THESIS

PU-239 ORGAN SPECIFIC DOSIMETRIC MODEL APPLIED TO NON-HUMAN BIOTA

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ABSTRACT

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There are few locations throughout the world, like the Maralinga nuclear test site located in south western Australia, where sufficient plutonium contaminate concentration levels exist that they can be utilized for studies of the long-term radionuclide accumulation in non-human biota. The information obtained will be useful for the potential human users of the site while also keeping with international efforts to better understand doses to non-human biota. In particular, this study focuses primarily on a rabbit sample set collected from the population located within the site. Our approach is intended to employ the same dose and dose rate methods selected by the International Commission on Radiological Protection and adapted by the scientific community for similar research questions. These models rely on a series of simplifying assumptions on biota and their geometry; in particular; organisms are treated as spherical and ellipsoidal representations displaying the animal mass and volume. These simplifications assume homogeneity of all animal tissues. In collaborative efforts between Colorado State University and the Australian Nuclear Science and Technology Organisation (ANSTO), we are expanding current knowledge on radionuclide accumulation in specific organs causing organ-specific dose rates, such as Pu-239 accumulating in bone, liver, and lungs. Organ-specific dose models have been developed for humans; however, little has been developed for the dose assessment to biota, in particular rabbits.

This study will determine if it is scientifically valid to use standard software, in particular ERICA Tool, as a means to determine organ-specific dosimetry due to Pu-239 accumulation in organs. ERICA Tool is normally applied to whole organisms as a means to determine radiological risk to whole ecosystems. We will focus on the aquatic model within ERICA Tool, as animal organs, like aquatic organisms, can be assumed to lie within an infinite uniform medium. This model would scientifically be valid for radionuclides emitting short-range radiation, as with Pu-239, where the energy is deposited locally. Two MCNPX models have been created and evaluated against ERICA Tool's aquatic model. One MCNPX model replicates ERICA Tool's intrinsic assumptions while the other uses a more realistic animal model adopted by ICRP Publication 108 and ERICA Tool for the organs "infinite" surrounding universe. In addition, the role of model geometry will be analyzed by focusing on four geometry sets

for the same organ, including a spherical geometry. ERICA Tool will be compared to MCNPX results within and between each organ geometry set. In addition, the organ absorbed dose rate will be calculated for six rabbits located on the Maralinga nuclear test site as a preliminary test for further investigation. Data in all cases will be compared using percent differences and Student's t-test with respect to ERICA Tool's results and the overall average organ mean absorbed dose rate.

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ABBREVIATIONS

AIRAC	Australian Ionizing Radiation Advisory Council
AMS	Atomic Mass Spectrometry
ANSTO	Australian Nuclear Science and Technology and Science Organisation
ANTERES	Australian National Tandem Research Accelerator
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
AWTSC	Australian Atomic Weapons Tests Safety Committee
DECDATA	ICRP Publication 107 radionuclide decay data
DOE	Department of Energy
ERICA/ERICA Tool	Environmental Risk from Ionizing Contaminates Assessment Management Tool
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ICRU	International Commission of Radiological Units
MARTAC	Maralinga Rehabilitation Technical Advisory Committee
MCG	Maralinga Consultative Group
MCNP	Monte Carlo N-Particle code (generic)
MCNP5	Monte Carlo N-Particle code Version 5
MCNPX	Monte Carlo N-Particle code Extended
N2BL	Normalized to Body Length
N2LI	Normalized to Literature Information
N2OM	Normalized to Organ Mass
SD	Standard Deviation
TAG	Technical Assessment Group
USDPHHS	U.S. Department of Health and Human Services

INTRODUCTION AND BACKGROUND

MOTIVATION FOR INVESTIGATION

Motivation

Increased public and scientific awareness have stressed the need for increased environmental protection (Copplestone, Howard, & Brechignac, 2004). With the International Commission on Radiological Protection (ICRP) Publication 108 the scientific community directly engages in protection of the environment when it had previously estimated that if man is protected then so is the environment (International Commission on Radiological Protection (ICRP), 2008) (International Commission on Radiological Protection (ICRP), 1991). The concept of environmental protection is not clearly defined and varies between countries. Long-lived contaminant radionuclides, such as Pu-239, can persist in the environment for thousands of years and be of major radiological concern if internally deposited. This is true for the former Maralinga nuclear testing area were elevated amounts (above background) have left the area contaminated with long-lived contaminates (Pu-239 + others) open to the environment. Scientifically, the residual contamination at the Maralinga nuclear test site presents an opportunity to study the long-term effects of long-term low-dose exposures due to alpha radiation, an area that is lacking in data according to the USDPHHS (U.S. Department of Health and Human Services, 2010).

Radiation damage has been studied extensively at the cellular level, but interaction at the organism and organ/tissue level become more complex due to the collective nature of cells and their function at the organ level (International Commission on Radiological Protection (ICRP), 2008) (Hall & Giaccia, 2012). Organ structure plays a vital role in its response to radiation, with different tissues having different responses to the same radiation. Larger organ/tissue volumes tend to be effected more than smaller volumes. Clinically this is known as the volume effect as the body has reduced healing capacity. With natural populations exposed to chronic or long-term exposures to radionuclides in the environment, as Pu-239, there tends to be bioaccumulation in specific organs (bone and liver for plutonium), which may affect the overall-health of the population either by a reduction in reproductive capacity or

early mortality. In studying organ specific doses in non-human biota such as rabbits we may better understand these effects.

The use of ERICA Tool for Internal Dosimetry

The Environmental Risk from Ionizing Contaminates Assessment Management or ERICA Tool may have limited use in internal organ-specific dosimitry. Radionuclides are known to accumulate in specific organs such as plutonium in liver and bone and are not necessarily distributed uniformly as assumed in the ERICA software. Although not specifically designed for organ dosimetry some of its underlying assumptions are based on organ data rather than a whole organism (Brown, et al., 2008) (European Commission - ERICA Project, 2012) (European Commission, 2004). ERICA Tool has the benefit of being already accepted by the European community and includes links to the latest radiation effects. If one assumes the uniform isotropic model originally developed by Loevinger in the 1970's then the use of ERICA Tool may be justified for short-range radiations such as those emitted by Pu-239, whose energy deposition is essentially localized. In this model, it is assumed that the surrounding medium and the organism are essentially the same material, which has relevance in internal dosimetry if we assume ICRU 4-component tissue. This is true in the aquatic model within the ERICA Tool where the surrounding medium, water, is essentially the same as the organisms of concern. The use of ERICA Tool for internal dosimetry purposes has the advantage over Monte Carlo methods such as MCNP, a Monte Carlo N-Particle code, in that an assessment can be made in a relatively short period of time. The user-input for ERICA Tool is essentially limited to the radionuclide of interest and its concentration, organ mass, and geometry. MCNP in comparison requires all information needed for ERICA but with numerous user-created input files for each radiation emitted and in some cases extensive computational power. For this study, we propose the use of the ERICA Tool as a means of determining organ-specific doses for Pu-239, which emits a short-range alpha-ray and other short-range radiations to specific organs in which plutonium has accumulated.

SITE HISTORY AND CHARACTERISTICS

United Kingdom

For almost a decade, during the times of above ground nuclear testing, Britain conducted nine major trials involving atomic explosions at Maralinga and Emu (Australia Royal Commission into British Nuclear Tests in Australia, 1985) (Maralinga Rehabilitation Technical Advisory Committee, 2003). In addition, five minor trials were conducted that did not involve nuclear explosions but were designed to assess performance and safety concerns. All minor trials involved radioactive materials in combination with high explosives and left significant amounts of radioactive contamination in comparison to the major trials.

Major Trials

Of the nine major trials conducted by the United Kingdom, seven were performed at Maralinga in Operation Buffalo and Operation Antler in 1956 and 1967, respectively. All tests were conducted on 30 m towers with the three exceptions of Marcoo (ground), Kite (air drop at 150 m), and Taranaki (balloon at 300 m) and had varying degrees of TNT equivalent as presented in Table 1. However, the whole site as of 1997 did not pose a significant health risk due to widespread dispersal of the contaminant plume and/or has experienced sufficient decay.

Table 1 Summary of the major weapons tests at Emu and Maralinga

Year	Code Name	Site of Test		Yield (as kilotons of TNT)	Position (m)
1953	Totem	Emu:	Totem 1	10	30
			Totem 2	8	30
1956	Buffalo	Maralinga:	One Tree	15	30
			Marcoo	1.5	0
			Kite	3	150
			Breakaway	10	30
1957	Antler	Maralinga:	Tadje	1	30
			Biak	6	30
			Taranaki	27	300

(Maralinga Rehabilitation Technical Advisory Committee, 2003)

Minor Trials

Developmental trials were designed to test the integrity of the nuclear devices. Nearly all minor trials involved radioactive materials commonly associated with nuclear devices and were detonated with conventional high explosives. The characteristics of the trials are summed in Table 2. Many sites have already experienced sufficient levels of clean up efforts or have radionuclide concentrations that are no longer detectable, according the Australian Radiation Laboratory, with the exception of four trials: Wewak, TM100, TM101, and Taranaki (Cooper, Martin, Williams, & Harries, 1997).

Table 2 Summary of the minor trials carried out at Maralinga and Emu (entries refer to the Maralinga site except where noted)

Code Name	Characteristics
Kittens	Neutron initiator development trials carried out between 1955 and 1961. These experiments involved the use of Po-210 and beryllium. A series of Kitten trials was also conducted at Emu in 1953.
Tims	Fissile material compression tests (some plutonium, but generally with natural or depleted uranium used in place of fissile material). Extensive multiple series spanning 1955–1961 and 1963, involving predominantly uranium and beryllium.
Rats	Fissile material compression tests. Involved uranium, and intense gamma sources.
Vixen A	Burning trials on rods of plutonium, uranium and beryllium. Conducted during 1959. Minimal combustion and dispersion (VK33). Four explosive dispersions involving plutonium in 1961 (VK60A and VK60C).
Vixen B	Safety/development trials to determine the characteristics of nuclear warheads. Three series, in 1960, 1961, and 1963. Detonations with emphasis on measurement of nuclear characteristics.

(Maralinga Rehabilitation Technical Advisory Committee, 2003)

Taranaki is generally considered as having the highest allotment of plutonium and therefore the highest potential health risk of all the sites at Maralinga. From 1960 until 1963, twelve trials codenamed “Vixen B” left 22 kg of Pu-239, and in addition 22 kg U-235 and 18 kg of Be with the plume extending as far as 100 km. In addition, the site was left with thousands of contaminated fragments considered large enough to attract souvenir collectors.

