up the GI tract dosimetric model from ingestion to excretion [1]

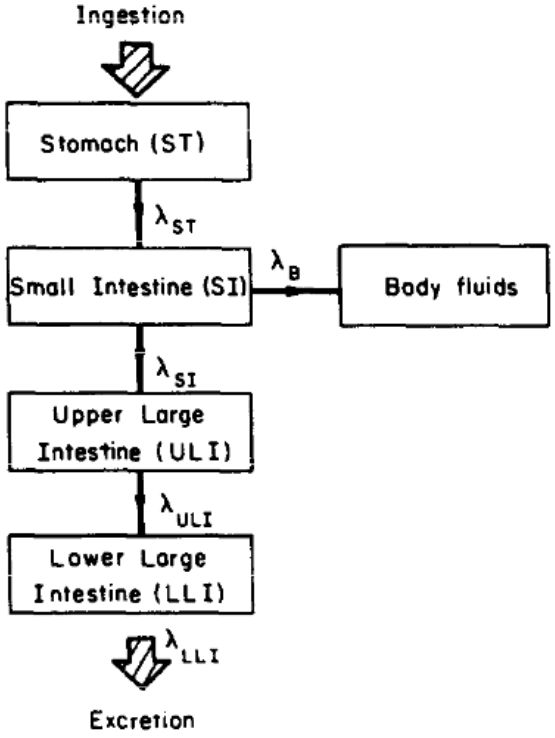

Figure 1: ICRP 30 Gastrointestinal Tract Model

Table 2: ICRP 30 transfer rates for each compartment of the GI tract model

Section of GI tract	Mass of walls* (g)	Mass of contents* (g)	Mean residence time (day)	λ day^{-1}
Stomach (ST)	150	250	1/24	24
Small Intestine (SI)	640	400	4/24	6
Upper Large Intestine (ULI)	210	220	13/24	1.8
Lower Large Intestine (LLI)	160	135	24/24	1

* From *ICRP Publication 23* (1975).

The value λ_B, corresponds to the transfer rate of material to the body fluids and can be estimated from $\mathbf{f_1}$, the fraction of a stable element that reaches the body fluids following ingestion [1].

$$\lambda_B = \frac{f_1 \lambda_{SI}}{1 - f_1} \quad (6)$$

The values of f_1 are provided by metabolic data for various classes of compounds of individual isotopes. In addition, in the case of radioactive daughter isotopes the value of f_1 is taken to be the stable isotope from which the ingested radionuclide is an isotope [1].

$$f_1 = \frac{\lambda_B}{\lambda_{SI} + \lambda_B} \quad (7)$$

In addition, absorption of ingested radioactivity is assumed to occur in the small intestine and can be described by element specific "$\mathbf{f_1}$" values [1]. The $\mathbf{f_1}$ values represent fractional absorption of the stable element to the blood.

Absorbed fractions estimations for beta and alpha particles due to the contents in the GI tract are assumed to be 1 and 0.01, respectively [1]. This is in addition to the dose to the walls of the GI tract from absorbed activity, particularly long-lived radionuclides. This is usually the dominant source of dose to the walls in the GI tract.

2.6 ICRP 100 Human Alimentary Tract Model

In 2006, the ICRP updated the ICRP 30 gastrointestinal tract model in ICRP publication 100. In 2015, the ICRP published ICRP publication 130 adopting the ICRP 100 HATM, formally replacing ICRP Publication 30 gastrointestinal tract model [8]. This replacement of the ICRP 30 model was motivated by a number of developments including improved information on the gut transit of materials and the increased awareness of the location of sensitive cells [9]. The most important feature of the HATM is the calculation of doses to target regions containing sensitive cells for cancer induction [9]. The ICRP 100 HATM also allows for retention in alimentary tract walls and absorption to the blood from other areas within the GI tract. One prominent difference between the ICRP30 model and the HATM is that the

HATM assumes a longer transit time through the alimentary tract and therefore a slower rate of fecal excretion for the first few days after ingestion of a radionuclide.

Unlike the dosimetric model for the GI tract, the HATM also accounts for entrance into the esophagus after particle transport from the respiratory tract [9]. It describes the sequential transfer through all alimentary tract regions including the oral cavity, esophagus, stomach, the small intestine, and colon, followed by the excretion of feces. The doses are calculated for each region. Based on the availability of transit time data, the colon is separated into right colon, left colon, rectosigmoid (the sigmoid colon and rectum) [9]. The sigmoid colon and the rectum are considered together because the transit times for each separately have not been determined and there is no specific W_T value for the rectum. The HATM and the ICRP 30 model yield similar tissue dose estimates for most radionuclides. However, in some cases the HATM will yield substantially different doses to walls of the alimentary tract due to the specification of retention of radionuclides in the walls of the tract and the explicit modeling of the sensitive cells of different regions of the GI tract in the HATM model [9]. The HATM is compatible with and inter-connected to the Human Respiratory Tract Model (HRTM) published in ICRP 66. Figure 2 displays the HATM model [9].

The updated HATM is much more complex than the ICRP 30 GI tract model. The HATM depicts the entry of a radionuclide into the oral cavity through ingestion or into the esophagus following mechanical clearance from the respiratory tract. In addition, the model also incorporates radionuclide deposition and retention on or between the teeth and return to the oral cavity and in the walls of the stomach and intestine, transfer from the walls of the stomach and the intestines back into luminal contents or the blood [9]. This process is referred to as absorption.

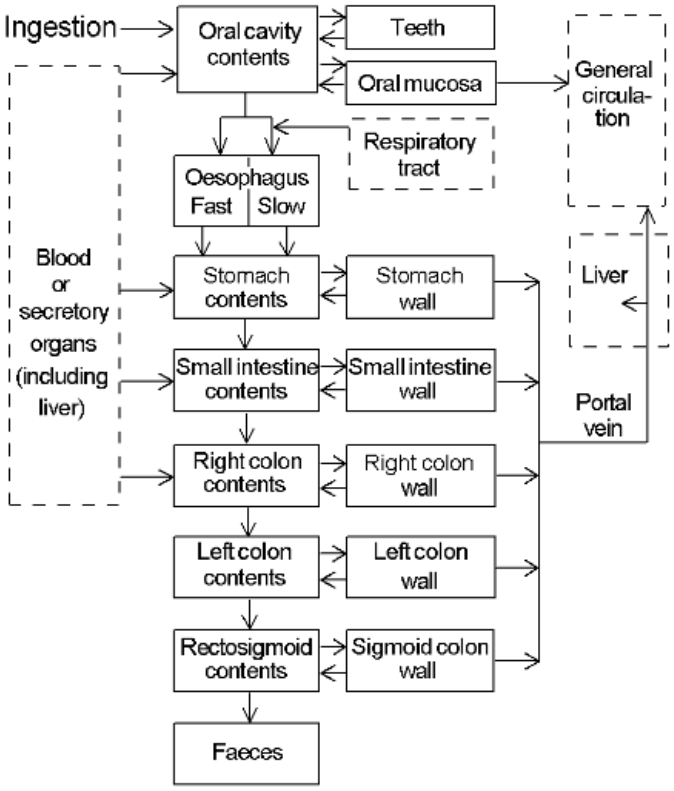

Figure 2: ICRP 100 Human Alimentary Tract Model

The dashed boxes represent connection to organs with the respiratory tract model or systemic biokinetic model and are therefore, not part of the HATM model [9]. In addition, the HATM model assumes first order kinetics, which provides simplification of the process but provides an accurate representation of the mean residence time of a radionuclide in each element of the tract. Each parameter in the model is represented by a transfer coefficient, which describes the outflow rate of a material from a compartment. The transfer coefficient is described as the instantaneous fraction of the contained material leaving the compartment per unit time. Parameters used in the model may be generic values or element specific values. Generic values refer to values that describe bulk flow of material through the lumen of the alimentary tract [9]. These values are given in the form of age, gender, and material specific transit times. The element specific values are those that describe retention in or on the tissue, absorption to blood, and secretion from systemic organs or blood into the

lumen of the tract. Minimal element specific parameters are available and where not available, the coefficient is assumed to be zero [9].

2.6.1. Transit Times

Transit through the lumen of the tract depends on the compartment of concern. The transfer of material from the oral cavity to the esophagus is represented by a single transit time that is dependent on the type of material entering the oral cavity [9]. Default times are available for liquids, solids, and total diet.

The transfer of material from the esophagus to the stomach is described by two transfer rates. Most swallowed food reaches the stomach in a matter of a few seconds. However, there is evidence from studies of labeled material fed by mouth that a portion of swallowed food may take longer for clearance, usually within a few minutes but sometimes longer [9]. This longer retention time may also be present in the case of inhaled material transferred to the alimentary tract by mechanical transport. Each of the two components of transfer from the esophagus to the stomach is represented by a single transit time, which is dependent on the type of material

Transfer from the stomach to the small intestine is represented by a single transit time that depends on the type of material entering the stomach. Default transit times are provided for water or other non-caloric liquids, caloric liquids, solids, and total diet. After the small intestine, the transit time is assumed to be independent of the type of material that initially entered the alimentary tract [9]. In addition, transfer from the small intestine to the right colon as well as each following sequential transfer is represented by a single transit time.

Table 3: Transfer Coefficients from ICRP 100 for the HATM

From	To	Transfer coefficient‡ (d^{-1})
Oral cavity contents	Oesophagus fast	6480
Oral cavity contents	Oesophagus slow	720
Oesophagus fast	Stomach contents	12,343
Oesophagus slow	Stomach contents	2160
Stomach contents	Small intestine contents	20.57
Small intestine contents	Right colon contents	6
Right colon contents	Left colon contents	2
Left colon contents	Rectosigmoid contents	2
Rectosigmoid contents	Faeces	2

2.6.2 Absorbed Fraction

ICRP 100 also updated the way absorbed fractions were determined for alpha particles and electrons. For electrons, it was determined that the approach taken in ICRP 30 may lead to a substantial overestimation. In most cases, the absorbed fraction for alpha particles will be zero based on the location of the sensitive cells. This is true for all isotopes of uranium. Absorbed fractions for electrons are based on geometric models and were calculated using MCNP General Purpose Monte Carlo Code. The absorbed fractions for electrons in each region of the alimentary tract can be found in Table F.1 in Annex F of ICRP 100 [9].

2.6.3 Absorption, Retention, and Secretion of Radionuclides

The dose delivered to regions of the alimentary tract depends on two main things, the rate of transfer through the lumen and the extent of the radionuclide's absorption to the blood and distribution in other tissues. Certain regions of the alimentary tract account for a great amount of absorption with the main region being the small intestine [9]. Absorption refers to the process that leads to the transfer of radionuclides from the alimentary tract to the blood and then to other tissues in the body. With high levels of absorption in the small intestines, smaller doses are usually present in the large intestine. Since the alimentary tract is a route of excretion variable portions of certain radionuclides may pass through

the large intestine. Doses to regions of the alimentary tract may also arise from radionuclides carried in the blood or deposited in tissues after absorption. Absorption depends on the chemical properties of the radionuclide as well as the specific form of the intake [9]. For example, cesium behaves similar to potassium and therefore will be rapidly absorbed. Additional dose may result with retention of radionuclides on the tissues of the alimentary tract. This is of particular concern because there is evidence of retention in the small intestine.

In general, the absorption of radionuclides occurs with nutrient absorption in the small intestine. Absorption may occur through two different processes. The first involves passive diffusion while the second is active transport through the single layer of epithelial cells lining the small intestine. Although a majority of absorption occurs within the small intestine there is evidence to suggest that absorption of some elements and their radioisotopes may occur in other regions of the alimentary tract. The other regions include the mouth, stomach, and colon [9]. The large intestine is known to absorb water and electrolytes such as sodium and chloride while the stomach absorbs highly lipid soluble substances. In addition, there is some evidence to suggest the absorption of some elements including iodine, copper, and mercury in the stomach.

2.6.4 Details of the Colon

The fraction of the alimentary tract extending from the caecum to the anus contains three regions: right colon, left colon, and rectosigmoid. The right colon is defined as the caecum, ascending colon, and proximal half of the transverse colon. The left colon is the distal half of the transverse colon plus the descending colon . Finally, the rectosigmoid includes the sigmoid colon and the rectum [9]. This division of the colon differs from the previous model of the gastrointestinal tract but is a standard division for diagnostic and experimental examinations of colonic transit. In addition, considerable information is available on transit times through each of these three sections. From ICRP Publication 100, the Task

Group concluded that the division of the large intestine into these segments allows for the best estimate of the time-dependent distribution of ingestion, inhalation, or secreted activity in the colon [9].

Although the rectum serves mainly as a channel for conveying, it may also serve as a storage organ when the amount of material is too small to induce defecation or is not convenient leading to a large amount of material being stored. Therefore since the transit time for material in the rectum is difficult, the rectum is not considered as a separate compartment [9].

2.7 ICRP 30 Metabolic Data for Uranium

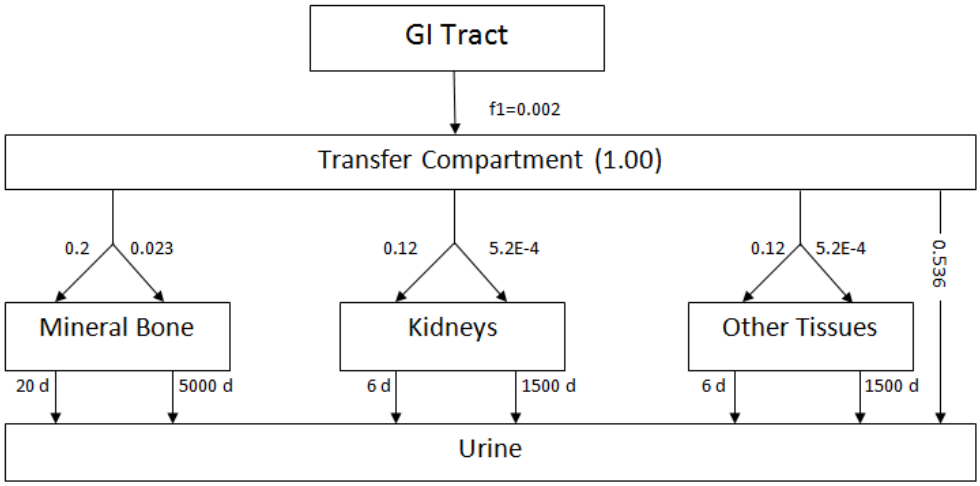

Figure 3: Metabolic model for uranium

Figure 3 outlines the uranium metabolic model from ICRP 30 [10]. Based on numerous studies investigating the uptake of uranium to the blood, anywhere from 0.005 and 0.05 of the compound is absorbed. ICRP 30 assumes an $\mathbf{f_1}$ value of 0.002 for relatively insoluble compounds of uranium such as UF_4, UO_2, and U_3O_8 and water-soluble inorganic compounds of uranium, the $\mathbf{f_1}$ is taken to be 0.05 [10].

