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DOE HANDBOOK

RADIOLOGICAL CONTROL PROGRAMS FOR SPECIAL TRITIUM COMPOUNDS

U.S. Department of Energy
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AREA OCSH

Table of Changes

Page	Change
67 (near bottom)	In row 1, column 2 of the table titled “dosimetric properties” 6 mrem was changed to 6 x 10^{-2} mrem

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Technical Standards Program

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Foreword

The Department of Energy (DOE) and its predecessor agencies have undertaken a wide variety of national security and basic science missions over the past several decades. Many of these missions have involved work with hazardous and/or exotic materials and agents, and byproducts of their production, storage, and use. DOE and its predecessor agencies have invested significant efforts and resources into research to identify, and programs to control and assess exposure to, the physical, chemical, and radiological hazards created by these agents and materials. Included among these materials are combinations of tritium with host metals and organic materials (metal tritides and organically-bound tritium, respectively), referred to collectively as special tritium compounds (STCs).

The physical, chemical, and radiological properties of special tritium compounds may present challenges to DOE radiation protection programs established to ensure protection against more common radionuclide forms. Special tritium compounds differ from the more common forms of tritium (elemental tritium and tritium oxide) in a variety of characteristics, including particle sizes and chemical behavior. The physical properties of special tritium compounds may make their detection, characterization and subsequent assessments of hazards and exposure effects (i.e., individual dose assessment) difficult. Specialized methods may be necessary for workplace and individual monitoring and individual dose assessment. In addition, previous control regimens, which were primarily based on permanently-installed design and engineering features, may be disabled or ineffective under those aspects of DOE's current mission that focus on disposition activities such as deactivation, decommissioning, environmental remediation, and environmental restoration.

This handbook has been prepared by DOE to assist its employees and contractors in developing and implementing radiation protection programs that will provide adequate protection against the hazards presented by special tritium compounds. While this handbook is not intended to be a guide to compliance with any specific regulation or other mandatory standard, the technical information provided herein may be used as a technical basis for those programs that are developed and implemented to ensure regulatory compliance. In addition to the material provided herein, DOE suggests that individuals setting up programs for radiological control of STCs contact sites that either work with or have worked with tritium to learn of their experiences with STCs.

The science and practice of special tritium compound identification, measurement, and hazards assessments are in a state of rapid advancement. DOE encourages those individuals who are concerned with these fields to use this handbook as a basic source document, and to remain abreast of ongoing advances in the field that may add value to the information provided herein.

Copies of electronic files of this DOE Handbook may be obtained from the DOE Technical Standards Program Internet site (http://tis.eh.doe.gov/techstds/)

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TABLE OF CONTENTS

FIGURES

TABLES

ACRONYMS AND ABBREVIATIONS

ACV	air concentration value
ACV_o	air concentration value based on observed activity
AI	alveolar-interstitial region
ALARA	as low as reasonably achievable
AMAD	activity median aerodynamic diameter
AMD	activity median diameter
bb	bronchiolar region
BB	bronchial region
Bq	becquerel
BS	bone surface
BZA	breathing zone air sampler
CDE	committed dose equivalent
CEDE	committed effective dose equivalent
CFR	Code of Federal Regulations
Ci	curie
cm	centimeter
CMD	Count median diameter
DAC	derived air concentration
DCF	dose conversion factor
DCF_o	dose conversion factor based on observed activity
D&D	decontamination and decommissioning
DOE	U.S. Department of Energy
ET	extra-thoracic
f_1	fraction of radionuclide absorbed from the GI tract
GI	gastrointestinal
HEPA	high efficiency particulate air
HT	elemental tritium/tritium gas
HTO	tritium vapor/aqueous tritium
ICRP	International Commission on Radiological Protection
IMT	insoluble metal tritide
ISM	Integrated Safety Management
ITP	Insoluble tritiated particulate
l	liter
LLI	lower large intestine
LN	lymph nodes
LSC	liquid scintillation counting
m	meter
ml	milliliter
NP	nasal passage region
NRPB	National Radiological Protection Board
o	observed
OBT	organically bound tritium
P	pulmonary parenchyma region
PPE	personal protective equipment
RCS	Radiological Control Standard
RM	remainder organs
RWP	radiological work permit
S	stomach or specific source organ (used with SEE)
SAF	self absorption factor

SEE	specific effective energy
SEM	scanning electron microscope
SI	small intestine
STC	special tritium compound
Sv	sievert
s_g	Geometric standard deviation
T	tissue
TB	trachea and bronchial region
TWD	technical work document
UB	urinary bladder
ULI	upper large intestine

DEFINITIONS

Many technical terms used in this document are defined in 10 CFR Part 835 (DOE 1998a), its implementation guidance documents, and associated technical standards. These terms are used in this document consistent with their regulatory or guidance definitions.

Actual Activity: The total quantity of radioactive material within a particulate. Sometimes referred to as true activity.

Air Concentration Value (ACV): For special tritium compounds, the airborne concentration that, when breathed by a worker continuously for the period of one year (2000 hours), would result in a committed effective dose equivalent of 5 rem (0.05 sievert).

Biokinetic Model: A mathematical model that describes in quantitative terms the retention and transport of a material in the body. The biokinetic model used in ICRP 78 is recommended to evaluate intakes of STCs.

Breathing Zone Air Sampler (BZA): An air sampler that draws air from the area close enough to the nose so the sample can be considered representative of the air a person breathes. (ANSI Z88.2-1992). An example of a breathing zone air sampler is a lapel monitor.

Dose Assessment: Process of determining radiation dose and uncertainty included in the dose estimate, through the use of exposure scenarios, bioassay results, monitoring data, source term information and pathway analysis.

Dose Conversion Factor (DCF): Dose per unit intake.

Dosimetric Model: A mathematical model that prescribes how to use the biokinetic and radiation transport models to quantify the dose to specific organs and tissues and how to calculate effective dose. The dosimetric models for STC are described primarily in ICRP publications 67 and 71.

Gastrointestinal (GI) Tract Model: A mathematical representation of the behavior of radionuclides in the contents of the human gastrointestinal tract.

Insoluble Metal Tritide (IMT): A type of insoluble special tritium compound in which tritium has formed a chemical bond to a metal.

Insoluble Special Tritium Compound: A special tritium compound, for which the tritium cannot be rapidly taken up by the systemic compartment of the body.

Insoluble Tritiated Particle (ITP): Any tritiated particle from which the tritium is not readily released in air or aqueous solutions during the time interval over which the sample is collected and initially analyzed. This time interval may vary significantly, typically ranging from minutes to days.

LuDEP (Lung Dose Evaluation Program): A computer program that is used to calculate doses to the respiratory tract and other body organs from inhaled, ingested, or injected radionuclides. The code incorporates the model of the human respiratory tract issued by ICRP Publication 66.

Observed Activity: The apparent quantity of radioactive material within a particulate as determined by liquid scintillation counting - without attempting to correct for beta particle self-absorption, bremsstrahlung, or the emissions from HT or HTO.

Organically Bound Tritium (OBT): A type of tritiated material in which the tritium has formed a chemical bond with an organic material – typically via a carbon-tritium bond.

Self-Absorption Factor for Beta Particles (SAF_β): The fraction of beta particles emitted from within a particulate that escapes the particulate.

Self-Absorption Factor for Energy (SAF_e): The fraction of energy emitted from within a particulate that escapes the particulate.

Soluble Special Tritium Compound: A special tritium compound, for which the tritium can be rapidly taken up by the systemic compartment of the body (bloodstream).

Soluble Tritiated Particle: Any tritiated particle from which the tritium is readily released in air or aqueous solutions during the time interval over which the sample is collected and initially analyzed. This time interval may vary significantly, typically ranging from minutes to days.

Special Tritium Compound (STC): Any compound, except for H_2O, that contains tritium, either intentionally (e.g., by synthesis) or inadvertently (e.g., by contamination mechanisms). Also referred to as tritiated material.

Uptake: For STCs, the process by which the tritium atoms in STCs are taken into the systemic compartment of the body. This process includes the uptake of tritium that has been dissociated from the host molecule as well as the uptake of an entire STC molecule.

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1 - INTRODUCTION

Over the past several decades, DOE and its predecessor agencies have undertaken a variety of missions related to basic scientific research and national defense. A number of these missions have involved development, processing, storage, and disposal of a wide variety of exotic and/or hazardous materials, requiring comprehensive health and safety programs to ensure protection of affected workers, the public, and the environment. DOE's programs for protection of individuals from exposure to these materials have evolved over the years in response to changes in scientific knowledge and societal perceptions and impacts. In some cases, the physical and hazardous properties of the materials were not well known at the time of their development or use. In other cases, the hazards were fairly well known and characterized, but changes in scientific knowledge and public risk perceptions have required improvements in associated protection programs.

1.1 Purpose

Tritium is one of the many hazardous materials that has been produced and used at DOE facilities over the past several decades. Tritium has been produced and used in a wide variety of physical and chemical forms, with significantly differing properties and hazards. Among these many forms are those compounds referred to as special tritium compounds, which consist of tritium chemically combined with any one of a wide variety of metals or organic substances. These compounds may exhibit unique properties when ingested, absorbed, or inhaled into the human body. As a result of these unique behaviors, specific guidance is being provided to facilitate the development and implementation of appropriate protective programs.

1.2 Basic Properties of Tritium

One of the hazardous materials commonly produced, used, handled, and stored at DOE sites is tritium. Tritium is a radioactive form of hydrogen in which the nucleus of each atom is composed of one proton and two neutrons. Tritium undergoes decay by emission of a low-energy beta particle, with a half-life of approximately 12.3 years. Due to their low penetrating ability, tritium emissions are not readily detectable through use of instruments that are commonly used to monitor for other common radionuclides that may contaminate the workplace (e.g., pancake Geiger-Mueller detectors connected to count rate meters). The most common technique used for tritium air sampling (HT/HTO) is the flow-through ionization chamber. Tritium surface contamination can be detected through liquid scintillation counting, and this analytical method is in widespread use for analysis of workplace (contamination smears) and biological (urine) sample media.

A summary of the significant physical, chemical, and radiological properties of tritium and special tritium compounds is provided in Appendix A of this handbook. In addition, Appendix D contains information on the dissolution of insoluble tritiated particulate materials. This information may be useful in establishing facility-specific programs for analysis and control of tritium hazards.

Because it decays by emission of low energy beta particles that cannot penetrate human skin, tritium is not typically considered a significant external radiation exposure hazard. However, inhalation, ingestion or skin absorption of tritium can result in internal radiation doses. Because tritium, in its prevalent oxide form, behaves chemically identically to water, it undergoes fairly rapid uptake by, and elimination from, the human body. These biological processes make tritium oxide relatively easy to detect in bodily excretions (primarily urine) at very low levels, simplifying the radiobioassay, dose assessment, and exposure control processes.

DOE has provided a significant amount of information applicable to basic tritium processes and properties in DOE-HDBK-1079-94 (DOE 1994), *Primer on Tritium Safe Handling Practices*, and DOE-HDBK-1129-99 (DOE 1999e), *Tritium Handling and Safe Storage*.

1.3 Special Tritium Compounds

The detection and control of tritium are complicated when it is produced, used, and stored in some chemical and physical forms. Hydrogen atoms tend to migrate through surfaces with which they come into contact, and form chemical bonds with the host material. The hydrogen atoms may be released at a later time (commonly referred to as "outgassing"). While this property of hydrogen atoms may complicate measures implemented to contain tritium, it has been well characterized, and appropriate materials can be specified to minimize adverse effects. This property can also be used to practical advantage, as hydrogen atoms (including tritium) can be diffused through other materials, particularly metals, such as uranium, and stored within the matrix for subsequent extraction and use.

Tritium atoms may also diffuse into, and form chemical bonds with, organic materials with which they come into contact. The most common of these host materials are lubricating oils, solvents, and plastics.

The term "special tritium compound" (STC) is used to describe these compounds of tritium with host metals and organic materials.

The diffusion of tritium atoms into host metals and organic materials can complicate efforts to detect, and quantify levels of, tritium contamination in the workplace, environment, and individuals. These complications generally fall into three categories:

- Detection – Once the tritium atom has migrated into the matrix of the host material, some fraction of its emissions may not be able to escape that matrix.

- Physical and Chemical Behavior – If a tritiated material exists in a particulate state, or is subjected to any forces (e.g., heat, abrasion, cutting) that reduce it into a particulate state, the tritiated particles will behave physically and chemically like the host material particles, not like hydrogen. Therefore, the characteristics that are important variables in the internal dose assessment process (e.g., particle size, solubility, disassociation, inter-compartment transport, etc.) differ from those of tritium in elemental or oxide form.

- Emitted Radiation – Although only a small percentage of the beta particles emitted by the decaying tritium atoms may be detected, they may interact with surrounding host material atoms, resulting in emission of bremsstrahlung radiation and internal bremsstrahlung from the nucleus.

The behavior of STCs can present a variety of challenges to a facility's radiation protection program. For example:

- It may be difficult to differentiate between STCs and the more common forms of tritium using routine workplace monitoring techniques.

- The physical and chemical behavior of STCs may render commonly used tritium bioassay and available internal dose models ineffective.

- Difficulties in identifying and quantifying STC contamination can cause significant delays between performance of workplace monitoring and completion of analyses.

In the absence of effective detection methods, workplace hazards cannot be accurately assessed. Without accurate hazard assessments, associated activities such as area posting, material labeling, job planning, access control, and material release, are made difficult.

The risk associated with STCs can be put into perspective by comparing the effective dose equivalent per unit uptake (DCF) of various STCs with the effective dose equivalent per unit uptake of other representative radionuclides. As shown in Table 1-1, the DCF for Hf-T, a very insoluble tritiated particle is about 24 times that of HTO, while it is one twentieth that of ^{137}Cs, and one 270,000th that of ^{239}Pu. Thus, while the risk associated with STC that results in the greatest dose per unit uptake is greater that that from tritium oxide, it is less than the risk associated from fission products and actinides. Note that when assessing the hazard from STCs and other forms of radioactive material, it is necessary to know the quantities of material available for uptake, as well as the opportunities for uptake in addition to the inherent risk associated with the radioactive material.

Table 1-1 Ratio of DCF for Selected STC to DCF for Selected Radioactive Isotope or Compound

STC/Isotope	Ratio of DCF for selected STC to DCF for selected radioactive isotope or compound
$\frac{H_f - T}{HTO}$	24
$\frac{OBT}{HTO}$	2
$\frac{H_f - T}{^{137}Cs}$	1/20
$\frac{H_f - T}{^{235}U}$	1/77,000
$\frac{H_f - T}{^{239}Pu}$	1/270,000

1.4 Prevalence of STCs in the DOE Complex

STCs typically occur in much smaller quantities than other more common types of radioactive materials such as plutonium, uranium and HTO. However, STCs are found at many DOE sites as a result of past and present DOE operations. Table 1.1 lists examples of the types of processes involving the production or handling of STCs as well as various types of structures that could contain or be contaminated with STCs. The important consideration is that there is a wide variety of processes and locations where STCs may exist. Accordingly, it is prudent to consider the need for radiological protection measures specific to STCs when planning work in areas where any form of tritium has been handled or stored.

Table 1-2 Examples of Processes and Locations where STCs Could Exist.

Processes	Locations
Tritium targets for neutron Generators	Gloveboxes
Reactor operations	Fumehoods
Fusion Experiments	Ventilation systems
Extrication of tritium from fuel elements	Waste containers
Isotope separation	Sampling equipment
Storage of tritium,	Ground water
Stripping tritium from non-hydrogen gas streams	Uranium beds
	Spent fuel
Operations involving tritium labeled compounds	Alcohol wash systems
	Weapons components
Operations producing tritium contaminated oils and solvents	Molecular sieves and getters
	Kiln piping
Waste treatment and storage	Be reflector blocks
D&D Operations	Neutron Generators
Weapons testing	Heavy water purification evaporators
	Fuel storage basins

Although the DOE radiological protection community has been aware of STCs for many years, to date their impact has been limited by the design features that are incorporated into DOE facilities that handle significant quantities of tritium. These design features include various forms of material containment and control, such as gloveboxes and HEPA-filtered ventilation systems that effectively prevented significant releases of STCs to occupied areas of the workplace or the environment. Recently, sensitivity to STC contamination has been increased as a result of recent DOE activities involving decontamination and decommissioning of older facilities. These activities may compromise the effectiveness of the installed design features and allow releases of STC contamination to the surrounding areas. Such releases may cause exposures to individuals in the area and releases of STCs to the environment, both on- and off-site. In light of such experiences, DOE suggests that individuals setting up programs for radiological control of

STCs contact sites that either work, with or have worked, with tritium to learn of their experiences with STCs[1].

1.5 Handbook Overview

This handbook examines the difficulties associated with STC detection, assessment, and control, and provides guidance for incorporating effective STC monitoring and control regimens into the facility's radiation protection program. It has been developed based on currently available technology for detecting, identifying, characterizing and monitoring STCs. Accordingly, in some cases a more conservative approach to radiological controls is recommended when compared to oxide and gaseous forms of tritium. As technology in this area changes, more efficient approaches to radiological protection may be instituted.

This handbook should be used in conjunction with DOE's existing requirements and guidance documents, including:

- 10 CFR Part 835, *Occupational Radiation Protection*;
- The DOE G 441.1 series of Guides (10 CFR Part 835 Implementation Guides);
- DOE-STD-1098-99, *Radiological Control Standard*;
- DOE-STD-1121-98, *Internal Dosimetry Standard*;
- DOE-STD-1111-98, *DOE Laboratory Accreditation Program Administration*, and its supporting standards; and
- DOE's Radiological Control Technical Positions.

The information provided in this handbook also supplements that provided in DOE's guidance documents for tritium facility operations and safety, including:

- DOE-HDBK-1129-99, *Tritium Handling and Safe Storage*;
- DOE-HDBK-1105-96, *Radiological Training for Tritium Facilities*; and
- DOE-HDBK-1079-94, *Primer on Tritium Safe Handling Practices*.

Should any conflict exist between the guidance provided in this handbook and DOE's requirements for radiation protection, DOE's requirements take precedence. Such conflicts should be brought to the attention of the DOE office responsible for worker protection policy.

[1] The Mound Site performed decontamination and decommissioning (D&D) operations involving STCs during the period this document was developed.

2 - NATURE OF SPECIAL TRITIUM COMPOUNDS

2.1 General

Hydrogen atoms (including those that exist in the form of tritium) tend to diffuse through materials with which they come into contact, and may be released at a later time (commonly referred to as “outgassing”). While this property of hydrogen atoms may complicate measures implemented to contain tritium, it has been well characterized, and appropriate materials can be specified to minimize unintended adverse effects. This property can also be used to practical advantage, as hydrogen atoms can be diffused through other materials and stored within the matrix for subsequent storage, transportation, release, and use. The diffusion and outgassing processes may be accelerated through application of heat.

2.2 STC Host Materials

STCs can be created by intentional combination of tritium with the desired materials or by inadvertent contamination of a material that has been subjected to the presence of tritium for a period of time. DOE facilities have used a wide variety of metals (e.g., Ti, Zr, U, and Hf) in tritium research, purification, and storage, creating an equally wide variety of materials referred to as “metal tritides.” Metal oxides (e.g., rust), siliceous materials (environmental dust), and carbonaceous materials (e.g., polymers or environmental dust) can also become tritium contaminated and exhibit particulate properties. Tritium may also react with organic materials, resulting in the formation of organically-bound tritium (OBT). The main types of OBT encountered in the DOE complex are solvents, oils, and solid particulates (e.g., plastics, nylon, and organic dust forms). OBT can be particulate or non-particulate in nature.

2.3 STC categorization

In this handbook, STCs will be categorized according to (1) the ease with which the tritium (either unbound or bound to an STC) can be taken into the blood stream and (2) the physical form of the STC (e.g. particle, vapor, large solid, and liquid). Table 2-1 illustrates this classification scheme.

Table 2-1: Categorization of Special Tritium Compounds

Ease of Uptake	**Insoluble**			**Soluble**	
Physical Form	**Liquid/ vapor**	**Particle**	**Large Solid Form**	**Liquid/ Vapor**	**Particle**
Examples of STCs	Tritiated Pump Oil,	Hf-T Ti-T Eu-T Zr-T Dust Rust Pump oil Droplets, Tritiated Flyash	Tritiated Ti source for neutron generator, Tritiated nylon	Tritated Methane, Tritiated Solvents (acetone, octane)	U-T Pd-T

2.3.1 Ease of Uptake

Ease of uptake refers to the rate at which radioactive material can be taken into the bloodstream. For STCs this process includes both uptake of tritium that has dissociated from a host or carrier material and uptake of an entire STC molecule. The International Commission on Radiological Protection (ICRP) (ICRP 1994) categorizes most radioactive materials in terms of the rate of absorption from the respiratory tract to the bloodstream. Materials absorbed on the order days are classified as Type F (fast), those absorbed on the order of weeks are classified as Type M (moderate) and those absorbed on the order of years are classified as Type S (slow). (In addition to the three absorption classes, ICRP (ICRP 1998b) categorizes certain vaporous substances that are very rapidly absorbed by the body as Type V.) For purposes of understanding some of the radiation protection elements expounded in this handbook, Type S and M materials can be considered insoluble and Type F material can be considered soluble. Note that the ICRP classification forms the basis of the dosimetric calculations contained in Chapter 5.

NOTE: In the Mound Technical Basis Document (Mound 2000), the document from which much of the material in this handbook is derived, the term stable is used instead of insoluble to describe particles from which the tritium dissociates slowly, and the term unstable is used instead of soluble to describe particles from which the tritium dissociates more rapidly. The terms soluble and insoluble are selected for this hand book in order to apply the same terminology to describe ease of tritium uptake by the body for all STCs.

Particles or particulates can be formed from all types of STCs. To explain the uptake of these particles, the ICRP in publication 71 (ICRP 1995) assumes that the tritium dissociates from the rest of the particle and is then taken up by the body. The tritium that is not dissociated from the particle irradiates those tissues it comes in contact with while it remains in the body. Tritiated particles from which the tritium dissociates slowly may be considered insoluble. Tritiated particles from which the tritium dissociates rapidly may be considered soluble. In this handbook the operational distinction between soluble and insoluble particles is that insoluble particles do not readily release the bound tritium to either aqueous solutions or air during the interval between sample collection and analysis.