Cleanup

Immediately following the tests, three remediation campaigns took place until 1967 with Operations Clean-Up (1963), Hercules (1964), and Brumby (1967), the latter being the most substantial and included the burial of large fragments in pits 2-3 m deep. The final cleanup stage did not address plutonium deposited on fragments and presumed plowing to a depth of 10 cm would sufficiently reduce the radiological hazard due to plutonium. In 1968, Australia assumed responsibility, including liability, for the test sites due to the proceedings of the Pearce Report provided by the United Kingdom.

Absent from the report, now totals over 470 GBq of activity due to Am-241 (used to locate Pu-239) along with 7.2x that in Pu-239 activity are spread over 130 km^2 (O'Brien, Carpenter, Grzechnik, Long, & Green, 2012). The radiotoxicity due to plutonium was the headlining issue that prompted further radionuclide contaminant removal efforts or site rehabilitation in 2003 (Maralinga Rehabilitation Technical Advisory Committee, 2003).

Australian Management & Cleanup

Over time, Australia created several organizations whose goals were site monitoring and cleanup efforts. It was the Australian Atomic Weapons Tests Safety Committee (AWTSC) that suggested to the Commonwealth of Australia to leave the Maralinga test site "as is" on the assumption that the Pearce Report was accurate. Then in 1971, the Australian Department of Defense determined they had no valid reason to retain control of the area for defense purposes, and handed the deed over to the Department of Supply. A year later, the Minister for the Department of Supply authorized the removal of restraints around the sites with the exception for the onsite burial pits by the airport runway. The following year, in 1973, the AWTSC considered any residual contamination, including waste pits, and deemed the area as non-hazardous. This action removed government presence at the site until the following year, in 1974, when the Australian Ionizing Radiation Advisory Council (AIRAC) replaced AWTSC and took an opposing view and replaced the hazard signs and fences.

From 1979 into the late 1980's, The Royal Commission Into British Nuclear Tests in Australia conducted a series of investigations of the Maralinga and Emu areas in hope of better understanding possible health effects among Aborigines (Native Australians), Australian participants (in the tests), and for future management of the area. This led to the establishment of the Technical Assessment Group (TAG) in 1986. TAG's focus was to report on options and associated cost of decontamination and rehabilitation for the site. Their findings confirmed previous suspicions of a modest cleanup effort due to three reasons; cleanup time took less than two weeks, inaccurate radiochemical analysis of Pu-239, and rejection of large soil fragments when considering the inhalation hazard of plutonium. Alongside TAG was the Maralinga Consultative Group (MCG) essentially representing the stakeholders of the area including the Commonwealth of Australia, the State of South Australia, the State of Western Australia, and the Maralinga Tjarutia, the traditional land owners of the site. This was the first time the Aborigines were given consideration for the site and were provided close involvement in TAG's work and subsequently their final report in 1990 to the Commission.

After the release of the TAG Report in 1990, both Australia and the Maralinga Tjarutia sought financial support given land use loss and cleanup efforts, which the United Kingdom was initially reluctant to accommodate, but later settled financially. Additionally, the Maralinga Tjarutia received support from the Commonwealth of Australia. In 1996, cleanup operations began, that addressed issues raised by the TAG Report, including consideration of future land use by the Maralinga Tjarutia using a traditional lifestyle. The year 2000 saw the completion of what was supposed to be the final cleanup effort.

With the successful cleanup effort completed, the site is now open and considered safe. However, a small 120 km^2 portion of the original 3200 km^2 is still marked for limited use (Australian Government: Department of Resources, Energy and Tourism, 2012). The 2009 year saw the return of the Maralinga site to its original owners the Maralinga Tjarutia with the Maralinga Nuclear Test Site Handback Deed. The following two years saw the return of fieldwork to the area, in order to reassess potential radiological hazards to the Maralinga Tjarutia people and biota. This work resulted in two publications by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) and current works at the Australian Nuclear Science and Technology and Science Organisation (ANSTO), including this manuscript.

Site Characteristics

The Maralinga area has been extensively characterized elsewhere, but is summarized here (Australian Government: Department of Resources, Energy and Tourism, 2012) (Richard O'Brien, 2011) (Stephen Long, 2012) (Maralinga Rehabilitation Technical Advisory Committee, 2003). The site is physically located 40 km north of the town of Watson, South Australia on the southern edge of the Great Victoria Desert and north of the Nullarbor Plain and encompasses approximately 3200 km^2. Geologically, the site is comprised of a sparse coating of aeolian sand and calcretisted dolomite. This surface is the primary layer for plutonium contamination. The climate is considered arid and sunny with day temperatures above 40^oC and the annual evaporation exceeding that of precipitation. Typically winds are less then 18 km/h but records have shown dust storms and wind storms reaching as high as 125 km/h. Biologically, the area is full of flora and fauna that have adapted to survive the arid open woodland and grassland (Maralinga Rehabilitation Technical Advisory Committee, 2003).

Inhalation is a primary exposure pathway for a significant proportion of the dose for human and non-human biota, and several inhalation dose studies specific to the site have been conducted (Maralinga Rehabilitation Technical Advisory Committee, 2003) (O'Brien, Carpenter, Grzechnik, Long, & Green, 2012). Although there are times of high winds, in general the risk of re-suspending dust particles is very small. The high calcium content in the dolomite helps form a crust of calcretisted dolomite, providing an effective containment for the Pu-239 and Am-241. In addition to the geologic crust, it has been demonstrated that a microphytic crust covers between 30-50% of the surface having an average depth of 5 mm. The biological crust retains almost 85% of the total Am-241 and possibly Pu-239, too (Maralinga Rehabilitation Technical Advisory Committee, 2003). Although contamination due to Pu-239 and Am-241 is effectively contained due to low winds and natural crust formation there might still be a potential radiological health hazard associated with the site.

EXPOSURE PATHWAYS

Two exposure pathways are generally considered relevant for internal dosimetry purposes, inhalation and ingestion (International Commission on Radiological Protection (ICRP), 1994) (International Commission on Radiological Protection (ICRP), 1995). Wound contamination might need to be added for certain exposure scenarios. Biokinetic models are used for dose calculations in an effort to better understand how much and where radionuclides are present in the body (International Commission on Radiological Protection (ICRP), 2002). Once entered into the blood stream, radionuclides are able to distribute throughout the body, depending on many physical, chemical and biological aspects, although the primary body burden resides in the skeleton, liver, and lungs following inhalation (U.S. Department of Health and Human Services, 2010). Rabbits and other animals located on the Maralinga area have the potential for acute ($t < 15$ d), intermediate (15 d $< t < 365$ d), and chronic ($t > 365$ d) exposure situations, due to Pu-239 and other radionuclides as defined by the USDHHS (U.S. Department of Health and Human Services, 2010). Many models such as ARPANSA's 2011 dose assessment to Oak Valley residents located near the nuclear test site often make assumptions of 100% occupancy in contaminated zones (O'Brien, Carpenter, Grzechnik, Long, & Green, 2012). There are many exposure situations and potential consequences for each individual exposure condition. The case of routine exposure as considered most likely for many animals located at the Maralinga nuclear test site is more relevant as they are not restricted from entering the site as is the case of humans.

Inhalation

The MARTAC Report considered inhalation as the cause of major concern for children playing outside (Maralinga Rehabilitation Technical Advisory Committee, 2003). For human exposure situations, inhalation primarily focuses on particles that are respirable, particles with aerodynamic diameters ≤ 10 μ (Shinn, 1998). Resuspension or any similar process is able to transport particles from a contaminated surface to the air. For rabbits living near the ground this has the potential for a significant dose contribution. The respiratory system is defined structurally in ICRP Publication 89 as being comprised of nasal passages, mouth, pharanx, larynx, trachea, bronchi, and lungs. However, breathing rates and lung volumes contribute immensely to the doses received by the respective tissues (International Commission on Radiological Protection (ICRP), 2002). Although people can breath either

through the nose or mouth, rabbits are obligate nose breathers (International Commission on Radiological Protection (ICRP), 2002) (O'Malley, 2005) (Weisbroth, Flatt, & Kraus, 1974). Concerning rabbit respiration specifically, various measurements have been made and have been described in great detail by others; rabbits have a respiratory rate of 32 to 60 breaths/min and a tidal volume ranging between 19 and 25 mL (Weisbroth, Flatt, & Kraus, 1974). As an animal that resides just a few cm from the ground surface, inhalation can be a major contributor to the total dose received by rabbits.

Numerous studies conducted primarily on dogs (beagles) and mice have shown that plutonium oxides, like those found in the Maralinga test area, have long retention times on the order of years, due to being chemically stable and having a long physical half life in the case of Pu-239 (International Commission on Radiological Protection (ICRP), 1994) (U.S. Department of Health and Human Services, 2010). Some effects associated with inhalation exposure to $^{239}PuO_2$ have shown decreased responses to antigens, decrease in pulmonary alveolar macrophages in mice, depressed anti-body forming cells in hamsters, and adverse hematological effects in dogs in addition to elevated liver enzyme levels. Radiation pneumonitis has been observed in many animals and in some cases can be considered a major contributor to premature death. Primarily, this is attributed to impaired or decreased lung function, by an increased respiratory rate, and decreased tidal lung volume. Studies by PNNL have shown decreased survival with a lung burden as low as 0.63 kBq/kg of plutonium oxide following lung exposure (U.S. Department of Health and Human Services, 2010).

Ingestion

In the work place, ingestion is of least concern according to the IAEA, as it is unlikely that a person will ingest and absorb quantities of significance of plutonium (INTERNATIONAL ATOMIC ENERGY AGENCY, 1998). This can be attributed to the fact that plutonium compounds, oxides specifically, have a low fractional absorption, or a low degree of passage into the blood stream through the gastrointestinal tract (International Commission on Radiological Protection (ICRP), 1986; International Commission on Radiological Protection (ICRP), 1990; International Commission on Radiological Protection (ICRP), 1991) (INTERNATIONAL ATOMIC ENERGY AGENCY, 1998). Several animal studies involving different isotopic and chemical forms have

substantiated this claim, and the ICRP adopted the absorption coefficient value of 10^{-5} in publication 48 although 10^{-6} was proposed (INTERNATIONAL ATOMIC ENERGY AGENCY, 1998) (United States Atomic Energy Commission Division of Technical Information, 1980). The fractional amount absorbed is highly variable, depending on metabolic and physiological factors, with much of the plutonium excreted in feces and urine (U.S. Department of Health and Human Services, 2010) (INTERNATIONAL ATOMIC ENERGY AGENCY, 1998) (International Commission on Radiological Protection (ICRP), 1995). In 1995, ICRP (Publication 72) stated that ingestion is generally the most significant exposure pathway for the general public. Although they were referring to elements incorporated into the food, rather than on it (International Commission on Radiological Protection (ICRP), 1995).