The retention and distribution of uranium in bone and kidney have been determined using post-mortem data as well as intake from normal dietary uranium. It is assumed fractions 0.2 and 0.023 go to mineral bone and are retained with a half-life of 20 and 5000 days. In addition, fractions 0.12 and 0.00052 are assumed to go to the kidneys with half-lives of 6 and 1500 days, respectively. Finally, fractions 0.12 and 0.00052 are assumed to go to all other tissues and are retained for 6 and 1500 days [10]. The remaining fraction of uranium entering the transfer compartment is assumed to go directly to excretion.

2.8 ICRP 69 Uranium Systemic Model

Due to updated available information on actinides, the ICRP 30 metabolic data for was updated in 1995 in ICRP publication 60 to include additional compartments [11]. This general model for actinides was adapted for uranium in ICRP 69. The model is based on an age-specific biokinetic model for calcium like elements proposed by Leggett [12]. One difference between the proposed model by Leggett and the updated ICRP model is the inclusion of two liver compartments in the ICRP model for actinides [11].

The model includes entrance of uranium into the blood compartment through the gastrointestinal tract as well as the respiratory tract. The blood is treated as a uniform mixed pool. The uranium model also includes a red blood cell compartment, which exchanges with the plasma. As mentioned, the liver is separated into two compartments, Liver 1 and Liver 2. Liver 1 is considered the transit compartment and has a short retention time. Liver 2 is considered the storage compartment and has a long retention time ($T_{1/2}$> 1 year). Soft tissues, excluding liver and kidneys, are divided into three different compartments, slow, intermediate, and fast return of activity to the plasma. These compartments are labeled ST2, ST1, and ST0 in the ICRP 69 biokinetic model. ST0 includes extracellular fluids and transfers material over hours or days. This compartment serves two purposes, to represent early build up and decline of material as well as to account for early feedback into the blood. On the other hand, compartment ST1

represents intermediate retention, up to 2 years and ST2 represents long-term retention, for many years. Both compartments represent “massive soft tissue” including muscle, skin, and subcutaneous fat. The bone is broken down into cortical surface, cortical volume, exchange and non-exchange, trabecular surface, and trabecular volume, exchange and non-exchange. Activity transferring from the bone surface to the bone volume, is assumed to enter the exchange compartment where it is removed to either the non-exchange volume or to the blood system with an element specific half-time. From the non-exchange volume, material is assumed to be removed to plasma by bone resorption [11]. For dosimetry purposes it is assumed that activity is evenly distributed in the bone volume, exchange and non-exchange. In addition, bone marrow is considered as part of other soft tissues. In the case of excretion, activity is assumed to go directly to urine from the plasma and the gastrointestinal tract for feces. The additional compartment in the kidneys represents the retention in the renal tubes before excretion. Figure 4 displays the uranium systemic model from ICRP 69 [11].

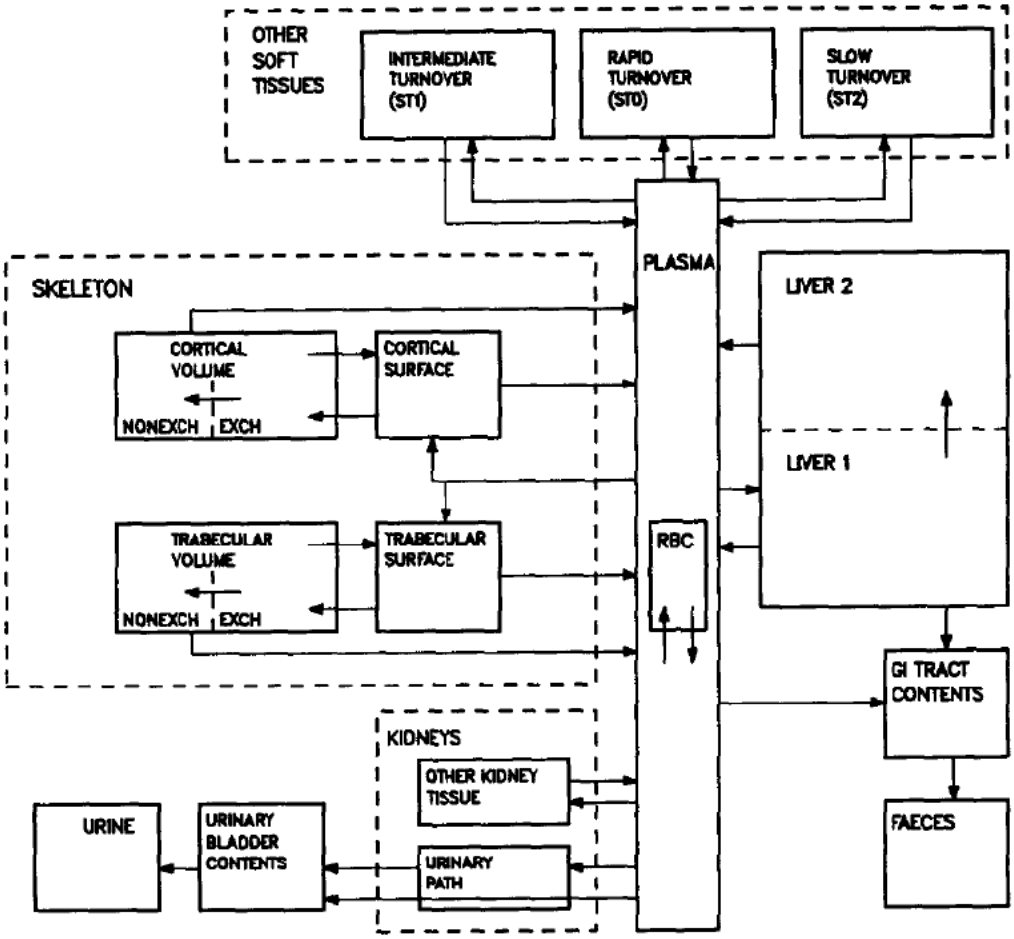

Figure 4: ICRP 69 systemic system biokinetic model for uranium

Table 4 displays the transfer coefficients for the ICRP 69 uranium systemic model.

Table 4: ICRP 69 transfer coefficients for the uranium systemic model

ICRP 69 Uranium Systemic System Transfer Coefficients	
Path	**Transfer Coefficient (s^{-1})**
From Plasma to:	
ST0	0.000121528
RBC	2.83565E-06
Urinary bladder contents	0.000178588
Kidney 1	3.40278E-05
Kidney 2	1.41204E-07
Upper large intestines content	1.41204E-06
Liver 1	4.24769E-06
ST1	1.88657E-05
ST2	8.50694E-07
Trabecular bone surface	2.36111E-05
Cortical bone surfaces	1.88657E-05
To Plasma From:	
ST0	9.62963E-05
RBC	4.0162E-06
Kidney 2	4.39815E-09
Liver 1	1.06481E-06
Liver 2	2.19907E-09
ST1	4.0162E-07
ST2	2.19907E-10
Bone surfaces	8.02083E-07
Nonexch trabecular Bone Volume	5.70602E-09
Nonexch cortical Bone Volume	9.50231E-10
Kidney 1 to urinary bladder contents	1.14583E-06
Liver 1 to liver 2	8.02083E-08
Bone surfaces to exchangeable bone volume	8.02083E-07
Exchangeable bone volume to bone surfaces	2.00231E-07
Exchangeable bone volume to nonexchangeable volume	6.68981E-08

2.9 Gastrointestinal Procedures

There is an increasing number of patients who undergo surgery on their GI tract for various reason including cancer, Crohns disease, as well as other medical conditions. These surgeries result in a change in pathway for an ingested radionuclide. According to United Ostomy Association of America**,** 750,000

are living with an ostomy and over 130,000 new life-saving ostomies occur in America every year [13]. An ostomy refers to a surgically created opening in the body for the discharge of wastes. When temporarily implemented, this allows time for the organ to heal. On the other hand, some ostomies may be permanent. There are two main types of ostomies performed each year that affect the GI tract, including colostomy and Ileostomy.

2.9.1 Colostomy

A colostomy requires bringing one end of the large intestine out through an opening made in the abdominal wall [13]. The large intestine is connected to the small intestine and consists of the two main sections, the colon and the rectum. The small intestine is the primary area of nutrient digestion, including fats, protein, and carbohydrates, which are then absorbed into the blood vessels. The food that cannot be absorbed moves from the small intestine to the large intestine, or more specifically, the colon, where mainly water is absorbed from the waste. The waste is continuously stored in the colon until the next bowel movement where it will eventually make its way down to the rectum.

As indicated in Figure 5, there are various colostomy types [14]. There are three main types of colostomies. The ascending colostomy is performed in the ascending colon and allows a majority of the colon to rest. A traverse colostomy, which affects the upper large intestine in the transverse colon, like the ascending colostomy allows for the colon to rest but allows a shorter segment of the colon to recover. The descending and sigmoid colostomies, which affect the lower large intestine and mainly allows for the rectum to heal [13].

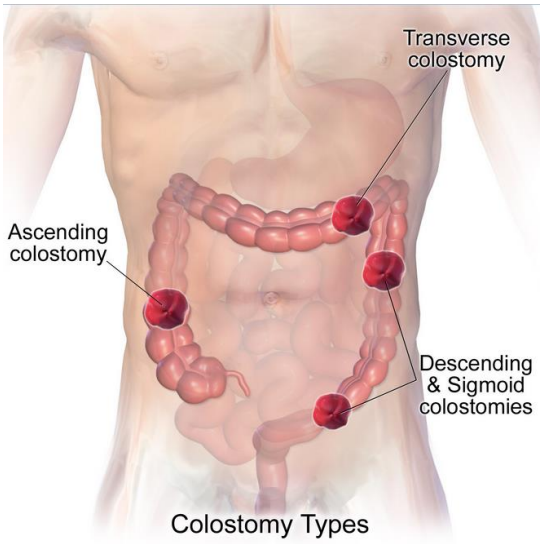

Figure 5: Location in the large intestine for each type of colostomy

The type of approach the surgeon takes depends on the other types of procedures that need to be performed. In general, the incision is made in the middle of the abdomen and the bowel resection and repair is done as needed. An incision is made in the abdomen wall. Once the incision is made, one end of the healthy colon is brought through the opening, normally on the left side. The surgically created opening of the large intestine is referred to as the stoma [13]. The edge of the bowl are stitched to the skin of the opening creating a stoma. On the outside of the opening a bag is placed called a stoma appliance. The bags allows for the collection of stool. The pouching systems may include a one or two-piece system. The one piece system consists of a plastic bag for collection. The two-piece system includes a mounting plate and the collection pouch. The bag attaches to the skin barrier and is fit over the stoma [13]. The colostomy bag is attached with an adhesive. The bags are designed to be air and watertight but may become dislodged or loose overtime due to loss of adhesion. Figure 6 displays an example of a colostomy bag [15].

Figure 6: Colostomy collection bag

If a person requires surgery on a portion of their large intestine, a colostomy provides short-term rest and allows for recovery [13]. Once the large intestine has recovered from surgery, the patient will have to undergo another surgery to reattach the ends of the large intestine. There are numerous reasons a person may have to undergo a colostomy. These range from infection of the abdomen, injury to the colon or rectum, blockage of the large bowel, rectal or colon cancer, or wounds in the perineum [13].

2.9.2 Descending and Sigmoid Colostomies

A descending colostomy is located in the descending portion of the colon. This portion of the colon takes the waste down the left hand side of the abdomen as shown in Figure 5 [13]**.** In a similar fashion, a sigmoid colostomy is located in the bottom portion of the large intestine.

2.2.3 Transverse Colostomy

A transverse colostomy is located in the transverse colon, as seen in Figure 5 [13]. The transverse colon crosses the top of the abdomen. There are two types of transverse colostomies, the loop colostomy where the entire loop of bowel brought to the skin surface and the end is opened to create a non-

functioning end. The second is a double barrel colostomy where the colon is divided into two stomas [13].

2.2.4 Ascending Colostomy

As indicated in Figure 5, an ascending colostomy is located in the ascending colon [13]. This is an extension of the beginning of the large intestine to the right side of the abdomen. This procedure results in only partial function of the colon. This type of procedure is rare and an Ileostomy is usually more appropriate [13].

2.3 Ileostomy

The ileum is the lowest portion of the small intestine. Therefore, an Ileostomy refers to the a procedure in which the surgeon creates an opening in the stomach wall and brings the end of the ileum through the opening and attaches it the skin to create the stoma [9]. Figure 7 shows the placement of an Ileostomy in the small intestine [13].

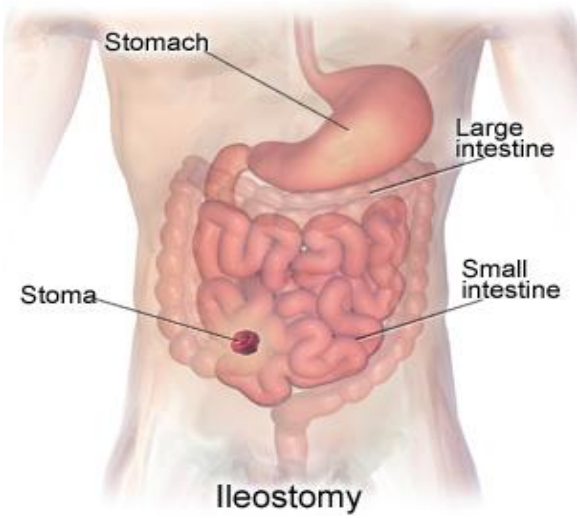

Figure 7: Location of Ileostomy

From the image, it is evident that through an Ileostomy, both the colon and the rectum are removed from the pathway for exiting waste. Like the other colostomies, ileostomies can be permanent or

temporary and varies between patients depending on the severity of the medical issue [13]. If an Ileostomy is temporary, this most likely means part of the colon has been removed but part of the rectum remains. This could result from surgery performed on part of the large intestine. The surgeon would perform an Ileostomy, allowing the large intestine to rest. When the Ileostomy is no longer required, another surgery is required to reattach the small intestine. An Ileostomy is required long term if both the large intestine and rectum have been removed [13]. There are numerous reasons a person would require an Ileostomy including, inflammatory bowel disease, colon or rectal cancer, familial polyposis , birth defects, or an accident involving damage to the intestines [13]. The pouching system for an ileostomy is the same appliance used for a colostomy and is attached through adhesion.