Another class of STCs is organically bound tritium (OBT) compounds. For these types of STCs, the tritium is not readily released from the carbon-tritium bonds to air or aqueous solution (Hill, 1993), therefore, the classification as either soluble or insoluble is based on the ease by which the entire molecule is taken up by the body.

Soluble OBT is rapidly taken up by the body while insoluble OBT is more slowly taken up by the body.

2.3.2 Physical Form

The manner in which in the body takes up STCs, and hence the radiological controls for STCs, is determined by the physical form of the STC. In this handbook,

the primary physical forms considered are particles, liquids/vapors and large solid forms.

Radiological controls for STC particles that are considered to be insoluble should be based on the controls used for radioactive particles rather than the controls used for HT, HTO, or vaporous forms of OBTs. Such tritiated particles are called insoluble tritiated particulates (ITPs). Examples of ITPs are tritiated metals, and metal oxides; the large molecule component of OBT oil; and solid OBTs such as flyash, nylon, and organic dust.

Soluble types of particulates rapidly release their bound tritium. For these types of triated particles, radiation protection measures should be based on those for HT or HTO. In addition, the detection problems that arise from the binding of tritium within the host particle are not an issue (see section 3.1). Examples of such particles are metal tritides of palladium and uranium.

STCs that are liquids and vapors are primarily comprised of OBTs. Soluble OBT can be incorporated into the body by inhalation, ingestion, or absorption through skin. Soluble OBT distributes throughout the body causing a whole body dose. ICRP 78 (ICRP 1998b) categorizes the dissolution rate for soluble vaporous OBT as Type V (very fast dissolution). Solvents are considered to be soluble. Radiological protection measures for vaporous OBTs are identical to those used for HT and HTO. When establishing controls for liquid forms of OBTs, it is important to consider absorption of the OBT through the skin, the vapor pressure of the liquid, the possibility that the liquid is composed of more than one OBT, and dispersal mechanisms that could aerosolize the liquid. An example of a liquid OBT is tritiated oil that has been used in pumps and air compressors.

Tritiated oils are a type of OBT that contains both soluble and insoluble components. Oils can be taken into the body by inhalation when they are in particulate form or can be absorbed through the skin. Because tritiated oils primarily consist of insoluble components (see section 4.4.3) tritiated oils will be treated in this handbook as insoluble particulates when they become airborne droplets.

The term “large solid forms” denotes the types of STCs that cannot be easily taken into the body, such as a piece of tritiated metal. Radiological controls for these types of tritides consist primarily of planning for situations in which portions these materials could be converted to airborne particles. Otherwise, standard radiation protection measures for the control of radioactive materials should be applied to these types of STCs. See section 3.2.1.2 for additional guidance that may be applicable to large solid forms of STCs.

2.4 Sources of STCs

As discussed previously, tritium, including that contained in STCs, is not considered an external exposure hazard. However, particulate tritiated materials, both metals and organic materials, can be ingested or inhaled, creating an internal exposure hazard. Solid particulate OBTs, such as plastic, nylon, organic dust, or the large molecule component of OBT oil, can become airborne by dispersal mechanisms. Equipment that can impart energy to oil through motion or release of pressure (e.g. pumps and air compressors) can cause an oil mist aerosol to be generated.

2.5 Hazards Associated with STCs

2.5.1 Ingestion of Tritiated Particulates

Following ingestion, STCs lose some fraction of their tritium as HTO or soluble OBT in digestive fluids. The fraction of the infused tritium lost via this mechanism varies depending on the stability of the specific material in the gastrointestinal (GI) tract; some particles lose essentially all of the tritium and others lose very little. In any case, the only significant dose following ingestion of tritiated particles is due to the resulting HTO or soluble OBT that is released. The remaining intact particles will undergo fairly rapid elimination from the body, resulting in negligible internal doses. Since HTO or soluble OBT is rapidly assimilated physiologically, this dose component is readily assessed via urine bioassay.

2.5.2 Inhalation of Tritiated Particles

Following inhalation, tritiated particles may be deposited in the lung. Once deposited in the lung, the infused tritium is removed from the body via two mechanisms:

1. Dissolution of tritium from the particulate and absorption into the body as HTO or soluble OBT, and removal through urine, expired air, and perspiration.

2. Mechanical transport of the particulate itself to the GI tract and removal through feces. (Inhaled tritiated particles removed to the GI tract will cause dose in the same manner as ingested triatiated particles, as described above.)

Removal of ITPs from the lung through mechanical transport can be slow. ITPs can, therefore, reside in the lung for a considerable amount of time. Accordingly, a significant portion of the entire committed effective dose equivalent resulting from the decay of the associated tritium atoms results from deposition in the lungs. The lung receives 85% of the committed effective dose equivalent (CEDE) from Type M ITPs and 96% of the CEDE from Type S ITPs (ICRP 71).

2.5.3 Skin absorption of OBT

Solvent OBT

Solvent OBT can, if spilled as liquid on the skin, produce a skin absorption pathway. The potential hazard of this pathway should be assessed using known or analyzed activity of the liquid. Solvent OBT absorbed through the skin can be assessed using urine bioassay.

OBT Oils

Tritiated oils can be found in pumps and compressors located in areas where work with tritium has been conducted. Trivedi (1995), in experiments on rats, has shown that tritiated oils can be absorbed by mammalian skin. Accordingly, skin absorption is a valid intake pathway for oil components. See section 4.4.3 for additional information on skin absorption of OBTs.

2.6 Challenges to Radiological Control Programs

Based on the previous discussion, STCs may present the following challenges to a facility's radiological control program (above and beyond the challenges presented by more common types and forms of radioactive material):

- Because some of the tritium emissions may be shielded by the particle, routine area monitoring efforts may not yield an accurate assessment of radionuclide levels on surfaces and dispersed in workplace atmospheres.

- The difficulties in area monitoring may cause corresponding difficulties in related activities, such as posting, labeling, work planning, access control, decontamination, personal protective equipment handling, and material control and release.

- Retention of insoluble tritiated particles in the body may render conventional tritium bioassay methods (urinalysis) ineffective. While ITPs behave as other particulates that are inhaled, an acceptable bioassay procedure is not currently available for some types of ITPs.

3 – WORKPLACE MONITORING FOR STCS

3.1 Observed Versus Actual Activity

Because of the difficulties associated with detection and quantification of STC levels on surfaces and in sample media, two terms are used in this handbook to describe analysis results. The *observed activity* is that activity that is detected by the prescribed analysis method. Because of the self-shielding attribute of particulate STCs, the *observed activity* (the activity detected by the sample analysis equipment, corrected for efficiency and detector-to-sample geometric considerations) may not reflect the total quantity of radioactive material present. The term *actual activity* is used to describe the total activity present in STCs. In practice, the actual activity may be estimated from the observed activity by use of appropriate conversions to adjust for particle self-shielding and other factors that may interfere with accurate sample analysis. However, in many cases, characterization of metal tritide species make it difficult to quantify and correct observed activity to actual activity. As discussed in this document, the use of observed activity is particularly relevant for internal dose assignment.

Current regulations require that certain radiation protection measures (e.g., contamination area posting and access control, radioactive material labeling and control) be implemented based on assessments of the quantities or concentrations of radioactive material present. This handbook adopts the concept of observed activity (discussed above) as an appropriate surrogate for the actual activity for STCs. 10 CFR 835 Appendix D, Footnote 2 provides surface contamination values in disintegrations per minute as meaning "the rate of emission by radioactive material as determined by correcting the counts per minute observed by an appropriate detector for background, efficiency, and geometric factors associated with the instrumentation." The use of observed activity is consistent with this provision. This handbook will demonstrate that certain other measures, such as individual dose estimates, may be based on assessments of observed activity.

3.1.1 Conversion from Observed to Actual Activity

The conversion of analysis results from observed to actual activity is relatively straightforward, once the various factors that introduce analytical uncertainties are understood and quantified. First, corrections must be applied to convert the analysis results presented by the instrument, usually counts per unit time, to the desired activity units and to eliminate the more common analytical uncertainties (e.g., uncertainties arising from detector efficiencies and counting geometry considerations). Further discussion on the use of observed activity is discussed in Section 5.2, especially considerations given to self-absorption of emissions that do not escape the STC particle.

In more conventional sample counting applications, application of these corrections will yield the actual activity present in the sample, usually in units of disintegrations per minute per 100 square centimeters (dpm/100cm^2) for surface contamination monitoring or microcuries per cubic centimeter (µCi/cm^3) for airborne radioactivity monitoring. (These are the units used for surface contamination and airborne radioactivity control criteria, respectively, in 10 CFR Part 835). However, due to the physical characteristics of STCs, application of these corrections yields only the observed activity. Further corrections may be made to account for that fraction of

the tritium decays that have escaped detection and accurate quantification due to the physical characteristics of the STC.

The corrections needed for conversion from observed to actual STC activity typically include the following:

- A correction to increase the observed activity to account for the number of tritium disintegrations that have escaped detection due to shielding effects of the host particle;

- A correction to reduce the observed activity to account for detected events resulting from bremsstrahlung radiation created by tritium beta interactions with the host particles;

- A correction to reduce the observed activity to account for detected events resulting from tritium that is present in non-STC form.

Application of these corrections will require knowledge of, or conservative assumptions regarding, the host particle characteristics, including atomic number, size, and density. However, using currently available technology, it is difficult to determine the actual activity in a manner that will make it a better indicator of the hazard to a worker than observed activity.

3.2 Area Monitoring

Because tritium emits only low energy beta particles, it is not considered an external radiation exposure hazard. Therefore, area monitoring efforts are restricted to surface contamination monitoring and airborne radioactivity monitoring.

Tritiated metals, metal oxides, dust, and oil can occur in nearly any tritium area. Any tritium contamination collected on a swipe survey or a particulate filter should be viewed as a potential combination of these. This is particularly the case for residual concentrations of tritium, i.e., where elemental (HT), aqueous (HTO), or solvent (soluble OBT) tritium sources have been removed or evaporated. However, it is the insoluble tritiated particulates with very long biological retention times (i.e. ICRP Type S or M) that pose the greatest hazard to workers. As a result, workplace sampling/monitoring programs that can quantify specific, and distinguish between various types of STCs, will allow one to depart from the conservative approaches recommended in this handbook.

3.2.1 Surface Contamination Monitoring

DOE - G 441.1-10, *Contamination Monitoring and Control Guide (DOE 1999d)*, establishes appropriate guidance for developing and implementing a surface contamination monitoring program. This Guide addresses such issues as monitoring requirements, techniques, frequencies, and actions. This guidance is generally applicable to monitoring for STC contamination; however, the sample analysis and activity determination techniques may be different due to the difficulties in accurately assessing STC levels. Note that if the host material of the STC is radioactive, the conventional methods in the DOE guidance can be used to assess the extent and level of surface contamination.

3.2.1.1 Removable Contamination

The first step in establishing a surface contamination monitoring program for STCs is to identify the likelihood that STCs may exist in an area, and if they do, identify the most likely locations. The best sources of this type of information are historical records and workers' memories of facility usage. Facility management should consult these sources for information regarding previous usage of the facility and specific areas. Almost any area in which tritium was used, handled, or stored may be considered a candidate for possible STC contamination. For larger facilities, identification of all STC contaminated areas may be quite time-consuming. Priority should be placed on identifying and controlling those areas that are likely to have the highest STC contamination levels. In many cases, this will include areas where STCs were intentionally created, and areas that have (or had) the highest tritium contamination levels and the highest probability of host particle formation and distribution. Such a determination should be made by review of historical radiological monitoring records and facility processes.

Following identification of those areas most likely to be contaminated with STCs, detailed radiological monitoring should be performed to identify tritium contamination levels in the area(s). Such monitoring should be performed using routine tritium contamination monitoring techniques, commonly using either wet or dry smears and liquid scintillation counting (LSC). In the past, many facilities have used styrofoam smears for collection of surface contamination samples for tritium analyses. Recent changes in the composition of scintillation cocktail fluid have largely eliminated this practice. The actual sample medium used is not particularly significant as long as its efficacy in collection of particulate material and suitability for LSC analysis can be demonstrated. Counting techniques should be capable of detecting contamination at or below the values provided in Appendix D of 10 CFR Part 835.

If the results of comprehensive smear surveys indicate that tritium surface contamination levels are less than one tenth of the 10 CFR 835 Appendix D value, then it may be appropriate to assume that there are no significant levels of STC contamination (i.e., levels requiring additional controls, such as posting, access control, or personnel monitoring). If the results of the smear surveys indicate that tritium contamination levels equal or exceed one tenth of the 10 CFR 835 Appendix D values, then further surveys may be conducted to identify sources of STCs in the area. It may also be necessary to identify the host material(s) so that appropriate assumptions may be made regarding assimilation and elimination.

3.2.1.2 Total Contamination

DOE has not established a total (fixed pus removable) surface contamination value for tritium and tritium compounds. The reason is that tritium can diffuse into the volume of any material to which it is exposed – at least in the gaseous forms normally encountered. After the exposure, the tritium migrates to the surface, making a definitive distinction between fixed and removable contamination difficult to ascertain.

NOTE: There is no tritium value for total surface contamination in 10 CFR 835 Appendix D. Accordingly, those provisions in 10 CFR Part 835 that apply to surfaces with total surface contamination levels greater than Appendix D levels do not apply to tritium.

The external hazard from tritium radiation is not considered to be a significant source of radiation exposure. Accordingly, compliance with the tritium value for removable contamination will provide an acceptable level of protection to individuals in controlled areas. This approach is considered acceptable for most tritium contamination.

However, there may be cases where tritium binds tightly to the matrix into which it has diffused, and removable contamination levels are below the values in 10 CFR Part 835. Such cases could occur when insoluble tritiated particles are fixed to a surface or from tritium exposure to bulk quantities of metals of the types from which insoluble metal tritides are formed. In such cases it is recommended that the provisions in 10 CFR 835 subpart L pertaining to total surface contamination values be applied, when the total surface contamination level exceeds 10,000 dpm/100 cm^2. In addition, when performing operations on these types of tritiated materials, it is important to assess the potential for producing airborne concentrations of respirable ITPs, and if needed, institute radiological controls appropriate to this hazard.

3.2.2 Air Monitoring

DOE Guide DOE G 441.1-8 (DOE 1999b), *Air Monitoring*, provides detailed guidance for developing and implementing an air monitoring program. This guidance is supplemented by that provided in the RCS (DOE 1999g) and in DOE-STD-1121-98 (DOE 1999h), *Internal Dosimetry*. This guidance, combined with that provided above for identifying areas possibly affected by STC contamination, is applicable to the air monitoring program for STCs. Likewise, the guidance that follows regarding identification of STCs and analysis of samples, is applicable to the air monitoring program.

3.2.3 Identification of STCs

After collecting samples of surface contamination or airborne radioactive materials, it is necessary to conduct radioanalyses to identify the levels of tritium (and other radionuclides) present in the sample. Tritium analyses are most commonly performed by liquid scintillation analysis of surface smears and air samples. Although liquid scintillation analysis is very effective in analyzing for the presence of tritium, this technique does not differentiate between the various forms of tritium (HT, HTO, STCs). Thus, non-standard techniques must be used to distinguish STCs from HT and HTO, and to distinguish among the various STC species. To date, a rapid, simple and reliable method for identifying STCs has not yet been developed.

In the following paragraphs, several techniques for identifying ITP species are described. However, all of these approaches have some drawbacks. In practice, some combination of the suggested analyses, or an entirely new approach, may be needed to evaluate the ITP contamination levels present in the samples. Such

efforts will probably not be straightforward, and conservatism must be used to ensure that the hazards associated with ITPs are adequately addressed to provide an adequate level of protection to DOE workers. If the analyses cannot definitively identify the ITP species, identity of the ITP species may be based on process or historical knowledge.

In all cases, a conservative approach should be used in identifying STC-contaminated samples. If the combination of factors identified below (facility history, radioanalytical identification of tritium, particle species identification) leads to a conclusion that the presence of STCs is likely, then the appropriate controls should be implemented consistent with this manual.

For ITPs, a scanning electron microscope (SEM) may be used to identify the presence of particles that are likely hosts for tritium atoms. In combination with conventional radioanalysis using LSC, an estimate of the gross ITP contamination levels may be obtained. This technique does have limitations however. While the LSC can definitively establish the levels of tritium emissions, and the SEM can definitively establish the presence and size of possible host particles, it is difficult to establish a direct correlation between the detected tritium emissions and the particulate levels. That is, it is not possible to state with any degree of certainty what fraction of the detected emissions arise from ITPs versus that fraction that arises from the more common tritium forms that may also be present. The presence of likely host particles does not definitely prove the presence of tritium within those particles.

The presence, of but not the amount of, ITPs may also be inferred by performance of multiple LSC analyses of individual samples, and trending the results to evaluate the change in observed tritium activity as the tritium atoms are released from the host material in the sample. (The observed tritium activity increases because the betas emitted by the tritium molecules that have been released from the metal particle are not absorbed by the metal particle.) This method may only be effective for those ITPs where the tritium is released from the host particle over a time period ranging from a few hours to a few weeks. If the tritium binds to the host material very tightly, the growth in observed activity will not be apparent over any reasonable time interval between repetitive sample analyses. If the ITP species is soluble, then all of the captured tritium may be released into the counting solution before the sample is counted. Because the lack of an effect does not mean ITPs are not present, the use of this method depends on reliable knowledge of the strength of the bond between the tritium and the host material in the ITPs expected to be present in the work area. Information on dissolution is contained in Appendix D. If tritium is likely to be present in both ITP and conventional forms, efforts should be undertaken to differentiate between the different species so that the appropriate controls (e.g., based on applicable limiting values) may be applied. One approach is to count a survey or air filter sample in LSC cocktail. This measurement gives a value for ITP plus HTO content. Addition of fresh water to the cocktail followed by evaporation (thus removing HTO from the sample) and then recounting the sample, provides a value for ITP alone. Other approaches at differentiating between the species may include attempts at ITP dissolution, following by sample counting to detect changes in analysis results due to particle dissolution and subsequent increase in detected tritium atom disintegrations. The accuracy of this approach is dependent on knowledge of the specific species present, the fraction of tritium

intra-particle disintegrations that may be detected, and the effectiveness of the dissolution technique for that species.

A useful characterization method, which could also be considered, is solubility testing: workplace survey samples tested for tritium released from particulates into simulated lung fluid. The results of this testing directly affect dose modeling via use of the critical parameter of ICRP solubility Type (F, M, S) for tritiated particulates in the lung.

In the absence of acceptable information with regard to differentiation of species, it may be necessary to base protective actions on conservative assumptions. Specifically, base protective actions on the most limiting values for dose conversion factors, airborne concentration and surface radioactivity levels associated with species likely to be present.

3.3 Individual and Workplace Controls for STC-Contaminated Areas

Following identification and quantification of STC contamination in an area, certain protective actions may be warranted and necessary to ensure compliance with DOE requirements for protection of individuals in or near the area. These protective actions and their regulatory basis include:

- Dose limits in accordance with 10 CFR 835 subpart C;
- Area posting in accordance with 10 CFR 835 subpart G;
- Material labeling in accordance with 10 CFR 835 subpart G;
- Material controls in accordance with 10 CFR 835 subpart L;
- Area control in accordance with 10 CFR 835 subpart F;
- Individual monitoring in accordance with 10 CFR 835 subpart E; and
- Area monitoring in accordance with 10 CFR 835 subpart E.

Guidance needed to implement these requirements is contained in the following sections of this handbook.

- Guidance on individual monitoring is in Chapter 4;
- Guidance on intake and dose assessment is in Chapter 5;
- Guidance on dose conversion factors for insoluble tritiated particles (Sv per unit of observed activity) Table 5-14 and Appendix A; and
- Guidance on workplace controls is in Chapter 6.

NOTE: Both individual and workplace monitoring may require air monitoring, such as breathing zone air monitoring, grab sampling, and continuous air monitoring.

4 – INDIVIDUAL MONITORING

As noted previously, 10 CFR Part 835 requires monitoring of certain individuals' internal and external doses. Except for rare situations, exposure to STCs will not result in a significant external dose; therefore, this handbook does not address external monitoring program requirements. STCs may contribute to an individual's internal dose. DOE has provided internal dose monitoring program guidance in DOE G 441.1-3 (DOE 1999a), *Internal Dose Monitoring Program Guide*, and detailed internal dose monitoring guidance in DOE-STD-1121-98 (DOE 1999h), *Internal Dosimetry Standard*. The guidance provided herein supplements that provided in those two standards and addresses issues that are specifically related to STCs.

The first step in determining an individual's internal dose as a result of a radioactive material intake, is to determine the magnitude of the intake (in units of activity). Determinations of individual radioactive material intakes generally fall under three different methods: 1) in-vivo analyses, such as whole body or organ counting; 2) in-vitro analyses, using analyses of excreta (urine or fecal analyses); and 3) air monitoring, using results of airborne contamination monitoring programs. The actual method used depends on a number of factors, including the characteristics of the material to be analyzed, results of prior scientific analyses to develop applicable protocols, and the analytical equipment available. This chapter discusses evaluations of the need for individual monitoring and the applicability of these various methods to evaluating intakes of STCs.

4.1 Identifying Individuals to be Monitored

Compliance with the internal dose monitoring requirements requires consideration of several factors. One of the first steps in implementing the internal dose monitoring program is identifying those individuals for whom internal dose monitoring will be required. This determination depends on the individual's classification (i.e., radiological worker, declared pregnant worker, occupationally-exposed minor, or member of the public) and likely dose. An estimate of an individual's likely dose requires knowledge of multiple factors, including:

- Areas to which the individual has access;
- Radiological conditions in those areas;
- Amount of time to be spent in affected areas; and
- Activities that the individual will be performing.

Consistent with DOE G 441.1-3 (DOE 1999a), this type of assessment is typically conducted on a work-group, rather than on an individual, basis. However, individual assessments may be required occasionally to address special or unique activities (e.g., declared pregnant workers, short term specialist assignments). The assessment should include all of the individual's internal exposures at the DOE activity, including those not related to STC exposure.