Surface contaminated foodstuffs and water have been indicated as the most likely mechanism for ingestion for humans and for grazing animals (U.S. Department of Health and Human Services, 2010) (Beresford, 1991) (Crout, 1993). For rabbits, this may be significant as they are low lying animals that eat vegetation that is within reach were soil deposition onto vegetation surfaces may be the greatest. Livestock studies have shown that surface erosion and soil deposition on vegetation increases with grazing animals present (Beresford, 1991). This may prove vital to rabbits and other biota at the Maralinga area as rabbits are known burrowers and have caused significant ecological damage to the local area to vegetation and due to land erosion. A single test conducted in Canberra has shown that a warren (nest) is a collective effort, with over 10 m^3 of soil removed spanning over 500 m in total length (Thompson, 1994). Warrens can be as common as 114 km^{-2} in arid Australian environments. A rabbit's personal grooming habits may also contribute a significant proportion as soil adheres to the nose and fur in large quantities and they groom constantly. Wild herbivores, like rabbits, have been observed to eat soil directly for the mineral content (Beresford, 1991). The direct and indirect ingestion of soil may serve as an important pathway for plutonium exposure.

Wounds/Dermis

Concerning plutonium compounds, oxides in particular, intact skin acts as an effective barrier. However, plutonium can be absorbed through contaminated wounds (U.S. Department of Health and Human Services, 2010)

(Langham, 1959). Information on both human and animal wound studies are relatively scarce compared to inhalation and ingestion studies but is often acknowledged as a small contributor to internal dose (U.S. Department of Health and Human Services, 2010) (Langham, 1959) (INTERNATIONAL ATOMIC ENERGY AGENCY, 1998) (International Commission on Radiological Protection (ICRP), 2002). However, contaminated wounds offer a direct route into the blood stream and circulate to various organs including the local lymph nodes and liver (Langham, 1959) (U.S. Department of Health and Human Services, 2010). In the case of occupational workers, almost 50% of plutonium particulates (oxides) may be removed by surgical cleansing and when the scab falls off (Langham, 1959). However, wild animals like rabbits are not subject to surgical procedures.

Skin wounds on rabbits may happen for various reasons. Rabbits are known to be aggressive to each other during the mating season, males protecting females and females against other females for burrows. They have also been known to be aggressive in defending natural resources but is a rare trait (Thompson, 1994). If fortunate enough to escape capture from a predatory animal, they may also suffer external wounds.

RABBIT BIOLOGY-PHYSIOLOGY

There are many studies that have collectively described the European rabbit as a whole (Harcourt-Brown, 2002) (Harkness, 2010) (Latimer & Shawn, 1957) (Latimer & Sawin, 1957) (O'Malley, 2005) (Thompson, 1994) (Weisbroth, Flatt, & Kraus, 1974). Many of these studies provide minute details as a result of extensive biological research in various sciences (veterinary, pharmacy…). Internal dosimetry calculations rely on many factors such as body/organ mass, geometry, and radionuclide concentrations (International Commission on Radiological Protection (ICRP), 2008) (International Commission on Radiological Protection (ICRP), 1994). Simplified organ geometry will be the basis on which rabbit biology and physiology will be described.

European rabbits can vary greatly in size (O'Malley, 2005). Captive breeds can range from 1 kg to 7 kg depending on the breed, and feral strains, showing large diversity based on their environment (O'Malley, 2005) (Thompson, 1994). While specific biological and physiological information on wild rabbits is scarce, information regarding domesticated strains is readily available (Harcourt-Brown, 2002) (Harkness, 2010) (Latimer & Shawn, 1957) (Latimer & Sawin, 1957) (Thompson, 1994) (Weisbroth, Flatt, & Kraus, 1974). Specifically, organ mass data in relation to whole animal mass, as displayed in Table 3.

Obtaining rabbit specific organ dimensions other than mass has proven difficult. Of all the organs, the gastrointestinal tract has been characterized by organ length with small intestine, cecum, and colon having lengths of 3.56, 0.61, and 1.65 m, respectively. The rabbit is unique in that its intestines average 10x its body length with cecum volume content averaging 10x that of the stomach. The rabbit cecum is the largest of all animals relative to their sizes (O'Malley, 2005) (Weisbroth, Flatt, & Kraus, 1974).

Rabbits are non-ruminant animals, simular to horses and cows, and do not digest plant matter as easily as ruminants. This means much of their food passes quickly through their digestive system without being digested. However, they will routinely eat their own feces. This allows for re-ingestion of previously undigested food. Rabbits rely on microbial fermentation within the cecum to provide much of their nutrient intake (Harcourt-Brown, 2002).

Rabbits are very thirsty and in the laboratory have been recorded to consume between 50 - 120 mL/kg of water in a 24 h period (Harcourt-Brown, 2002) (O'Malley, 2005).

Table 3 Organ masses as a percentage of whole body mass

Organ/tissue	% Organ Mass	SD
Blood	6.3%	1.0%
Heart	0.2%	1.0%
Large Intestine	2.8%	0.3%
Small intestine	3.0%	0.3%
Kidney (one)	0.4%	0.0%
Liver	4.5%	0.6%
Lung (one)	0.3%	0.0%
Muscle	55.9%	1.1%
Skeleton	6.1%	0.0%
Skin	13.0%	0.9%
Spleen	0.1%	0.0%
Stomach	0.8%	0.2%

(Jelenko, III, Anderson, Scott, Jr., & Wheeler, 1971) (O'Malley, 2005)

Arid Australia Specific

British colonists first introduced wild rabbits to Australia in the 1880's, and by 1980 rabbits had spread throughout all of Australia (Thompson, 1994). Rabbits are thought to have originated in Spain, leaving them biologically ill-suited for life in an arid region such as Maralinga. Mother rabbits give birth to young that show signs of severe stunting as well as other biological and physiological differences compared to those born in less stressful environments. Studies by Myers and Gilbert in 1968 have demonstrated that rabbits born in an arid environment located in the State of New South Wales, Australia have larger kidneys and smaller livers compared to those living in more favorable conditions (Thompson, 1994). In arid regions like Maralinga, rabbits will selectively seek plants, like chenopods, that are high in both protein and water while minimizing sodium content in which the ground at Maralinga is rich. During food and water shortages, adult rabbits will loose 22% to 50% of their body weight. Younger rabbits often do not live through these events, as their nutritional requirements are much higher. In dry conditions, rabbits have a water turnover rate of about 46 mL/kg body mass /day. Home ranges of rabbits living in

arid conditions vary depending on the season with an average range of 490 m^2 for males and 410 m^2 for females. This range can extend considerably during mating season with Newsome in 1989 reporting movements as far as 1500 m. The arid conditions located at Maralinga provide a stressed environment for the European rabbit, which should be taken into consideration of the overall health of the animal in biological assessments.

RAW ENVIRONMENTAL SAMPLES

Sample Collection

Our colleague, Dr. Mathew Johansen with the Australian Nuclear Science and Technology Organisation (ANSTO), collected eight rabbit samples from five sites located on the edge of the Taranaki plume for a pilot study on the Maralinga nuclear test site in 2011. Samples were collected using live traps on locations with varying degrees of Pu-239 contamination based on Am-241 concentration ratios. Two of the eight rabbit samples were collected 10 km South East of the plumes edge and were used as control samples. All samples had immediate blood collection, were humanely euthanized according to ANSTO's handling procedures and kept on ice until proper refrigeration was available (see Johansen el al, 2013a for description of sampling methods).

Pu-239 Analysis and Preparation

Rabbit samples were analyzed on an atomic mass spectrometer (AMS) known as the ANTERES or Australian National Tandem Research Accelerator at the ANSTO. Mass spectrometry allows for improved atomic measurements for low-level long-lived actinide elements over the traditional alpha spectrometry by at least three orders of magnitude in addition to determining isotopic ratios (Child, Hotchkis, & Williams, 2008). Plutonium concentrations in various rabbit organs were determined by removing a subsample of tissue and chemically preparing and loading the sample into the AMS. Dr. David Childs of the ANTERES team analyzed the initial results, which were used as the basis for this study. The exact method used to prepare and deliver plutonium concentrations have been described in other literature (Hotchkis, Child, & Zorko, 2010) (Childs & Hotchkis, 2013).

COMPUTER MODELING PRINCIPLES

ERICA – Tool

ERICA Tool is an integrated three-tiered software program (European Commission - ERICA Project, 2012) (European Commission, 2004). The tier system is designed with Tier 1 as the most conservative and easiest to use. Tiers 2 and 3 is designed to require more site-specific information from the user, with Tier 3 allowing for statistical distributions of various parameters, and more complex analysis. The tiers are intended such that if an assessment passes the first two, the radiation situation poses no or negligible effects. However, if the user-defined assessment fails, the user is encouraged to use Tier 3. This third tier uses the most recent scientific data available from the FREDERICA radiation effects data base. Each of the tiers relies on the accumulation of scientific research, using the four biological endpoints of morbidity, mortality, reproduction, and mutation. The user is asked to supply the activity concentrations in the surrounding media and the organism; if they are not known, the ERICA software program may estimate them. The output generated for each assessment is given in units of μ E/h. ERICA was designed specifically to address non-human biota and ecological issues associated with radiological risk to whole organisms.

ERICA Tool - Previous Studies

The aquatic dosimetric model used by ERICA Tool, warranted by the FASSET and ERICA projects, has been around since the late 1970's (Ulanovsky & Prohl, A Practical Method for Assessment of Dose Conversion Coefficients for Aquatic Biota, 2006). ERICA Tool's use and intrinsic assumptions are described elsewhere but will be further detailed here only as information is relevant to our work (Ulanovsky & Prohl, A Practical Method for Assessment of Dose Conversion Coefficients for Aquatic Biota, 2006) (Ulanovsky, Prohl, & Gomez-Ros, Methods for Calculating Dose Conversion Coefficients for Terrestrial and Aquatic Biota, 2008). Organisms are treated as either spherical or elliptical shapes surrounded by an infinite homogenous medium. The medium and the organism have identical or approximate densities with a homogenous distribution including the radionuclide contaminant(s). Work commissioned by the ERICA project as conducted by Ulanovsky and Prohl in 2006 assumed ICRU (1993) 4-element tissue organism composition surrounded by an infinite water source. Infinite was defined as 20 mean free

paths of the initial photon in water. This is equivalent to a reduction of initial photon intensity by orders of magnitude, or essentially zero. The work completed by Ulanovsky and Prohl in 2006 will be the basis for the research methods applied to individual organs instead of whole organisms.