3.0 Model Development

3.1 MATLAB Simulink

For this research, MATLAB Simulink is utilized to model each dosimetric system. MATLAB is a software for scientists and engineers to analyze data, develop algorithms, and create models [16]. The Simulink suite was included in the MATLAB student version 8.6.0.267246 (R2015b). Simulink is a block diagram setting that allows for modeling and simulating dynamic systems [16]. Simulink provides a graphical interface, predefined blocks as well as user defined blocks that can be combined to create a unique system. One of Simulink's key features is the simulation engine with fixed step and variable-step ODE solvers. The solvers are numerical integration algorithms that compute the system dynamics over time using the information contained within the model [16]. The fixed step solver computes the time of the next simulation step by adding a fixed step to the current time. A variable-step solver varies the step size based on the local error to achieve the specified tolerance [16]. With the availability of fixed step and variable-step solvers in Simulink and the customizable block diagram setting a series of ordinary differential equations can be solved sequentially.

3.2 MATLAB Simulink Modeling

With the use of Simulink, the determination of the distribution and exchange of a radionuclide and its daughters through the human body using a series of ordinary differential equations is possible. The setup of each compartment in the model was based on previous research performed by Hrychushko [17].With the use of Simulink modeling, the initial intake and model pathways can be easily altered to allow for varying simulations and dose determinations.

For example, when looking at the transfer of material in the stomach compartment to the ULI from the ICRP 30 gastrointestinal tract model, shown in Figure 8.

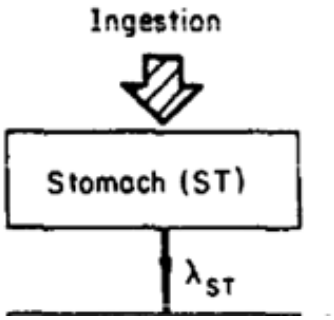

Figure 8: Stomach compartment from ICRP 30 GI tract model

The resulting differential equation, using Equation 3, for the activity as a function of time within the stomach is given by equation 8 [1].

$$\frac{d}{dt}q_{ST} = -\lambda_{ST}q_{ST}(t) - \lambda_R q_{ST}(t) + I(t) \tag{8}$$

Where:

$\boldsymbol{\lambda_{ST}}$ is the transfer coefficient of the stomach

$\boldsymbol{\lambda_R}$ is the radioactive decay constant of the radionuclide

$\boldsymbol{q_{ST}(t)}$ is the activity of the radionuclide ingested at time t in the stomach

I(t) is the rate of ingestion of activity of the radionuclide

The integration over 50 years, solved using MATLAB Simulink's variable step ODE solver, gives the total number of transformations in the stomach. Figure 9 displays the blocks used to determine the number of transformations in 50 years in the stomach compartment from the ICRP 30 GI tract model based on Equation 9.

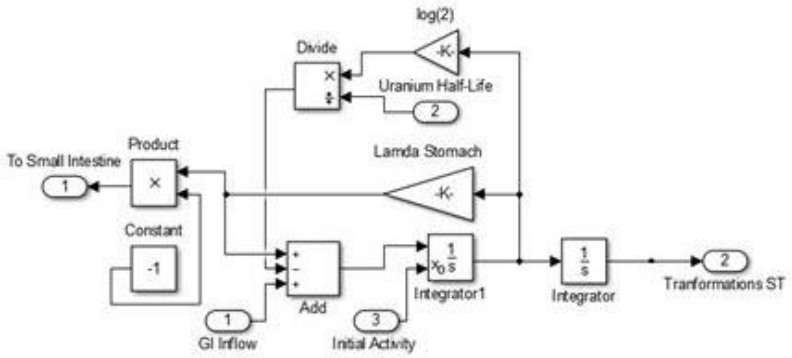

Figure 9: Detail showing the blocks used to calculate transformations in 50 years in the stomach compartment

The calculation of the contribution to dose from the presence of the daughter isotopes, where applicable, was included in the dose calculation since it improved the accuracy of the total dose to the ICRP reported values. For example, the activity of the daughter radionuclide in the stomach compartment is determined by Equation 9 [1].

$$\frac{d}{dt}q'(t) = -\lambda_{ST}q'_{ST}(t) - \lambda'_R q'_{ST}(t) + \lambda'_R q_{ST}(t) \quad (9)$$

Where

$\boldsymbol{\lambda'_R}$ is the decay constant of the daughter radionuclide

$\boldsymbol{q'_{ST}(t)}$ is the activity of the daughter in the stomach and q(t) is the activity of the immediate parent

Figure 10 displays the blocks used to calculate the number of transformations for the first daughter in the stomach compartment based on Equation 9.

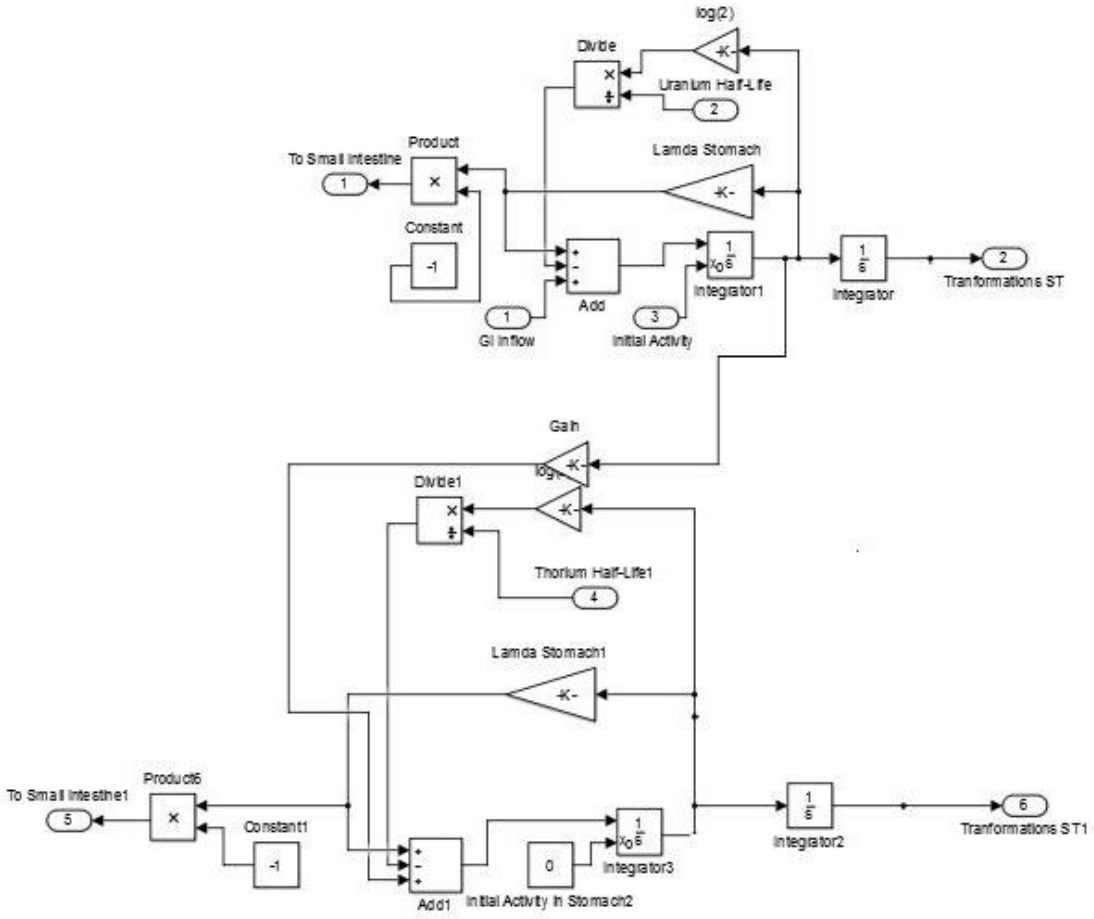

Figure 10: Blocks used to calculated the number of transformations for the parent and first daughter in the stomach compartment

Each compartment also included the calculation to determine the SEE. This calculation is based on Equation 2 and is given by Equation 10 [1].

$$SEE(ST \leftarrow ST) = \frac{Y_i E_i AF(ST \leftarrow ST)_i Q_i}{M_T} \quad (10)$$

Where

$\mathbf{Y_i}$ is the yield of radiations of time i per transformation

$\mathbf{E_i}$ is the energy of radiation I

AF is the absorbed fraction in the stomach from radiation i

$\mathbf{M_T}$ is the mass of the target organ

Q_i is the quality factor of the radiation; Q is 20 for alpha particles and 1 for electrons

For alpha particles and electrons the specific absorbed fraction (SAF) is given by equation 11 [1].

$$SAF = \frac{1}{2M_T}\nu \tag{11}$$

Where $\boldsymbol{\nu}$ represents the degree to which the radiation penetrates the mucus and ranges between 0 and 1. The value of $\boldsymbol{\nu}$ for electrons and alpha particles is 1 and 0.01, respectively [1]. The absorbed fraction is determined by the energy of the radiation for photons. Therefore, in order to determine the absorbed fraction for photons, a user defined Simulink function block was used to interpolate the values given in ICRP 23 with the target being the stomach wall and the source being the stomach contents. The organ dose was then determined by Equation 1. Figure 11 displays the blocks used to determine the number of transformations, SEE value, and organ dose for the stomach compartment.

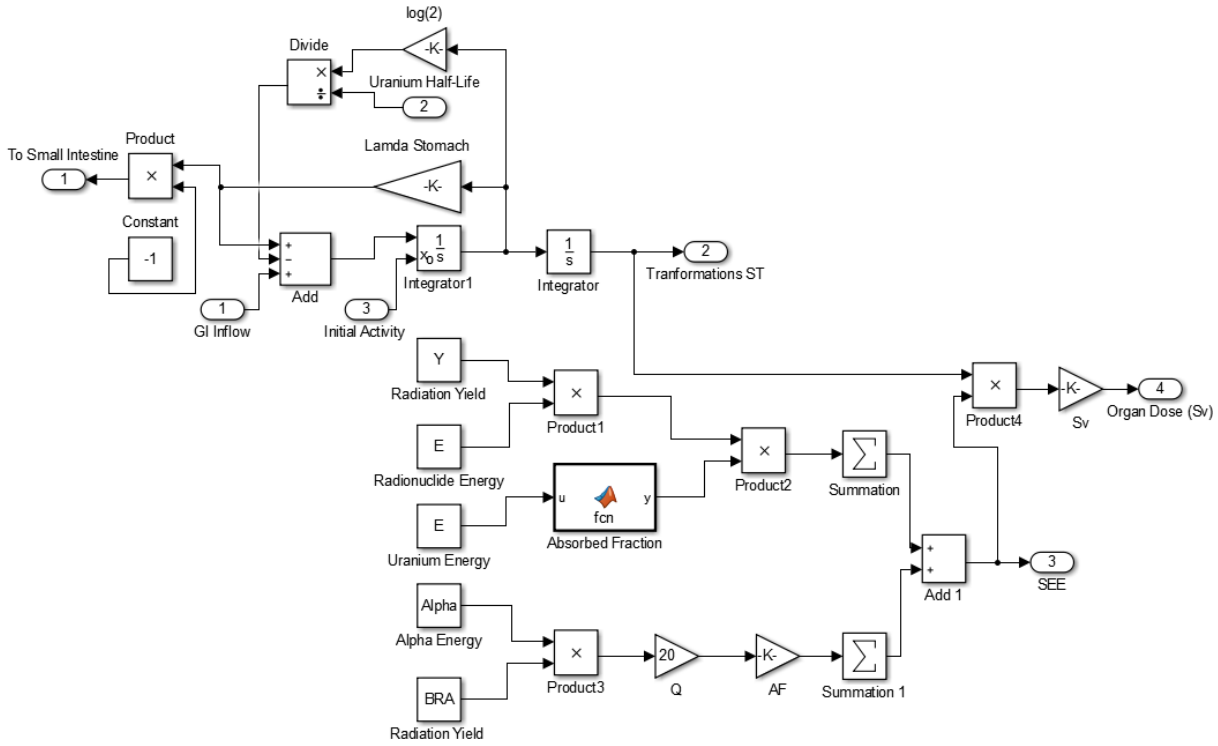

Figure 11: Details including the various blocks used in the stomach subsystem

Figure 11 only displays the detail of the stomach but the same approach was applied to each organ in the biokinetic model. In order to simplify the display of each model each organ was represented by

creating a subsystem. A subsystem displays only the basic information including any blocks used for inputs into inports such as constants or functions. It also displays outputs from the exports, represented by sinks. Sinks may include graphs or numerical displays. In the model, a subsystem represents a specific organ or tissue. This keeps blocks functionally related to one another together. Each subsystem can be connected through inports and exports to represent the exchange of a radionuclide from one compartment to the next.

Figure 12 displays an example of a subsystem, the stomach compartment of the gastrointestinal tract model from ICRP 30.