If estimates indicate that the individual's dose is unlikely to exceed the applicable mandatory monitoring threshold provided in 10 CFR 835.402, then no individual monitoring is required. However, the area monitoring program should provide sufficient data to

support decisions regarding individual participation in the individual monitoring program. See Chapter 3 of this handbook for guidance on the area monitoring program for STCs.

4.2 Air Monitoring for STCs

Should an individual monitoring program be required, a decision must be made regarding the relative merits of radiobioassay versus application of air monitoring results to determine individual doses. Generally, radiobioassay is the preferred monitoring method for assessment of individual internal dose. However, 10 CFR 835.209 allows the use of air monitoring data under certain conditions, including when air monitoring data will provide more reliable and accurate results. In many cases (as discussed in the remainder of this chapter), this condition may exist with exposure to certain types of STCs. For more information on development and implementation of an air monitoring program for purposes of individual dose assessment, see DOE G 441.1-8 (DOE 1999b), *Air Monitoring Guide*, and DOE-STD-1121-98 (DOE 1999h), *Internal Dosimetry.*

Historically, insufficient information has been available to facilitate development and implementation of effective radiobioassay programs for certain insoluble STCs with long biological retention periods. However, there has been a significant amount of recent research into such programs, the practical results of which are summarized in this handbook.

4.2.1 Air Monitoring - Area Monitoring vs. Individual Monitoring

It is important to differentiate between the purposes and scope of the various facets of the air monitoring program. Monitoring of the air in any specified area is usually performed using portable air samplers, fixed head air samplers, or continuous air monitors. As a facet of the area monitoring program, such monitoring is subject to the regulatory requirements found in 10 CFR 835.401 and 835.403. Air monitoring for the purposes of individual dose determination is usually performed using a lapel (personal) sampler worn by each affected individual. Because a lapel sampler is worn by, and monitors the breathing zone of a specified individual, the results of that sample analysis are applicable to that individual. If such monitoring meets the conditions of 10 CFR 835.209(b) it may be used to monitor individuals for exposure to internal radiation. The results of such monitoring may be used to meet the regulatory requirements in 10 CFR 835.401, 835.402(c), and 835.403. Because air sampling is distinct from bioassay, the requirements in 10 CFR 835.402(d) for performance accreditation of radiobioassay analysis do not apply to air sampling programs.

Note however, that the results of area monitoring (using portable, fixed head, or continuous air monitors) may be used for individual dose assessment under certain conditions (given that assurance can be provided that the sample is representative of the air actually breathed by the affected individual(s)). See section 5.2.4.1c for guidance on calculating dose from air sampling measurements.

4.3 Radiobioassay

4.3.1 Urinalysis

Soluble materials ingested or inhaled into the body will be excreted via urine. Given a known concentration of the contaminant in the urine and knowledge of the time of exposure and rate of dissolution of the material in body fluids, one can derive a total intake quantity. While determinations of the exposure time and urine concentration may be relatively straightforward for STCs, determination of dissolution rates is more difficult. Chapter 5 discusses the use of urinalysis in performing internal dose assessments for intakes of STCs.

4.3.2 Fecal Analysis

Insoluble materials that are inhaled into the body will be excreted via feces. Retention factors and total intake quantity can be calculated based on the models described in Section 5.1, given a known concentration of the contaminant in the feces and knowledge of the time of exposure, radioactive decay rate and solubility. Determination of exposure time is straight forward, but no reliable protocol currently exists for determining concentrations of STCs in feces[2].

4.3.3 In-Vivo Analyses

In-vivo analyses depend on the detection of radiation emitted by radioactive materials within the body by radiation detectors external to the body. In-vivo analysis is not considered to be a viable means of assessing tritium intakes, including STC intakes. The are two reasons for this: 1) Tritium decays by emission of low energy beta particles that will not penetrate through the body to the external detector, and 2) A significant number of bremastrahlung x-rays resulting from the interaction of the tritium beta with the metal atoms of the host particle are not expected to escape to an external detector unless the STC uptake is massive.

4.4 Organically Bound Tritium (OBT)

4.4.1 Soluble OBT

Soluble OBT migrates through the skin or lung into the bloodstream by the physical processes of dissolution and diffusion. The two processes are inseparably linked and often simply called "absorption." Soluble OBT is also readily absorbed through the GI tract following ingestion. Rapid dispersion minimizes organ-specific (e.g., lung) differential doses. Following absorption into the body, soluble OBT is excreted via urine. A biokinetic model is available which relates intakes of soluble OBT to urine excretion rates, and a dose conversion factor is available for soluble OBT intakes. Urine bioassay is therefore considered to be a viable approach to estimating intake and dose from soluble OBT. More information on dose assessment for soluble OBT is found in Section 5.2.5.1.

[2] For intakes expected to result in doses greater than 2 rem CEDE, one may want to collect and store fecal samples pending development of a fecal biokinetic model and assay technique.

Solvents such as octane, cyclohexane, or acetone have been used in pump cleaning and material dispersion processes. They can become tritium-labeled from extended exposure to tritiated materials. Since these solvents are volatile, they are considered soluble. Individual intake of tritiated solvents can occur through inhalation, ingestion, or by diffusion through the skin. Evaluation of solvent OBT intakes should be performed via urine bioassay.

The potential hazard of the skin absorption pathway should be assessed using known or analyzed activity of the liquid. Volatile OBT also produces vapors that can become dispersed in air, resulting in a second potential intake pathway of vapor inhalation and skin absorption. Therefore, an air concentration value (ACV) will be derived in the next section to relate volatile OBT air concentration to the annual CEDE. Volatile OBT vapors are readily detected by the tritium gas air monitoring method (e.g. ion chamber).

If a solid particle OBT that has been determined to be soluble in lung fluids is discovered, urine bioassay should be used to determine internal dose.

4.4.2 Insoluble OBT

For insoluble OBT, absorption through the skin is not an intake pathway. Following ingestion (or inhalation), some fraction of insoluble OBT will likely be digested in the stomach and converted to HTO or soluble OBT. Since HTO and soluble OBT are rapidly assimilated physiologically, these dose components are readily assessed via urine bioassay. In addition however, following inhalation, insoluble OBT may reside in the lung for a period of time, delivering dose to the lung. This material is largely formed by incidental contamination of environmental dust and is found in many tritium contamination areas. Solid particulate OBT is considered primarily insoluble, and intake by skin absorption is not expected, but inhalation is a possible intake mechanism. Inhalation of this material, including determination of intake through air monitoring, assignment of doses, and use of DCFs and ACVs, should be treated the same as inhalation of ITPs. Because monitoring and intake/dose assessments are the same for solid particulate OBT and for general ITP, these two materials do not need to be distinguished during workplace characterizations when the dose conversion assumptions are applied.

4.4.3 OBT Oils

Trivedi (1995) has shown that tritiated oils can be absorbed by mammalian skin. In this section skin absorption and inhalation are both discussed as valid intake pathways for various components of tritiated oils. Tritiated oils can be found in pumps and compressors located in tritium areas. Tritiated pump oils are considered to be a mixture of three components: insoluble large molecule OBT (original molecules of oil labeled by tritium), soluble small molecule OBT (created by radiolytic and degradation processes and labeled by tritium), and HTO. As a reasonable hypothesis, the tritium in OBT oils should be expected to partition into the above three components in approximately an 80:10:10 ratio, respectively. This is consistent with a ~70:20:10 ratio of tritium components removable from oily surfaces (Johnson, 1988), where all three components were observed. The small molecule OBT is expected to be more concentrated on surfaces than in bulk oil due to absorption of small polar molecules created from degradation processes. Data

on liquid tritiated oil (Trivedi, 1995) indicates that the 80:10:10 assumption should be conservative.

The latter two of the three expected OBT oil components can in fact diffuse through the skin. The HTO component can migrate quickly through the skin into body water and intake should be assessed via urine bioassay. Small molecule OBT can also migrate through skin and is considered soluble; intake of this component should also be assessed via urine bioassay. Estimation of potential absorption intakes of HTO and soluble OBT resulting from direct skin contact with liquid oil should be performed via analysis of oil samples for total tritium, and application of the above 80:10:10 ratio. Inhalation intakes of vapors liberated from volatile HTO and soluble OBT components of oil can also occur. Estimation of potential vapor intakes should be performed via monitoring of air above the oil by ion chamber.

Large molecule OBT is considered to be insoluble. Estimates of diffusivity of large organic molecules such as pump oils in polymer films, extrapolated from data for chemically similar but smaller molecules (Rogers, 1985), suggest that oils migrate extremely slowly (if at all) into and though polymeric materials. For this reason, the large molecule OBT component of oils is estimated not to absorb into (or through) skin and therefore not to impart skin (or other tissue) dose via this pathway.

The large molecule component of oil is not volatile. However, this oil component can be dispersed into air from the either operation of equipment or the sudden release of residual pressure, and therefore can be inhaled as a mist (and deliver a lung dose). Tritium from the insoluble large oil molecules does not dissolve into the body, due to the stability of the carbon-tritium bond in oils. Oil absorption in lung tissues is low, and clearance rate of oil from lung could be as slow as that of particulates. Therefore, an oil mist intake should be treated like an intake of solid particulate OBT (i.e., as an intake of ITP). Oil mist inhalation should be monitored by air sampling and assessed as ITP inhalation.

Estimation of potential inhalation intakes of OBT oil mists should be performed via analysis of oil samples for total tritium, and application of the above 80:10:10 ratio. Because OBT oils are expected to be a mixture of HTO, soluble OBT, and insoluble OBT as discussed above, radiological protection planning for activities involving OBT oils should consider potential intakes of, and air monitoring for, all three components. To avoid mist formation, energetic activities involving unencapsulated OBT oil should be discouraged.

5 – INTAKE AND DOSE ASSESSMENT

5.1 Biokinetic and Dosimetric Models

A *biokinetic model* describes in quantitative terms the retention and transport of a material in the body. A *dosimetric model* prescribes how to use the biokinetic and radiation transport models to quantify the dose to specific organs and tissues and how to calculate effective dose. The biokinetic model used in ICRP 78 is recommended to evaluate intakes of STC. The dosimetric models for STC are described primarily in ICRP 67 and 71. The STC biokinetic and dosimetric models will be briefly reviewed in this section and a detailed benchmark calculation is provided in Appendix B. The relevant ICRP publications should be consulted for a more detailed discussion of the models and their application.

The STC biokinetic model may be broken down into three major components:

- The respiratory tract model from ICRP 66;
- The systemic retention and excretion model from ICRP 67 and 78; and
- The gastrointestinal (GI) tract model from ICRP 30 and 78.

An example of how these models are coupled is shown in Figure 5-1. Inhaled aerosols of insoluble metal tritides (IMTs) that are initially deposited in the respiratory tract are:

- mechanically cleared from the body (e.g., by blowing the nose);
- dissolved and absorbed into the bloodstream; or
- mechanically cleared to the GI tract.

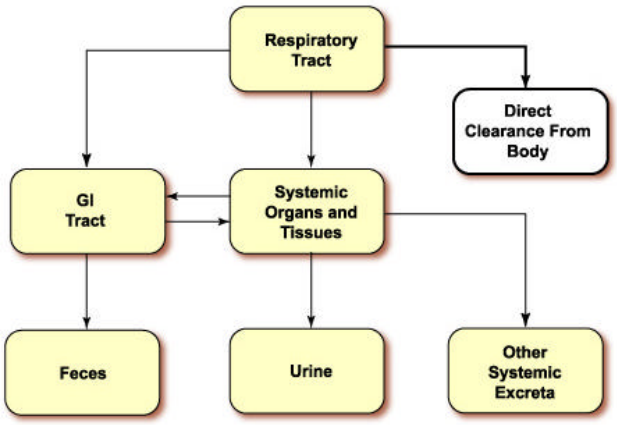

Figure 5-1. Simplified Overview of How the Major Components of the ICRP 78 Biokinetic Model for Insoluble Metal Tritides are Connected.

Note: “Other systemic excreta” refers to ICRP Publication 23 and includes insensible losses, breath, sweat, diffusion, and transpiration.

Tritium absorbed from the respiratory and GI tracts is assumed to be in the form of tritiated water (HTO) and to behave exactly like HTO that was absorbed directly into the bloodstream. The systemic biokinetic model is discussed in more detail in Section 5.1.1.

Material cleared to the GI tract may be dissolved and absorbed into the bloodstream or cleared to the feces. The ICRP 30 GI tract biokinetic model is used to quantify these processes, but some modifications have been made to the dosimetric model. More details on the biokinetic and dosimetric models are provided in section 5.1.2.

5.1.1 The Systemic Biokinetic Model

The systemic biokinetic model and relevant portions of the GI tract model are shown in Figure 5-2. STC particles that dissolve in the respiratory tract release tritium that is converted to HTO and absorbed into the bloodstream. STC particles that dissolve in the GI tract are also converted into HTO and absorbed into the bloodstream from the small intestines (SI). The fraction of STC that enters the GI tract and is subsequently absorbed from the SI is referred to as f_1.

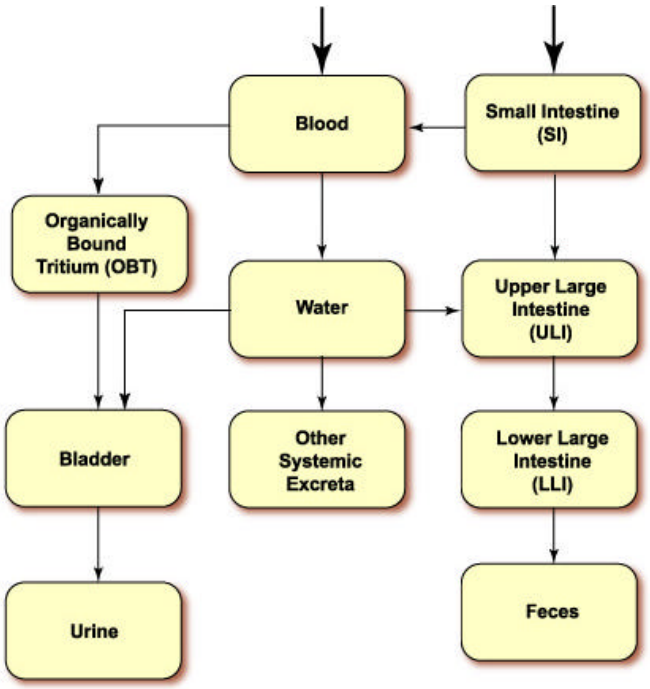

Figure 5- 2. Systemic Biokinetic Model for Tritiated Water Coupled to the GI Tract Model.

Of the HTO that is absorbed into the bloodstream, 3% is converted to organically bound tritium (OBT) that is retained in the body with a 40-day half-life and the remaining 97% remains as HTO and is retained with a 10-day half-life. All of the OBT is excreted into the urinary bladder and ultimately the urine. HTO is excreted from the systemic compartment in the following ratios:

- 1.4/3 fraction to the urinary bladder and ultimately the urine;
- 0.1/3 fraction to ULI and ultimately the feces; and
- 1.5/3 fraction to other systemic excreta (e.g., "insensible losses" and sweat).

These ratios are derived from the ICRP 23 (ICRP 1975) Reference Man water balance.

5.1.2 Urinary and Fecal Excretion Functions

Urinary and fecal excretion are expressed as 24-hour incremental quantities. For example, the 24-hour incremental urinary excretion $\Delta E_u(t)$ of tritium (not accounting for radioactive decay) at t days after intake is given by

$$\Delta E_u(t) = Q_u(t) - Q_u(t-1) \qquad \text{(Eq. 5-1)}$$

where $Q_u(t)$ is the content of the urine compartment at time t and $Q_u(t-1)$ is the content of the urine compartment one day earlier. The 24-hour incremental urinary excretion of tritium that does not account for radioactive decay is adjusted for radioactive decay to give the incremental excretion of tritium $\Delta e_u(t)$

$$\Delta e_u(t) = \Delta E_u(t) e^{-\lambda t} \qquad \text{(Eq. 5-2)}$$

Urinary excretion of tritium following an intake of HTO is typically expressed as the concentration of radioactivity per unit volume of urine such as μCi/L, based on the assumption that the concentration of HTO is the same in all body fluids. The presence of the OBT compartment in the ICRP 78 model precludes this approach and warrants the use of 24-hour incremental urinary excretion functions. Incremental fecal excretion is calculated in an analogous fashion. A detailed example of how to calculate urinary and fecal excretion is given in Appendix B.

5.1.3 The Respiratory Tract Biokinetic Model

The ICRP respiratory tract model is rather complex and is discussed in great detail in ICRP Publication 66. A brief overview is provided here as an introduction to the model. The respiratory tract model is composed of five major components:

- anatomical model;
- deposition model;
- particle mechanical clearance model;

- particle dissolution model; and
- dosimetric model.

The respiratory tract is divided into the thoracic and extra-thoracic (ET) regions, which are divided further into compartments that are used in the deposition and clearance models. These compartments are listed in Table 5-1. Comparing the regions of the ICRP 66 and ICRP 30 respiratory tract models, the ET region corresponds to the nasal passage (NP) region, the BB and bb regions correspond to the trachea and bronchial tree (TB) region, and the AI region corresponds to the pulmonary parenchyma (P) region.

The deposition model describes quantitatively where inhaled particles will be deposited in the different regions of the respiratory tract. The sites of initial particle deposition are all the compartments listed above except for the thoracic and extra-thoracic lymph nodes. Although it is possible to calculate deposition fractions from first principles, in practice we usually obtain the fractions from published tables like Table 5-2 below. These deposition fractions for occupational exposure were taken from the ICRP-CD[3].

Table 5-1. Compartments of the Respiratory Tract Model.

Extra-thoracic

ET_1 Anterior nose
ET_2 Posterior nose, larynx, pharynx, mouth
ET_{seq} sequestered particles
LN_{et} extra-thoracic lymph nodes

Thoracic

BB - bronchial region
- BB_1 - fast clearing compartment
- BB_2 - slow clearing compartment
- BB_{seq} - sequestered particles

bb - bronchiolar region
- bb_1 - fast clearing compartment
- bb_2 - slow clearing compartment
- bb_{seq} - sequestered particles

AI - alveolar-interstitial region
- AI_1 - fast clearing compartment
- AI_2 - moderate clearing compartment
- AI_3 - slow clearing compartment

LN_{th} - thoracic lymph nodes

[3]The ICRP Database of Dose Coefficients for Workers and Members of the General Public, Version 1.0 (Pergamon Press: New York) 1998.

Table 5-2. Deposition Tractions for Different Compartments of the Respiratory Tract as a Function of Particle AMAD.

	AMAD (:m)									
	0.001	0.003	0.01	0.03	0.1	0.3	1	3	5	10
AI1	1.359E-04	6.714E-03	8.229E-02	1.525E-01	8.688E-02	4.458E-02	3.198E-02	2.314E-02	1.596E-02	7.104E-03
AI2	2.718E-04	1.343E-02	1.646E-01	3.051E-01	1.738E-01	8.916E-02	6.396E-02	4.627E-02	3.191E-02	1.421E-02
AI3	4.530E-05	2.238E-03	2.743E-02	5.085E-02	2.896E-02	1.486E-02	1.066E-02	7.712E-03	5.319E-03	2.368E-03
bbf	2.262E-02	8.770E-02	1.291E-01	7.188E-02	3.328E-02	1.523E-02	8.327E-03	7.580E-03	6.569E-03	4.131E-03
bbs	2.294E-02	8.895E-02	1.309E-01	7.290E-02	3.376E-02	1.544E-02	8.087E-03	5.954E-03	4.384E-03	2.099E-03
bbseq	3.212E-04	1.245E-03	1.833E-03	1.021E-03	4.726E-04	2.162E-04	1.157E-04	9.541E-05	7.721E-05	4.392E-05
BBf	3.117E-02	4.420E-02	2.685E-02	1.035E-02	4.746E-03	3.260E-03	6.489E-03	1.127E-02	1.171E-02	9.436E-03
BBs	3.161E-02	4.483E-02	2.723E-02	1.049E-02	4.813E-03	3.293E-03	5.844E-03	7.290E-03	5.921E-03	3.116E-03
BBseq	4.425E-04	6.276E-04	3.812E-04	1.469E-04	6.738E-05	4.619E-05	8.694E-05	1.308E-04	1.243E-04	8.848E-05
ET2	4.390E-01	3.494E-01	1.735E-01	6.994E-02	3.218E-02	5.820E-02	2.111E-01	3.699E-01	3.989E-01	3.836E-01
ETseq	2.196E-04	1.748E-04	8.680E-05	3.499E-05	1.610E-05	2.912E-05	1.056E-04	1.850E-04	1.996E-04	1.919E-04
ET1	4.433E-01	3.327E-01	1.539E-01	6.248E-02	3.071E-02	5.217E-02	1.652E-01	3.001E-01	3.385E-01	3.471E-01

Note that an “f” in Table 5-2 corresponds to a “1” or “fast clearance compartment” in Table 5-1 and an “s” corresponds to a “2” or “slow clearance compartment.” For example, bbf in Table 5-2 is the same as bb1 in Table 5-1.

The model for mechanical clearance of particles from the lung is shown in Figure 5-3. While particles are being mechanically cleared, they are also dissolving and being absorbed into the bloodstream. Mechanical clearance and dissolution are therefore competitive processes.