MCNPX

MCNPX and MCNP5, or Monte Carlo N-Particle, codes are US Government software developed and maintained by Los Alamos National Laboratory for the Department of Energy (X-5 Monte Carlo Team, 2008) (Pelowitz, 2011). The software employs Monte Carlo simulation techniques and has a wide variety of applications involving nuclear particles, including internal dosimetry calculations. As a statistics based physics software program it relies on user supplied problem data such as geometry, materials, and initial and subsequent particle characteristics (energies, nuclear interactions, etcetera). Results are obtained by determining atomic interactions, normalized to one starting particle, based on cross-sectional data supplied with the software. The software is highly adaptable and easy to use with a wide variety of applications, including internal dosimetry applications.

METHODOLOGY AND DOSIMETRIC APPROACHES

The calculation of absorbed dose, or the amount of energy absorbed per unit of mass, is a measureable physical quantity and is considered appropriate for radiological safety measurements (International Commission on Radiological Protection (ICRP), 2008). However, animal dosimetry is usually expressed in terms of dose rate or exposure at various stages in the life cycle for reference animal populations. In keeping with the simplified organism concept of ICRP 108 and ERICA, organs were treated as simplified spheres and ellipsoids normalized to human literature sources (European Commission, 2004) (International Commission on Radiological Protection (ICRP), 2008). We believe this has relevance, as each human is geometrically unique and so are rabbits (International Commission on Radiological Protection (ICRP), 2002). Also, radiological protection of the environment is based on a population and not an individual, so a generalized approach should be acceptable (International Commission on Radiological Protection (ICRP), 2008).

Organ Mass Determination

Several authors have reported on rabbit organ masses in relation to body mass but those of Jelenko et al and O'Malley are used here (Jelenko, III, Anderson, Scott, Jr., & Wheeler, 1971) (Latimer & Shawn, 1957) (Latimer & Sawin, 1957) (O'Malley, 2005). Organ masses were calculated for the ICRP 108's reference duck (ICRP Duck/Rabbit) as similarly employed by Taranenko et al. in 2004 and the FASSET Project, by multiplying the organ mass data in units of g/ 100 g whole body mass obtained by Jelenko et al in 1971 (Taranenko, Prohl, & Gomez-Ros, 2004) (Jelenko, III, Anderson, Scott, Jr., & Wheeler, 1971). Organ mass data, as relevant to the ICRP Duck/Rabbit can be found in Table 4.

Organ Dimension Scaling

Settling on a specific organ dimension proved difficult, resulting in the use of multiple ellipsoidal geometries for the same organ. All organs were normalized to ICRP108 reference Duck/Rabbit and ICRP 89 reference man according to the body length and organ mass. Normalizing to body length (N2BL) used a simple ratio

of ICRP 89's reference man's organ length to body length and multiplying the quotient by ICRP 108's Duck/Rabbit (International Commission on Radiological Protection (ICRP), 2002) (International Commission on Radiological Protection (ICRP), 2008). The process was similar when normalizing to organ mass (N2OM), but instead taking the ratio of reference man's organ length to organ mass and multiplying the result by ICRP Duck/Rabbit's organ mass to obtain the organ length. Rabbit specific literature was available for the small and large intestine only (O'Malley, 2005). Since intestine longitudinal dimensions were known in terms of body length the quotient of organ length and body length were again used but this time for the average rabbit as indicated by O'Malley, and multiplying by ICRP Duck/Rabbit's length (O'Malley, 2005). Organ geometries for the liver, spleen, and kidney were normalized from data on children to broaden the geometry sample set (Konus, Ozdemir, Akkaya, Erbas, Celik, & Isik, 1998). According to the Konus group, body length has the greatest association with organ length. Their data was then applied to the ICRP Duck/Rabbit by assuming a height of 30 cm to get the longitudinal organ length. Organ's whose dimensions could be found in literature; intestines and those normalized from children data are abbreviated as N2LI. For simplicity all remaining dimensions were assumed symmetrical (equal). In addition, all organs were treated as simple spheres. Geometry information is listed in Tables 5 through 8 along with standard deviations (SD) when relevant. Regardless of geometry, all identical organs have equal masses.

Activity Concentration Calculation

Data supplied by ANSTO first had to be converted from Pu-239 concentration (mBq/kg) in ash to Pu-239 concentration (Bq/kg) in fresh mass for each organ listed in Table 9. This was first done Rabbit-1, as it had the most complete Pu-239 organ concentrations and was applied to the ICRP Duck/Rabbit organs. These activity concentrations, calculated using scaled reference organ masses, are similar to, but slightly different from those reported in Johansen et al., (2013b) which were based on actual tissue masses. The average Pu-239 concentration of all organs was used to calculate the activity concentration in Bq/L in the "infinite universe" in ERICA and MCNPX, in addition to being used as the activity concentration in the ICRP Duck/Rabbit as a whole.

Table 4 ICRP 108 Duck/Rabbit organ mass

Organ/Tissue	Organ Weight (g)	SD
Blood* (mL/kg)	78.56	12.59
Heart (empty)	3.02	12.82
Large Intestine	35.32	3.53
Small intestine	37.46	3.28
Kidney (one)	5.09	0.25
Liver	56.69	7.56
Lung (one)	4.02	0.19
Muscle	702.16	14.56
Skeleton	77.05	0.65
Skin	163.03	11.51
Spleen	1.01	0.13
Stomach	10.56	2.52
Total	1173.98	27.47

(Jelenko, III, Anderson, Scott, Jr., & Wheeler, 1971)

(International Commission on Radiological Protection (ICRP), 2008)

Table 5 Rabbit organ length (diameter) when treated as spheres (Round)

Organ/Tissue	Length (cm)
Heart*	1.794
Large Intestine*	4.074
Small intestine*	4.155
Kidney* (one)	2.136
Liver*	4.770
Lung* (one)	1.975
Muscle	11.036
Skeleton*	5.284
Skin*	6.783
Spleen*	1.244
Stomach*	2.724

* Indicates organ fits within ICRP 108's reference Duck/Rabbit

Table 6 Organ dimensions (diameter) normalized to ICPRP 89 reference man's total body length (N2BL)

Organ/Tissue	Length (cm)	Width (cm)	Hight (cm)
Heart*	1.461	-	-
Large Intestine*	18.750	1.899	1.899
Small intestine	47.727	1.226	1.226
Kidney* (one)	1.875	2.280	2.280
Liver*	3.460	5.600	5.600
Lung* (one)	3.068	1.584	1.584
Muscle	-	-	-
Skeleton	854.554	0.415	0.415
Skin	-	-	-
Spleen*	2.045	0.970	0.970
Stomach*	6.307	1.790	1.790

* Indicates organ fits within ICRP 108's reference Duck/Rabbit

Table 7 Rabbit organ dimensions (diameter) normalized to ICRP 89 reference man's organ mass (N2OM)

Organ/Tissue	Length (cm)	Width (cm)	Height (cm)
Heart	-	-	-
Large Intestine*	10.526	2.535	2.535
Small intestine*	16.175	2.106	2.106
Kidney* (one)	0.362	5.188	5.188
Liver	0.641	13.013	13.013
Lung (one)	0.121	7.979	7.979
Muscle	-	-	-
Skeleton	36.878	2.000	2.000
Skin	-	-	-
Spleen*	0.081	4.886	4.886
Stomach*	2.611	2.783	2.783

* Indicates organ fits within ICRP 108's reference Duck/Rabbit

Table 8 Rabbit organ dimension (diameter) normalized to data on children (N2LI)

Organ/Tissue	Length (cm)	Width (cm)	Height (cm)
Heart*	1.794	-	-
Large Intestine	161.429	0.647	0.647
Small intestine	254.286	0.531	0.531
Kidney* (one)	5.460	1.336	1.336
Liver*	5.640	4.387	4.387
Lung (one)	-	-	-
Muscle	-	-	-
Skeleton	-	-	-
Skin	-	-	-
Spleen*	4.450	0.658	0.658
Stomach	-	-	-

* Indicates organ fits within ICRP 108's reference Duck/Rabbit

Table 9 Organ weighted activity concentration

Organ/tissue	Activity Concentration (mBq/kg)	SD
Blood	0.28	0.17
Heart	0.004	0.016
Large Intestine	17.36	2.10
Small intestine	18.41	2.04
Kidney (one)	0.03	0.01
Liver	3.17	0.57
Lung (one)	0.87	0.06
Muscle	0.85	0.39
Skeleton	3.13	1.28
Spleen	0.06	0.01
Stomach	5.19	1.29
Total	50.23	3.52

ERICA Tool

The activity concentration ratio was calculated for ERICA as required by the Tier 3 assessment. Radionuclide concentrations obtained by AMS measurements were entered as having a normal distribution as indicated by the AMS results. All organ geometries listed previously were used with like organs being compared to one another. Default values, including the radiation weighting factors, were assumed throughout the assessment. The ERICA Tool output was then compared to the output generated by MCNPX.

MCNPX

MCNPX required considerably more user input compared to ERICA Tool. Two models were created in MCNPX, one using an infinite universe and one using a more realistic universe as the reference duck/rabbit from ICRP Publication 108. The same rabbit organs used in ERICA Tool were modeled in MNCPX. Emitted radiation, emission fractions, and energies were obtained from ICRP's DECDATA disk and are listed in Table 10 (International Commission on Radiological Protection (ICRP), 2007; International Commission on Radiological Protection (ICRP), 2008). Each organ and the surrounding universe were treated as ICRU 4-element tissue with a

density of 1.0 g/cm^3. The infinite universe for both alpha and beta rays was 0.1 cm from the surface of the organ and amounts to 20x and 60x the particle range in tissue respectively. The ICRP Publication 107 averaged 65 keV gamma ray required an infinite universe extending 22.0 cm from the organ surface. This amounts to photon intensity reduction of more than 98% or 4 mean free paths and was determined by the XCOM: Photon Cross Sections Database or NIST Standard Reference Database 8 (XGAM) (Nuclear Data Center, 2000). MCNPX default particle transport was used including the photon and electron energy cutoff of 1 keV and the formation of secondary particles when modeling photons and electrons. Organ energy deposition was determined using the MCNP energy deposition tally, *F8. Simulations were conducted until the relative error was below 1% for internally and below 5% for externally emitted radiation in addition to passing the MCNP recommended statistical checks. Radiation weighting factors of 10 for alpha rays and 1 for beta and gamma rays were applied in keeping with ERICA Tool default settings. The infinite universe model used two uniform source particle sampling distributions cylindrical and spherical. This provided an internal check for the source particle sampling. The cylindrical source sampling distribution was used for dose rate calculations, although the results were identical to the spherical distribution. Organs whose geometry allowed for complete immersion within the ICRP 108 Duck/Rabbit were calculated and compared to results using the infinite universe model. Each MCNPX model was compared to results computed by ERICA.