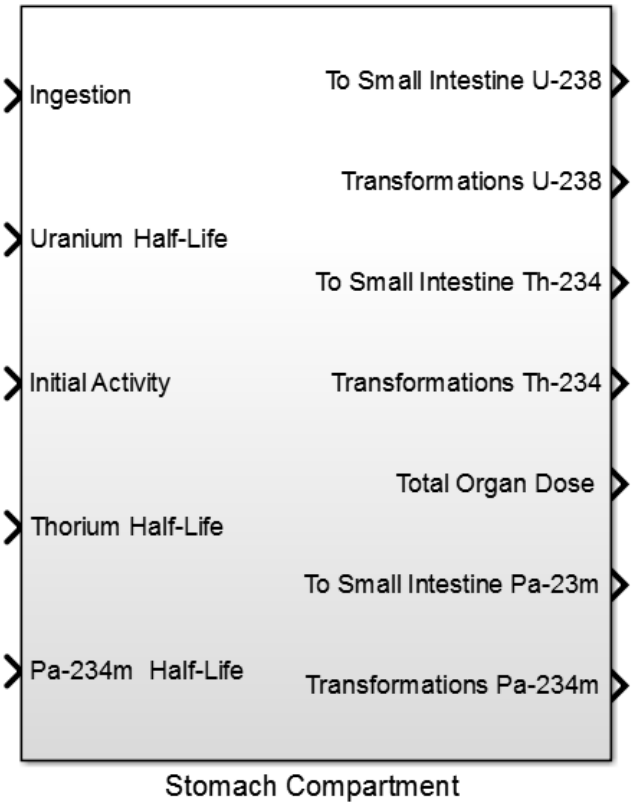

Figure 12: Single subsystem, the stomach, from the ICRP 30 GI tract model

From the subsystem, the inports include the ingestion, uranium half-life, thorium half-life, protactinium half life, and the initial activity in the stomach. The values were input based on the properties of the uranium isotope of interest and its daughters. For example, constants were used for the half-lives and initial activity as inputs into the inports. On the other side, the exports include the transfer of material to the small intestine, the transformations for each radionuclide, $\mathbf{U_s}$, occurring in the stomach, and the organ dose. Exports can be used to output values, using sinks, or connect subsystems. For example, the export for transfer of material to the small intestine was connected to the inport on small intestine subsystem and the number of transformations were output using a display block.

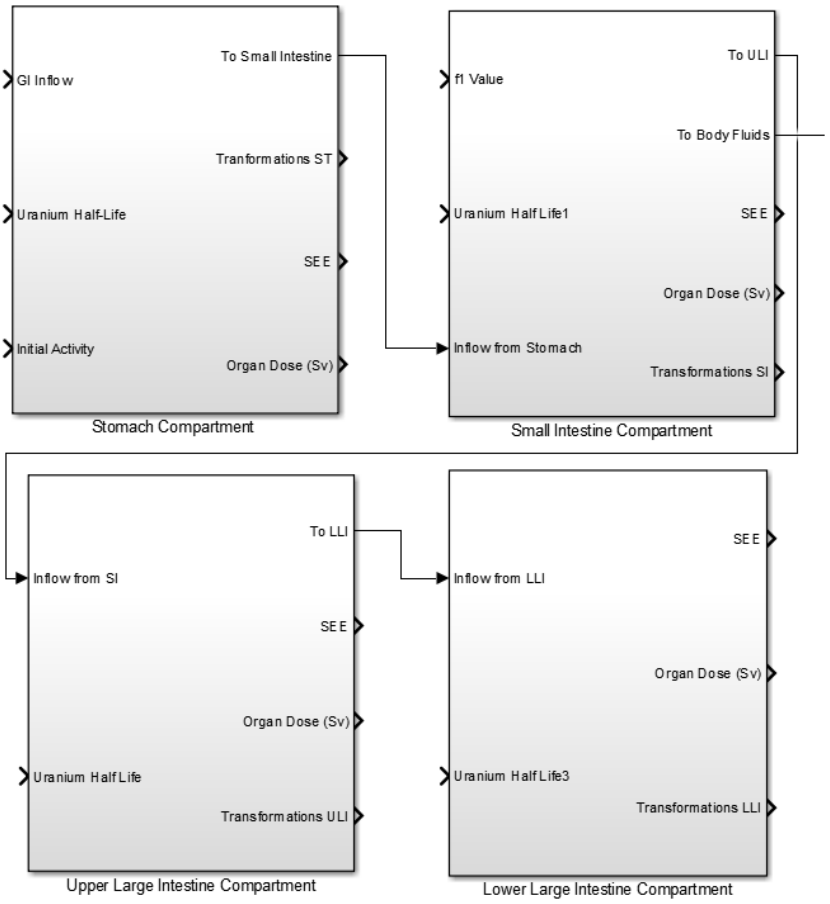

Figure 13: The four subsystems of the ICRP 30 GI tract model and how each inport and export connects

Figure 13 displays the four subsystems (stomach, SI, ULI, LLI) comprising the ICRP 30 GI tract model and how the inport and export of each subsystem can be connected to couple the differential equations described by each subsystem.

3.3 Development of Baseline Model

In order to perform analysis to determine the effects a gastrointestinal procedure may have on internal dosimetry, ICRP 30 gastrointestinal tract model, ICRP 30 metabolic data for uranium, ICRP 100 Human Alimentary Tract Model (HATM), and ICRP 69 uranium systemic model were modeled using Simulink in the same manner as described in Figures 9-13. The ICRP 30 GI tract model was connected to the ICRP 30 metabolic model for uranium and the ICRP 100 HATM and ICRP 69 uranium systemic model were connected. The ICRP 30 GI tract model was used because it is currently used by the NRC for federal regulation. On the other hand, ICRP 100 HATM model and ICRP 69 uranium systemic model was used because they are the most up to date models of the GI tract and blood system due to the updated available information since the ICRP 30 model.

Each model was used to determine the number of transformations, the SEE values, and organ equivalent dose. Using the organ equivalent doses and the tissue weighting factors from Table 1, the total body effective dose was determined for ingestion and injection pathways for each uranium isotope. The effective dose was determined using ICRP 26 tissue weighting factors for the ICRP 30 GI tract and ICRP 30 uranium systemic model combination. The whole body effective dose was determined using two methods for the ICRP 100 HATM and ICRP 69 systemic system model combination. The tissue weighting factors from ICRP 60 and ICRP 103 were applied and compared.

An instantaneous ingestion of 1 Bq was modeled for each combination. Specific model configuration parameters values were input into the system and were held constant. This allowed for reproducibility. For example, the half-life for ^{238}U is $4.47x10^{9}$ years and the initial activity in each organ was assumed to be zero. A variable-step type solver was utilized in each model. The use of a variable-step type solver reduces the step size when the state of the model changes rapidly to increase the accuracy [16]. It was determined running a fixed step size had no effect on the final dose calculation and resulted in significantly longer run times. Therefore, the step size was set to auto. In addition, the default differential equation solver, ode45, was used in each model. Ode45 is a MATLAB solver that uses a Runge-Kutta method for solving ordinary differential equations [16]. Finally, the relative and absolute tolerances were set to default as changing the tolerance to low values did not change the accuracy of the results. Simulink automatically sets the relative tolerance and absolute tolerance to 10^{-3} and 10^{-6}, respectively [16].

3.4 Benchmarking the Baseline Model

In order to validate each model was running as expected the values output from the model were compared to the ICRP 30 literature values [1]. The ICRP 30 GI tract model was connected with the model for ICRP 30 metabolic data for uranium. To achieve this, an instantaneous ingestion of 1 Bq was assumed to occur at time t=0 and was represented by a step function in the Simulink model. Table 5 displays a comparison between the SEE values output by the Simulink model and the ICRP 30 literature values for ^{238}U and its daughters, ^{234}Th and ^{234m}Pa [1].

Table 5: SEE values determined by the Simulink model and literature values from ICRP 30

Specific Effective Energy (MeV per g per transformation) of U-238									
Target Organ	U-238			Th-234			Pa-234m		
	Simulink Model	ICRP 30	% Error	Simulink Model	ICRP 30	% Error	Simulink Model	ICRP 30	% Error
ULI	1.9E-03	1.9E-03	0	1.3E-04	1.4E-04	7.14	1.7E-03	1.9E-03	10.53
LLI	3.1E-03	3.1E-03	0	2.1E-04	2.2E-04	4.55	2.8E-03	3.0E-03	6.67
Cortical Bone	7.0E-03	7.0E-03	0	7.7E-06	7.8E-06	1.28	9.8E-05	1.0E-04	2.00
Trabecular Bone	1.7E-02	1.7E-02	0	1.2E-05	1.3E-05	7.69	1.6E-04	1.7E-04	5.88
Kidney	2.7E-01	2.8E-01	3.57	1.9E-04	2.0E-04	5.00	2.4E-03	2.7E-03	11.11

Similarly, the number of nuclear transformations over 50 years per unit intake of ^{238}U resulting from the Simulink model were compared to the ICRP literature values. The values for ^{238}U, ^{234}Th and ^{234m}Pa are displayed in Table 6 [1].

Table 6: Number of nuclear transformations, Us, determined by the Simulink model and literature values from ICRP 30

Number of Transformations Over 50 Years per Unit of Intake (Transformations/Bq) U-238									
Target Organ	U-238			Th-234			Pa-234m		
	Simulink Model	ICRP 30	% Error	Simulink Model	ICRP 30	% Error	Simulink Model	ICRP 30	% Error
ULI	47900	47000	1.91	1034	990	4.4	1033	990	4.3
LLI	86230	86000	0.27	4220	4200	0.5	4218	4200	0.4
Cortical Bone	21888	22000	0.51	14880	21000	29.1	10312	21000	50.9
Trabecular Bone	5472	5500	0.51	3720	5300	29.8	2578	5300	51.4
Kidney	374	370	1.08	167	230	27.4	115	230	50.0

Finally, the committed dose equivalent values and weighted dose equivalent output from the ICRP 30 GI tract Simulink model were compared to the literature values in ICRP 30 for ^{238}U. The values are displayed in Table 7 and Table 8, respectively [1].

Table 7: Committed dose equivalent for target organs resulting from the Simulink model and literature values from ICRP 30 for U-238

Committed Dose Equivalent per Unit of Intake (Sv/Bq) U-238			
Target Organ	**Simulink Model**	**ICRP 30**	**% Error**
ULI	1.49×10^{-8}	1.50×10^{-8}	0.67
LLI	4.483×10^{-8}	4.60×10^{-8}	2.54
Bone Surface	3.993×10^{-8}	4.0×10^{-8}	0.25
Kidney	1.621×10^{-8}	1.70×10^{-8}	4.65

Table 8: Effective Dose for target organs calculated by the Simulink model compared to the literature ICRP 30 values for U-238

Effective Dose per Unit of Intake (Sv/Bq) U-238			
Target Organ	**Simulink Model**	**ICRP 30**	**% Error**
ULI	8.94×10^{-10}	8.7×10^{-10}	2.76
LLI	2.69×10^{-9}	2.7×10^{-9}	0.37
Bone Surface	1.2×10^{-9}	1.2×10^{-9}	0
Kidney	9.73×10^{-10}	1.0^{-9}	2.7

The same benchmark procedure was performed for ^{233}U, ^{234}U, and ^{235}U for the ICRP 30 model. Tables 9-14 display the committed dose equivalent and the effective dose for each target organ from the Simulink model as well as the literature values from ICRP 30 and the calculated percent error.

Table 9: Committed Dose Equivalent for target organs calculated by the Simulink model compared to the literature ICRP 30 values for U-234

Committed Dose Equivalent per Unit Intake (Sv/Bq) U-234			
Target organ	**Simulink Model**	**ICRP 30**	**% Error**
ULI	1.66E-08	1.60E-08	3.44
LLI	4.85E-08	4.90E-08	0.94
Bone Surface	4.51E-08	4.50E-08	0.2
Kidney	1.83E-08	1.90E-08	3.53

Table 10: Effective Dose for target organs calculated by the Simulink model compared to the literature ICRP 30 values for U-234

Effective Dose per Unit Intake (Sv/Bq) U-234			
Target organ	**Simulink Model**	**ICRP 30**	**% Error**
ULI	9.93E-10	9.7E-10	2.37
LLI	2.91E-09	3.0E-09	3.00
Bone Surface	1.35E-09	1.4E-09	3.57
Kidney	1.10E-09	1.1E-09	0.00

Table 11: Committed Dose Equivalent for target organs calculated by the Simulink model compared to the literature ICRP 30 values for U-233

Committed Dose Equivalent per Unit Intake (Sv/Bq) U-233			
Target organ	Simulink Model	ICRP 30	% Error
ULI	1.67E-08	1.60E-08	4.06
LLI	4.88E-08	5.00E-08	2.32
Bone Surface	4.54E-08	4.60E-08	1.26
Kidney	1.85E-08	1.90E-08	2.89

Table 12:Effective Dose for target organs calculated by the Simulink model compared to the literature ICRP 30 values for U-233

Effective Dose per Unit Intake (Sv/Bq) U-233			
Target organ	Simulink Model	ICRP 30	% Error
ULI	9.99E-10	9.8E-10	1.94
LLI	2.93E-09	3.0E-09	2.33
Bone Surface	1.36E-09	1.4E-09	2.86
Kidney	1.11E-09	1.1E-09	0.91

Table 13: Committed Dose Equivalent for target organs calculated by the Simulink model compared to the literature ICRP 30 values for U-235

Committed Dose Equivalent per Unit Intake (Sv/Bq) U-235			
Target organ	Simulink Model	ICRP 30	% Error
ULI	1.72E-08	1.70E-08	1.12
LLI	5.26E-08	5.20E-08	1.10
Bone Surface	4.15E-08	4.20E-08	1.26
Kidney	1.74E-08	1.70E-08	2.24

Table 14: Effective Dose for target organs calculated by the Simulink model compared to the literature ICRP 30 values for U-235

Effective Dose per Unit Intake (Sv/Bq) U-235			
Target organ	Simulink Model	ICRP 30	% Error
ULI	1.03E-09	1.00E-09	3.00
LLI	3.15E-09	3.20E-09	1.56
Bone Surface	1.24E-09	1.3E-09	4.62
Kidney	1.04E-09	1.00E-09	4.00

The ICRP 100 model could not be benchmarked for the alimentary tract because the ICRP has not released updated dose coefficients for uranium using the new model. However, ICRP 130 plans to update the uranium dose coefficients in a future publication, which are necessary for benchmarking the model. However, the systemic system, ICRP 69 used in conjunction with ICRP 100 HATM was benchmarked using the dose coefficients provided in ICRP 69 for ^{238}U. ICRP 69 uses an $\mathbf{f_1}$ value of 0.02. Therefore, in order to benchmark the ICRP 69 uranium systemic model, an $\mathbf{f_1}$ value of 0.02 was used. Table 15 provides the committed dose equivalent from the Simulink model and the ICRP 69 literature values.