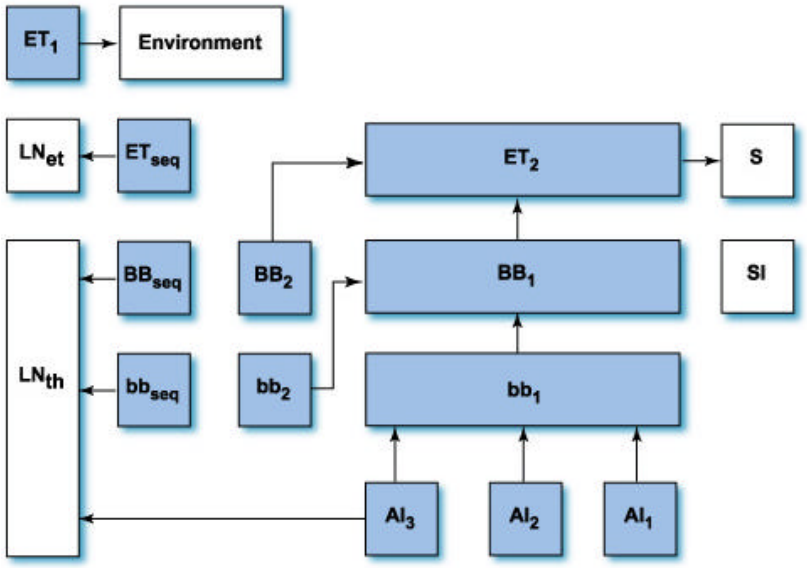

Figure 5-3. Deposition of Aerosols in the Respiratory Tract and Their Subsequent Mechanical Clearance.

NOTE: Shaded compartments are sites of initial deposition.

According to the model, the rate of mechanical clearance is dependent on where the particle is deposited, but is independent of the chemical form of the particle. On the other hand, the dissolution rate is dependent on the chemical form of the particle, but independent of where the particle is in the respiratory tract[4]. The dissolution model is shown in Figure 5-4. To account for time-dependent dissolution a two-stage dissolution model is used. In this model, particles either dissolve directly (and are absorbed) or are transformed to an intermediate form before they dissolve.

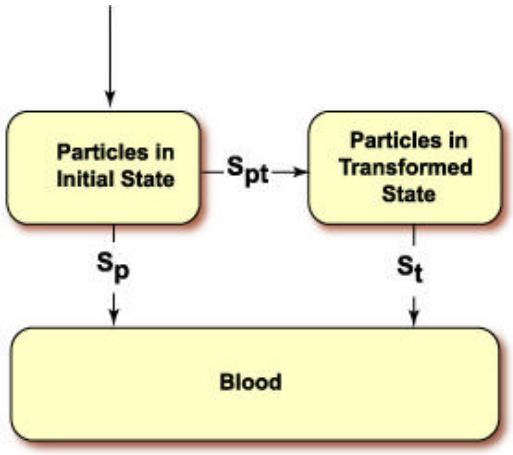

Figure 5-4. Two-stage Dissolution of STC Particles in the Respiratory Tract.

Default parameters are supplied in ICRP 66 for the mechanical clearance and dissolution models. The dissolution rate of particles may be classified as Type F (fast), M (moderate), or S (slow). These classes correlate roughly with the Class D/W/Y classes in the ICRP 30 respiratory tract model. However, note that D/W/Y refers to total clearance rates (mechanical plus dissolution) whereas F/M/S refers to dissolution rates only. The parameters for the time-dependent dissolution model can be experimentally determined by measuring the dissolution rate in-vitro over time, which is usually represented with two exponents[5]:

$$r(t) = f_r \cdot e^{-s_r t} + (1 - f_r) \cdot e^{-s_s t} \qquad \text{(Eq. 5-3)}$$

where

- r(t) is the fraction of material not dissolved at time t;
- f_r is the fraction that dissolves rapidly with rate constant s_r; and
- s_s is the rate constant for the fraction (1 - f_r) that dissolves slowly.

[4] Except for the ET1, where no dissolution or absorption is assumed to occur.

[5] See ICRP 71, Annexe D, Assignment of Compounds to Absorption Types from Experimental Data.

These parameters may then be converted to the s_p, s_{pt}, and s_t in the dissolution model (Figure 5-4).

5.1.4 The GI Tract Biokinetic Model

The GI tract biokinetic model, which has already been discussed to some extent in Section 5.1.1, is essentially the same model used in ICRP 30. STC particles enter the GI tract though the stomach via clearance from the lungs and oral ingestion. The f_1 is assumed to be 0.1 for Type M) STC particles and 0.01 for Type S STC particles. The tritium released from STC particles is absorbed into the bloodstream from the small intestines as HTO. Ingestion of HTO is treated as a direct injection into the bloodstream, bypassing the GI tract. A fraction of the HTO excreted from the body leaves via the feces. As mentioned before, this fraction is (0.1)/3 and it is assumed to enter the GI tract through the upper large intestine.

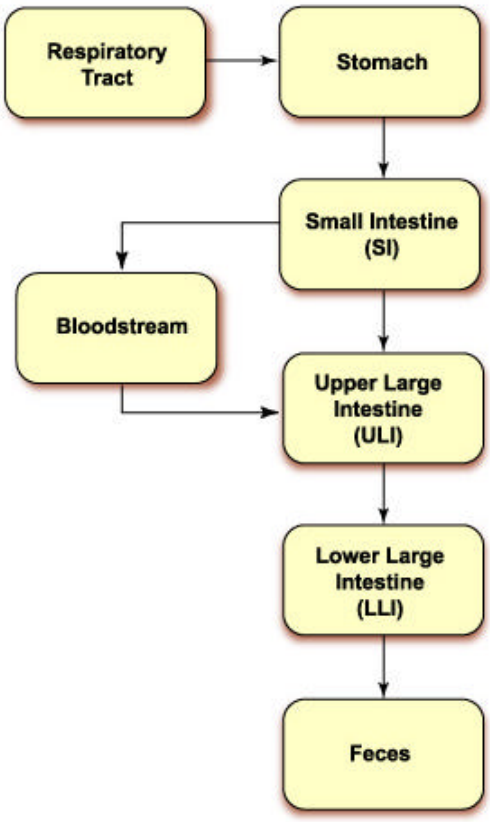

Figure 5-5. GI Tract Biokinetic Model.

5.1.5 Dosimetric Models

Ultimately, we would like to calculate the equivalent dose[6] to the organs and tissues listed in the first column of Table 5-3. These doses are then weighted with the

[6] ICRP 60 terminology that is similar to the ICRP 26 dose equivalent.

appropriate tissue weighting factor from the second column and summed to give effective dose H_e:

$$H_e = \sum_{i=gonads}^{remainder} w_i \, H_i \qquad \text{(Eq. 5-4)}$$

Table 5-3. Organs and Tissues with Explicit ICRP 60 Tissue Weighting Factors.

Tissue or Organ	Tissue Weighting Factor
gonads	0.20
bone marrow	0.12
colon	0.12
lung	0.12
stomach	0.12
bladder	0.05
breast	0.05
liver	0.05
esophagus	0.05
thyroid	0.05
skin	0.01
bone surface	0.01
remainder	0.05

NOTE: ICRP 60 tissue weighting factors are not permitted to be used when determining internal doses for compliance with version of 10 CFR Part 835 issued on December 14, 1993 and amended on November 8, 1997. The tissue weighting factors used in 10 CFR Part 835 were derived from ICRP 26[7] (See table 5-4 below).

[7] *Organs and tissues with explicit ICRP 26 tissue weighting factors:*

Tissue or Organ	Tissue Weighting Factor
gonads	0.25
bone marrow	0.12
lung	0.12
breasts	0.15
thyroid	0.03
bone surfaces	0.03
remainder	0.30

The first step in calculating H_e is to calculate the individual organ doses. To do this we must know:

- The source organs[8];
- The number of decays that take place in the source organs;
- The target organs[9]; and
- The fraction of energy released in the source organs that is absorbed in a target organ.

The source organs for STC are listed in Table 5-4.

Table 5-4. Dosimetric source organs for intakes of STC.

ET1sur	bbseq
ET2sur	AI
ET2seq	LNth
LNet	UBcont
BBgel	SI
BBsol	ULI
BBseq	LLI
bbsol	tissue
bbgel	

The abbreviation “sur” refers to surface, “seq” refers to sequestered, “gel” refers to material in the fast clearing mucus on top of the cilia, and “sol” refers to material in the slow clearing solution between cilia. The source organ “tissue” is the soft tissues of the body.

A source organ may be associated with more than one biokinetic compartment. For example, the source organ ET1sur is composed of only the ET1 biokinetic compartment, whereas the ET2sur source organ is composed of the ET2 and transformed ET2 (TET2) biokinetic compartments. The “tissue” source organ is composed of the OBT, HTO, and blood biokinetic compartments (see Appendix B). The decays U that take place in the source organs are calculated by integrating the retention function for the biokinetic compartments that compose the source organ.

Once the source organs and their associated biokinetic compartments are specified, the target organs must be specified. The target organs for STC are listed in Table 5-5.

[8] The organs in which tritium will decay and release radiation.

[9] The organs that absorb the radiation emitted by the source organs.

Table 5-5. Dosimetric Target Organs.

Adrenals	kidneys	muscle
UB wall	liver	ovaries
BS	ET1bas	pancreas
brain	ET2bas	RM
breasts	LNet	skin
S wall	BBbas	spleen
SI wall	BBsec	testes
ULI wall	bbsec	thymus
LLI wall	AI	thyroid
	LNth	uterus

In this table “bas” refers to basal cells, “sec” to secretory cells, “UB” to urinary bladder, and BS to bone surface.

The specific effective energy (SEE) describes the dose delivered to a specific target organ T for each decay in a specific source organ S. The SEE are calculated with the computer code SEECAL[10]. The SEE calculated with SEECAL do not account for self absorption of the tritium beta radiation in the tritide particle. If corrections for self absorption are made, care should be taken not to adjust the dose received from HTO. The dose H_T to target organ T from the decays in source organ S is given by

$$H_T = U_S \; SEE(T \leftarrow S) \qquad \text{(Eq. 5-5)}$$

The total dose to the target organ is the sum of the dose from all source organs.

$$H_T = \sum_i U_{S_i} \; SEE(T \leftarrow S_i) \qquad \text{(Eq. 5-6)}$$

The doses to some target organs are combined in a prescribed fashion to calculate the dose to an organ composed of two or more other organs or tissues. For example, 57% of the dose to the upper large intestine is added to 43% of the dose to the lower large intestine to give the dose to the colon. The tissues of the respiratory tract are another example of this procedure. Two organs in Table 5-3 deserve special note. First, the dose to the thymus is assumed to be the same as the dose to the esophagus. Second, the dose to the remainder is the mass weighted mean of the doses to the *i* organs not listed in Table 5-3.

$$H_{remainder} = \frac{\sum_i H_i \; m_i}{\sum_i m_i} \qquad \text{(Eq. 5-7)}$$

[10] M. Cristy and K. F. Eckerman, "SEECAL: Program to Calculate Age-Dependent Specific Effective Energies," ORNL/TM-12351 (1993).

5.2 Internal Dose Determination

The first step in determining an individual's dose resulting from a radionuclide intake is the intake assessment (i.e., determining the amount of radioactive material present in the body). Intake assessments for tritium exposure usually rely on radiobioassay. Common radiobiossay techniques for tritium (urinalysis) are rendered ineffective for some forms of STC intakes (especially insoluble particulates) because of the difficulties associated with relating the results of these analyses to specific intake levels. Therefore, representative air monitoring results are often used for assessment of doses resulting from exposure to particulate STCs. Variations in individual biological characteristics and statistical uncertainty associated with any measurement make dose assessment a process that must be approached with reasonable assumptions and documentation that support the calculation methodology.

Personal intake and dose assessments can be based on data from representative air monitoring using any appropriate technique, most commonly lapel sampling. Fixed air sample heads and portable air samplers may be used for individual dose assessment if one can ensure the sample is representative of the air inhaled. But, they are primarily used to verify the adequacy of radiological controls and postings and to document radiological conditions in the area of interest. See DOE-STD-1211-98 (DOE 1999h) *Internal Dosimetry.*

5.2.1 Intake Determination Methodology for Tritiated Particulates

Determinations of individual radioactive material intakes generally fall under three different methods: 1) in-vivo analyses, such as whole body or organ counting; 2) in-vitro analyses, using analyses of excreta (urine or fecal analyses); and 3) area monitoring, using results of area surface and air contamination monitoring programs. The actual method used depends on a number of factors, including the characteristics of the material to be analyzed, results of prior scientific analyses to develop applicable protocols, and the equipment available. This section discusses the applicability of these various methods to evaluating intakes of particulate STCs.

5.2.1.1 Air Monitoring

Air monitoring can be used to estimate intake directly, as opposed to indirect bioassay methods. Intake is considered to be proportional to the actual activity captured on the filter of an air-sampling device (assuming that the sample is representative of the breathing air for the individual in question). Particulates tend to shield their tritium beta activity by self-absorption of the beta radiation within the mass of the particle. Observed activity on a filter sample, measured by suspending particulates from the filter into liquid scintillation counting (LSC) solution, therefore under-represents the actual activity available for deposition to the lung, i.e., intake. Self-absorption factors (SAFs) vary, as a function of respirable (<10 μm AMAD) particulate size and material, by a factor of approximately 10. However, when tritiated particulate intake is defined in terms of observed activity (and when DCF is correspondingly defined in terms of observed activity intake), the uncertainty in the observed intake essentially disappears, since self-absorption is accounted for.

If large non-respirable tritiated particulates are captured on an air filter, intake amounts are somewhat overestimated. However, non-respirable particulates are not efficiently suspended in breathable air and are therefore discriminated against during air monitoring. Also, some dissolution can occur in the scintillation cocktail, which measures the activity captured on a filter. Dissolved tritium is not subject to self-absorption. Intake calculations are therefore overestimated if all activity observed by LSC is taken as "insoluble" and treated as Type S particulate. Since SAFs vary by a factor of ~10, dissolution in cocktail will not increase intake computations by more than a factor of ~10. Either non-respirable particulate collection or dissolution in cocktail will act to provide overestimation of intake (and ultimately dose) from air monitoring results.

Intake (and dose rate) in this case may be expressed as follows:

$$D(t) \mu I_O + DI_O \qquad \text{(Eq. 5-8)}$$

where: D(t) = dose rate to lung from observed intake at time t
I_O = observed intake to lung from air monitoring results at time zero
ΔI_O = incremental observed activity from particle dissolution or non-respirable particulates at time zero.

Shortfalls

The main shortfalls associated with this methodology for intake (and dose) estimation are: 1) actual activity intakes are uncertain by a factor of 10 because of self-absorption. 2) activity collected and measured on filters may over-represent the intake because of capture of non-respirable particulates and dissolution in scintillation cocktail.

As previously discussed in this handbook, intakes in terms of actual activity do not need to be determined. Intakes of observed activity are adequate to provide dose estimates as long as dose conversion factors are available which are described in terms of observed activity. In Section 5.2.3, self-absorption is investigated in detail. The section shows that actual activity of an intake is underrepresented by the observed results from scintillation counting of an air filter sample, but that the actual activity is correspondingly not fully available to impart dose to lung tissue. In fact, the observed activity more nearly represents dose or dose potential, since only that beta radiation that is not self-absorbed and escapes the particulate (i.e., that beta radiation "observed" via LSC analysis) is available to impart dose.

In Section 5.2.4, the ICRP 66 lung model is used to tabulate dose conversion factors for a given actual intake of tritiated particulate of various materials and various particle size distributions, assuming an ICRP 78 biokinetic model and Absorption Type S (slow). ICRP 66 dose, which does not account for self-absorption, is corrected by a "self-absorption factor for energy" (SAF_e) for the various particulates to determine the actual dose from the actual intake. SAF_e is the fraction of the total tritium beta energy generated within a particulate which is released from that particulate. The tritium beta activity expected to be observed in LSC analysis from the actual intake is then determined using the "self-absorption factor for beta particles" ($SAF_ß$) for the various particulates. The result of these

calculations is a table of actual dose conversion factors for intakes, based on observed data, for a variety of materials and particulate sizes. Because actual activity is not needed to assign dose from air sampling data, uncertainty in actual activity (because of uncertainty in particle size and hence SAFs) is not a shortfall to the air monitoring method for dose estimation. In addition, uncertainty in observed activity is only a function of the LSC assay technique, which is expected to be small and comparable to the uncertainty when LSC is used to analyze in urine or fecal bioassay samples.

The remaining expected shortfall is an overrepresentation of tritiated particulate intake because of capture of non-respirable particulates or dissolution in scintillation cocktail. These factors are not expected to increase dose calculations significantly. Non-respirable particulates will tend to be less available to sampling than respirable particulates, due to rapid settling. Dissolution in scintillation cocktail would have to occur within the few-hour period prior to analysis during which samples are immersed in the cocktail. These factors would serve to exaggerate intake estimates. The extent of this overestimation is the only significant uncertainty in the intake determination from air sampling methodology.

Another uncertainty occurs in the air sampling method which affects all methods. For a given intake, an expected dissolution rate must be chosen for the determination of the DCF. If Type S is chosen, when in fact captured particulates on an air-sampling filter more rapidly dissolve in the lung, this constitutes dose overestimation. Dose can be overestimated by a factor of 50 for this reason. The typical overestimate is expected to be a factor of less than 10, because the fastest dissolving particulates lose tritium to air during sampling and prior to analysis.

For the case of materials with extremely slow dissolution rates, such as hafnium tritide, the assumption of Type S is reasonable (Cheng 1999a), and would not lead to significantly underestimated doses. For Type S and Type "Super S" materials, mechanical clearance is the predominant removal mechanism, as opposed to dissolution. ("Super S" is a term used to describe any material where the absorption rate for tritium is less than that of Type S.) Section 5.2.2 shows that dose conversion factors for Hf, as derived from Type S and "Super S" input data, differ by only a few percent.

Detectable intake (and dose) is small in the case of air sampling. Section 5.2.2 determines an air concentration value (ACV) for Type S tritiated particulate which, when inhaled for one hour, imparts a CEDE of 2.5×10^{-5} Sv (2.5 mrem); this value is shown to be 4.8×10^{4} Bq observed/m^3. Sub-millirem doses are measurable and can be readily assigned in the case of air monitoring. Sensitivity is not a shortfall, but is in fact an advantage to air monitoring.

An additional shortfall for analyzing air samples using LSC is self-absorption of tritium beta radiation due to dust loading. An effective compensatory measure for this shortfall is the use of detergent in preparing air samples to remove dust from samples and suspend it in the counting solution.

The ability to obtain air samples that are representative of the monitored individual's breathing zone is another potential shortfall of air monitoring. However, according to U. S. Nuclear Regulatory Commission Regulatory Guide 8.25, samplers located within about 1 foot of the worker's head may be accepted as representative without

further determination. Therefore, when lapel breathing zone air samplers are properly used, representative air sampling is not considered a shortfall.

5.2.1.2 Urinalysis

Note: This section is reserved pending development of a relevant protocol.

5.2.1.3 Fecal Analysis

Note: This section is reserved pending development of a relevant protocol.

5.2.1.4 In-Vivo Analyses

As noted in section 4.3.3, in-vivo analyses depend on the detection of radiation emitted by radioactive materials within the body by radiation detectors external to the body. Because tritium decays by emission of low energy beta particles that will not penetrate through the body to the external detector, in-vivo analysis is not considered to be a viable means of assessing tritium intakes, including STC intakes.

5.2.2 Dose Conversion Factor for Insoluble Tritiated Particulates

Following the intake assessment, the intake amount may be converted to internal dose using a DCF. Determination of internal dose from a tritiated particulate is mainly dependent on two factors: particle size distribution, and dissolution rates of tritium from the particulate into lung fluid. The impact of these factors on DCF or intake determination, as derived from either bioassay or air concentration data, is discussed below.

5.2.2.1 Particle Size Distribution

For any given exposure scenario, the particle size distribution will affect both the dissolution rates (discussed below) and the deposition fractions (i.e., the fractions of the material that are deposited into each compartment of the lung). Smaller particle sizes tend to deposit deeper into the lung, causing a greater dose than particles that are physically larger, but otherwise similar (e.g., chemical characteristics, quantity of infused tritium). Uncertainty in the particle size distribution causes uncertainty in the DCF, regardless of the method used (e.g., bioassay or air monitoring) to determine activity intake. Therefore, the particle size distribution factor cannot be used to choose a preferred data collection method (urine bioassay vs. fecal bioassay vs. air concentration values).

Fortunately, errors in determining the particle size distribution tend to result in self-canceling errors in the dose assessment. If particle sizes are smaller than assumed, the particles will deposit deeper in the lungs, resulting in the use of a larger DCF and calculation of a larger dose. However, because the dissolution rate for the smaller particles will be higher than assumed, intake will be overestimated. Because intake is overestimated while DCF is under-estimated, the effects of particle size uncertainty on assigned dose tend to cancel. These effects are explored later in this Chapter.

Deposition fractions affect clearance rates of particulates from the lung to the gastrointestinal (GI) tract. Since urine excretion of tritium dissolved from tritiated particulate over time is a function of those particles which have not cleared from the lung, interpretation of urine excretion curves can extract particle size information. This requires extended monitoring without additional tritium intakes, which can adversely affect project management activities. To estimate intakes (and therefore doses) accurately and promptly from urine data, detailed knowledge of the particulate dissolution rates must be available. Tritiated material and particle size distribution involved in the intake, and the expected dissolution rate for that material and size, must be known. When tritiated materials and sizes are likely to range broadly, it will be difficult to provide material identification and size characterizations in the workplace. Moreover, although dissolution rate data are available for several materials, these data do not include all the possible combinations of materials and particle sizes that might be encountered.

5.2.2.2 Physical Diameter versus AMAD for Particulates

The ICRP and most technical papers that address respirability of particulate contamination use the term "activity median aerodynamic diameter" or "AMAD" when referring to particle size distributions. The AMAD can be very different from the physical diameter of a median particle, as it is a function of the particle's density and shape. The relative deposition of particles in the respiratory tract is dependent on the AMAD. Particles with small AMADs tend to deposit deeper (higher percentage in the alveolar interstitial region) in the lung than larger AMAD particles; because of the slow clearance rates of the deep lung, smaller particles generally cause higher lung doses than larger ones. For particles with AMADs greater than about 10 μm, the fractional deposition in the deep respiratory region is considered negligible. The larger sized particles tend to be deposited in the upper respiratory region where they are rapidly removed to the gut and eliminated in feces. The lung dose per unit intake is less for larger AMAD particles than for smaller AMAD particles. Table 5-6 shows a comparison of physical diameter versus AMAD (calculated per Cheng 1999a) for a variety of materials from low density to high density.