Rabbit Sample Set Dosimetry

The sample set consisted of 8 rabbits all with varying degrees of Pu-239 concentration. All rabbits had blood, muscle, and bone samples removed and analyzed for Pu-239 concentration as displayed in Table 11 (Johansen, et al., Plutonium in wildlife and soils at the Maralinga legacy site; persistence of bioavailable Pu over decadal time scales, submitted 2013a) (Johansen, et al., Accumulation of plutonium in mammalian wildlife tissues at semi-arid legacy sites, submitted 2013b). Negative values indicate that the tissue sample used had a lower Pu-239 concentration that the chemical blank used in the AMS. The average organ absorbed dose rate from all simulations were averaged and scaled to each rabbit.

Table 10 ICRP Publication 107 DECDATA emitted radiations from Pu-239

Particle	Energy (MeV)	Yeild/nt	Tissue Range (cm)
Alpha	5.148E+00	1.000E+00	5.000E-03
Gamma - ray	6.558E-02	9.758E-04	5.490E+00
X-ray*	3.335E-04	3.042E+00	2.611E-04
IC electrons	1.915E-02	3.045E-01	2.000E-03
Auger electron*	6.276E-04	2.590E+00	1.550E-05

*Omitted from this study, energies were below MCNPX particle cutoff

Table 11 Pu-239 activity concentrations (mBq/kg)

Rabbit	Blood		Muscle		Bone	
	Mean	SD	Mean	SD	Mean	SD
Rabbit-1*	4.4	2.6	1.5	0.7	48	20
Rabbit-2	252	97	3.9	0.9	49	14
Rabbit-3	3.2	8.0	4.1	1.0	62	10
Rabbit-4	4.9	5.9	-	-	-	-
Rabbit-5	6.5	1.6	4.8	1.1	961	112
Rabbit-6	1.8	2.1	92	6	42	10
Rabbit-7	-60	-74	-0.7	-1.0	32	20
Rabbit-8	-1.3	-0.9	-0.2	-0.2	-	-

*Used in ICRP Duck/Rabbit

(Johansen, et al., Plutonium in wildlife and soils at the Maralinga legacy site; persistence of bioavailable Pu over decadal time scales, submitted 2013a), (Johansen, et al., Accumulation of plutonium in mammalian wildlife tissues at semi-arid legacy sites, submitted 2013b)

RESULTS AND DISCUSSION

Absorbed Dose Rate – ICRP Duck/Rabbit

The absorbed dose rate along with relevant statistics for Pu-239 tissue accumulation has been calculated using ERICA Tool and MCNPX. Multiple organ geometries were created for the same organ, being modeled as elliptical and spherical shapes. Elliptical geometries were scaled using up to three parameters, ICRP Publication 89 reference man's body length, and organ mass, and to one other literature source based on children's dimensions for the liver, kidney, and spleen. All simulations assumed a uniform Pu-239 source distribution in addition to a uniform ICRU 4-element tissue distribution. The ERICA Tool model assumed source particles in accordance with ICRP Publication 38, while the MCNPX model made use of the more updated ICRP Publication 107.

Comparison between ERICA and MCNPX Models

The absorbed dose rate and statistical comparisons for all simulations are provided in Tables 12 and 13. With the exception of the heart, all ERICA and MCNPX computations had a percent difference of 4% or less. The t-test scores were all below 0.5, well below 1.96 or the value considered to be within 95% certainty of the mean for a two-tailed test. With statistical values close to zero in either case, it can be assumed, for all relevant purposes, that the values are identical when considering the scaling parameters.

Comparison between Scaling Parameters

Tables 14 and 15 summarize the average absorbed dose rates according to each scaling parameter in addition to the overall average. Statistical results between scaling parameters for each organ were similarly close to zero with percent differences and t-test scores all less than 1. This would indicate for Pu-239 and possibly other radionuclides with short-range radiations that are locally deposited, that organ geometry has a negligible effect. This result is surprising considering the small intestine when normalized to literature data extends over 250 cm in one

direction, resulting in minor radii ≈ 0.5 cm but when statistically compared to its spherical representative gives a nearly identical result.

Absorbed Dose Rate – Maralinga Rabbit Samples

Figure 1 and Table 16 summarize the scaled absorbed dose rates for the six rabbits located on the Maralinga test that had given finite values for Pu-239 tissue content. Due to the scaling process, the 25% quartile also represents the average absorbed dose rate for all organs calculated for the ICRP Duck/Rabbit. For the rabbit samples collected with finite plutonium content, the scaled mean absorbed dose rate was 17% higher for all organs than that calculated for the ICRP Duck/Rabbit, which again can be attributed to the scaling process. One reason for the collected sample set having an overall higher absorbed dose rate is due to Rabbit-1 organ plutonium content used in the ICRP Duck/Rabbit model had some of the lowest blood, muscle, and bone plutonium concentrations. Absorbed dose rates for all organs are lower by orders of magnitude than the DOE and IAEA recommendation of 40 μGy/h, which is based on reproduction effects.

Absorbed Dose Rate – Maralinga Rabbit Bone and Muscle Samples

The specific absorbed dose rates for the six rabbits found on the Maralinga site are provided in Table 17 with statistical comparisons between scaled values provided in Table 18. The two rabbits with negative Pu-239 concentrations were excluded from absorbed dose rate estimation. In general, percent differences were between 42-100 %, indicating that scaled values were 1-2 orders of magnitude different to values derived specifically for the rabbit of interest and would have under-estimated the absorbed dose rate. All the values having a negative percent difference had t-scores less than 2, indicating statistically similar dose rates. Overall dose rates scaled to ICRP muscle tissue compared to muscle associated with a specific rabbit had the lowest percent differences and t-scores. This may be due to the less variability in Pu-239 concentration in the muscle tissue as compared to the wide range in concentrations between bone and blood. Rabbit-1 data was used in the dose rate calculation for the ICRP Duck/Rabbit, so it was expected that the scaled and organism specific dose rates would have similar values.

Table 12 ERICA Tool and MCNPX absorbed dose rates (μGy/h)

			N2BL			N2OM			N2LI			Round	
Organ	Statistic	ERICA	Infinite	Rabbit	ERICA	Infinite	Rabbit	ERICA	Infinite	Rabbit	ERICA	Infinite	Rabbit
Heart	Mean										4.4E-07	1.1E-07	1.1E-07
	SD										3.1E-07	6.5E-07	1.6E-06
Large Intestine	Mean	5.1E-04	5.2E-04	5.2E-04	5.0E-04	5.2E-04	5.2E-04	5.1E-04	5.2E-04	-	5.0E-04	5.2E-04	5.2E-04
	SD	6.2E-05	8.1E-05	8.1E-05	6.4E-05	8.1E-05	8.1E-05	6.3E-05	8.1E-05		6.0E-05	8.1E-05	8.1E-05
Small Intestine	Mean	5.4E-04	5.5E-04	-	5.4E-04	5.5E-04	5.5E-04	5.4E-04	5.5E-04	-	5.4E-04	5.5E-04	5.5E-04
	SD	5.9E-05	7.7E-05		5.9E-05	7.7E-05	7.7E-05	5.8E-05	7.7E-05		6.0E-05	7.7E-05	7.7E-05
Kidney (one)	Mean	8.8E-07	8.5E-07	8.5E-07	8.8E-07	8.5E-07	8.5E-07	8.8E-07	8.5E-07	8.5E-07	8.9E-07	8.5E-07	8.5E-07
	SD	3.2E-07	3.2E-07	1.4E-06	3.2E-07	3.2E-07	2.2E-06	3.2E-07	3.2E-07	1.3E-06	3.2E-07	3.2E-07	1.4E-06
Liver	Mean	9.5E-05	9.4E-05	9.4E-05	9.5E-05	9.4E-05	-	9.5E-05	9.4E-05	9.4E-05	9.5E-05	9.4E-05	9.4E-05
	SD	1.7E-05	2.1E-05	2.1E-05	1.7E-05	2.1E-05		1.7E-05	2.1E-05	2.1E-05	1.7E-05	2.1E-05	2.1E-05
Lung (one)	Mean	2.6E-05	2.6E-05	2.6E-05	2.6E-05	2.6E-05	-				2.6E-05	2.6E-05	2.6E-05
	SD	1.7E-06	2.1E-06	2.5E-06	1.6E-06	2.1E-06					1.6E-06	2.1E-06	2.5E-06
Muscle	Mean										2.6E-05	2.5E-05	-
	SD										1.1E-05	1.1E-05	
Skeleton	Mean	9.3E-05	9.3E-05	-	9.4E-05	9.3E-05	-				9.4E-05	9.3E-05	9.3E-05
	SD	3.8E-05	3.8E-05		3.7E-05	3.8E-05					3.7E-05	3.8E-05	3.8E-05
Skin	Mean										7.1E-03	7.1E-03	7.1E-03
	SD										7.5E-04	8.9E-04	8.9E-04
Spleen	Mean	1.7E-06	1.7E-06	1.7E-06	1.7E-06	1.7E-06	1.7E-06	1.7E-06	1.7E-06	1.7E-06	1.7E-06	1.7E-06	1.7E-06
	SD	2.9E-07	3.6E-07	1.9E-06	2.9E-07	3.6E-07	7.3E-06	2.9E-07	3.6E-07	2.1E-06	2.9E-07	3.6E-07	1.7E-06
Stomach	Mean	1.5E-04	1.5E-04	1.5E-04	1.6E-04	1.5E-04	1.5E-04				1.6E-04	1.5E-04	1.5E-04
	SD	3.9E-05	5.3E-05	5.3E-05	3.8E-05	5.3E-05	5.3E-05				3.8E-05	5.3E-05	5.3E-05