Table 15: Committed Dose Equivalent for ICRP 69 uranium systemic model

Committed Dose Equivalent ICRP 69 (Sv/Bq) for U-238			
	Simulink Model	ICRP 69	% Error
Bone Surface	6.75E-07	7.10E-07	5.0
Kidney	2.49E-07	2.50E-07	0.4
Liver	9.37E-08	9.60E-08	2.4

After each system was modeled in Simulink and benchmarked against the ICRP literature values for each uranium isotope, both models combinations were used to make alterations and analyzed for all gastrointestinal procedures.

4.0 Development of Modified Anatomy Models

Radionuclides may enter the alimentary tract directly as a result of the ingestion or indirectly through inhalation for a person with unmodified anatomy. However, when an ostomy patient enters the workforce following the procedure, a potential new entrance point exists. This could lead to an accidental injection of radioactive material through the stoma. To determine the potential impacts to ostomies workers exposed to unsealed radioactive material, three pathways will be examined. The pathways include ingestion, injection and stoma contamination or skin contamination. For this work, injection refers to the entrance of material through the stoma, or hole created during a colostomy.

For this work, inhalation is not considered as a pathway. While inhalation is a main intake pathway, inhalation is not considered due to the small fraction of material transferred to the GI tract. The small fraction of material transferred to the GI tract would result in little to no change in dose estimates compared to unmodified anatomy. If significant changes occur in the ingestion pathway, the assumption can be re-examined.

When looking at the internal dose received by a worker it is important to consider the organs that the ingested radionuclide passes through. For a normal healthy individual, the pathway would look similar to that seen in Figure 1 or Figure 2, where the ingested radionuclide of concern would enter the mouth and continue through the body from the stomach to the small intestine, small intestine to the large intestine and though to excretion. The ICRP dosimetric model of the gastrointestinal tract discussed in section 2 models this type of anatomy. However, in the case of an ostomy patient, this generic model and must be modified to reflect the anatomical changes that occur. In each of the colostomy cases, the ostomy will result in a truncated colon. Therefore, when implementing changes to the base model, a new transfer coefficient will have to be determined. This is dependent on the length of the colon. In

addition, for the ICRP 30 model, the mass of the content will have to be altered to reflect what is present in the colon. It is assumed the content of the colon is uniformly distributed.

4.1 Adapting Models to Modified Anatomy

For a healthy person, the length of an individual's colon may vary depending on gender and age. Therefore, in order to use the models to simulate each gastrointestinal procedure, a few assumptions had to be made about the gastrointestinal system. The lengths are based on the average colon lengths for an adult human. The colon has a total length of 150 cm [18]. In addition, the following lengths of the various sections of the colon are given; the ascending colon, 20 cm, the transverse colon, 45 cm, descending colon, 30 cm, sigmoid colon, 45 cm, and the rectum, 10 cm [18]**.**

ICRP 30 assumes the ULI consists of the ascending colon and the transverse colon. In addition, the LLI consists of the descending colon, sigmoid colon, and rectum. Based on the listed lengths and the predetermined section breakup listed from ICRP 30, the total length of the ULI and LLI were determined. It was determined when using ICRP 30 GI tract model, that ULI had a total length of 65 cm and the LLI had a total length of 85 cm. For the ULI this included adding the length of the ascending colon, 20 cm, and the length of the transverse colon, 45 cm, to given 65 cm. In the case of the LLI this included adding the length of the descending colon, 30 cm, the sigmoid colon, 45 cm, and the rectum, 10 cm.

ICRP 100 divides the colon into three sections instead of two. Therefore, the length of each compartment, right colon, left colon, and rectosigmoid colon were determined. ICRP 100 assumes the right colon consists of the ascending colon and the distal half of the transverse colon, the left colon consists of the distal half of the transverse colon and the descending colon, and the rectosigmoid colon, consist of the sigmoid colon and the rectum. Therefore, the base ICRP 100 HATM model assumed the

right colon had a length of 42.5 cm. This was determined adding the ascending colon, 20 cm, and half the transverse, 22.5 cm. The left colon was determined to have a total length of 52.5 cm. This was determined by adding the length of the distal half of the transverse colon, 22.5 cm and the descending colon, 30 cm. Finally, the rectosigmoid colon had a total length of 55 cm. This was determined by adding the length of the sigmoid colon, 45 cm, and the rectum, 10 cm.

4.2 Transit Times

It was determined the change in dose to the colon was not sensitive to the location of the colostomy and differed by less than 1%. Table displays the dose of a transverse colostomy at 25%, 50%, and 75% of the transverse colon. Since 75% was the location used for dose calculation, the percent difference between the dose from 75% was determined for 25% and 50%.

Table 16: CDE in the ULI for a transverse colostomy at various locations

Committed Dose Equivalent in the ULI for ICRP 30 for a Transverse Colon					
Organ	**Transverse (75%)**	**Transverse (25%)**	**% Difference from 75%**	**Transverse (50%)**	**% Difference from 75%**
ULI	1.451E-08	1.462E-08	0.76	1.46E-08	0.62

While in reality, each colostomy case is different and can be located at any point in the colon, for purposes of this report, it was assumed that each procedure occurs at point halfway in the specified section of the colon with the exception of the transverse colostomy. In order to represent the location of the colostomy as accurately as possible, the transverse colostomy was assumed to be located at a point 75% along the transverse colon. For example, in the case of the transverse colostomy, it was assumed to occur at 75% of the transverse colon or based on the length, at 33.75 cm. With this assumption, 17% of the ULI compartment would be removed as well as the LLI. Therefore, a transverse colostomy results in 83% of the ULI compartment remaining after the procedure and the transfer

coefficient was scaled to reflect the change. Table 16 displays the percentage of colon remaining for each procedure for the ICRP 30 and ICRP 100 model.

Table 17: Percent colon remaining for each ostomy case for ICRP 30 and ICRP 100

Procedure	% Colon Remaining ICRP 30	% Colon Remaining ICRP 100
Ascending Colostomy	ULI (16%)	RC (23.5%)
Transverse Colostomy	ULI (83%)	LC (21%)
Descending Colostomy	LLI (17.5%)	LC (71%)
Sigmoid Colostomy	LLI (61.5%)	Rectosigmoid (41%)
Ileostomy	Small Intestine (100%)	Small Intestine (100%)

Using the ICRP reported transfer coefficients, the lengths of the colon sections, and the location of the colostomy, new transfer coefficients were determined for each gastrointestinal procedure. For example, in the case of the transverse colostomy when applied to the ICRP 30 model, the new transfer coefficient was determine by

$$\lambda_{ULI} = \frac{2.1x10^{-5}}{0.83} = 2.57x10^{-5}\ \frac{1}{s} \quad (12)$$

Table 17 displays the new transfer coefficients calculated in reference to the ICRP 30 GI tract model for each colostomy case and ICRP 30 literature values [1].

Table 18:Transfer Coefficients used to simulate each procedure in the ICRP 30 configuration model

Procedure	Transfer Coefficient (s^{-1})	ICRP 30 Transfer Coeffcient (s^{-1})
Ascending Colostomy	$1.34x10^{-4}$	$2.1x10^{-5}$
Transverse Colostomy	$2.57x10^{-5}$	$2.1x10^{-5}$
Descending Colostomy	$6.61x10^{-5}$	$1.157x10^{-5}$
Sigmoid Colostomy	$1.887x10^{-5}$	$1.157x10^{-5}$
Ileostomy	$6.9x10^{-5}$	$6.9x10^{-5}$

In the same manner, the transfer coefficients were calculated for each colostomy case for the use in the ICRP 100 HATM model using the ICRP 100 transfer coefficients and the percent of remaining colon found in Table 16. In the case of the transverse colostomy applied to ICRP 100 HATM, the transfer coefficient does not change due to the division of sections in the model. The right colon consists of the proximal half of the transverse colon, this including up to the location where the transverse colostomy occurs. Table 18 displays the new transfer coefficients calculated for each colostomy procedure in reference to the ICRP 100 HATM model as well as the literature ICRP 100 transfer coefficients [9].

Table 19: Transfer Coefficients used to simulate each procedure in the ICRP 100 configuration model

Procedure	Transfer Coefficient (s^{-1})	ICRP 100 Transfer Coefficient
Ascending colostomy	1.013×10^{-4}	2.381×10^{-5}
Transverse colostomy	1.066×10^{-4}	2.381×10^{-5}
Descending colostomy	3.33×10^{-5}	2.381×10^{-5}
Sigmoid colostomy	5.82×10^{-5}	2.381×10^{-5}
Ileostomy	6.9×10^{-5}	2.381×10^{-5}

4.3 Ingestion Pathway

Figure 14 displays an example of the modified ICRP 30 model to reflect a transverse colostomy.

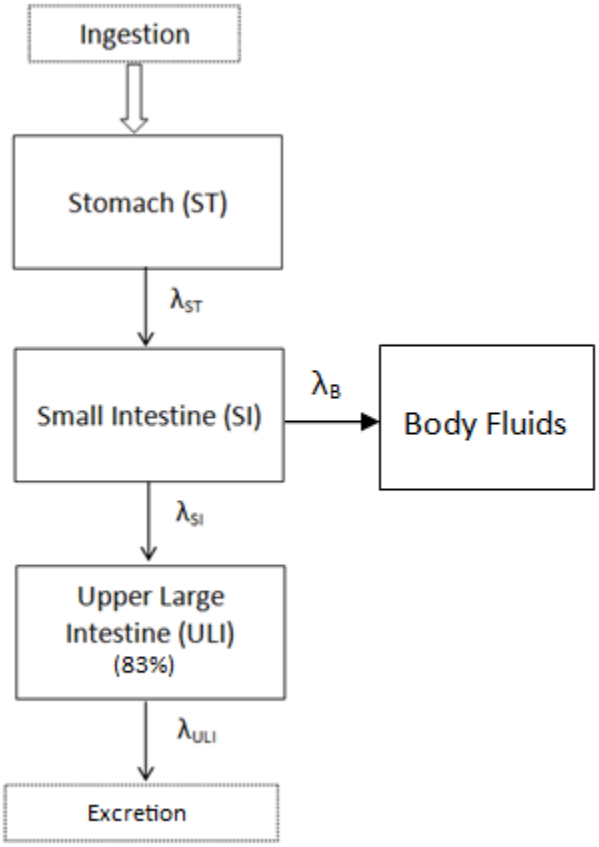

Figure 14: Block diagram representing the transfer between compartments in the case of a transverse colostomy for the ICRP 30 configuration

The radionuclide would follow the same pathway described in ICRP 30 model however, the transit time in Table 17 would be applied to λ_{ULI} to reflect a shortened ULI. In the case of the transverse colon, it was determined that 65% of the ULI would remain following an ostomy. The contents would then excrete into the bag application. The same procedure was applied to each ostomy case, in which the new transfer coefficient was applied to the model to reflect the anatomical changes occurring for each and the percentage of remaining colon found in Table 16. Figure 15 displays the transverse colostomy applied to ICRP 100 HATM.

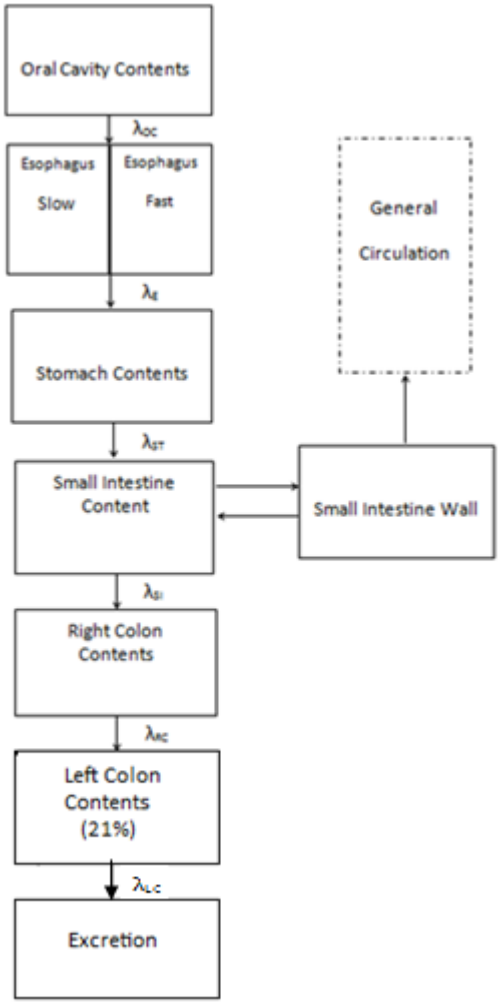

Figure 15: Block diagram representing the transfer between compartments in the case of a transverse colostomy for the ICRP 100 configuration

Like, ICRP 30, the radionuclide would follow the same pathway until it reaches the right colon in which the transit time would be modified. λ_{RC} would be replaced by the new transfer coefficient found in Table 18. The same procedure can be applied for each ostomy case depending on the compartment in which anatomical changes would occur, thus representing a shorter transit time due to a shortened colon. The percentages found in Table 16 can be used to reflect the modified pathway in which the radionuclide would follow for ingestion.

4.4 Injection Pathway

The injection pathway assumed an activity of 1 Bq is instantaneously injected at t=0 through the stoma into the intestine. It was assumed the radionuclide was uniformly distributed throughout the section of the colon in which the injection occurred. Since it was assumed uniform distribution took place within the colon section, the same transit times from Table 17 can be used in the ICRP 30 model. Figure 16 displays the schematic diagram of the injection pathway for the ICRP 30 model in the case of a transverse colostomy.

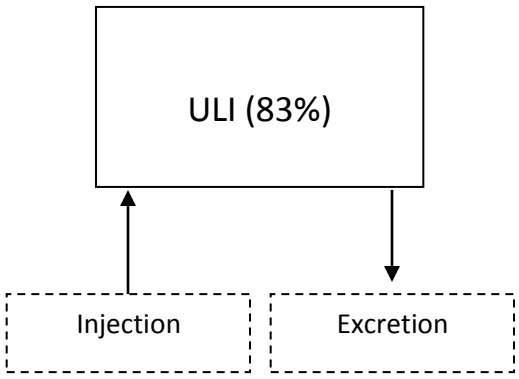

Figure 16: Injection pathway for a transverse colostomy for the ICRP 30 model

The same procedure can be applied to each ostomy case depending on which section the colostomy occurs. The transit times from Table 18 can be applied to the ICRP 100 HATM model to reflect the anatomical changes made by each ostomy. Figure 17 displays the transverse colostomy applied to the ICRP 100 HATM model.