Table 5-6. Physical diameter versus AMAD for monodisperse particle distribution (σ_g = 1)

Physical Diameter (μm) vs. AMAD (μm)					
Base Material*	**AMAD = 10**	**AMAD = 5**	**AMAD = 2**	**AMAD = 1**	**AMAD = 0.5**
Organic–[~$(CH_2)_n$]	12.9	6.48	2.61	1.31	0.668
Rust–[~FeO(OH)]	5.87	2.92	1.15	0.559	0.265
Ti H_2	6.17	3.07	1.21	0.591	0.282
Zr H_2	4.76	2.36	0.920	0.441	0.202
Hf H_2	3.53	1.74	0.666	0.310	0.133

* Variable amounts of elemental hydrogen are isotopically tritium.

NOTE: The organic row listed in this table is for insoluble OBT. In other words the row is for OBT that is particulate in nature, to include oil mists. See Section 5.2.5 for a discussion of soluble and insoluble OBT.

Particle size distributions which are "monodisperse" are comprised of particles which are all the same size. The parameter s_g is the geometric standard deviation of the distribution. When s_g=1, no variability in the size distribution exists. When s_g>1, the distribution is called "polydisperse".

Subsequent text in this chapter investigates the dose from tritiated particulates as a function of different particle size distribution assumptions, from 0.5 to 10 µm AMAD. Dose variability over this range can then be compared to the dose from a 1 µm default size. Sub-micrometer particle size distributions are only produced by hot processes such as combustion (Cheng 1999b). This assertion is supported by Newton, 1987, and Dorrian, 1995. These references show that high energy processes such as oxyacetylene torch, electric arc cut rod, and plasma torch produce sub-micrometer particle size distributions, while lower energy processes such as band saw, reciprocating saw, and grinder produce larger particle size distributions. High energy cutting of tritium contaminated objects will release tritium from the objects in the form of HTO. Evaluation of particle sizes from 0.5 to 10 µm is therefore expected to be an appropriate evaluation of most respirable particulate STCs.

5.2.2.3 Dissolution Rate

The dissolution rate for a tritiated material is the rate at which tritium is released from the material to physiological (lung) fluid as HTO. For a given tritiated particulate intake, the dissolution rate affects the amount of tritium that remains in the lung to impart dose there. The effect of a varying dissolution rate assumption on the dose assigned from a given intake would be the same regardless of the method used to determine intake. Therefore, uncertainty in the dissolution rate also cannot be used to choose a preferred data collection method (urine bioassay vs. fecal bioassay vs. air concentration values). ICRP 71 gives DCFs for tritiated particulate intakes that vary from 0.3 to 14 times the DCF for HTO intakes, depending on the Absorption Type, which is primarily a function of the dissolution rate. Assuming the slowest dissolution rate for an intake would be a conservative assumption, in lieu of characterizations to the contrary, but would not grossly overestimate dose for a given intake. This is the basis behind applying ICRP 66 Absorption Type S ("slow", 99.9% dissolving with a halftime of 7000 days) in the derivation of tritiated particulate DCF in Section 5.2.2.

5.2.2.4 Default Parameters For ITPs

Dose conversion factors for ITPs are dependent on the particle size distribution and absorption characteristics of the aerosols in question. ICRP 66 provides guidelines for default assumptions to be used when detailed characterization data are unavailable. In many cases, the characterization process may require breach of contaminated systems. The assumptions listed in Table 5-7 should therefore be used to assess dose from suspected ITP intakes. These assumptions are conservative and consistent with ICRP 66 recommendations for assessing occupational exposure.

Table 5-7. Default assumptions for insoluble tritiated particulate intakes

Mode of Intake	Inhalation
Particle Size	1μm AMAD
Geometric Standard Deviation (s_g)	2.5
Shape Factor	1.5
Absorption Type	Type S
Weighting Factors	10 CFR Part 835
Biokinetic Model	ICRP 78

NOTE: The default particle size assumption of 1 μm AMAD is consistent with 10 CFR Part 835. Dorrian (1995) concluded (through a compilation of studies) that ICRP 66's choice of 5 μm is a "realistic" assumption and 1 μm AMAD is conservative. Therefore, in order to maintain conservatism, 1 μm AMAD is the default assumption within this handbook, although doses from other particle sizes are evaluated here via LuDEP. However, values of the various self-absorption factors, dose conversion factors, and air concentration values are calculated for 5 μm and other values of AMAD. Such values may be used when justified.

5.2.2.5 Computer Codes

The National Radiological Protection Board of Great Britain (NPRB) developed a computer program, LuDEP, (Version 2.06) "Personal Computer Program for Calculating Internal Dose Using the ICRP Publication 66 Respiratory Tract Model." The model is discussed in Section 5.1. ICRP 71 (which defaults to a 1 μm AMAD polydisperse particle size distribution with a material density of 3 g/cm^3) also uses the ICRP 66 Human Respiratory Tract Model to calculate DCF. The DCFs for a 1 μm AMAD polydisperse particle size distribution and a material density of 3 g/cm^3 listed in ICRP 71 are the same as those calculated with LuDEP.

NOTE: NRPB has developed a successor to LuDEP called IMBA. A version of this computer program called "IMBA Expert USDOE" will have the capability to perform bioassay and dose calculations for insoluble tritiated compounds. However, adjustment for self-absorption of beta particles and their energy still has to be performed as described in the value to obtain DCF_os.

LuDEP was used at the Mound site to investigate the variability of the DCFs for ITPs of various particle sizes and material densities, when dissolution rate is taken as Type S, and an intake is known from air monitoring. LuDEP can also be used to refine the conclusions of this handbook, and to assess the dose from ITPs of known particle sizes and material densities or dissolution rates other than Type S.

ITP dose evaluations may be calculated either by using LuDEP directly, or by using DCFs (organ CDE and CEDE) that are developed in this handbook (or that can be calculated using LuDEP).

5.2.3 Self-Absorption Factor (SAF) for ITPs

Within the ITP, the mass of the particulate absorbs a portion of the beta particles emitted during tritium decay. The fraction of beta particles that escapes the ITP is called the “self-absorption factor for beta particles” (SAF_β). When analyzing air monitoring samples for ITPs using LSC, it is necessary to consider SAF_β, since ITPs do not dissolve appreciably and release tritium to LSC cocktail. Only beta radiation that escapes the particles in LSC cocktail is available for detection. The SAF_β is used to estimate the "actual" ITP activity that would be “observed” when samples are counted via LSC. This use of SAF_β has been confirmed experimentally (Kropf, 1998), although the supporting evidence is limited.

To assess dose to the lung from ITPs properly, the “self-absorption factor for energy” (SAF_e) is an important consideration. Absorbed dose is a measure of the energy deposited (per unit mass) in tissue. Only the beta energy that escapes the particles contributes to dose. SAF_e is the fraction of energy that escapes the particles. Because LuDEP does not account for SAF_e, refinement of the results of LuDEP computations is necessary.

The SAF_β and SAF_e for given physical particle sizes are calculated numerically here by the methods described by Kropf (1998). The determinations of SAF_β and SAF_e are dependent on the electron density of a given material, which is proportional to $A/(Z\Delta)$, where A is the atomic mass of the material’s empirical formula, Z is the number of protons in the empirical formula, and Δ is the density.

The values employed to calculate the self-absorption factors (SAFs) for several representative materials are given in Table 5-8 below. DOE has handled tritides of several metals, considered to be insoluble, which do not appear in the table (in the interest of brevity), including scandium, yttrium, and alloys of titanium and lanthanum. The derivation of SAF_s for a representative but broad range of tritiated particulate materials is the prime focus of this section. The materials investigated were selected to represent a wide range of self-absorption, itself a function of the parameter $A/(Z\Delta)$. The materials in the tables of this section have values of this parameter which vary from 0.2 to 1.9. Parameter values for scandium, yttrium, and lanthanum ditritides are 0.72, 0.52, and 0.47, respectively. [Values for lanthanum alloys are slightly larger than those for lanthanum because of the inclusion of lighter elements. Values for iron/titanium alloys are close to those for titanium as given in the tables.] With respect to SAFs, the materials included in the tables therefore bracket the metals and alloys not included.

Table 5-8. Constants for calculating SAF_s for various monodisperse ($s_g = 1$) ITPs

Base Material*	A	Z	D	A/(ZD)
Organic [$\sim(CH_2)_n$]	14	8	0.9	1.944
Rust [$\sim FeO(OH)$]	89	43	3	0.690
Ti H_2	47.9	22	3.9	0.558
Zr H_2	91.22	40	6.49	0.351
Hf H_2	178.49	72	11.68	0.212

* Variable amounts of elemental hydrogen are isotopically tritium.

NOTE: In Table 5-8, A and Z for organic and rust are based on the sum of the elements of the empirical formula. Δ for organic and rust are an average of a range of values from the Handbook of Chemistry and Physics (CRC, 1973). A and Z for hydrides are based on the metal only, since hydrogen is a minor contribution. Δ for hydrides are taken from Richardson, 1999 and Cheng, 1999a. Hydrogen in tritium-labeled compounds has been represented as protium only, as this has a minor effect on the ratio $A/(Z\Delta)$.

Functional representations (curve-fits) of numerically calculated SAF data (for monodisperse physical particle sizes), as a function of particle size, were further derived. These representations are a refinement of those by Kropf (1998), and more accurately fit the data at small particle sizes.

From the functional representations of SAFs for monodisperse physical particle sizes, SAFs for polydisperse AMAD particle size distributions were calculated using the methodology adapted from Kropf (1998) and Cheng (1999a). The resulting values are given in Tables 5-9 and 5-10.

Table 5-9. SAF_e for Various ITP Materials and Polydisperse (S_g = 2.5) Particle Size Distributions (in AMAD)

Base Material*	A/(ZD)	SAF_e vs. Particle Size [AMAD(μm), s_g=2.5]				
		10	5	2	1	0.5
Organic [~$(CH_2)_n$]	1.944	0.305	0.474	0.707	0.841	0.925
Rust [~FeO(OH)]	0.690	0.231	0.381	0.614	0.768	0.879
Ti H_2	0.558	0.215	0.362	0.594	0.753	0.871
Zr H_2	0.351	0.180	0.312	0.541	0.714	0.852
Hf H_2	0.212	0.142	0.260	0.490	0.680	0.842

* Variable amounts of elemental hydrogen are isotopically tritium.

Table 5-10. SAF_b for Various ITP Materials and Polydisperse (S_g = 2.5) Particle Size Distributions (in AMAD)

Base Material*	A/(ZD)	SAF_b vs. Particle Size [AMAD(μm), s_g=2.5]				
		10	5	2	1	0.5
Organic [~$(CH_2)_n$]	1.944	0.205	0.333	0.535	0.677	0.789
Rust [~FeO(OH)]	0.690	0.140	0.244	0.439	0.602	0.745
Ti H_2	0.558	0.133	0.231	0.423	0.590	0.739
Zr H_2	0.351	0.104	0.191	0.380	0.555	0.719
Hf H_2	0.212	0.077	0.154	0.343	0.529	0.707

* Variable amounts of elemental hydrogen are isotopically tritium.

Other published computations of self-absorption factors (Richardson, 1999; Traub, 1999) largely confirm the results above. Traub (1999) states that bremsstrahlung photons, created when beta particles are self-absorbed, are not expected to be a significant contribution to dose from tritiated particulates.

5.2.4 Dose Conversion Factors (DCFs) and Air Concentration Value (ACV) for ITPs

The broad range of SAF derivations in the previous section allows correction of dose conversion factors (DCFs) for self-absorption across a broad range of */-/rials and size distributions. The goal of these derivations and corrections in Section 5.2.2 is to determine a limiting ("worst case") self-absorption-corrected DCF among a variety of materials with wide variation in SAF. The variability of DCF as a function of particle size distribution is also assessed. This determination of a limiting DCF for ITPs allows a material-independent approach to air sampling and surface surveys following that point. A readily implemented approach, utilizing data obtained in terms of "observed" activity, is also provided.

5.2.4.1 Dose Conversion Factors (DCFs) for ITPs

Using LuDEP, the DCFs for lung CDE and CEDE were calculated for a variety of ITP materials and particle size distributions using the default assumptions given in Table 5-5 (except for particle size). The results are shown in Tables 5-11 and 5-12 below. LuDEP makes no allowance for self-absorption within particulates.

Table 5-11. Lung CDE DCFs (Sv/Bq) for Various ITPs and Particle Sizes (AMAD, σ_g = 2.5), Type S Assumed

	Lung DCF vs. Particle Size [AMAD (μm), σ_g = 2.5]				
Base Material*	**10**	**5**	**2**	**1**	**0.5**
Organic [~$(CH_2)_n$]	4.50×10^{-10}	9.90×10^{-10}	1.65×10^{-9}	1.74×10^{-9}	1.64×10^{-9}
Rust [~FeO(OH)]	4.51×10^{-10}	1.00×10^{-9}	1.71×10^{-9}	1.98×10^{-9}	2.29×10^{-9}
Ti H_2	4.51×10^{-10}	1.00×10^{-9}	1.74×10^{-9}	2.07×10^{-9}	2.52×10^{-9}
Zr H_2	4.53×10^{-10}	1.01×10^{-9}	1.81×10^{-9}	2.30×10^{-9}	3.07×10^{-9}
Hf H_2	4.56×10^{-10}	1.03×10^{-9}	1.94×10^{-9}	2.70×10^{-9}	3.87×10^{-9}

* Variable amounts of elemental hydrogen are isotopically tritium.

NOTE: The reason the DCFs differ slightly for a given AMAD in Table 5-11 is that the densities differ and the density affects the deposition fractions in the various lung compartments.

Table 5-12. DCF (Sv/Bq), CEDE, for Various ITPs and Particle Sizes (AMAD, σ_g = 2.5), Type S Assumed

	CEDE DCF vs. Particle Size [AMAD (μm), σ_g = 2.5]				
Base Material*	**10**	**5**	**2**	**1**	**0.5**
Organic [~$(CH_2)_n$]	6.10×10^{-11}	1.27×10^{-10}	2.05×10^{-10}	2.14×10^{-10}	2.00×10^{-10}
Rust [~FeO(OH)]	6.11×10^{-11}	1.28×10^{-10}	2.13×10^{-10}	2.43×10^{-10}	2.79×10^{-10}
Ti H_2	6.15×10^{-11}	1.28×10^{-10}	2.16×10^{-10}	2.54×10^{-10}	3.07×10^{-10}
Zr H_2	$6.17\text{H}\times10^{-11}$	1.3×10^{-10}	2.25×10^{-10}	2.83×10^{-10}	3.74×10^{-10}
Hf H_2	6.20×10^{-11}	1.32×10^{-10}	2.41×10^{-10}	3.30×10^{-10}	4.70×10^{-10}

* Variable amounts of elemental hydrogen are isotopically tritium.

NOTE: In Table 5-12, the CEDE DCF for rust, 1 µm AMAD, differs slightly from the CEDE DCF given in ICRP 71 for Type S tritiated aerosols (2.6×10^{-10} Sv/Bq), even though the particle size distribution and densities are identical. The reason for this difference is that the ICRP 71 value was computed using the default "Environmental" assumptions (e. g., individual is sleeping 33.3% of the time) and the values given in the table above were computed using the default "Occupational" assumptions because this document focuses on occupational protection.

The DCFs given in Tables 5-11 and 5-12 were not corrected to account for SAF_e. Therefore, the component of the lung DCFs is significantly exaggerated. In order to determine more realistic DCFs, it is necessary to correct the lung dose for SAF_e using the values from Table 5-9.

NOTE: This correction should only be applied to lung dose from particulates and not HTO in the lung that results from the dissolution of the particle. However for absorption class S materials, the rate of dissolution is so slow that the contribution to the lung dose is negligible.

The correction for SAF_e is made as follows:

$$DCF_{(corrected\ for\ SAF_e)} = DCF_{(uncorrected)} - 0.12*DCF_{lung} + 0.12*DCF_{lung} \times SAF_e \quad \text{(Eq.5-9)}$$

where: $DCF_{(uncorrected)}$ is CEDE per unit intake (Sv/Bq; values from Table 5-12)
0.12 is the ICRP 26 weighting factor for lung
DCF_{lung} is the Lung CDE per unit intake (Sv/Bq; values from Table5-11)
SAF_e is the corresponding value from Table5-9

Table 5-13 shows the CEDE DCFs, corrected for SAF_e, for various ITPs.

Table 5-13. DCF (Sv/Bq), CEDE, for Various ITPs and Particle Sizes (AMAD, S_g = 2.5), Type S Assumed, with SAF_e Corrections Applied to the Lung Dose Component

	CEDE DCF (w/ SAF_e) vs. Particle Size [AMAD (µm), S_g = 2.5]				
Base Material*	**10**	**5**	**2**	**1**	**0.5**
Organic [~$(CH_2)_n$]	2.35×10^{-11}	6.41×10^{-11}	1.47×10^{-10}	1.81×10^{-10}	1.85×10^{-10}
Rust [~FeO(OH)]	1.95×10^{-11}	5.35×10^{-11}	1.34×10^{-10}	1.88×10^{-10}	2.45×10^{-10}
Ti H_2	1.90×10^{-11}	5.17×10^{-1}	1.32×10^{-10}	1.93×10^{-10}	2.67×10^{-10}
Zr H_2	1.71×10^{-11}	4.62×10^{-11}	1.25×10^{-10}	2.03×10^{-10}	3.19×10^{-10}
Hf H_2	1.51×10^{-11}	4.03×10^{-11}	1.22×10^{-10}	2.27×10^{-10}	3.97×10^{-10}

* Variable amounts of elemental hydrogen are isotopically tritium.

CEDE DCFs in Table 5-13 are now smaller than the CEDE DCFs in Table 5-12, because of the corrections for particulate energy self-absorption. In order to use the values shown in Table 5-13, the "actual" activity inhaled must be known. Air monitoring can be performed via batch air filtration sampling and subsequent LSC analysis of the collected ITPs. An indicator of air concentration potential can also

be provided by pre-job or in-job contamination surveys. To determine the "actual" activity on a filter, it would be necessary to dissolve the ITPs. Otherwise, self-absorption of the beta radiation from tritium leads to underestimates of the airborne activity. However, many ITPs (especially Type S) are extremely difficult to dissolve, requiring strong acids for extended periods of time. CEDE DCFs for ITPs of Type S, when determined based on "actual" activity, are found to be highly dependent upon particle size. Table 5-13 data indicate that variations can be as much as a factor of 30 for particle sizes from 0.5 to 10 μm AMAD (for a given material).

Fortunately, it is not necessary to rely on "actual" activity or to dissolve ITPs prior to counting samples. Not only is dissolution cumbersome, but "observed" activity on filters counted by LSC without dissolution is a much better indicator of dose or dose potential than is "actual" activity. The reason for this is that (due to self-absorption) only the beta radiation that escapes ITPs is capable of causing lung dose and, if the ITPs are not dissolved prior to counting, only the beta radiation that escapes is counted.

Table 5-14 shows CEDE DCFs in terms of Sv per "observed" Bq when undissolved ITPs are counted via LSC. The values in the table were calculated by dividing the CEDE DCFs in Table 5-13 by the corresponding SAF_{β}s from Table 5-10. The term "DCF_o" is used to represent DCFs that are based on "observed" activity, as determined by LSC counting without dissolution.

Table 5-14. DCF_o (Sv/observed Bq), CEDE, for various ITPs and particle sizes (AMAD, s_g = 2.5), Type S assumed

	CEDE DCF_o vs. Particle Size [AMAD (μm), s_g = 2.5]				
Base Material*	**10**	**5**	**2**	**1**	**0.5**
Organic [~$(CH_2)_n$]	1.14×10^{-10}	1.92×10^{-10}	2.75×10^{-10}	2.67×10^{-10}	2.35×10^{-10}
Rust [~FeO(OH)]	1.39×10^{-10}	2.19×10^{-10}	3.04×10^{-10}	3.12×10^{-10}	3.29×10^{-10}
Ti H_2	1.42×10^{-10}	2.24×10^{-10}	3.11×10^{-10}	3.27×10^{-10}	3.62×10^{-10}
Zr H_2	1.64×10^{-10}	2.42×10^{-10}	3.30×10^{-10}	3.66×10^{-10}	4.44×10^{-10}
Hf H_2	1.97×10^{-10}	2.61×10^{-10}	3.55×10^{-10}	4.29×10^{-10}	5.61×10^{-10}

* Variable amounts of elemental hydrogen are isotopically tritium.

Table 5-14 data indicate that the CEDE DCF_os, based on "observed" activity of ITPs of Type S, are less dependent on particle size than are the CEDE DCFs, based on "actual" activity, from Table 5-13. The assumption of a single particle size distribution would result in much smaller errors than noted above; for example, when using "observed" activity, CEDE DCFs vary only by a factor of about 5 for particles ranging in sizes from 0.5 to 10 μm AMAD. Compare this with a factor of 25 when using "actual" activity.

The 10 CFR Part 835 recommended default particle size for occupational exposure is 1 μm AMAD (s_g = 2.5). From Table 5-14, the most conservative CEDE DCF_o for 1 μm AMAD is about 4.3×10^{-10} Sv per observed Bq (1.6×10^3 rem/Ci_o). This is the value that should be used to compute CEDE assessments for inhalation intakes of tritiated particulates, based on air monitoring and observed results from that monitoring.

To calculate internal dose using the various dose conversion factors for ITPs, it is necessary to estimate the intake of ITPs. Intake of ITPs (I) can be inferred from air sampling results using equations 5-10 and 5-11. (See DOE-STD 1121-98 for considerations to be applied when using air sampling results to determine internal dose.)

To calculate intake from air sampler measurements use equation 5-10

$$I\left(Bq\right) = \frac{A_F\left(Bq\right) \cdot BR\left(m^3 / hr\right)}{FR\left(m^3 / hr\right) \cdot T_C\left(hr\right)} \cdot T_E\left(hr\right) \qquad \text{(Eq 5-10)}$$

Where:

A_F is the activity on the filter sample (either observed or actual)
BR is the breathing rate of the worker
FR is the flow rate of the air sampler
T_E is the time period the worker was exposed to air containing radioactive material sampled
T_C is the time over which the sampler was operated.