Table 13 Comparisons between ERICA and MCNPX results

		N2BL		N2OM		N2LI		Round	
Organ	Statistic*	Infinite	Rabbit	Infinite	Rabbit	Infinite	Rabbit	Infinite	Rabbit
Heart	% Difference							75.34	75.22
	t-Test							0.46	0.00
Large Intestine	% Difference	-2.10	-2.10	-2.33	-2.31	-1.93	-	-2.30	-2.30
	t-Test	0.10	0.00	0.11	0.00	0.10		0.11	0.00
Small Intestine	% Difference	-2.21	-	-2.02	-2.01	-2.04	-	-2.21	-2.20
	t-Test	0.12		0.11	0.00	0.11		0.12	0.00
Kidney (one)	% Difference	3.59	3.62	3.69	3.84	3.51	3.56	4.03	4.06
	t-Test	0.07	0.00	0.07	0.00	0.07	0.02	0.08	0.00
Liver	% Difference	1.18	1.18	1.07	-	1.28	1.29	1.39	1.39
	t-Test	0.04	0.00	0.04		0.05	0.00	0.05	0.00
Lung (one)	% Difference	0.23	0.24	0.56	-			0.61	0.62
	t-Test	0.02	0.00	0.05				0.06	0.00
Muscle	% Difference							2.53	-
	t-Test							0.04	
Skeleton	% Difference	-0.33	-	1.19	-			1.19	1.20
	t-Test	0.01		0.02				0.02	0.00
Skin	% Difference							0.26	0.27
	t-Test							0.02	0.00
Spleen	% Difference	0.66	0.63	1.19	1.15	0.65	0.63	1.24	1.22
	t-Test	0.02	0.00	0.04	0.00	0.02	0.00	0.05	0.00
Stomach	% Difference	-0.09	-0.08	1.19	1.20			1.19	1.20
	t-Test	0.00	0.00	0.03	0.00			0.03	0.00

* Statistical comparisons are made with respect to ERICA Tool

Table 14 Overall averaged scaled organ results

Organ	Statistic	N2BL* Mean	N2OM* Mean	N2LI* Mean	Round Mean	Overall Mean
Heart	Mean				3.71E-07	3.71E-07
	SD				2.76E-07	2.76E-07
Large Intestine	Mean	5.11E-04	5.10E-04	5.10E-04	5.10E-04	5.10E-04
	SD	4.20E-05	4.26E-05	4.97E-05	4.15E-05	2.18E-05
Small Intestine	Mean	5.39E-04	5.42E-04	5.40E-04	5.41E-04	5.41E-04
	SD	4.68E-05	4.03E-05	4.65E-05	4.04E-05	2.16E-05
Kidney (one)	Mean	8.66E-07	8.67E-07	8.65E-07	8.68E-07	8.66E-07
	SD	2.25E-07	2.24E-07	2.24E-07	2.25E-07	1.12E-07
Liver	Mean	9.46E-05	9.47E-05	9.46E-05	9.47E-05	9.46E-05
	SD	1.11E-05	1.32E-05	1.12E-05	1.11E-05	5.79E-06
Lung (one)	Mean	2.58E-05	2.58E-05		2.58E-05	2.58E-05
	SD	1.16E-06	1.29E-06		1.14E-06	6.87E-07
Muscle	Mean				2.56E-05	2.56E-05
	SD				7.99E-06	7.99E-06
Skeleton	Mean	9.28E-05	9.34E-05		9.33E-05	9.32E-05
	SD	2.67E-05	2.66E-05		2.17E-05	1.42E-05
Skin	Mean				7.13E-03	7.13E-03
	SD				4.83E-04	4.83E-04
Spleen	Mean	1.68E-06	1.68E-06	1.68E-06	1.68E-06	1.68E-06
	SD	2.24E-07	2.23E-07	2.24E-07	2.24E-07	1.12E-07
Stomach	Mean	1.54E-04	1.55E-04		1.55E-04	1.55E-04
	SD	2.69E-05	2.67E-05		2.66E-05	1.54E-05

*Scaling parameters

Table 15 Statistical comparisons between different scaling parameters versus the overall mean

Organ	Statistic*	N2BL	N2OM	N2LI	Round
Heart	% Difference				-
	t-Test				
Large Intestine	% Difference	-0.08	-0.04	0.12	0.04
	t-Test	0.01	0.00	0.01	0.00
Small Intestine	% Difference	0.27	-0.20	0.16	-0.12
	t-Test	0.03	0.02	0.02	0.01
Kidney (one)	% Difference	0.07	-0.05	0.13	-0.15
	t-Test	0.00	0.00	0.00	0.01
Liver	% Difference	0.06	-0.07	0.02	-0.04
	t-Test	0.00	0.00	0.00	0.00
Lung (one)	% Difference	0.15	-0.14	-	-0.04
	t-Test	0.03	0.02		0.01
Muscle	% Difference				-
	t-Test				
Skeleton	% Difference	0.45	-0.30	-	-0.10
	t-Test	0.01	0.01		0.00
Skin	% Difference				-
	t-Test				
Spleen	% Difference	0.19	-0.20	0.18	-0.16
	t-Test	0.01	0.01	0.01	0.01
Stomach	% Difference	0.43	-0.21	-	-0.21
	t-Test	0.02	0.01		0.01

* Statistical comparisons are made with respect to the overall organ mean

Table 16 Absorbed dose rates (μGy/h) of the six Maralinga rabbits located on-site

Organ	ICRP Rabbit Mean	Min	25% Quartile	Mean	75% Quartile	Max
Heart	4E-07	2E-07	4E-07	4E-07	1E-06	2E-05
Large Intestine	5E-04	2E-04	5E-04	6E-04	1E-03	3E-02
Small Intestine	5E-04	2E-04	5E-04	6E-04	2E-03	3E-02
Kidney (one)	9E-07	4E-07	9E-07	1E-06	2E-06	5E-05
Liver	9E-05	4E-05	9E-05	1E-04	3E-04	6E-03
Lung (one)	3E-05	1E-05	3E-05	3E-05	7E-05	2E-03
Muscle	3E-05	1E-05	3E-05	3E-05	7E-05	2E-03
Skeleton	9E-05	4E-05	9E-05	1E-04	3E-04	6E-03
Skin	7E-03	3E-03	7E-03	9E-03	2E-02	4E-01
Spleen	2E-06	7E-07	2E-06	2E-06	5E-06	1E-04
Stomach	2E-04	6E-05	2E-04	2E-04	4E-04	9E-03

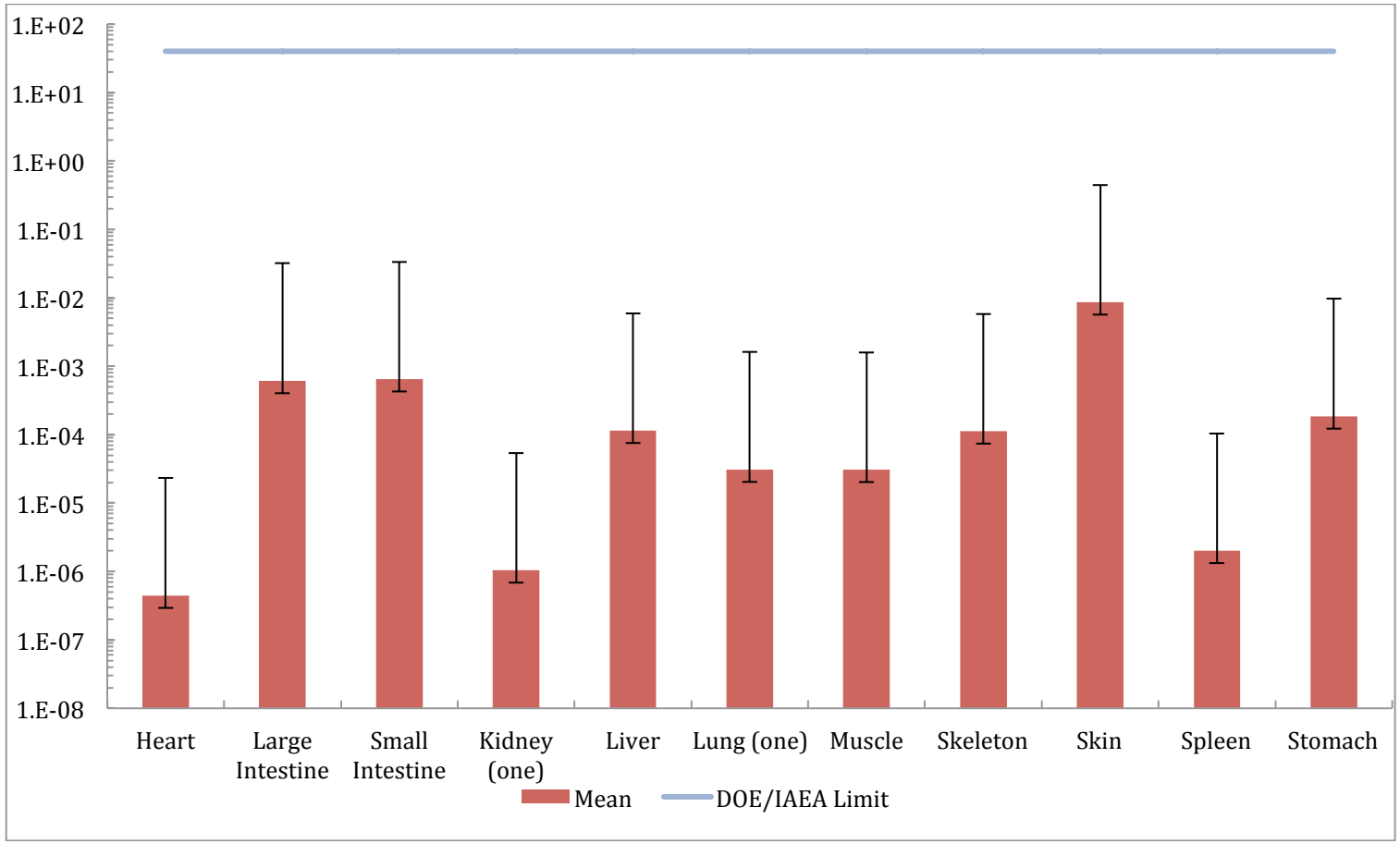

Figure 1 Absorbed dose rates (μGy/h) of the six Maralinga rabbits located on site