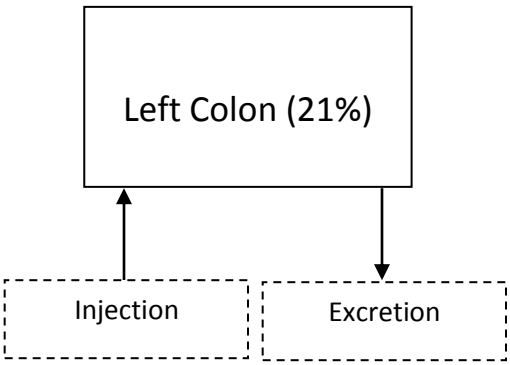

Figure 17: Schematic Diagram of the injection pathway for an ileostomy applied to the ICRP 100 model

4.5 Stoma Contamination

As part of the injection pathway, contamination to the stoma was considered. Using a similar methodology, the equation used by VARSKIN can be simplified and applied to the dose calculation for contamination to the stoma. Equation 4 gives the beta dose. In general, skin dose resulting from an alpha emitter is zero due to the layer of dead skin cell present. However, alpha dose must be considered in contamination to the stoma due to the ability of the alpha particles to penetrate the colon wall. The stoma consists of living tissue and does not have a layer of dead cells protecting it like skin does. The equation used to calculate the beta and alpha dose to stoma is given by equation 13.

$$D = \frac{0.5\, EY_i QAF}{m} \tag{13}$$

Where:

E is the energy of the radiation

Y is the branching ratio

AF is the fraction of energy absorbed by the medium

m is the mass of the target

The mass of the target was determined using the continuous slowing down approximation range of the alpha and beta particles. Assuming a 10 cm^2 area of tissue, the relationship between CSDA and mass is given by the following equation. 10 cm^2 was considered based on regulations.

$$m = CSDA\ x\ 10\ cm^2 \tag{14}$$

The CSDA for each alpha particle and beta particle was determined using tables provided by the National Institute of Standards and Technology (NIST)[19]. In order to determine the energy dependent CSDA from the tables provided by NIST, MATLAB was used to interpolate the energy specific values. This was achieved by utilizing the *interp1* function. MATLAB's *interp1* function is a 1-D data interpolation function, which returns interpolated values at specific query points using linear interpolation [16]. It was determined muscle provided the best CSDA estimate based on the biological properties of the colon and small intestine. Unlike skin dose in which alpha particles would provide zero dose due to the inability of the alpha particle to penetrate past the dead layer of cells, the colon does not provide shielding from alpha particles. It was also assumed the mucosa layer did not provide any shielding from the alpha particles. Therefore, they must be taken into consideration in the skin dose calculation. In order to determine the dose to the colon from each uranium isotope, the alpha and beta dose was calculated for each uranium isotope. The dose to the stoma was determined for an area of 10 cm^2 based on regulation. For example, using equation 5, the dose due to the 4.038 MeV alpha for 1 Bq of activity of ^{238}U was determined.

$$D = \frac{\left(4.038\frac{MeV}{dis}\right)1\ Bq\ (1.6x10^{-13}\frac{J}{MeV})(0.00078)(1)}{2\left(0.0027\ \frac{g}{cm^2}\right)(0.001\ \frac{kg}{g})(10\ cm^2)} = 9.17x10^{-12}\ \frac{J}{kg}\ (Gy) \tag{15}$$

Converting the dose from Gy to Sv per hour the equivalent dose per hour was determined.

$$H = \frac{9.17x10^{-12}(20)}{3600} = 2.55x10^{-15}\ \frac{Sv}{hr} \tag{16}$$

In the same manner, the equivalent dose was determined for each alpha particle emitted from ^{238}U. The result was then summed for all alpha particles emitted by the parent and if the parent included a short-lived daughter radionuclide, the radiation emitted by the daughter radionuclide was included. For

example, the beta particles emitted by ^{231}Th, the daughter radionuclide for ^{235}U, were included in the dose calculation because the half-life of ^{231}Th is 25.5 hours. The same process was repeated for all alpha particles and beta particles emitted for each specific uranium isotope, using the energy dependent CSDA.

5.0 Results

5.1 Ingestion Results ICRP 30 Model

Each combination, ICRP 30 GI tract model with ICRP 30 uranium systemic model and ICRP 100 HATM model with ICRP 69 uranium systemic model, were used to evaluate the internal dose due to ingestion, injection, and skin dose contamination for ^{233}U, ^{234}U, ^{235}U, and ^{238}U. In addition, for each isotope, the new transfer coefficients and colon mass changes were applied to reflect the anatomical changes present after an Ileostomy, ascending, transverse, descending, and sigmoid colostomy. Tables 19-22 display the internal dose calculated using ICRP 30 methodology for ingestion for ^{233}U, ^{234}U, ^{235}U, and ^{238}U, respectively. The dash (-) indicated there was no dose to the organ.

Table 20: Committed dose equivalent (CDE) and Committed Effective Dose Equivalent (CEDE) for each target organ per unit intake ingestion of 233U for each procedure case applied to the ICRP 30 configuration

Committed Dose Equivalent per Unit Intake Activity of U-233 Ingestion (Sv/Bq)						
Organ	**Baseline**	**Sigmoid**	**Descending**	**Transverse**	**Ascending**	**Ileostomy**
Stomach	1.10E-09	1.10E-09	1.10E-09	1.10E-09	1.10E-09	1.10E-09
Small Intestine	2.75E-09	2.75E-09	2.75E-09	2.75E-09	2.75E-09	2.75E-09
ULI	1.67E-08	1.67E-08	1.67E-08	1.63E-08	1.62E-08	-
LLI	4.88E-08	4.87E-08	4.89E-08	-	-	-
Bone Surface	4.54E-08	4.54E-08	4.54E-08	4.54E-08	4.54E-08	4.54E-08
Kidney	1.85E-08	1.85E-08	1.85E-08	1.85E-08	1.85E-08	1.85E-08
CEDE	6.63E-09	6.62E-09	6.63E-09	3.68E-09	3.67E-09	2.70E-09

Table 21: Committed dose equivalent (CDE) and Committed Effective Dose Equivalent (CEDE) for each target organ per unit intake ingestion of 234U for each procedure case applied to the ICRP 30 configuration

Committed Dose Equivalent per Unit Intake Activity of U-234 Ingestion (Sv/Bq)						
Organ	**Baseline**	**Sigmoid**	**Descending**	**Transverse**	**Ascending**	**Ileostomy**
Stomach	1.09E-09	1.09E-09	1.09E-09	1.09E-09	1.09E-09	1.09E-09
Small Intestine	2.73E-09	2.73E-09	2.73E-09	2.73E-09	2.73E-09	2.73E-09
ULI	1.66E-08	1.66E-08	1.66E-08	1.62E-08	1.67E-08	-
LLI	4.85E-08	4.84E-08	4.86E-08	-	-	-
Bone Surface	4.51E-08	4.51E-08	4.51E-08	4.51E-08	4.51E-08	4.51E-08
Kidney	1.83E-08	1.83E-08	1.83E-08	1.83E-08	1.83E-08	1.83E-08
CEDE	6.59E-09	6.58E-09	6.59E-09	3.65E-09	3.68E-09	2.68E-09

Table 22: Committed dose equivalent (CDE) and Committed Effective Dose Equivalent (CEDE) for each target organ per unit intake ingestion of 235U for each procedure case applied to the ICRP 30 configuration

Committed Dose Equivalent per Unit Intake Activity of U-235 Ingestion (Sv/Bq)						
Organ	**Baseline**	**Sigmoid**	**Descending**	**Transverse**	**Ascending**	**Ileostomy**
Stomach	1.12E-09	1.12E-09	1.12E-09	1.12E-09	1.12E-09	1.12E-09
Small Intestine	2.83E-09	2.83E-09	2.83E-09	2.83E-09	2.83E-09	2.83E-09
ULI	1.72E-08	1.72E-08	1.72E-08	1.40E-08	2.99E-09	-
LLI	5.26E-08	3.44E-08	1.21E-08	-	-	-
Bone Surface	4.15E-08	4.15E-08	4.15E-08	4.15E-08	4.15E-08	4.15E-08
Kidney	1.74E-08	1.74E-08	1.74E-08	1.74E-08	1.74E-08	1.74E-08
CEDE	6.71E-09	5.62E-09	4.28E-09	3.36E-09	2.70E-09	2.52E-09

Table 23: Committed dose equivalent (CDE) and Committed Effective Dose Equivalent (CEDE) for each target organ per unit intake ingestion of 238U for each procedure case applied to the ICRP 30 configuration

Committed Dose Equivalent per Unit Intake Activity of U-238 Ingestion (Sv/Bq)						
Organ	**Baseline**	**Sigmoid**	**Descending**	**Transverse**	**Ascending**	**Ileostomy**
Stomach	9.66E-10	9.66E-10	9.66E-10	9.66E-10	9.66E-10	9.66E-10
Small Intestine	2.42E-09	2.42E-09	2.42E-09	2.42E-09	2.42E-09	2.42E-09
ULI	1.49E-08	1.49E-08	1.49E-08	1.45E-08	1.48E-08	-
LLI	4.48E-08	4.44E-08	4.40E-08	-	-	-
Bone Surface	3.99E-08	3.99E-08	3.99E-08	3.99E-08	3.99E-08	3.99E-08
Kidney	1.62E-08	1.62E-08	1.62E-08	1.62E-08	1.62E-08	1.62E-08
CEDE	5.96E-09	5.93E-09	5.90E-09	3.24E-09	3.26E-09	2.37E-09

5.2 Ingestion Pathway ICRP 100 Model

Tables 23-26 display the committed equivalent dose calculated for each procedure for ^{233}U, ^{234}U, ^{235}U, and ^{238}U using the ICRP 100 HATM and ICRP systemic system methodology. The tables also provide the total body effective dose. The effective dose was calculated using two methods, ICRP 60 tissue weighting factors and the ICRP 103 tissue weighting factors, found in Table 1. These provide the two most up –to-date tissue weighting factors.

Table 24: Committed dose equivalent (CDE) and Committed Effective Dose Equivalent (CEDE) for each target organ per unit intake ingestion of 233U for each procedure case applied to the ICRP 100 configuration

Committed Dose Equivalent and Total Effective Dose per Unit Intake U-233 Ingestion (Sv/Bq)						
Organ	**Baseline**	**Sigmoid**	**Descending**	**Transverse**	**Ascending**	**Ileostomy**
Bone	8.09E-08	8.09E-08	8.09E-08	8.09E-08	8.09E-08	8.09E-08
Liver	1.13E-08	1.13E-08	1.13E-08	1.13E-08	1.13E-08	1.13E-08
Kidney	3.01E-08	3.01E-08	3.01E-08	3.01E-08	3.01E-08	3.01E-08
CEDE ICRP 60	1.52E-09	1.52E-09	1.52E-09	1.52E-09	1.52E-09	1.52E-09
CEDE ICRP 103	1.54E-09	1.54E-09	1.54E-09	1.54E-09	1.54E-09	1.54E-09

Table 25: Committed dose equivalent (CDE) and Committed Effective Dose Equivalent (CEDE) for each target organ per unit intake ingestion of 234U for each procedure case applied to the ICRP 100 configuration

Committed Dose Equivalent and Total Effective Dose per Unit Intake U-234 Ingestion (Sv/Bq)						
Organ	**Baseline**	**Sigmoid**	**Descending**	**Transverse**	**Ascending**	**Ileostomy**
Bone	8.03E-08	8.03E-08	8.03E-08	8.03E-08	8.03E-08	8.03E-08
Liver	1.12E-08	1.12E-08	1.12E-08	1.12E-08	1.12E-08	1.12E-08
Kidney	2.99E-08	2.99E-08	2.99E-08	2.99E-08	2.99E-08	2.99E-08
CEDE ICRP 60	1.51E-09	1.51E-09	1.51E-09	1.51E-09	1.51E-09	1.51E-09
CEDE ICRP 103	1.52E-09	1.52E-09	1.52E-09	1.52E-09	1.52E-09	1.52E-09

Table 26: Committed dose equivalent (CDE) and Committed Effective Dose Equivalent (CEDE) for each target organ per unit intake ingestion of 235U for each procedure case applied to the ICRP 100 configuration

Committed Dose Equivalent and Total Effective Dose per Unit Intake U-235 Ingestion (Sv/Bq)						
Organ	**Baseline**	**Sigmoid**	**Descending**	**Transverse**	**Ascending**	**Ileostomy**
Oral Contents	1.14E-17	1.14E-17	1.14E-17	1.14E-17	1.14E-17	1.14E-17
Esophagus	6.27E-17	6.27E-17	6.27E-17	6.27E-17	6.27E-17	6.27E-17
Stomach	2.05E-14	2.05E-14	2.05E-14	2.05E-14	2.05E-14	2.05E-14
Small Intestine	4.08E-14	4.08E-14	4.08E-14	4.08E-14	4.08E-14	4.08E-14
Small Intestine Wall	2.21E-14	2.21E-14	2.21E-14	2.21E-14	2.21E-14	2.21E-14
Right Colon	2.68E-14	2.68E-14	2.68E-14	2.68E-14	1.49E-14	-
Left Colon	4.72E-14	4.72E-14	4.40E-14	1.89E-14	-	-
Rectosigmoid	2.07E-13	1.86E-13	-	-	-	-
Bone	6.83E-08	6.83E-08	6.83E-08	6.83E-08	6.83E-08	6.83E-08
Liver	9.48E-09	9.48E-09	9.48E-09	9.48E-09	9.48E-09	9.48E-09
Kidney	2.53E-08	2.53E-08	2.53E-08	2.53E-08	2.53E-08	2.53E-08
CEDE ICRP 60	1.28E-09	1.28E-09	1.28E-09	1.28E-09	1.28E-09	1.28E-09
CEDE ICRP 103	1.29E-09	1.29E-09	1.29E-09	1.29E-09	1.29E-09	1.29E-09

Table 27: Committed dose equivalent (CDE) and Committed Effective Dose Equivalent (CEDE) for each target organ per unit intake ingestion of 238U for each procedure case applied to the ICRP 100 configuration

Committed Dose Equivalent and Total Effective Dose per Unit Intake U-238 Ingestion (Sv/Bq)						
Organ	**Baseline**	**Sigmoid**	**Descending**	**Transverse**	**Ascending**	**Ileostomy**
Oral Contents	1.31E-17	1.31E-17	1.31E-17	1.31E-17	1.31E-17	1.31E-17
Esophagus	7.19E-18	7.19E-18	7.19E-18	7.19E-18	7.19E-18	7.19E-18
Stomach	7.33E-15	7.33E-15	7.33E-15	7.33E-15	7.33E-15	7.33E-15
Small Intestine	2.77E-14	2.77E-14	2.77E-14	2.77E-14	2.77E-14	2.77E-14
Small Intestine Wall	7.73E-15	7.73E-15	7.73E-15	7.73E-15	7.73E-15	7.73E-15
Right Colon	3.21E-13	3.21E-13	3.21E-13	3.21E-13	1.66E-13	-
Left Colon	6.48E-13	6.48E-13	5.77E-13	2.32E-13	-	-
Rectosigmoid	3.24E-12	2.70E-12	-	-	-	-
Bone	7.17E-08	7.17E-08	7.17E-08	7.17E-08	7.17E-08	7.17E-08
Liver	9.96E-09	9.96E-09	9.96E-09	9.96E-09	9.96E-09	9.96E-09
Kidney	2.65E-08	2.65E-08	2.65E-08	2.65E-08	2.65E-08	2.65E-08
CEDE ICRP 60	1.35E-09	1.35E-09	1.35E-09	1.35E-09	1.35E-09	1.35E-09
CEDE ICRP 103	1.36E-09	1.36E-09	1.36E-09	1.36E-09	1.36E-09	1.36E-09

5.3 Injection Pathway ICRP 30 Model

Tables 27-30 provide the dose calculated using ICRP 30 methodology resulting from an injection through the stoma for each procedure for ^{233}U, ^{234}U, ^{235}U, and ^{238}U. In addition, the each table lists the calculated total body effective dose. The effective dose was calculated using ICRP 26 tissue weighting factors.