NOTE: It is important to make sure that T_C reflects the time the sampler was operating in an atmosphere expected to contain STPs. Including periods when the sampler is not in an STP containing atmosphere in the determination of T_C will tend to reduce the estimated STP concentration in air and thus, lead to an underestimate of intake.

To calculate intake from personal air sampler measurements use equation 5-11.

$$I\left(Bq\right) = \frac{A_F\left(Bq\right) \cdot BR\left(m^3 / hr\right)}{FR\left(m^3 / hr\right)} \qquad \text{(Eq 5-11)}$$

NOTE: To ensure that intake is not underestimated, the sampler should never be turned off when a worker is in an atmosphere expected to contain STPs.

NOTE: Equations 5-10 and 5-11 assume 100% collection efficiency. The filters used at the Mound Site (Mound 2000) had collection efficiencies that ranged between 0.981 – 0.9999 for 0.3 to 10 um particles. ANSI N13-1(ANSI 1999) contains a table of collection efficiencies for various types of filters.

Various types of internal doses for STCs can then be calculated from the product of equations 5-10 or 5-11 and the various DCFs provided in this handbook. For example, the DCFs in Table 5-14 table can be used to determine the CEDE from inhalation of ITPs of various sizes and composition using the observed activity on an air filter. In addition, Appendix A contains DCFs for STPs of density 11.7 gm/cm^3 (H_f) for absorption types S, M, and F and AMADs of 1 and 5 µm.

To calculate internal doses (using air sampling results) from inhalation of ITP species having particle sizes, densities, and compositions that differ from those cases addressed in this handbook, it will be necessary to obtain appropriate values for the self absorption factors for beta and energy, as they are not provided in tables 5-9 and 5-10. The observed air sample activity would then have to be

converted to actual activity by dividing it by the appropriate SAF_{β} or by otherwise determining the total activity in the STPs in the sample. Then use either equation 5-10 or 5-11, to calculate the intake in terms of actual activity.

Next, using a computer code such as LuDEP, the CEDE can be calculated. The component of the CEDE resulting from exposure to the lung would have to be corrected for energy absorption using the appropriate SAF_e in a manner analogous to that in equation 5-9.

NOTE: If the base material and particle size are not known, parameters and associated SAFs for the most conservative material (i.e., HfH_2), 1 μm AMAD particle size ($\mathbf{s}_g$ = 2.5), and Absorption Type S should be used for dose computations. (See Table 5-7 for default assumptions.) [Absorption Type S is believed to be sufficiently conservative: the DCF_o for 1 μm AMAD polydisperse HfH_2 is 4.29 x 10^{-10} Sv/Bq_o (assuming Type S) and 4.85 H 10^{-10} Sv/Bq_o (assuming dissolution rates determined by Cheng, 1999a). This represents only a 13% increase of Type "Super-S" over Type S.] Deviations from these parameters should only be allowed in situations where material and particle size are well known.

As noted above, the variability of CEDE DCF_o with material or particle size is not great (range is factor of 5). Therefore, using a conservative assumption of material and particle size distribution (1 μm AMAD) is accurate within that factor for any material or particle size distribution; this assumption can be readily implemented when air monitoring is the method of intake assessment. A factor of dose overestimation (~ 10 - 100) is further applied when all captured tritiated particulates are assumed to be Type S and are measured by LSC.

5.2.4.2 ACV's for ITPs

Air concentration values (ACV) can now also be computed; these are concentrations of tritiated particulate aerosols which, when inhaled, impart prescribed doses over a given time (i.e. 0.05 Sv in 200hrs).

Derived Air Concentrations (DACs) in 10 CFR Part 835 are derived from EPA Federal Guidance Report No. 11. Neither EPA Report No. 11 nor 10 CFR Part 835 specifically addresses DACs for ITPs. DOE Radiological Control Technical Position 99-02 addresses development of ACVs for ITPs, which may be used in lieu of regulatory DAC values until such values are developed and codified. ACVs are concentrations of tritiated particulate aerosols which, when inhaled, impart prescribed doses over a given time.

RCTP 01-02 provides an equation for calculating an ACV (Eq. 5-12) using dose conversion factors (DCFs):

$$ACV\left(\frac{Bq}{m^3}\right) = \frac{0.05 \quad (Sv)}{DCF \quad \left(\frac{Sv}{Bq}\right)} \cdot \frac{1}{2{,}400 \quad \left(m^3\right)} \qquad \text{(Eq. 5-12)}$$

If the DCF_o is used in place of DCF in Eq. 5-12, then this formula can be used to

calculate ACV_o. Accordingly, the most conservative ACV_o for ITPs (based on the CEDE DCF_o determined in Section 5.2.4.1 for ITPs [4.3×10^{-10} Sv/Bq_o]) is 4.8×10^4 Bq_o/m^3 (1.2 $\mu Ci_o/m^3$, 1.3×10^{-6} $\mu Ci_o/cm^3$).

5.2.5 Biokinetic Model for Soluble OBT

For soluble forms of OBT, particularly solvents and the small molecule component of OBT oil, the assumption can be made that all activity deposited is instantaneously absorbed into the body (ICRP 78, 1997). Soluble OBT is, therefore, amenable to available urine bioassay. However, the biokinetic model for soluble OBT is different from that for HTO. Table 5-15 shows the difference in fractional uptake and biological halftime for soluble OBTs and HTO (ICRP 78, 1997).

Table 5-15. Fractional Uptake and Biological Halftime for Soluble OBT and HTO (ICRP 78, 1997)

	Fractional uptake with 10 day biological $T_{1/2}$	Fractional uptake with 40 day biological $T_{1/2}$
HTO	97%	3%
OBT	50%	50%

5.2.5.1 Intake and Dose Assessment for Soluble OBT

Soluble OBT solvents or oil components do not cause self-absorption of tritium beta activity as do solid STCs. A DCF and ACV can therefore be expressed in terms of actual activity. The CEDE DCF that should be used for a soluble OBT intake is 4.1×10^{-11} Sv/Bq (152 rem/Ci) (ICRP 78), unless a more appropriate DCF is derived and documented for the type of soluble OBT encountered in the workplace.

To calculate the ACV for vapors of soluble OBT, there are two pathways that must be considered (which are similar to HTO pathways), inhalation and skin absorption. If there is no evidence that a soluble OBT is absorbed through the skin, then uptake via skin absorption is zero and the ACV can be calculated using Eq 5-12. Using the DCF for OBTs from ICRP 78 of 4.1×10^{-11} Sv/Bq, an ACV of 5.0×10^5 Bq/m^3 is calculated.

If there is evidence that an OBT is absorbed via the skin the following approach should be used to calculate the ACV. ICRP 30 states that for exposure to airborne HTO, two-thirds (2/3) of the intake is from inhalation and one-third (1/3) is from skin absorption. Therefore, the total intake of airborne HTO is 1.5 times the inhaled intake. To determine an ACV, the ICRP 30 assumptions for uptake of airborne HTO are assumed here to be valid for soluble OBT, i.e., 2/3 of the intake is due to inhalation and 1/3 is due to skin absorption. Therefore, equation 5-12 should be divided by a factor of 1.5 to account for the OBT taken into the body from skin absorption. Accordingly, dividing the result of the calculation from the previous paragraph by 1.5, the calculated ACV for soluble OBT, that accounts for skin absorption, is 3.3×10^5 Bq/m^3 (9.1 $\mu Ci/m^3$ or 9.1×10^{-6} $\mu Ci/cm^3$).

Soluble forms of OBTs are considered to be instantaneously absorbed into the body, therefore, urinalysis can be used to assess soluble OBT intakes. This approach is adequate to demonstrate compliance with the dose limits established in subpart C of 10 CFR 835. To determine the soluble OBT intake, the individual's average urine excretion volume (if not available, the ICRP 23 Reference Man value of 1.4 liter per day should be used) and the ICRP 78 expected excretion rate per unit intake of soluble OBT should be used.

Internal soluble OBT doses should be assessed by either:

1. Using the CEDE DCF listed above for soluble OBT (LuDEP may also be used to calculate individual organ CDE DCFs); or

2. Using LuDEP to convert the intake amount to final CEDE (LuDEP may also be used to calculate individual organ CDEs).

NOTE: LuDEP can accommodate injection and ingestion intakes of soluble materials, as well as inhalations of particulates, and can be used to document the soluble OBT dose calculations. Using the ICRP 78 biokinetic model for soluble OBT above, LuDEP calculates 4.2×10^{-11} Sievert CEDE per Bequerel intake by injection or ingestion, which is the same as the ICRP 78 CEDE DCF for soluble OBT intake by ingestion. This value is slightly larger than the DCF for soluble OBT (based on inhalation) quoted at the beginning of this section (4.1×10^{-11} Sv/Bq). Therefore, using LuDEP for soluble OBT intakes provides a slight overestimate of the CEDE, compared to that which would be obtained by simply using the DCF listed above.

6 - WORKPLACE CONTROLS

In establishing workplace controls for STCs, the extent of workplace controls should be commensurate with the hazard presented by the specific STC for which protection is required. For certain STCs such as certain types of organically bound tritium, existing technology permits institution of a radiological control system that is commensurate with current systems used to protect workers from exposure to the oxide and gaseous forms of tritium. Alternatively, establishing a level of workplace control commensurate with the hazard presented by other types of STCs (such as ITPs) poses a significant challenge because of difficulties in identifying and characterizing these types of STCs. As a result of such limitations in individual and workplace monitoring, the system of workplace controls should be conservative in order to demonstrate that workers are adequately protected.

6.1 Design/Engineering Controls

Current regulations and standard practices for occupational radiation protection require a primary reliance on design and engineering controls for protection, unless such controls are impractical or ineffective. The distinction between design/engineering controls and administrative controls is not always definitive. For example, an item of protective clothing that blocks the incident radiation is functioning as a form of shielding, but is most commonly considered an administrative control. Likewise, a temporary HEPA-filtered ventilation system may require adherence to administrative procedures to ensure its proper installation and operation, but is most commonly considered an engineering control. In this handbook, the term “design/engineering controls” includes such controls as shielding systems, confinement systems, and ventilation systems. Those controls that require direct intervention and proper operation by individual users, such as respiratory protection, protective clothing, and access controls, are considered to be administrative controls.

Because the physical behavior of ITPs mimics that of similar particulates, there are no design/engineering controls that are unique to ITP contamination in the workplace. Design/engineering controls for ITPs should be evaluated and applied in the same manner as for other particulate contaminants, with particular attention to such factors as likelihood of contamination spread, particle sizes, contamination levels, likely individual doses, planned and potential activities and events, and planned future uses for the affected area. Consistent with the as low as reasonably achievable (ALARA) process, consideration should be given to efforts that may be necessary to recover from the use of engineering control systems for STC contamination protection, such as special decontamination, storage and handling needs, purchase of new equipment, and special waste handling needs.

6.2 Administrative Controls

Following development and implementation of appropriate design features, including engineering controls, administrative controls are typically developed and applied to ensure that the design features are properly installed, maintained, and operated. In addition, administrative controls provide an additional level of safety above and beyond that provided by the design features alone, consistent with the ALARA process.

6.2.1 Administrative Systems

An adequate structure of administrative systems is necessary to ensure that projects are completed safely, satisfactorily, and in compliance with applicable requirements. The actual components of the administrative systems, and the content of those systems, is dependent on a number of factors, including the nature of the work to be performed, education, skills and training of the individuals performing the work, and the magnitude of any associated hazards. Management oversight is required to achieve the appropriate balance between the various components of the administrative systems. For example, certain high-hazard work may require extensive pre-job planning and rigid adherence to detailed written procedures and radiological work permits (RWPs). For lower hazard work, or more routine and repetitive work, it may be appropriate to place more reliance on employee training and experience. The appropriateness of the balance achieved should be routinely assured through a rigid system of management oversight that closely examines the work processes, and detects potential problems before they adversely affect safety and achievement of the facility's mission.

10 CFR 835.501 requires written authorizations to enter into and perform work in radiological areas. While there is a great deal of flexibility provided for establishing the exact nature of and details provided in these authorizations, they generally fall into one or more of the classifications discussed below.

Policies and Procedures

Facility requirements for safe work with STCs should be clearly delineated in written policies and procedures. These requirements may be established in either generally applicable procedures, or in procedures that are established and limited in scope to address STC affected areas and topics only. For example, requirements for controlling access to STC-contaminated areas may be specified in procedures that apply only to the specified areas, or the requirements may be established as a sub-section of a generally applicable procedure that addresses control of access to a wide variety of hazardous areas. Likewise, there need not be a separate ALARA policy addressing only exposure to STCs if the existing ALARA policy adequately addresses all radiation exposures, including STC exposure.

In addition to any procedures that may be implemented to ensure compliance with 10 CFR 835.501, 10 CFR 835.104 requires that written procedures be developed and implemented as necessary to ensure compliance with the applicable regulatory requirements of that rule. The procedures should be written in sufficient detail to ensure that the user is able to complete the relevant task properly, and in compliance with applicable requirements. The style of writing should be appropriate to the assigned procedure user.

Facilities should have written procedures to address the following issues associated with STCs, in addition to the procedural controls required for the remainder of the radiological control program:

- Methods for identifying and quantifying STC levels in the workplace;
- Methods for controlling the spread of airborne and surface STC contamination, including design features and engineering controls;
- Methods for controlling and handling materials (e.g., protective clothing, respirators, tools, etc.) that are exposed to STC contamination;
- Methods for tracking those areas of the facility affected by STC contamination;
- Methods for controlling individual exposure to STCs;
- Radiological and activity based criteria for which STC controls are required;
- Criteria for selecting individuals for participation in the STC-internal dose monitoring program;
- Methods for performing STC monitoring;
- Individual STC dose assessment techniques;
- Criteria for selecting individuals to participate in enhanced training required for STC control; and
- Requirements for assessing STC-control program effectiveness, identifying program shortcomings, and implementing programmatic changes as necessary to ensure continuing improvement.

Written procedures form only one component of an adequate administrative system. Active management involvement is required to determine the proper balance between the components of the administrative system. For example, details regarding techniques used to perform repetitive actions may be more appropriately addressed through radiation safety training. Certain job-specific actions may be more appropriately addressed in radiological work permits rather than written procedures.

Technical Work Documents

While generally applicable written procedures are frequently used to establish standardized methods where consistency of techniques or results (e.g., regulatory compliance) is important, technical work documents (TWDs) are often used to address measures associated with specific tasks. Included within the scope of technical work documents are certain specific procedures, work packages, and research plans.

TWDs should be developed and implemented for any task that requires more detailed written guidance than that provided in the generally applicable procedures.

Chapter 3 of the Radiological Control Standard (RCS) provides guidance for implementing a system of TWDs.

Radiological Work Permits

Radiological Work Permits (RWPs) are used to establish specific radiological control requirements for work in areas that exceed, or have the potential to exceed specified radiological hazard levels. This would usually include tasks that require specific worker actions due to the likelihood of severe radiological consequences, such as surface contamination levels or airborne radioactivity levels exceeding 100 times the applicable Appendix A or Appendix D levels, respectively. The RWP should address those issues discussed in the RCS, with emphasis on conditions and controls that are related to the presence of STCs. Chapter 3 of the RCS provides guidance for developing and implementing RWPs.

Administrative System Integration

The components of the administrative system are usually linked. For example, the administrative system may address the requirements for repairing a component located in a contamination area as follows:

- A written procedure establishes standard requirements for entering a contamination area;

- Another written procedure establishes criteria (radiological conditions, work activities, etc.) that require specific tasks to be performed in accordance with an RWP/TWD;

- The TWD establishes specific requirements (e.g., valve operation sequences, torque settings, sequence of operations, etc.) for performing the task; and

- The RWP provides more detailed radiological control requirements for repairing the component within the specified contamination area.

Pre- and Post-Job Briefings

For higher hazard work, many facilities include requirements for pre- and post-job briefings in the RWP. The pre-job briefing provides an opportunity to discuss the details of the job, its hazards, and required controls with affected workers. The post-job briefing provides an opportunity to review the completed work, identify both strengths and weaknesses associated with its planning and performance, and institutionalize these lessons for future reference. Briefings may also be conducted during job performance to analyze the current status and address emergent issues.

The thresholds and processes associated with briefings for STC work need not differ from those for other jobs. However, special attention should be paid to STC identification and control issues. Mechanisms should be in place to capture any lessons learned, not only for similar work, but for both similar and dissimilar work involving STC hazards. Specific guidance is provided in Chapter 3 of the RCS.

6.2.2 Administrative Control Levels

Facilities typically use a system of administrative control levels to limit individual doses and to direct management attention toward those individuals, work groups, and/or activities that result in the most significant doses. Management establishes the value(s) of the administrative control level(s) on a yearly basis, such that line management and workers are challenged to control, and find innovative ways to reduce, their individual and workgroup doses. Greater levels of control are achieved by establishing administrative control levels on a work group-specific basis, reflecting management attention to specific workgroup activities and hazards. As individual doses approach the established administrative control level, successively higher levels of management approval are required to raise the level, thereby bringing greater management attention to ALARA issues in the workplace. Administrative control levels should be set at a level that is challenging, but achievable in view of the planned activities and the radiological conditions in the workplace. However, if it is never necessary to consider authorizing an individual to exceed the previously established administrative control level (thus requiring active management attention), then the level probably has been set too high. On the other hand, if the administrative control level is set at an unnecessarily stringent level, costly delays in planned activities may result, reflecting inattention to the cost/benefit aspect of ALARA planning.

The presence of STCs in the workplace does not profoundly affect the administrative control level program. In setting or extending administrative control levels, consideration should be given to the levels of surface and airborne STC contamination, the individual doses likely to result from that contamination, uncertainties in relating workplace conditions to actual doses, and any delays in determination of individual doses following exposure to STCs. The administrative control level should be set in a manner that challenges individuals and organizations to seek innovative means of reducing their doses, while avoiding unnecessary interference with scheduled activities.

Chapter 2 of the RCS provides specific guidance for implementing a system of administrative control levels.

6.2.3 Decontamination

When it is necessary to perform work in an STC-contaminated area or on STC-contaminated equipment, consideration should be given to performing a thorough decontamination of the area/equipment prior to performing the required work. This assessment should be conducted in a manner consistent with the ALARA process. A thorough decontamination effort may eliminate any significant STC contamination levels, thus eliminating the need for STC controls for the remainder of the evolution. This may in turn reduce collateral impacts, such as the need to launder STC-contaminated protective clothing, maintain STC-contaminated respirators and ventilation systems, and determine STC doses for all individuals involved in the work. These benefits should be balanced against the costs of performing the decontamination (including the collateral impacts discussed above), the likelihood of success, the likelihood and possible impact of spreading STC contamination during the decontamination operation. With either approach, consideration should

be given to the costs and difficulties associated with handling any resulting waste products.

6.2.4 Personal Protective Equipment

Because STCs can exist in particulate form, the personal protective equipment (PPE) used for ITP control is not unique – that equipment used for control of other radioactive particulates in the workplace should be sufficient for ITP control also. Different from respiratory protection for exposure to HT and HTO, air purifying respirators may be used for ITP work. Consideration should be given to the need for special cleaning and handling needs for STC-contaminated PPE to reduce the probability of spreading STC contamination to previously unaffected areas or to minimizing the handling and cleaning of STC contaminated PPE. These needs may be met by establishing separate facilities for STC-contaminated PPE, by using disposable anti-contamination clothing, or by ensuring the handling areas are free of STC contamination before handling non-STC-contaminated PPE. In most cases, the cost of establishing special facilities for handling STC-contaminated PPE will be prohibitive. If offsite facilities are used for cleaning/processing of PPE (e.g., contracted laundry facilities for contaminated protective clothing), the contractor should be made aware of the possibility of STC contamination so that he may implement an effective STC control program at his facility.

6.2.5 Area Posting

10 CFR Part 835 requires that certain areas be posted to alert individuals to the presence of specific conditions, including specified levels of:

- penetrating external radiation;
- removable surface contamination; and
- airborne radioactivity.

These requirements are augmented by requirements for posting areas where radioactive items or containers of radioactive material are used, handled, or stored, and requirements for posting areas to which access is controlled for radiation protection purposes.

Because tritium, including STCs, is not typically considered an external radiation hazard, posting for penetrating external radiation hazards is not expected to be an issue for areas where STCs are used, handled or stored.

The need for posting to alert individuals to the presence of removable contamination, airborne radioactivity, and radioactive items or containers of radioactive materials, consisting in whole or part of STCs, depends on the results of efforts to identify the presence, and quantify levels of, STCs in specified areas. General guidance for establishing area postings for radiological hazards is provided in DOE G 441.1-10 (DOE 1999d)*, Posting and Labeling for Radiological Control Guide*. This guidance is applicable to posting for the presence of STCs; however, the STC surface or airborne contamination level should be evaluated consistent with the guidance provided in Sections 3.1 and 3.2 of this handbook. Section 3.2.1.2 provides guidance pertinent to areas or objects where tritium is bound tightly

to surfaces and/or to the matrix below such surfaces. This guidance is applicable to efforts to evaluate the total (fixed plus removable) STC activity levels, which are used as a basis for radioactive material area posting.

Circumstances may arise in which it is desirable to establish a controlled area due solely to the presence of STCs. 10 CFR Part 835 requires that controlled areas be established whenever radiological or radioactive material areas are present, but does not establish specific criteria that define the controlled area boundaries. Controlled area postings should be established to enclose any area where it is likely that personnel activities in the area will result in the spread of:

- STC removable surface contamination beyond the current area boundaries at levels exceeding one tenth of the levels specified in Appendix D of 10 CFR 835; or

- STC airborne radioactivity beyond the current area boundaries at levels exceeding one tenth of the airborne concentration value specified in Sections 5.2.4.2 and 5.2.5.1 of this handbook.

The controlled area boundaries should be established so that all of the affected area is encompassed, and area monitoring should be performed on a periodic basis to verify the adequacy of the boundaries. The area boundaries should be altered as necessary, based on the results of the area monitoring.

It is often desirable to restrict access to STC-contaminated areas, to specified individuals or workgroups so as to limit the scope of the STC dose assessment program. If this has been done, posting for STC-contaminated areas should provide additional information that will allow individuals to identify the area as one affected by STCs, and to take appropriate action to avoid or facilitate entry, as appropriate.