Table 17 Organ specific absorbed dose rates (μGy/h) for Maralinga rabbits

			Scaled from ICRP Skeleton				Scaled from ICRP Muscle		
Name	Statistic	Specific*	Blood	Muscle	Bone	ERICA	Blood	Muscle	Bone
Rabbit-1	Mean	1.4E-03	9.3E-05	9.3E-05	9.3E-05	4.6E-05	2.6E-05	2.6E-05	2.6E-05
	SD	5.9E-04	7.9E-05	6.3E-05	5.8E-05	1.9E-05	2.3E-05	1.9E-05	1.7E-05
Rabbit-2	Mean	1.5E-03	5.3E-03	2.4E-04	9.6E-05	1.2E-04	1.5E-03	6.7E-05	2.6E-05
	SD	4.4E-04	3.9E-03	1.3E-04	5.1E-05	2.7E-05	1.1E-03	4.0E-05	1.6E-05
Rabbit-3	Mean	1.8E-03	6.8E-05	2.5E-04	1.2E-04	1.2E-04	1.9E-05	7.0E-05	3.3E-05
	SD	2.9E-04	1.7E-04	1.4E-04	5.7E-05	3.0E-05	4.8E-05	4.3E-05	1.8E-05
Rabbit-5	Mean	2.9E-02	1.4E-04	3.0E-04	1.9E-03	1.4E-04	3.8E-05	8.2E-05	5.1E-04
	SD	3.3E-03	9.1E-05	1.6E-04	8.7E-04	3.2E-05	2.7E-05	5.0E-05	2.8E-04
Rabbit-6	Mean	1.3E-03	3.8E-05	5.7E-03	8.2E-05	2.7E-03	1.0E-05	1.6E-03	2.3E-05
	SD	3.0E-04	5.0E-05	2.8E-03	4.2E-05	1.7E-04	1.4E-05	8.8E-04	1.3E-05

*Absorbed dose rate was calculated for the specific rabbit of interest based on body mass and Pu-239 concentration

Table 18 Statistical comparisons between actual and scaled dose rates

		Scaled from ICRP Skeleton			Scaled from ICRP Muscle		
Name	Statistic*	Blood	Muscle	Bone	Blood	Muscle	Bone
Rabbit-1	% Difference	93.48	93.48	93.48	43.90	43.90	43.90
	t-Test	2.25	2.26	2.26	0.67	0.74	0.77
Rabbit-2	% Difference	-260.56	83.63	93.53	-1163.08	42.66	77.35
	t-Test	0.99	2.69	3.11	1.19	1.02	2.89
Rabbit-3	% Difference	96.32	86.16	93.49	84.75	42.68	73.06
	t-Test	5.25	4.94	5.83	1.82	0.99	2.52
Rabbit-5	% Difference	99.52	98.96	93.49	73.57	42.75	-257.28
	t-Test	8.54	8.48	7.77	2.53	1.04	1.33
Rabbit-6	% Difference	97.00	-348.01	93.52	99.62	42.78	99.17
	t-Test	4.10	1.56	3.97	15.60	1.30	15.54

*Taken with respect to the rabbit specific dose rate for the organ of interest

CONCLUSION

Absorbed dose rates from Pu-239 were calculated for 11 ICRP Duck/Rabbit organs using ERICA Tool and MCNPX. All organs were treated as elliptical and spherical in shape and were scaled according to ICRP and other literature according to body length and organ mass. All organs and their universes were treated as ICRU 4-elemental tissue in MCNPX. Statistical comparisons between ERICA Tool and MCNPX using percent differences and t-scores showed no statistical differences between all geometries. The statistical consistency between ERICA Tool and MCNPX demonstrates that ERICA Tool is a viable method to determine internal dose rates to organs for Pu-239 accumulation in tissue. When comparing absorbed dose rates between the four organ geometry sets, we found no statistical difference when comparing N2BL, N2OM, N2LI and round. This would suggest that for Pu-239 bioaccumulation, that organ geometry plays no role in determining absorbed dose rate . Results obtained for the absorbed dose in organs due to Pu-239 by using the spherical geometry which is the simplest to implement and the easiest to compute will not incur statistically significant bias with respect to other, more realistic organ models, allowing for savings in computational efforts in the future,

When the ICRP Duck/Rabbit data were scaled according to blood, bone, and muscle Pu-239 concentration, the new mean for the six rabbits that showed finite contamination values was 17 % higher than the values derived from the overall mean derived from ERICA and MCNPX values. This can be attributed to the use of the scaling factors. The scaled maximum for the six rabbits was orders of magnitude below 40 μGy/h, the dose rate associated with reproduction complications. The sampled rabbit organs are well below DOE and IAEA criteria for non-negligible risk of harm to the population/ecosystem as a whole. Absorbed dose rates were calculated from the Pu-239 concentration specifically to the individual rabbits that had finite contamination and were compared to the scaled values. In general, percent differences were between 42 % and 100 % indicating that the scaled values would underestimate the absorbed dose rate by one to two orders of magnitude with results being statistically significant according to the high t-scores.

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APPENDIX A: MCNPX INPUT: INTERNAL BETA SOURCE

Large Intestine:

```
c

c -----Cell Definitions-----------------------------------------------------

1 1 -1.0 -1 imp:p,e=4 $ Test Sphere

2 1 -1.0 +1 -2 imp:p,e=8 $ Universe

3 0 +2 imp:p,e=0 $ The Void

c ----Surface Definition ----------------------------------------------------

1 sq 2.6 44.486 44.486 0 0 0 -71.446 0 0 0 $ N2OM

2 sq 400 3600 5625 0 0 0 -90000 0 0 0 $ ICRP 108 Duck/Rabbit

c ----Data Cards ------------------------------------------------------------

mode p e                        $ Start electrons but track photons

sdef par=e erg=0.01915 pos=0 0 0 cell=1 rad=d1 axs=1 0 0 ext=d3 $ eff=0.001

c defines a spherical volume source
```

```
si1 h 0 1.367                $ Source can extend from [0<r<0.01] cm

sp1 -21 1                    $ Uniform particle distribution

si3 -5.363 5.363             $ Length of longest axis (Cylinder)

sp3 0 1                      $ Uniform axial distribution (Cylinder)

c -----materials ---------------------------------------------------------------

m1  1000  -0.101172      $ ICRU Soft Tissue den = 1.0 g/cc

      6000  -0.111000

      7000  -0.026000

      8000  -0.761828

*F18:p,e 1

*F78:p,e 2

PRDMP 0 -30              $ Creates a RNTPE every 30 min

nps 1e7                  $ Number of particles to run
```

APPENDIX B: EXAMPLE CALCULATIONS AND ERROR PROPAGATION

Data were assumed to be distributed normally. Calculations for ICRP Duck/Rabbit and Rabbit-1 will be used throughout, as an example, unless noted otherwise. All samples refer to Pu-239 unless noted otherwise.

Error associated with a sum and/or difference

$$(A \pm \sigma_A) \pm (B \pm \sigma_B) = (A \pm B) \pm \sigma_{A \pm B}$$

$$\sigma_{A \pm B} = \sqrt{\sigma_A^2 + \sigma_B^2}$$

Error associated with a product and/or quotient

$$(A \pm \sigma_A) \times (B \pm \sigma_B) \text{ or } \frac{(A \pm \sigma_A)}{(B \pm \sigma_B)} = C \pm \sigma_C$$

Where the standard error is given by

$$\sigma_C = C \times \sqrt{\left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_B}{B}\right)^2}$$

Calculation of Tissue Concentration

Ash Mass to Fresh Mass Pu-239 Tissue Concentration with blood as an example

Mass in Rabbit-1 Blood Sample

Total in Sample = (Sample Mass pg –Chemical Blank Mass pg)

Total in Sample = (0.0078 pg -0.0008 pg)

Total in Sample = 0.007 pg

Error in Pu Mass in Rabbit-1 Blood Sample

$$\sigma_{Mass} = \sqrt{(0.004\ pg)^2_{Sample} + (0.0006\ pg)^2_{Blank}}$$

σ_{Mass}=0.004 pg in blood

Pu Activity in Rabbit-1 Blood Sample

Activity = Mass (pg) × Specific Acitivy

$$\text{Activity} = 0.007\ pg \times \frac{2.295\ mBq}{pg}$$

Activity = 0.016 mBq

Error in Activity

$$\sigma_{Activity} = 0.016\ mBq \sqrt{\left(\frac{0.004\ pg}{0.007\ pg}\right)^2_{Sample} + \left(\frac{0.001\ \frac{mBq}{pg}}{2.295\ \frac{mBq}{pg}}\right)^2_{Specific\ Activity}}$$

$\sigma_{Activity}$ = 0.009 mBq

Correcting for the portion of ash sample lost and/or not used in AMS analysis:

$$\text{Fraction of Original Sample used in AMS analysis} = \frac{\text{Ash mass used}}{\text{Ash mass submitted}}$$

$$\text{Fraction of Original Sample used in AMS analysis} = \frac{0.0500\ g\ \text{Ash mass}}{0.0508\ g\ \text{Ash mass}}$$

Fraction of Original Sample used in AMS analysis = 0.984

Where ash mass used is the amount actually sent through the AMS for analysis and ash mass submitted by Mat Johansen

Error in Fraction of Original Sample

$$\sigma_{\text{Fraction}} = \sqrt{\left(\frac{0.0001\text{ pg}}{0.0500\text{ pg}}\right)^2_{\text{Sample}} + \left(\frac{0.0001\text{ pg}}{0.0508\text{ pg}}\right)^2_{\text{Specific Activity}}}$$

$$\sigma_{\text{Fraction}} = 0.003$$

Corrected Total Activity

$$\text{Corrected Total Activity} = \frac{\text{Total Acitivity in Sample}}{\text{Fraction of Original Sample used in AMS analysis}}$$

$$\text{Corrected Total Activity} = \frac{0.016\text{ mBq in blood}}{0.984}$$

$$\text{Corrected Total Activity} = 0.016\text{ mBq in blood}$$

Error in Corrected Activity

$$\sigma_{\text{Activity}} = 0.016\text{ mBq} \times \sqrt{\left(\frac{0.009\text{ mBq}}{0.016\text{ mBq}}\right)^2_{\text{Sample}} + \left(\frac{0.003}{0.984}\right)^2_{\text{Fraction}}}$$

$$\sigma_{\text{Activity}} = 0.009\text{ mBq}$$

Activity Concentration in Blood sample

$$\text{Activity Concentration} = \frac{\text{Corrected}}{\text{Fresh Mass of Organ Sample}}$$

$$\text{Activity Concentration} = \frac{0.016\text{ mBq in blood}}{3.68\text{ g blood} \times \frac{1\text{ kg}}{1000\text{g}}}$$

$$\text{Activity Concentration} = 4.4\frac{\text{mBq}}{\text{kg blood}}$$

Error in Activity Concentration

$$\sigma_{\text{Activity Concentration}} = \sqrt{\left(\frac{0.009\ \text{mBq}}{0.016\ \text{mBq}}\right)^2_{\text{Sample}} + \left(\frac{0.001\ \text{g} \times \frac{1\ \text{kg}}{1000\ \text{g}}}{3.68\ \text{g} \times \frac{1\ \text{kg}}{1000\ \text{g}}}\right)^2_{\text{Fraction}}}$$

$$\sigma_{\text{Activity Concentration}} = 2.6\ \frac{\text{mBq}}{\text{kg blood}}$$

Universe Activity Concentration

The activity concentration for the infinite and rabbit universes was calculated by taking the activity concentration from each organ in Rabbit-1 and multiplying it by the percent whole body organ mass. This accounts for the fact that some organs contribute more or less to the whole organism than others.