Table 28: Committed dose equivalent (CDE) and Committed Effective Dose Equivalent (CEDE) for each target organ per unit intake injection of 233U for each procedure case applied to the ICRP 30 configuration

Committed Dose Equivalent and Committed Effective Dose per Unit Intake Activity of U-233 Injection (Sv/Bq)					
Organ	**Sigmoid**	**Descending**	**Transverse**	**Ascending**	**Ileostomy**
Small Intestine	-	-	-	-	2.75E-09
ULI	-	-	1.63E-08	1.62E-08	-
LLI	4.88E-08	4.90E-08	-	-	-
Bone Surface	-	-	-	-	4.54E-08
Kidney	-	-	-	-	1.85E-08
CEDE	2.93E-09	2.94E-09	9.77E-10	9.73E-10	2.63E-09

Table 29: Committed dose equivalent (CDE) and Committed Effective Dose Equivalent (CEDE) for each target organ per unit intake injection of 234U for each procedure case applied to the ICRP 30 configuration

Committed Dose Equivalent and Committed Effective Dose per Unit Intake Activity of U-234 Injection (Sv/Bq)					
Organ	**Sigmoid**	**Descending**	**Transverse**	**Ascending**	**Ileostomy**
Small Intestine	-	-	-	-	2.73E-09
ULI	-	-	1.62E-08	1.67E-08	-
LLI	4.85E-08	4.87E-08	-	-	-
Bone Surface	-	-	-	-	4.51E-08
Kidney	-	-	-	-	1.83E-08
CEDE	2.91E-09	2.92E-09	9.71E-10	1.00E-09	2.62E-09

Table 30: Committed dose equivalent (CDE) and Committed Effective Dose Equivalent (CEDE) for each target organ per unit intake injection of 235U for each procedure case applied to the ICRP 30 configuration

Committed Dose Equivalent and Committed Effective Dose per Unit Intake Activity of U-235 Injection (Sv/Bq)					
Organ	**Sigmoid**	**Descending**	**Transverse**	**Ascending**	**Ileostomy**
Small Intestine	-	-	-	-	2.82E-09
ULI	-	-	1.38E-08	2.66E-09	-
LLI	3.22E-08	9.37E-09	-	-	-
Bone Surface	-	-	-	-	4.15E-08
Kidney	-	-	-	-	1.74E-08
CEDE	1.93E-09	5.62E-10	8.25E-10	1.60E-10	2.46E-09

Table 31: Committed dose equivalent (CDE) and Committed Effective Dose Equivalent (CEDE) for each target organ per unit intake injection of 238U for each procedure case applied to the ICRP 30 configuration

Committed Dose Equivalent and Committed Effective Dose per Unit Intake Activity of U-238 Injection (Sv/Bq)					
Organ	**Sigmoid**	**Descending**	**Transverse**	**Ascending**	**Ileostomy**
Small Intestine	-	-	-	-	2.42E-09
ULI	-	-	1.45E-08	1.47E-08	-
LLI	4.36E-08	4.32E-08	-	-	-
Bone Surface	-	-	-	-	3.99E-08
Kidney	-	-	-	-	1.62E-08
CEDE	2.61E-09	2.59E-09	8.68E-10	8.84E-10	2.32E-09

5.4 Injection Pathway ICRP 100 Model

Tables 31-32 provides the dose calculated due to injection of ^{235}U and ^{238}U. Under ICRP 100 methodology, no dose results to the colon from alpha particles. Therefore, ^{233}U and ^{234}U are not included because they do have short lived daughter radionuclides that emit beta particles. For the ileostomy, dose would result in the bone, liver, and kidney compartments but would be the same as if ingested because the fraction of material transferred to the blood system remains the same. The tables also provide the total body effective dose. The effective dose was calculated using two methods, ICRP 60 tissue weighting factors and the ICRP 103 tissue weighting factors.

Table 32:Committed dose equivalent (CDE) and Committed Effective Dose Equivalent (CEDE) for each target organ per unit intake injection of 235U for each procedure case applied to the ICRP 100 configuration

Committed Dose Equivalent and Committed Effective Dose per Unit Intake U-235 Injection (Sv/Bq)					
Organ	**Sigmoid**	**Descending**	**Transverse**	**Ascending**	**Ileostomy**
Small Intestine	-	-	-	-	3.14E-14
Small Intestine Wall	-	-	-	-	2.06E-14
Right Colon	-	-	-	6.09E-15	-
Left Colon	-	1.78E-14	3.30E-15	-	-
Rectosigmoid	3.89E-14	-	-	-	-
Bone	-	-	-	-	6.83E-08
Liver	-	-	-	-	9.48E-09
Kidney	-	-	-	-	2.53E-08
CEDE ICRP 60	1.56E-15	7.14E-16	7.74E-16	2.43E-16	1.28E-09
CEDE ICRP 103	1.56E-15	7.14E-16	7.74E-16	2.43E-16	1.29E-09

Table 33: Committed dose equivalent (CDE) and Committed Effective Dose Equivalent (CEDE) for each target organ per unit intake injection of 238U for each procedure case applied to the ICRP 100 configuration

Committed Dose Equivalent and Total Effective Dose per Unit Intake U-238 Injection (Sv/Bq)					
Organ	**Sigmoid**	**Descending**	**Transverse**	**Ascending**	**Ileostomy**
Small Intestine	-	-	-	-	2.13E-14
Small Intestine Wall	-	-	-	-	7.18E-15
Right Colon	-	-	-	5.77E-14	-
Left Colon	-	1.94E-13	3.14E-14	-	-
Rectosigmoid	3.97E-13	-	-	-	-
Bone	-	-	-	-	7.17E-08
Liver	-	-	-	-	9.96E-09
Kidney	-	-	-	-	2.65E-08
CEDE ICRP 60	1.59E-14	7.77E-15	8.97E-15	2.31E-15	1.35E-09
CEDE ICRP 103	1.59E-14	7.77E-15	8.97E-15	2.31E-15	1.36E-09

5.5 Annual Limit on Intake

To determine the potential risk to ostomy patients working with radioactive material, the annual limit on intake was calculated for each uranium isotope and for each ostomy case. The ALI must be satisfied by both the committed effective dose equivalent (CEDE) less than 0.05 Sv per year and the committed dose equivalent (CDE) less than 0.5 Sv per year [1]. Therefore, the ALI is determined by the limiting value. Tables 33-36 display the ALI's for ingestion and injection for the ICRP 30 and ICRP 100 HATM model configurations. The limiting organ is listed in the table where applicable, if the ALI is limited by the CEDE, no organ is listed.

5.5.1 Annual Limit on Intake Ingestion

Table 34: Annual limit on intake (ALI) for ingestion using the ICRP 30 configuration in Bq

	Base Model	**Sigmoid**	**Descending**	**Transverse**	**Ascending**	**Ileostomy**
U-233	7.54E+06	7.55E+06	7.54E+06	1.10E+07 (Bone surf)	1.10E+07 (Bone surf)	1.10E+07 (Bone surf)
U-234	7.59E+06	7.60E+06	7.58E+06	1.11E+07 (Bone surf)	1.11E+07 (Bone surf)	1.11E+07 (Bone surf)
U-235	7.45E+06	8.90E+06	1.17E+07	1.21E+07 (Bone surf)	1.21E+07 (Bone surf)	1.21E+07 (Bone surf)
U-238	8.39E+06	8.43E+06	8.47E+06	1.25E+07 (Bone Surf)	1.25E+07 (Bone Surf)	1.25E+07 (Bone Surf)

Table 35: Annual limit on intake (ALI) for ingestion using the ICRP 100 configuration in Bq

	Base Model	Sigmoid	Descending	Transverse	Ascending	Ileostomy
U-233	6.18E+06 (Bone surf)	6.18E+06 (Bone surf)	6.18E+06 (Bone surf)	6.18E+06 (Bone surf)	6.18E+06 (Bone surf)	6.18E+06 (Bone surf)
U-234	6.23E+06 (Bone surf)	6.23E+06 (Bone surf)	6.23E+06 (Bone surf)	6.23E+06 (Bone surf)	6.23E+06 (Bone surf)	6.23E+06 (Bone surf)
U-235	7.32E+06 (Bone surf)	7.32E+06 (Bone surf)	7.32E+06 (Bone surf)	7.32E+06 (Bone surf)	7.32E+06 (Bone surf)	7.32E+06 (Bone surf)
U-238	6.98E+06 (Bone surf)	6.98E+06 (Bone surf)	6.98E+06 (Bone surf)	6.98E+06 (Bone surf)	6.98E+06 (Bone surf)	6.98E+06 (Bone surf)

5.5.2 Annual Limit on Intake Injection

Table 36: Annual limit on intake (ALI) for injection using the ICRP 30 configuration in Bq

	Sigmoid	Descending	Transverse	Ascending	Ileostomy
U-233	1.02E+07 (LLI)	1.02E+07 (LLI)	3.07E+07 (ULI)	3.08E+07 (ULI)	1.10E+07 (Bone surf)
U-234	1.03E+07 (LLI)	1.03E+07 (LLI)	3.09E+07 (ULI)	3.00E+07 (ULI)	1.11E+07 (Bone surf)
U-235	1.55E+07 (LLI)	5.34E+07 (LLI)	3.64E+07 (ULI)	1.88E+08 (ULI)	1.21E+07 (Bone surf)
U-238	1.15E+07 (LLI)	1.16E+07 (LLI)	3.46E+07 (ULI)	3.39E+07 (ULI)	1.25E+07 (Bone surf)

Table 37: Annual limit on intake (ALI) for injection using the ICRP 100 configuration in Bq

	Sigmoid	Descending	Transverse	Ascending	Ileostomy
U-233	-	-	-	-	6.18E+06 (Bone surf)
U-234	-	-	-	-	6.23E+06 (Bone surf)
U-235	1.29E+13 (RS)	2.80E+13 (LC)	2.59E+13 (RC)	8.21E+13 (RC)	7.32E+06 (Bone surf)
U-238	1.26E+12 (RS)	2.57E+12 (LC)	2.23E+12 (RC)	8.66E+12 (RC)	6.98E+06 (Bone surf)

Based on Tables 33- 36, the ALI for each isotope and each case either remains the same as the benchmarked case or has a greater ALI than the benchmarked case in the case of ingestion for both model configurations. In the case of injection, for the ICRP 30 model configuration, the ALI for all uranium isotopes are determined by the CDE which applies the dose of the limiting organ. All ALI for the injection pathway are less than the ingestion pathway. The ICRP 100 model configuration results in the

same CEDE and CDE values for all cases. One exception is the ileostomy, which results in the same ALI as the ingestion pathway and is limited by the CDE value.

5.6 Stoma Contamination Dose

Table 37 provides the dose per unit activity per hour in the event skin contamination occurs.

Table 38: Calculated skin dose in Sv per hour per Bq for a 10 cm^2 area for each uranium isotope

Dose per Bq per Hour per 10 cm^2 (Sv per hour)	
U-233	1.17E-10
U-234	6.03E-11
U-235	5.73E-11
U-238	6.42E-11

The values listed in Table 38 can be used to determine the dose to the colon dependent on the isotope in order to further assess the contamination hazards. Table 39 displays dose to the stoma as a function of contact time.

Table 39: Dose per Bq as a function of contact time for each uranium isotope

	Dose per Bq (Sv/Bq)			
Time (min)	U-233	U-234	U-235	U-238
15	2.93E-11	1.51E-11	1.43E-11	1.61E-11
30	5.86E-11	3.02E-11	2.86E-11	3.21E-11
45	8.78E-11	4.53E-11	4.30E-11	4.82E-11
60	1.17E-10	6.03E-11	5.73E-11	6.42E-11
75	1.46E-10	7.54E-11	7.16E-11	8.03E-11
90	1.76E-10	9.05E-11	8.59E-11	9.63E-11
105	2.05E-10	1.06E-10	1.00E-10	1.12E-10
120	2.34E-10	1.21E-10	1.15E-10	1.28E-10

In addition, Table 39 displays the activity required to reach 10% of the annual limit to any organ of 0.5 Sv per year in one hour.