6.2.6 Access Control

NOTE: The access control measures discussed in this section are in addition to the radiation safety training measures discussed in Section 6.2.9 of this handbook.

Access control measures may be necessary to control individual access to areas where STC surface contamination or airborne radioactivity is present. 10 CFR Part 835 requires entry control measures for all radiological areas. The established controls should be appropriate for the radiological conditions in the area and the planned activities, some of which may cause changes in the radiological conditions or in the conditions (e.g., relative position, exposure time, contaminant resuspension) under which individuals are exposed. DOE has provided guidance in the RCS.

For low levels of STC contamination (e.g., surface contamination levels less than the 10 CFR 835 Appendix D values; airborne radioactivity levels resulting in an intake less than 12 ACV-hours in a week [0.3 times the ACV values]), only rudimentary entry control measures are necessary. These measures may include basic engineering and administrative controls.

NOTE: Although repeated exposure to STCs in unposted areas with airborne radioactive materials could lead to a dose of up to 1500 mrem (CEDE) in a year, DOE requirements in 10 CFR Part 835 specify initiation of individual and workplace monitoring when annual exposures are expected to exceed 40 ACV-hours (100 mrem). In addition, 10 CFR Part 835 requires the institution of the ALARA process when establishing workplace controls for radiation exposure during routine operations. Thus, it is unlikely planned exposures exceeding 100 mrem would occur without knowledge of either the site or the facility's radiological protection organization.

If the STC contamination levels are elevated (e.g., surface contamination levels exceed the 10 CFR 835 Appendix D values, but are less than 10 times those values; exposures to airborne radioactivity could exceed 12 ACV-hours, but are less than 120 ACV-hours, per week), more aggressive measures should be implemented. Such measures may include both design features and administrative controls, such as filtered ventilation systems, physical barriers to both individual access and contamination spread, area decontamination, individual sign-in (written or electronic), written procedures and/or radiological work permits, as appropriate, designated access routes, etc. These controls should be considered in addition to those discussed above for lower levels of contamination. Note that these levels correspond to those levels defining a radiological area as provided in 10 CFR 835.2(a); therefore, specific actions are required to ensure compliance.

If STC contamination levels are very high (e.g., surface contamination levels exceed ten times the 10 CFR 835 Appendix D values; airborne radioactivity levels exceed ten times the ACV values), then the most aggressive contamination control measures should be considered and implemented, consistent with the ALARA process.

See section 3.2.1.2 for guidance relating to areas containing locations where tritium is bound tightly to the surface and/or to the matrix below the surface.

6.2.7 Radioactive Material Labeling

Labeling of radioactive items and containers of radioactive material is required under some circumstances to alert individuals to the radiological hazards associated with those items or containers. DOE has provided appropriate guidance for implementing these requirements in G 441.1-10, *Posting and Labeling for Radiological Control Guide*, and in the RCS.

The thresholds under which radioactive material labeling is required are provided in 10 CFR 835.605, which requires labeling when the total quantity of radioactive material exceeds one tenth of the 10 CFR 835 Appendix E values. Appendix E does not currently provide a specific value for STCs, but does provide a value for tritium. This value is applicable to radioactive items and containers of radioactive material containing STCs.

It is often desirable to restrict access to STC-contaminated materials to specified individuals or workgroups so as to limit the scope of the STC dose assessment program. If this has been done, labels for STC-contaminated materials should provide additional information that will allow individuals to identify the material as

affected by STCs, and to take appropriate action to avoid exposure or facilitate proper handling.

10 CFR 835.606 establishes several conditions under which labeling of radioactive items and containers of radioactive material is not required. When using these exceptions, caution should be exercised to ensure that individuals working in the vicinity of radioactive items and containers of radioactive material are provided appropriate information in the absence of radioactive material labels. For example, inclusion of appropriate information on area postings or in employee training or pre-job briefings may prove to be an effective substitute for radioactive material labeling under the specified conditions.

Note that the 10 CFR Part 835 radioactive material labeling requirements are applicable only to "items and containers." Piles and areas of granular solids, such as soil and sand, are generally not considered to be "items" or "containers"; therefore, labeling of such piles and areas may not be required or practical. However, consideration should be given to the need for posting such piles or areas as contaminated areas consistent with 10 CFR 835.603. See DOE G 441.1-10 for further guidance on application of the 10 CFR Part 835 posting requirements to areas of soil and similar materials.

Another situation for which labeling may not be required by 10 CFR Part 835, but for which labeling would be useful, is for materials that have been exposed to tritium long enough for the tritum to bind tightly in the matrix of the material. Labels could be used to warn individuals that operations performed on these materials that generate particles could create an airborne radiological hazard.

6.2.8 Contaminated Material Control

Appropriate controls on the storage, use, and movement of materials contaminated with STCs are necessary to limit the spread of STC contamination to other materials, areas, and individuals. Such a spread would result in a need to expand the scope of the STC monitoring program beyond its initial boundaries. This is undesirable due to both the possible individual and environmental exposures that may occur, and the relative expense and complexity of the STC monitoring and control program.

Subpart L of 10 CFR 835 establishes DOE's regulatory requirements for control of contaminated material and equipment. In general, the regulations require that material and equipment that is located in a contamination, high contamination, or airborne radioactivity area be monitored for the presence of surface contamination prior to release to the controlled area. The regulations also establish provisions allowing for release of contaminated materials under certain controlled conditions.

Material and equipment that is located in areas where STC contamination is known to exist should be monitored consistent with the requirements of 10 CFR 835 Subpart L prior to release to the controlled area. The monitoring should be performed consistent with Sections 3.1 and 3.2 of this handbook and should be capable of identifying STC contamination at or below the 10 CFR 835 Appendix D values.

If STC contamination is discovered on material and equipment that is to be moved, or that is located in an area that is to be released from contaminated area status, efforts should be made to both contain the contamination, and to warn individuals of its presence. All contaminated items should be securely packaged or wrapped in such a manner that the STC contamination will not be inadvertently disturbed by individual activities, environmental forces (such as air or liquid flow), or work activities (such as the application of mechanical force or heat). Packages and wrapping materials should be appropriate for the surface to be contained and the expected environment. Programs should be established to periodically inspect packages and wrapping materials to ensure they do not degrade in long-term storage or use. If degradation is noted, surface contamination monitoring should be performed to detect and determine the magnitude of the release of STC contamination. The package or wrapping material should be repaired or replaced, as appropriate.

Material and equipment that are contaminated with STCs should be clearly labeled to indicate the type and extent of the contamination, and thereby facilitate tracking of the items and ensure implementation of appropriate controls and monitoring during activities involving the contaminated items. If practical, a log of STC-contaminated material and equipment should be maintained. Such a document may prove useful when planning work activities and associated monitoring and control activities. STC-contaminated material and equipment that is no longer in use should be decontaminated and released or disposed of as soon as practicable. This will reduce the likelihood of spreading STC contamination during storage periods, and as a result, any unplanned or unauthorized access to the material.

If practicable, separate spaces and facilities should be dedicated to storage, use, and decontamination of STC-contaminated material and equipment. Likewise, consideration should be given to laundering STC-contaminated protective clothing and other launderable items separately. These measures will reduce the likelihood of spreading STC contamination to previously unaffected areas, systems, and items, necessitating expansion of the STC monitoring and control program, and will facilitate control over these items. Should it be necessary to use, handle, or store STC-contaminated items in common areas, then it will be necessary to expand the STC contamination monitoring program to encompass affected surfaces and systems, such as ventilation and drain systems and surrounding areas. Similarly, areas, items, and systems that are dedicated to STC-contamination purposes, such as decontamination areas and laundry equipment, should be routinely monitored for residual STC contamination.

See section 3.2.1.2 for guidance relating to areas containing materials or equipment where tritium is bound tightly to the surface and/or to the matrix below the surface.

6.2.9 Training

General Employee and Radiological Worker Training

Because of the specialized control and monitoring requirements that are necessary for STCs, enhanced training should be provided to individuals entering affected areas, or working in the vicinity of affected items to ensure they are equipped to recognize and respond to STC hazards.

Subpart J of 10 CFR 835 establishes regulatory requirements for radiation safety training for DOE activities. DOE G 441.1-9, *Radiation Safety Training Guide*, provides guidance for achieving compliance with these requirements. The training requirements are generally divided into two levels, depending on the types of hazards encountered. General Employee Radiological Training is provided to individuals who enter only the controlled area and receive minimal exposure to radiation. Radiological Worker Training is provided to individuals who enter radiological areas or perform radiological work that is likely to result in doses exceeding 0.1 rem in a year. These requirements are augmented by 10 CFR 835.103, which requires that all individuals who are responsible for developing and implementing measures necessary for ensuring compliance with the requirements of 10 CFR Part 835 have the appropriate education, training, and skills to discharge their responsibilities.

For those activities affected by radiological hazards arising from STCs, General Employee Radiological Training and Radiological Worker Training should include material on the following topics, to the extent appropriate for the target audience:

- The physical and radiological characteristics of STCs;
- Radiological hazards associated with exposure to STCs;
- Measures used to monitor (areas and individuals) for STC contamination;
- Limits and action levels associated with STCs;
- Radiological controls implemented to control the spread of STC contamination;
- Special considerations for work planning and execution;
- Special warning signs and labels used in areas affected by STCs, and appropriate responses to those signs and labels;
- Any special records or reports associated with STCs that may be generated and retrieved; and
- Appropriate responses to emergency situations involving STCs.

Although members of the public entering the controlled area are subject to the radiation safety training requirements of 10 CFR 835.901, these requirements may be met, in part, through provision of an escort or area entry controls to ensure the individual's safety and compliance with the documented RPP. If members of the public are granted unescorted access to the controlled area, then radiation safety training is required. DOE does not expect members of the public to receive any significant exposure to STCs; therefore, the required training should be augmented by provisions to identify, and a warning to avoid entering, the affected areas.

Training of Radiological Control Staff

Individuals in the radiological control organization will require specialized training to allow them to develop and coordinate implementation of effective programs for STC control. Training should be provided to affected radiological control organization managers, supervisors, engineers, administrators, and technicians. The training should address the same subjects as those specified above, but in more detail as is appropriate to the individuals' responsibilities.

Training of Facility Managers, Supervisors and Work Planners

Managers and supervisors should complete the same or higher level of radiation safety training as the individuals who report to them. Managers and supervisors should receive additional training that will prepare them to address employee concerns about radiological hazards, including occupational exposure to STCs. Managers, supervisors, and work planners should also receive training that will prepare them to complete any measures that are necessary to execute their responsibilities for coordinating, planning, and completing work in areas affected by STCs.

6.2.10 Work Processes

DOE's requirements for safety management are established in the DOE P 450.4 series of directives and guides focusing on Integrated Safety Management (ISM). The ISM system addresses the following seven guiding principles:

1. Line management responsibility for safety
2. Clearly defined roles and responsibilities
3. Personnel competence commensurate with responsibilities
4. Balance of priorities
5. Identification of safety standards and requirements
6. Hazard controls tailored to the work being performed
7. Operations authorization

For any particular facility, most of these guiding principles are unaffected by the presence of STCs; that is, the implementation of the guiding principles spans a wide range of issues and is not hazard- or isotope-specific. The STC protection and control program should not be separated from other radiological and industrial safety programs; it should be fully integrated with related safety programs so that the hazards associated with STCs are considered in a manner consistent with those arising from other sources of workplace hazards. However, the provisions of this handbook should be considered in developing safety programs for STCs. For example, Guiding Principle #1 will require consideration of the training guidance provided above. Likewise, Guiding Principles # 6 and #7 will require consideration

of the results of the workplace monitoring program to provide an accurate assessment of the relative hazards arising from the presence of STCs in the workplace.

Finally, it is important that implementation of work processes be carried out in a manner that involves all categories of individuals. These categories should include workers, supervisors and managers as well as individuals from the various safety disciplines who will participate in operations involving exposure to STCs.

7 – REFERENCES

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APPENDIX A – VALUES OF SIGNIFICANT PHYSICAL, CHEMICAL, AND RADIOLOGICAL PROPERTIES OF HT, HTO, AND STCS

Physical/Chemical Properties

Atomic weight[1] of a tritium atom	3.01605 g/mole
Diameter of a tritium atom (approximate) [1]	1.1 Angstroms
Dissociation energy[1], T_2 to 2T	4.59 eV
Ionization energy[1], T to T+ e-	13.55 eV
Gram molecular weight of tritium[1] (T_2)	6.0321 g
Density of tritium gas (T_2) at STP[1]	0.269122 g/l
Boiling point of tritium (T_2) at 1 atmosphere[1]	25.0° K

Physical/Radiological Properties

Half Life[1]	12.323 ± 0.004 years
Biological Half Life	Approximately 10 days
Tritium decay factor[1]	0.99984601/day
Maximum beta energy of decay (E_{max}) [1]	18.6 keV
Mean beta energy of decay (E_{mean}) [1]	5.69 keV
Volume of 1 Ci of tritium at STP[1]	0.386 ml
Specific Activity of tritium gas (T_2) [1]	9619 Ci/g
Activity per mole, T_2 gas[1]	58023 Ci/mole
Activity per volume of T_2 at STP[1]	2589 Ci/l
Activity per volume at 1 ATM pressure and 25°C[1]	2372 Ci/l
Activity per volume of tritiated water[1] (T_2O)	3200 Ci/cm^3
Range of Tritium Beta Particles (18.6 Kev):	
Independent of density	0.59 mg/cm2
In Air[1]	0.45 cm
In Water[1]	0.0006 cm
In Tissue[1]	0.0007 cm

Dosimetric Properties

Thumb-rules for Dose Conversion

Dose from a single intake of HTO per activity taken up by the body[1]	6×10^{-2} mrem CEDE/µCi
Dose from a single intake of HTO per activity in urine[1]	3 mrem CEDE/ µCi/l in urine
Effective dose rate from inhalation of HT	4.3×10^{-6} (rem/hr)/(µCi/ m^3)

Derived Air Concentration (DAC) Values

DAC for HTO[2] (Includes a 50% allowance for skin absorption)	2×10^{-5} µCi/ml 8×10^{5} Bq/m^3
DAC for HT[2]	5×10^{-1} µCi/ml 2×10^{10} Bq/m^3

Air Concentration Values (ACV)

ACVo for ITPs (If host material not known) AMAD = 1 µm	4.8×10^{4} Bq_o/m^3 1.2 x μCi_o/ml
ACVo for ITPs (If host material not known) AMAD = 5 µm	8.0×10^{4} Bq_o/m^3 2.0 x μCi_o/ml
ACV for soluble OBTs (Divide by 1.5 if skin absorption expected but magnitude not known)	5.0×10^{5} Bq/m^3 1.4×10^{-5} µCi/ml

Dose Conversion Factors (DCFs) for Inhalation of HTO and STCs

HTO (Does not include an allowance for skin absorption. Multiply estimated intake by 1.5 to account for skin absorption when calculating derived exposure controls) [2]	1.8×10^{-11} Sv/Bq 6.7×10^{-2} mrem/ µCi
ITPs AMAD = 1 µm	
ITP Type F Density = 11.7 gm/cm^3	1.3×10^{-11} Sv/Bq_o 4.8×10^{-2} mrem/ μCi_o
ITP Type M Density = 11.7 gm/cm^3	7.6×10^{-11} Sv/Bq_o 2.8×10^{-1} mrem/ μCi_o
ITP Type S Density = 11.7 gm/cm^3 (use this DCF_o if host material not known)	4.3×10^{-10} Sv/Bq_o 6.7×10^{-2} mrem/ μCi_o
DCF_o (Ti, Zr, Hf, rust, Organic [oil droplets]) Type S	See Table 5-14
ITPs AMAD = 5 µm	
ITP Type F Density = 11.7 gm/cm^3	5.5×10^{-11} Sv/Bq_o 2.0×10^{-1} mrem/ μCi_o
ITP Type M Density = 11.7 gm/cm^3	8.6×10^{-11} Sv/Bq_o 3.1×10^{-1} mrem/ μCi_o
ITP Type S Density = 11.7 gm/cm^3 (use this DCF_o if host material not known)	2.6×10^{-10} Sv/Bq_o 9.6×10^{-1} mrem/ μCi_o
DCF_o (Ti, Zr, Hf, rust, Organic [oil droplets]) Type S	See Table 5-14
Soluble OBT Compounds (Adjustment for skin absorption, if applicable, should be accounted for when calculating ACVs [see section 5.2.5.1])	
OBT[3]	4.1×10^{-11} Sv/Bq 1.5×10^{-1} mrem/ µCi
Tritiated Methane[4] ($CH_{4-x}T_x$)	1.8×10^{-13} Sv/Bq 6.7×10^{-2} mrem/ µCi

1 DOE 1999e
2 ICRP 1979
3 ICRP 1995
4 ICRP 1998b

APPENDIX B – INSOLUBLE METAL TRITIDE BENCHMARK

This is a benchmark calculation of dose and excretion following an intake of a type M Insoluble Metal Tritide (IMT) using the ICRP 66 respiratory tract model and ICRP 78 systemic model. The calculations were implemented in MathCad 2000[11] and Excel 97[12]. (Note that when performing internal dose estimated for the purpose of demonstrating compliance with 10 CFR Part 835, the tissues weighting factors specified in 10 CFR Part 835 must be used.) A basic knowledge of Mathcad syntax will facilitate the study of this benchmark, but anyone having experience with a higher level language (e.g., FORTRAN) should be able to follow the calculations.

First, load in definitions and subroutines from the file FUNCTIONS.MCD. The content of this file is given in the end of this appendix.

The physical decay constant for tritium in units of 1/day is given by

$$\lambda = \frac{\ln(2)}{(12.3 \cdot 365)}$$

The deposition of the SMT aerosol in the compartments of the respiratory tract is a function of the AMAD of the aerosol and is calculated with the subroutine “Depo” (which is defined in the next appendix). For occupational exposure, an AMAD of 5 :m is assumed.

$$AMAD = 5$$

$$D = \text{Depo}(AMAD)$$

The initial content q0 of the compartments are defined below. The initial content of any compartment not explicitly defined has a value of zero because the initial content of the last compartment (i.e., urine) is defined as zero[13]. The intake of the SMT I_{SMT} is defined as unity and the intake of HTO I_{HTO} as zero. Intakes of HTO are modeled as direct instantaneous depositions into the blood compartment.

$$I_{smt} \equiv 1$$

$$I_{hto} \equiv 0$$

$$i = AI1 .. ET1$$

$$q0_i = I_{smt} \cdot D_i$$

$$q0_{urine} = 0$$

$$q0_{blood} = I_{hto}$$

[11] Mathsoft, Inc. 101 Main Street, Cambridge MA.
[12] Microsoft
[13] This is a characteristic of Mathcad.

The lung dissolution rate constants and f_1 are defined below. All rate constants are in units of 1/days. Defaults are for type M SMT are: f_r=0.1, s_r=100, s_S=0.005, f_1=0.1. For type S: f_r=0.001, s_r=100, s_S=0.0001, f_1=0.01.

$$f_r = 0.1$$
$$s_r = 100$$
$$s_s = 0.005$$

$$s_p = s_s + f_r \cdot (s_r - s_s)$$
$$s_{pt} = (1 - f_r) \cdot (s_r - s_s)$$
$$s_t = s_s$$
$$f_1 = 1 \cdot 10^{-1}$$

Setting the total removal rate constant for urine to zero defines a zero matrix that has dimensions of urine x urine (39 x 39 for this model). The individual transfer rate constants for the respiratory tract are then defined per ICRP 66.

$$k_{urine,urine} = 0$$

$k_{AI1,bb1} = 0.02$
$k_{bb2,BB1} = 0.03$
$k_{ETseq,LNet} = 0.001$
$k_{AI1,blood} = s_p$
$k_{bb2,blood} = s_p$
$k_{ETseq,blood} = s_p$
$k_{AI1,TAI1} = s_{pt}$
$k_{bb2,Tbb2} = s_{pt}$
$k_{ETseq,TETseq} = s_{pt}$
$k_{AI2,bb1} = 0.001$
$k_{BB1,ET2} = 10$
$k_{BBseq,LNth} = 0.01$
$k_{AI2,blood} = s_p$

$k_{BB1,blood} = s_p$
$k_{BBseq,blood} = s_p$
$k_{AI2,TAI2} = s_{pt}$
$k_{BB1,TBB1} = s_{pt}$
$k_{BBseq,TBBseq} = s_{pt}$
$k_{AI3,bb1} = 0.0001$
$k_{BB2,ET2} = 0.03$
$k_{bbseq,LNth} = 0.01$
$k_{AI3,LNth} = 0.00002$
$k_{BB2,blood} = s_p$
$k_{bbseq,blood} = s_p$
$k_{AI3,blood} = s_p$
$k_{BB2,TBB2} = s_{pt}$

$k_{bbseq,Tbbseq} = s_{pt}$
$k_{AI3,TAI3} = s_{pt}$
$k_{ET2,S} = 100$
$k_{LNth,TLNth} = s_{pt}$
$k_{bb1,BB1} = 2$
$k_{ET2,blood} = s_p$
$k_{LNet,blood} = s_p$
$k_{bb1,blood} = s_p$
$k_{ET2,TET2} = s_{pt}$
$k_{LNet,TLNet} = s_{pt}$
$k_{bb1,Tbb1} = s_{pt}$
$k_{ET1,ENV} = 1$
$k_{LNth,blood} = s_p$

The transfer rate constants for the transformed respiratory tract compartments are defined:

$k_{TAI1,Tbb1} = k_{AI1,bb1}$
$k_{TBB2,TET2} = k_{BB2,ET2}$
$k_{TAI1,blood} = s_t$
$k_{TBB2,blood} = s_t$

$k_{TAI2,Tbb1} = k_{AI2,bb1}$
$k_{TET2,S} = k_{ET2,S}$
$k_{TAI2,blood} = s_t$
$k_{TET2,blood} = s_t$

$k_{TAI3,Tbb1} = k_{AI3,bb1}$
$k_{TETseq,TLNet} = k_{ETseq,LNet}$
$k_{TAI3,TLNth} = k_{AI3,LNth}$
$k_{TETseq,blood} = s_t$