Blood's Contribution

$$\text{Weighted Activity Concentration} = \text{Acitivity Concentration} \times \text{Percent Organ Mass}$$

$$\text{Weighted Activity Concentration} = 4.4\frac{\text{mBq}}{\text{kg}} \times 6.25\ \%$$

$$\text{Weighted Activity Concentration} = 0.277\frac{\text{mBq}}{\text{kg}}$$

Error in Blood's Contribution

$$\sigma_{\text{Organ Activity}} = 0.277\frac{\text{mBq}}{\text{kg}} \times \sqrt{\left(\frac{2.6\ \frac{\text{mBq}}{\text{kg}}}{4.4\frac{\text{mBq}}{\text{kg}}}\right)^2_{\text{Concentration}} + \left(\frac{1.00\ \%}{6.25\ \%}\right)^2_{\text{Percent Organ}}}$$

$$\sigma_{\text{Organ Activity}} = 0.166\frac{\text{mBq}}{\text{kg}}$$

Repeating the process above for each organ (except the skin) and taking the sum of the results provides the values for the universe activity concentration. The error associated with the universe concentration was calculated by applying the summation error equation.

Calculation of Organ Mass

Organ mass for the ICRP Duck/Rabbit was calculated by taking the rabbit's mass and multiplying it by the appropriate percentage the particular organ contributes to the whole body mass. This process was applied to all organs listed previously, with an example using blood below. The error due to the ICRP Duck/Rabbit was considered zero as it is considered a reference animal.

Blood in Rabbit-1

$$\text{Mass} = \text{Mass of ICRP Rabbit} \times \text{Percent of Body Mass}$$

$$\text{Mass} = 1257\ \text{g} \times 6.25\ \%$$

$$\text{Mass} = 78.56\ \text{g blood}$$

Error in Blood Mass

$$\sigma_{\text{Organ Mass}} = (78.56\ \text{g blood}) \times \sqrt{\left(\frac{0}{1257\ \text{g}}\right)^2_{\text{ICRP Rabbit}} + \left(\frac{1.00\%}{6.25\ \%}\right)^2_{\text{Percent Organ}}}$$

$$\sigma_{\text{Organ Mass}} = 12.59\ \text{g blood}$$

Organ Dimension Determination

Three methods were derived to give a non-biased estimate of organ diameters. All derived geometries have the same mass for the given organ. Since organ dimensions were derived from ICRP reference data, all calculated dimensions were assumed absolute. What error, if any, could be attributed to the normalization process was considered negligible due to the use of multiple dimensions for the given organ. Example organ length calculations are displayed below, using the large intestine as an example. For simplicity and consistency all remaining dimensions were assumed symmetrical (equal) and calculated according to the formula for the volume of an ellipsoid with unit tissue density while rounding values to the nearest decimal.

$$\text{Mass} = \text{Density} \times \text{Volume}$$

$$\text{Volume} = \frac{\pi}{6}abc$$

Where a is the diameter calculated below and b = c.

Normalized to ICRP 89 Reference man length/height and ICRP 108 Duck/Rabbit Length

$$\text{Organ Length}_{\text{Rabbit}} = \left(\frac{\text{Organ Length}_{\text{Reference Man}}}{\text{Body Length}_{\text{Reference Man}}}\right) \times \text{Body Length}_{\text{ICRP Rabbit}}$$

$$\text{Organ Length}_{\text{Rabbit}} = \left(\frac{110\text{ cm}}{176\text{ cm}}\right) \times 30\text{ cm}$$

$$\text{Organ Length}_{\text{Rabbit}} = 18.750\text{ cm}$$

Normalized to ICRP 89 Reference man organ mass and ICRP 108 Duck/Rabbit organ mass

$$\text{Organ Length}_{\text{Rabbit}} = \left(\frac{\text{Organ Length}_{\text{Reference Man}}}{\text{Organ Mass}_{\text{Reference Man}}}\right) \times \text{Organ Mass}_{\text{ICRP Rabbit}}$$

$$\text{Organ Length}_{\text{Rabbit}} = \left(\frac{110\text{ cm}}{370\text{ g}}\right) \times 35.4\text{ g}$$

$$\text{Organ Length}_{\text{Rabbit}} = 10.526 \text{ cm}$$

Normalized to Literature Information and ICRP 108 Duck/Rabbit: Large and Small Intestines Only

$$\text{Organ Length}_{\text{Rabbit}} = \left(\frac{\text{Organ Length}_{\text{Average Rabbit}}}{\text{Body Length}_{\text{Average Rabbit}}}\right) \times \text{Body Length}_{\text{ICRP Rabbit}}$$

$$\text{Organ Length}_{\text{Rabbit}} = \left(\frac{226 \text{ cm}}{42 \text{ cm}}\right) \times 30 \text{ cm}$$

$$\text{Organ Length}_{\text{Rabbit}} = 161.429 \text{ cm}$$

Normalized to Literature Information for Children's Height and ICRP 108 Duck/Rabbit Length:

This was applied only for the liver, spleen, and kidney. Body length has the best association with organ length for the liver, spleen, and kidney as determined by the Konus group in 1998 (Konus, Ozdemir, Akkaya, Erbas, Celik, & Isik, 1998). These data were applied to the ICRP Duck/Rabbit by assuming a height of 30 cm for the length of the reference organism. Each organ being unique was scaled separately in a standard linear regression format. Outputs were given in millimeter dimensions so they had to be converted to centimeters.

Liver

$$\text{Organ Length (mm)} = \left(\frac{0.48 \text{ mm}}{\text{cm}}\right) \times (\text{Body Length}_{\text{ICRP Rabbit}}) + 42 \text{ mm}$$

$$\text{Organ Length (mm)} = \left(\frac{0.48 \text{ mm}}{\text{cm}}\right) \times 30 \text{ cm} + 42 \text{ mm}$$

$$\text{Organ Length} = 56.4 \text{ mm} = 5.64 \text{ cm}$$

Spleen

$$\text{Organ Length (mm)} = \left(\frac{0.45 \text{ mm}}{\text{cm}}\right) \times (\text{Body Length}_{\text{ICRP Rabbit}}) + 31 \text{ mm}$$

$$\text{Organ Length (mm)} = \left(\frac{0.45\ \text{mm}}{\text{cm}}\right) \times 30\ \text{cm} + 31\ \text{mm}$$

$$\text{Organ Length} = 44.5\ \text{mm} = 4.45\ \text{cm}$$

Kidney

$$\text{Organ Length (mm)} = \left(\frac{0.22\ \text{mm}}{\text{cm}}\right) \times \left(\text{Body Length}_{\text{ICRP Rabbit}}\right) + 48\ \text{mm}$$

$$\text{Organ Length (mm)} = \left(\frac{0.22\ \text{mm}}{\text{cm}}\right) \times 30\ \text{cm} + 48\ \text{mm}$$

$$\text{Organ Length} = 54.6\ \text{mm} = 5.46\ \text{cm}$$

Absorbed Dose Rate Calculations in μGy/h from MCNPX Output

The output generated by MNCPX was in terms of absorbed energy normalized per starting particle, plus relative error. This necessitates multiplying the tally result by multipliers to account for the source volume and source activity. The following is an example of taking the tally result and transforming it into terms of absorbed dose rate, for self-absorption of alpha particles in the large intestine normalized to body length. Source volume is the organ of interest

Energy Deposition in MeV/s

$$= (\text{Tally Result}) \times (\text{Source Volume } (\text{cm}^3)) \times (\text{Activity Concentration}) \times (\text{Particle Yield})$$

$$\text{Activity Concentration} = \frac{17.36\ \text{mBq}}{\text{kg}} \times \frac{1\ \text{kg}}{1000\ \text{g}} \times \frac{1\ \text{g}}{\text{cm}^3} \times \frac{1\ \text{Bq}}{1000\ \text{mBq}}$$

$$\text{Activity Concentration} = 1.736 \times 10^{-5}\ \frac{\text{Bq}}{\text{cm}^3}$$

$$\text{Particle Yield} = \frac{1 \text{ decay/s}}{\text{Bq}} \times \frac{1 \text{ alpha}}{\text{decay}} \times \frac{5.148 \text{ MeV}}{1 \text{ alpha}}$$

$$\text{Particle Yield} = \frac{5.148 \frac{\text{MeV}}{\text{s}}}{\text{Bq}}$$

$$\text{Energy Deposition} = \left(\frac{5.1446 \text{ MeV}}{5.148 \text{ MeV}}\right) \times (35.4 \text{ cm}^3) \times \left(1.736 \times 10^{-5} \frac{\text{Bq}}{\text{cm}^3}\right) \times \left(\frac{5.148 \frac{\text{MeV}}{\text{s}}}{\text{Bq}}\right)$$

$$\text{Energy Deposition} = 3.16 \times 10^{-3} \frac{\text{MeV}}{\text{s}}$$

Absorbed Dose Rate in μbs/h

$$\text{Absorbed Dose Rate} = \frac{\text{Energy Deposition Rate in Organ}}{\text{Mass of Organ}}$$

$$\text{Absorbed Dose} = \frac{\left(3.16 \times 10^{-3} \frac{\text{MeV}}{\text{s}}\right) \times \left(\frac{3600 \text{ s}}{\text{h}}\right) \times \left(\frac{1.602 \times 10^{-13}}{\text{MeV}}\right)}{\left(\frac{1}{35.4 \text{ g}} \times \frac{1000 \text{ g}}{1 \text{ kg}}\right) \times \left(\frac{1 \frac{\text{J}}{\text{kg}}}{\text{Gy}}\right)}$$

$$\text{Absorbed Dose} = 5.15 \times 10^{-5} \frac{\mu 5 \text{s}}{\text{h}}$$

Calculation of Statistical Comparisons

Calculation of % Differences

$$\% \text{ Difference} = \left(\frac{\text{ERICA - MCNPX}}{\text{ERICA}}\right) \times 100\ \%$$

Calculation of t-Test scores

$$\text{t-Test Score} = \frac{(\text{ERICA - MCNPX})}{\sqrt{\sigma_{\text{ERICA}}^2 + \sigma_{\text{MCNPX}}^2}}$$