Table 40: Activity of uranium required to reach 10% of annual limit in one hour

	Dose Per hour (Sv per Bq per hour)	Activity (Bq)
U-233	1.17E-10	4.27E+08
U-234	6.03E-11	8.29E+08
U-235	5.73E-11	8.73E+08
U-238	6.42E-11	7.78E+08

6.0 Discussion

As mentioned the chemical form of the radionuclide of concern may vary depending on the type of exposure. For example, occupational exposures may result from specific inorganic forms of radionuclides not present in the environment. It is important to note that the chemical form of the radionuclide is likely changed during the digestive process [9]. These changes in chemical form will determine the availability of the radionuclide for absorption and therefore the extent of uptake through the intestinal epithelium to the bloodstream. As mentioned, this report will look at relatively insoluble compounds with an $\mathbf{f_1}$ value of 0.002. By changing the $\mathbf{f_1}$ value to reflect a more soluble compound, the fraction of material transferred to the blood system would increase leading to an increase in dose to the organs within the systemic system but would not result in greater risk to the GI tract.

6.1 Ingestion Model 30

The dose resulting to each section of the colon does not significantly change regardless of an alteration to the colon. In the case of a descending colostomy ^{233}U and ^{234}U the dose increases slightly from the benchmarked case. This is not true of any other colostomy scenario where the dose decreases from the unaltered case. This is not true for ^{235}U and ^{238}U where all committed dose equivalents are less than the benchmarked case. However, while the committed dose equivalent increased slightly in the case of the descending colostomy, it was determined to be insignificant, as it only differed from the unaltered case by 0.16%. In addition, the slight increase in dose did not change the total body effective dose. The total body effective dose is the same or less than the dose recorded for the benchmarked model. This is true for all uranium isotopes analyzed. This is due to the slight increase in dose in the colon in which the colostomy would take place for the sigmoid and descending colostomy as well as the dose to the LLI being absent from the transverse and ascending colostomy. In addition, the CEDE for the ileostomy is the lowest due to the radionuclide not passing through the ULI and LLI resulting in no dose for both compartments.

Table 41: CEDE doses for the ingestion using the ICRP 30 model configuration

Committed Effective Dose Equivalent for Ingestion Pathway						
	Base Model	Sigmoid	Descending	Transverse	Ascending	Ileostomy
U-233	6.63E-09	6.62E-09	6.63E-09	3.68E-09	3.67E-09	2.70E-09
U-234	6.59E-09	6.58E-09	6.59E-09	3.65E-09	3.68E-09	2.68E-09
U-235	6.71E-09	5.62E-09	4.28E-09	3.36E-09	2.70E-09	2.52E-09
U-238	5.96E-09	5.93E-09	5.90E-09	3.24E-09	3.26E-09	2.37E-09

6.3 Injection Model 30

In the case of an injection, the recorded dose occurred within the section of the colon the injection through the stoma would occur except in the case of the ileostomy. This is because transfer to the blood system only occurs within the small intestine in the ICRP 30 model. Therefore, an injection outside the region of the small intestine would result in no dose to the bone or kidney. Although transfer to the blood would occur in the case of an ileostomy, the fraction of material transferred is the same as the baseline model, f_1= 0.002, and does not result in additional dose to the bone or kidney. From the tables, the total body effective dose is less than the dose for a 1 Bq ingestion. Therefore, when looking at the annual limit on intake, the ALI for the case of the injection would be greater than the ALI for ingestion of the radionuclide.

Table 42: CEDE for the injection pathway using the ICRP 30 model configuration

Committed Effective Dose Equivalent for Injection Pathway					
	Sigmoid	Descending	Transverse	Ascending	Ileostomy
U-233	2.93E-09	2.94E-09	9.77E-10	9.73E-10	2.63E-09
U-234	2.91E-09	2.92E-09	9.71E-10	1.00E-09	2.62E-09
U-235	1.93E-09	5.62E-10	8.25E-10	1.60E-10	2.46E-09
U-238	2.61E-09	2.59E-09	8.68E-10	8.84E-10	2.32E-09

6.2 Ingestion Model 100

When comparing the data for the ICRP 100 HATM and ICRP 69 systemic model combination, the committed dose equivalent in the section of the colon in which the specific colostomy occurs is lower than the benchmarked equivalent dose. In all cases, the dose to the bone, liver, and kidney remains unchanged. This is due to the transfer value $\mathbf{f_1}$ not changing from the baseline model. While there is retention in the small intestine wall the fraction transferred to the blood system remains the same. Due to the way the absorbed fractions are handled for alpha particles in the alimentary tract in ICRP 100, alpha dose is negligible in the colon due to the location of the cancer inducing cells. The cancer susceptible cells are located at a depth beyond the penetration depth of the alpha particle. This results in a significantly lower dose equivalent in the ICRP 100 HATM model than ICRP 30. This is especially apparent in the cases of ^{233}U and ^{234}U. The dose to all sections of the colon is negligible and the only recorded dose results from the transfer of material to the organs within the systemic system. In the other case of ^{235}U and ^{238}U, the dose in the colon is due purely to the beta emissions from the daughter isotopes.

Due to the low equivalent doses in the alimentary tract and the most significant dose occurring in the bone compartment for uranium, the committed effective dose equivalent does not change for each procedure for each isotope. In addition, there is no significant difference in the total body effective dose when using the ICRP 60 methodology versus the ICRP 103 methodology. Table 42 displays the CEDE using ICRP 103 methodology because they are more conservative than the ICRP 60.

Table 43: CEDE values for ingestions using the ICRP 100 model configuration

Committed Effective Dose Equivalent for Ingestion						
	Base Model	Sigmoid	Descending	Transverse	Ascending	Ileostomy
U-233	1.54E-09	1.54E-09	1.54E-09	1.54E-09	1.54E-09	1.54E-09
U-234	1.52E-09	1.52E-09	1.52E-09	1.52E-09	1.52E-09	1.52E-09
U-235	1.29E-09	1.29E-09	1.29E-09	1.29E-09	1.29E-09	1.29E-09
U-238	1.36E-09	1.36E-09	1.36E-09	1.36E-09	1.36E-09	1.36E-09

6.4 Injection Model 100

Finally, when looking at the injection pathway, the resulting total body effective dose is significantly lower than the ingestion pathway with the exception of the ileostomy in which the effective dose is consistent with the ingestion pathway. This is due to the transfer of material to the blood system from the small intestine and no transfer from additional compartments in the alimentary tract for uranium. In all other cases, the material would enter the colon through the stoma and transfer out in the same manner as the ingestion pathway thus, resulting in no transfer to the blood system. The injection pathway was insignificant for ^{233}U and ^{234}U due to each isotope and daughter emitting only alpha particles. The only dose that would result is the dose due to transfer through the blood system but would not be increased from the ingestion case due to the constant transfer fraction.

Table 44: CEDE values for the injection pathway using ICRP 100

Committed Effective Dose for Injection					
	Sigmoid	Descending	Transverse	Ascending	Ileostomy
U-235	1.56E-15	7.14E-16	7.74E-16	2.43E-16	1.29E-09
U-238	1.59E-14	7.77E-15	8.97E-15	2.31E-15	1.36E-09

6.6 Stoma Dose

The major question regarding skin contamination is what level of activity would prompt medical intervention. The decision should ultimately be left up to the treating physician but the decision should take dosimetry into consideration. No definitive guidance exists, as every case is different [20]. The intervention required may range from washing the contaminated area to surgical excision. The NCRP

report suggests intervention when the dose to the skin exceeds one to ten times the annual limit [20]. Doses to the stoma can be calculated using Table 37. The first step in any contamination case is decontamination, removing any visible fragments and irrigation using a saline solution followed by assessment of remaining activity using an appropriate detector [20]. Soap and water may also be used in decontaminating the stoma and surrounding area. Any required additional action may want to be performed by a medical professional . While it is important to consult a health physicist, based on the length of time required to reach a dose level of concern or the level of activity that would have to present, the chemical hazard of the contaminant would be of greater concern than the radiological concerns of uranium.

6.7 Conclusions

Both the ICRP 30 gastrointestinal tract connected to the ICRP 30 uranium systemic model and the ICRP 100 HATM and ICRP 69 uranium systemic model resulted in the same conclusion for ingestion. The equivalent dose in the affected colon was reduced below the benchmarked value. This in turn, led to a reduced overall total effective dose for the ICRP 30 model for a transverse or ascending colostomy, and in the case of an ileostomy. The total effective dose remained the same in the case of a sigmoid or descending colostomy. Table 44 displays the CEDE values determined from the ingestion pathway for the ICRP 30 model.

Table 45: CEDE values for the ingestion pathway using ICRP 30 model for each uranium isotope

Committed Effective Dose Equivalent for Ingestion Pathway						
	Base Model	Sigmoid	Descending	Transverse	Ascending	Ileostomy
U-233	6.63E-09	6.62E-09	6.63E-09	3.68E-09	3.67E-09	2.70E-09
U-234	6.59E-09	6.58E-09	6.59E-09	3.65E-09	3.68E-09	2.68E-09
U-235	6.71E-09	5.62E-09	4.28E-09	3.36E-09	2.70E-09	2.52E-09
U-238	5.96E-09	5.93E-09	5.90E-09	3.24E-09	3.26E-09	2.37E-09

Due to the change in tissue weighting factors for the ICRP 60 and ICRP 103, the total effective dose remained the same in the ICRP 100 combination regardless of whether the colon was anatomically changed due to a colostomy or not. This is because the ALI is determined by the greatest intake of a radionuclide that satisfies a total effective dose less than 0.05 Sv or a committed dose equivalent less than 0.5 Sv. In the case of ICRP 100 the bone is the limiting organ and since the dose does not change, the ALI remains constant. In addition, the ALI is the lowest in the baseline case for the ICRP 30 combination and does not change in the case of the ICRP 100 combination..

Based on the data, the injection pathway does not pose an additional risk to an occupational worker in regard to uranium. The ALI calculated for injection is equivalent or orders of magnitude greater than the ingestion pathway. Therefore, it does not require additional limits on the amount of activity in use. Since the small intestine is the only section in which a fraction of material is transferred the systemic system, the ileostomy is the only scenario in which material can be passed to the blood for both model combinations. This resulted in no additional dose to any section in the gastrointestinal tract or systemic system. Finally, when looking at the ALI for all cases of injection for the ICRP 30 model combination, the ALI is greater than the baseline case for all colostomies except the Ileostomy. In the case of the Ileostomy, the ALI is the same as the ingestion pathway.

Due to the unique pathway, there is no base model or ICRP reported ALI's for the injection pathway. However, the ALI for all cases of injection for the ICRP 100 combination is significantly greater than the base model ingestion pathway in all cases except for the ileostomy, which is the same as the ingestion case. Therefore, due to a decrease in equivalent doses and an increase in ALI's, no additional precautions need to be taken in the event a worker enters the workforce with a colostomy when considering injection as an individual pathway.

Due to the possibility of the adhesion on the bag application becoming loose over time there is a possibility for the appliance to become dislodged, leading to the possibility of stoma contamination. Stoma contamination is also necessary in the event injection occurs. Although the dose per hour does not appear to be significant, alpha particles can penetrate the wall of the intestine due to the lack of shielding. Therefore, the potential dose to the skin of the intestine should be taken into account. However, when looking at the skin dose due to each uranium isotope, the dose received to the stoma per hour is low. Furthermore, the activity required to reach 10% of the annual limit in one hour is on the order of 10^8 Bq. Oftentimes, uranium is dissolved in an acid solution like nitric or sulfuric acid. Therefore, due to low dose rate, the chemical hazards would be of more concern than the radiological risks.

Taking into account all three potential pathways, ingestion, injection, and stoma contamination; there is no additional risk to an ostomy patient working with uranium. Furthermore, additional precautions do not need to be taken for an ostomy patient working with uranium. This means additional guidance is not necessary for ostomy patients to reduce potential exposure. In addition, if contamination of the stoma does occur, the chemical hazards are a greater concern than the radiological hazards.

6.7 Future Work

This work focused on uranium as it is commonly used for actinide research. With the base models built for each ICRP biokinetic model, the research can be expanded in a number of ways. The systemic model designed by Leggett and published in ICRP 69 is the base model for all actinides. This is due to the similarity in biological behavior of actinides once incorporated inside the body. In order to apply the model to other actinides, the transfer coefficients are element specific and would need to be updated for the specific radionuclide. This research focused on different uranium isotopes and the transfer values were specific to the uranium. In order to get a better look at the effects a gastrointestinal tract operation that alters the standard anatomy may have on internal dosimetry, other radionuclides

commonly used should be looked at. This could include the other actinides such as plutonium, thorium, and americium. Skin contamination may be of greater risk for a gamma emitter like ^{137}Cs. It may also include radionuclides with unique transfer to the blood system from areas in the alimentary tract other than the small intestine. For example, there is some evidence to suggest iodine is absorbed in the stomach. While uranium gave a good indication that no additional restrictions should be placed on an individual with a colostomy who has reentered the workforce, it should not be assumed this is true for all radionuclides. Therefore, it would be beneficial to look at other radionuclides. In particular, the other actinides would be a simple addition, as it would require minimal changes to the already existing models but would provide a better understanding about the effects.

In addition, ICRP plans to publish updated dose coefficients for uranium and therefore, in the future will allow the ICRP 100 HATM model to be benchmarked against the literature values. With the publication of 130, ICRP also plans to include updated bone dosimetry [1]. Both the ICRP 30 and ICRP 69 systemic model used ICRP 30 methodology for calculation of bone equivalent dose as it is currently the only methodology for bone dosimetry. With the updated methodology, the model can be updated with the new methodology for bone dosimetry. With the new updated bone dosimetry and uranium dose coefficients, the model would have to be benchmarked against the updated values. This will provide the most up to date calculation for the dose to bone. This is especially important for uranium, as the bone is the limiting dose. While, this will not change the outcome of the research due to the transfer of material to the blood system being constant, it will allow for the most up to date dose calculation for bone. In addition, with the ability to benchmark the model against published ICRP 130 values for uranium in the GI tract, it will also ensure the dose to the alimentary tract is up to date.

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Curriculum Vitae

Name: Sara Taylor

Education: **University of Nevada Las Vegas, Las Vegas, NV**
M.S. in Health Physics
August 2013 – July 2016

California Polytechnic State University, San Luis Obispo, CA
B.S in Physics
September 2009 - June 2013

Email: Taylos4@unlv.nevada.edu