$k_{TAI3,\,blood} = s_t$

$k_{TBBseq,\,TLNth} = k_{BBseq,\,LNth}$

$k_{Tbb1,\,TBB1} = k_{bb1,\,BB1}$

$k_{TBBseq,\,blood} = s_t$

$k_{Tbb1,\,blood} = s_t$

$k_{Tbbseq,\,TLNth} = k_{bbseq,\,LNth}$

$k_{Tbb2,\,TBB1} = k_{bb2,\,BB1}$

$k_{Tbbseq,\,blood} = s_t$

$k_{Tbb2,\,blood} = s_t$

$k_{TLNet,\,blood} = s_t$

$k_{TBB1,\,TET2} = k_{BB1,\,ET2}$

$k_{TLNth,\,blood} = s_t$

$k_{TBB1,\,blood} = s_t$

The transfer rate constants for the systemic compartments, urine, feces, and other excreta are defined:

$$k_{hto,\,bladder} = \frac{1.4}{3}\cdot\frac{\ln(2)}{10}$$

$$k_{hto,\,ULI} = \frac{0.1}{3}\cdot\frac{\ln(2)}{10}$$

$$k_{obt,\,bladder} = \frac{\ln(2)}{40}$$

$$k_{blood,\,obt} = 0.03\cdot\frac{\ln(2)}{0.25}$$

$$k_{blood,\,hto} = 0.97\cdot\frac{\ln(2)}{0.25}$$

$$k_{hto,\,excreta} = \frac{1.5}{3}\cdot\frac{\ln(2)}{10}$$

$$k_{bladder,\,urine} = 12$$

Finally, the transfer rate constants for the GI tract are defined:

$$k_{S,\,SI} = 24$$

$$k_{SI,\,ULI} = 6$$

$$k_{SI,\,blood} = \frac{k_{SI,\,ULI}\cdot f_1}{1 - f_1}$$

$$k_{ULI,\,LLI} = \frac{24}{13}$$

$$k_{LLI,\,feces} = 1$$

APPENDIX C – MATHCAD DEFINITIONS AND SUBROUTINES

As an alternative to calculating each total removal rate constant individually, one may use the function *total*, which sums the rate constants in each row and assigns the sum to the diagonal element of the rate matrix. The function is defined in the next appendix.

$$k = \text{total}(k, \lambda)$$

The eigenvalues and coefficients for each compartment are calculated. Note that the content of each compartment at time t is defined in the function q(t,comp) by a sum of 39 exponential terms.

$$e = \text{eigenvals}\left(k^{T}\right)$$

$$C = \text{coeff}(k, q0)$$

$$q(t, comp) = \sum_{i=1}^{\text{cols}(k)} C_{comp,i} \cdot \exp\left[\left(e_i\right) \cdot t\right]$$

The content of all compartments at time t=0 calculated with the function q_{all} should equal the sum of what was deposited in the body.

$$q_{all}(t) = \sum_{j=1}^{\text{cols}(k)} q(t, j)$$

In other words, if everything goes OK, what goes into the system

$$\sum_{i=AI1}^{urine} q0_i = 0.81957$$

should equal the material that is in the system at t=0 days for a radioactive material(or any other time for insoluble material).

$$q_{all}(0) = 0.81957$$

The function Decays is used to calculate the number of decays that occur in each compartment of the biokinetic model.

$$\begin{aligned}
&\text{Decays}(x) = \\
&\quad s \leftarrow 0 \\
&\quad \text{for } j \in AI1 .. urine \\
&\qquad s \leftarrow s - \frac{C_{x,j}}{e_j} \cdot \left(\exp\left(e_j \cdot 0\right) - \exp\left(e_j \cdot 50 \cdot 365\right)\right) \quad \text{if } \left|C_{x,j}\right| > 0 \\
&\quad \text{Decays} \leftarrow s \cdot 24 \cdot 3600
\end{aligned}$$

Note that a dosimetric source organ may consist of more than one biokinetic compartment. For example, the number of decays on the surfaces of ET2 is the sum of the decays in the ET2 and TET2 biokinetic compartments.

$U_{sET1sur}$ = Decays(ET1)

$U_{sET2sur}$ = Decays(ET2) + Decays(TET2)

$U_{sET2seq}$ = Decays(ETseq) + Decays(TETseq)

U_{sBBsol} = Decays(BB2) + Decays(TBB2)

U_{sBBgel} = Decays(BB1) + Decays(TBB1)

U_{sBBseq} = Decays(BBseq) + Decays(TBBseq)

U_{sbbsol} = Decays(bb2) + Decays(Tbb2)

U_{sbbgel} = Decays(bb1) + Decays(Tbb1)

U_{sbbseq} = Decays(bbseq) + Decays(Tbbseq)

a = Decays(TAI2) + (Decays(AI3) + Decays(TAI3))

b = Decays(AI1) + Decays(TAI1) + Decays(AI2)

U_{sAI} = a + b

U_{sLNet} = Decays(LNet) + Decays(TLNet)

U_{sLNth} = Decays(LNth) + Decays(TLNth)

U_{sS} = Decays(S)

U_{sSI} = Decays(SI)

U_{sULI} = Decays(ULI)

U_{sLLI} = Decays(LLI)

$U_{sUBcont}$ = Decays(bladder)

$U_{sTissue}$ = Decays(obt) + Decays(hto) + Decays(blood)

In summary, the decays in the source organs are given in array U:

U =

	1
1	29241.9
2	362.4
3	2522.4
4	489.5
5	311.3
6	13098
7	637.9
8	952.5
9	9697.9
10	396.2
11	531041
12	2311.1
13	355.5
14	1510
15	5436
16	17820.4
17	32894.2
18	142132

The dose to each target organ is the sum of the decays in each organ and the appropriate SEE:

$$\text{target} = \text{tAdrenals} \,..\, \text{tUterus}$$

$$H_{\text{target}} = \sum_{\text{source}=\text{sET1sur}}^{\text{sTissue}} U_{\text{source}} \cdot SEE_{\text{target},\,\text{source}}$$

The array H is loaded into an Excel 97 spreadsheet to complete the dose calculation. The organ doses are combined as shown in the spreadsheet to give ICRP 60 50-year committed effective dose in units of Sv/Bq.

ICRP 60 Committed Effective Dose in Sv							
	Ht	A	A x Ht	Wt	Mass (g)	Ht x Mass	Ht x Wt
Adrenals	1.88E-12				14	2.63E-11	
UB_Wall	1.88E-12			0.050			9.40E-14
Bone_Sur	1.88E-12			0.010			1.88E-14
Brain	1.88E-12				1400	2.63E-09	
Breasts	1.88E-12			0.050			9.40E-14
St_Wall	4.63E-12			0.120			5.56E-13
SI_Wall	8.07E-12				640	5.16E-09	
ULI_Wall	3.88E-11	0.570	2.21E-11				
LLI_Wall	1.13E-10	0.430	4.85E-11				
Kidneys	1.88E-12				310	5.83E-10	
Liver	1.88E-12			0.050			9.40E-14
ET1-bas	1.88E-12	0.001	1.88E-15				
ET2-bas	1.91E-12	0.998	1.90E-12				
LN-ET	3.16E-11	0.001	3.16E-14				
BBi-bas	1.88E-12	0.167	3.13E-13				
BBi-sec	1.88E-12	0.167	3.13E-13				
bbe-sec	1.98E-12	0.333	6.58E-13				
AI	4.42E-10	0.333	1.47E-10				
LN-Th	7.20E-11	0.001	7.20E-14				
Muscle	1.88E-12				28000	5.27E-08	
Ovaries	1.88E-12						
Pancreas	1.88E-12				100	1.88E-10	
R_Marrow	1.88E-12			0.120			2.26E-13
Skin	1.88E-12			0.010			1.88E-14
Spleen	1.88E-12				180	3.38E-10	
Testes	1.88E-12			0.200			3.76E-13
Thymus	1.88E-12				20	3.76E-11	
Thyroid	1.88E-12			0.050			9.40E-14
Uterus	1.88E-12				80	1.50E-10	
Composite Organs							
lungs	1.49E-10			0.120			1.78E-11
ET	1.94E-12				15	2.91E-11	
colon	7.06E-11			0.120			8.47E-12
oesophagus	1.88E-12			0.050			9.40E-14
remainder	2.01E-12			0.050			1.00E-13
				1.000	30759	6.18E-08	
effective							**2.81E-11**

The 24-hour incremental urinary and fecal excretion functions are defined as shown below. Note that the increment excreted in urine and feces is calculated with “insoluble” tritium. The incremental excretion is then adjusted for radioactive decay. Because we are starting with radioactive tritium, the incremental excretion is adjusted to insoluble tritium first.

$$\Delta e_u(t) = \exp(-\lambda \cdot t) \cdot \left[q(t, \text{urine}) \cdot \exp(\lambda \cdot t) - q(t-1, \text{urine}) \cdot \exp\left[\lambda \cdot (t-1)\right] \right]$$

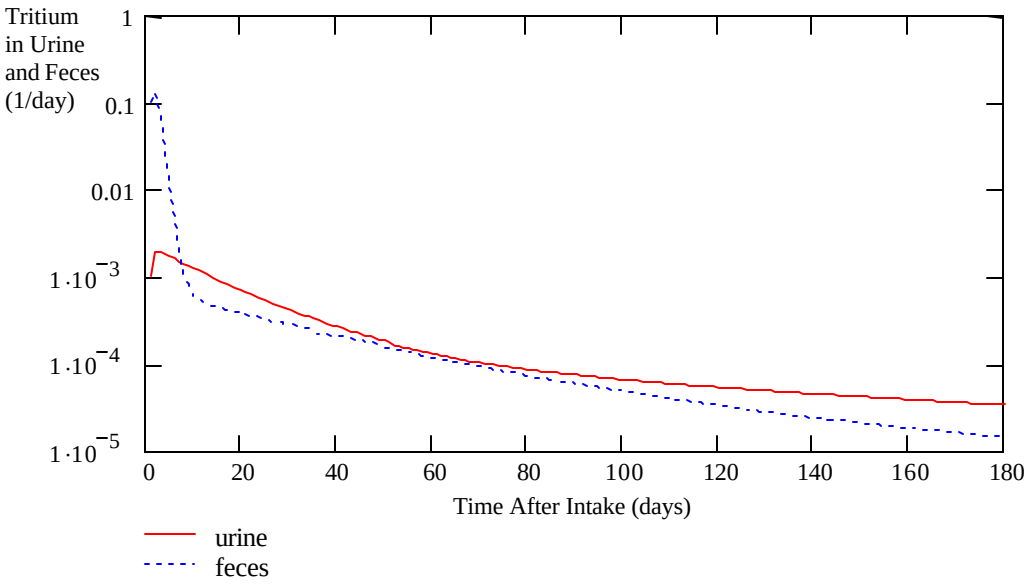
$$\Delta e_f(t) = \exp(-\lambda \cdot t) \cdot \left[q(t, \text{feces}) \cdot \exp(\lambda \cdot t) - q(t-1, \text{feces}) \cdot \exp\left[\lambda \cdot (t-1)\right] \right]$$

The following plot shows the 24-hour urinary and fecal excretion for days 1 through 180 after an acute inhalation intake of 5 µm AMAD type M IMT.

$t = 1 .. 180$

$e_{u_t} = \Delta e_u(t)$

$e_{f_t} = \Delta e_f(t)$



In Mathcad, the first element is designated as being in the zeroth row and zeroth column, i.e., having the (0,0) coordinate. When defining a matrix for biokinetic models it is useful for the matrix to begin with the (1,1) coordinate. This is accomplished by setting the built-in variable ORIGIN to 1.

$$ORIGIN \equiv 1$$

The compartments in the biokinetic model are assigned names to clarify their use in the definition of the rate matrix. For example, rather than define the transfer rate constant $k_{1,4}$, we define it as $k_{AI1,bb1}$. The respiratory tract compartments are:

AI1 = 1	bb2 = 5	BBseq = 9	LNet = 13
AI2 = 2	bbseq = 6	ET2 = 10	LNth = 14
AI3 = 3	BB1 = 7	ETseq = 11	ENV = 15
bb1 = 4	BB2 = 8	ET1 = 12	

The transformed respiratory tract compartments are:

TAI1 = 16	Tbb2 = 20	TBBseq = 24	TLNet = 28
TAI2 = 17	Tbbseq = 21	TLNth = 25	
TAI3 = 18	TBB1 = 22	TET2 = 26	
Tbb1 = 19	TBB2 = 23	TETseq = 27	

Finally, the GI tract, systemic compartments, and excreta compartments are:

S = 29	LLI = 32	bladder = 35	hto = 38
SI = 30	feces = 33	excreta = 36	urine = 39
ULI = 31	blood = 34	obt = 37	

The sources (beginning with "s") in the dosimetric model are assigned names to clarify their use in the definition of the SEE and dose matrices:

sET1sur = 1	sBBsol = 6	sAI = 11	sULI = 16
sET2sur = 2	sBBseq = 7	sLNth = 12	sLLI = 17
sET2seq = 3	sbbgel = 8	sUBcont = 13	sTissue = 18
sLNet = 4	sbbsol = 9	sS = 14	
sBBgel = 5	sbbseq = 10	sSI = 15	

Likewise, the targets (beginning with "t") in the dosimetric model are assigned numbers to clarify their use in the definition of the SEE and dose matrices:

tAdrenals = 1
tUB = 2
tBS = 3
tBrain = 4
tBreasts = 5
tS = 6
tSI = 7
tULI = 8
tLLI = 9
tKidneys = 10
tLiver = 11
tET1bas = 12
tET2bas = 13
tLNet = 14
tBBbas = 15
tBBsec = 16
tbbsec = 17
tAI = 18
tLNth = 19
tMuscle = 20
tOvaries = 21
tPancreas = 22
tRM = 23
tSkin = 24
tSpleen = 25
tTestes = 26
tThymus = 27
tThyroid = 28
tUterus = 29

Once the transfer rate constants are defined, the total removal rate constants may be calculated by summing across the rows of the rate matrix:

$$\text{total}(k,\lambda) = \left|\begin{array}{l} K \leftarrow k \\ \text{for } comp \in 1..\text{cols}(k) \\ \quad \left|\begin{array}{l} K_{comp,comp} \leftarrow 0 \\ \text{for } j \in 1..\text{cols}(k) \\ \quad K_{comp,comp} \leftarrow K_{comp,comp} + k_{comp,j} \text{ if } comp \neq j \\ K_{comp,comp} \leftarrow -\left(K_{comp,comp} + \lambda\right) \end{array}\right. \\ K \end{array}\right.$$

The coefficients and rate constants for the retention functions are calculated by the eigensystem method. This approach to solving systems of ODEs is described by G. G. Killough and K. F.

Eckerman in "A Conversational Eigenanalysis Program for Solving Differential Equations," in Computer Applications in Health Physics, Proceedings of the Seventeenth Midyear Topical Symposium of the Health Physics Society, 1984 (Killough 1984). Excellent examples may be found in "The Linear Algebra Problem Solver" by the Research and Education Association, 1980, gives excellent examples and discussion of the method (see problems 18-6 through 18-11). Given the initial content of each compartment at t=0 and the rate matrix, the following function calculates the coefficients for the retention functions:

$$\text{coeff}(k, q0) = \left| \begin{array}{l} q0 \leftarrow \text{submatrix}(q0, 1, \text{rows}(k), 1, 1) \\ V \leftarrow \text{eigenvecs}\left(k^{T}\right) \\ M \leftarrow \text{lsolve}(V, q0) \\ \text{for } j \in 1..\text{cols}(k) \\ \quad \text{for } i \in 1..\text{cols}(k) \\ \quad\quad C_{i,j} \leftarrow V_{i,j} \cdot M_{j} \\ C \end{array} \right.$$

Deposition fractions for aerosol AMADs in the range of 0.001 to 10 microns are calculated by interpolating from the respiratory tract deposition table given in the ICRP CD-ROM[14]. The ICRP 66 respiratory tract model for occupational exposure (light work) was used to calculate the values given in this table.

D =

	0.001	0.003	0.01	0.03	0.1	0.3
AI1	1.359E-04	6.714E-03	8.229E-02	1.525E-01	8.688E-02	4.458E-02
AI2	2.718E-04	1.343E-02	1.646E-01	3.051E-01	1.738E-01	8.916E-02
AI3	4.530E-05	2.238E-03	2.743E-02	5.085E-02	2.896E-02	1.486E-02
bbf	2.262E-02	8.770E-02	1.291E-01	7.188E-02	3.328E-02	1.523E-02
bbs	2.294E-02	8.895E-02	1.309E-01	7.290E-02	3.376E-02	1.544E-02
bbseq	3.212E-04	1.245E-03	1.833E-03	1.021E-03	4.726E-04	2.162E-04
BBf	3.117E-02	4.420E-02	2.685E-02	1.035E-02	4.746E-03	3.260E-03
BBs	3.161E-02	4.483E-02	2.723E-02	1.049E-02	4.813E-03	3.293E-03
BBseq	4.425E-04	6.276E-04	3.812E-04	1.469E-04	6.738E-05	4.619E-05
ET2	4.390E-01	3.494E-01	1.735E-01	6.994E-02	3.218E-02	5.820E-02
ETseq	2.196E-04	1.748E-04	8.680E-05	3.499E-05	1.610E-05	2.912E-05
ET1	4.433E-01	3.327E-01	1.539E-01	6.248E-02	3.071E-02	5.217E-02

The following function performs a linear interpolation of the values in the table to calculate the deposition fractions in each compartment of the respiratory tract.

[14] The ICRP Database of Dose Coefficients for Workers and Members of the General Public, Version 1.0 (Pergamon Press: New York) 1998 (ICRP 1998a).

$$\text{Depo}(\text{AMAD}) = \left| \begin{array}{l} d \leftarrow \text{submatrix}(D, 1, 13, 2, 11) \\ \text{for } i \in 2..13 \\ \quad \text{Depo}_{i-1} \leftarrow \text{linterp}\left[\left(d^T\right)^{\langle 1 \rangle}, \left(d^T\right)^{\langle i \rangle}, \text{AMAD}\right] \\ \text{Depo} \end{array} \right.$$

All SEEs are from SEECAL[15] except for the SEE for the bladder wall <--- bladder contents, which is set to zero in accordance with ICRP 67[16]. The SEE have the units of SV/decay. The SEE for the body tissues as source and all body tissues and organs as targets is defined by

$$\text{target} = \text{tAdrenals} .. \text{tUterus}$$

$$\text{SEE}_{\text{target}, \text{sTissue}} = 1.323 \cdot 10^{-17}$$

Specific target-source combinations for the respiratory and GI tract are:

$$\text{SEE}_{\text{tET2bas}, \text{sET2seq}} = 1.088 \cdot 10^{-17}$$

$$\text{SEE}_{\text{tLNet}, \text{sLNet}} = 6.069 \cdot 10^{-14}$$

$$\text{SEE}_{\text{tbbsec}, \text{sbbsol}} = 9.853 \cdot 10^{-18}$$

$$\text{SEE}_{\text{tAI}, \text{sAI}} = 8.276 \cdot 10^{-16}$$

$$\text{SEE}_{\text{tAI}, \text{sLNth}} = 4.138 \cdot 10^{-16}$$

$$\text{SEE}_{\text{tLNth}, \text{sLNth}} = 3.035 \cdot 10^{-14}$$

$$\text{SEE}_{\text{tS}, \text{sS}} = 1.821 \cdot 10^{-15}$$

$$\text{SEE}_{\text{tSI}, \text{sSI}} = 1.138 \cdot 10^{-15}$$

$$\text{SEE}_{\text{tULI}, \text{sULI}} = 2.069 \cdot 10^{-15}$$

$$\text{SEE}_{\text{tLLI}, \text{sLLI}} = 3.372 \cdot 10^{-15}$$

[15] M. Cristy and K. F. Eckerman, "SEECAL: Program to Calculate Age-Dependent Specific Effective Energies," ORNL/TM-12351 (Cristy 1993).

[16] "Urinary excretion will not result in a significant additional dose to the bladder wall which is assumed to receive the same dose as other tissues," Table C-1.1, ICRP 67 (ICRP 1994b).

APPENDIX D - PARAMETERS FOR DISSOLUTION OF INSOLUBLE TRITIATED PARTICULATE MATERIALS

(From Mound Technical Basis Document for Stable Tritiated and Particulate and Organically Bound Tritium (Mound 2000))

The following table compiles literature data for dissolution of tritium into physiological fluid from various forms of tritium-containing particulate materials. Parameters are given for retention of tritium in the source material as described by (typically) the double exponential:

$S(t) = F_r \exp(-R_r t) + F_S \exp(-R_S t)$ (eq. D-1)

Where: S(t) = the tritium fraction retained in source material at time t
F_r = the fraction of rapidly dissolving material ("fast component")
F_S = the fraction of slowly dissolving material ("slow component")
R_r = the dissolution rate of rapidly dissolving material
R_S = the dissolution rate of slowly dissolving material

Particle size characteristics and literature references are also provided.

Source Material	F_r	R_r, d^{-1}	F_s	R_s, d^{-1}	Size Parameters (μm)	Reference
TiT_x	0.55	4.6	0.35 (a)	0.093 (a)	CMD=0.95 s_g=1.93 AMD=3.5 AMAD=5.7	Cheng (1999a)
TiT_x	0.24	0.71	0.76	0.021	Same as above	Cheng (1997)
TiT_x	-	-	1.0	0.0019	CMD=103 s_g=1.58 AMD=193 AMAD=312	Cheng (1997)
ZrT_x	0.48	0.0165	0.52	0.0018	CMD=0.32 s_g=2.24 AMD=2.25 AMAD=4.78	Cheng(1999b) Kropf (1998)
HfT_x (b)	0.0006	0.0095	0.9994	2.3E-6	CMD=1.04 s_g=2.41 AMD=10.6 AMAD=30	Cheng (1999c)
HfT_x (b)	0.00015 (c)	0.02 (c)	0.9997	1E-7	Same as above	Cheng (1999c)
HfT_x	0.008	0.2	0.992	~5E-6	"respirable"	Ref 4 in McConville (1995)
Glass	0.23	0.079	0.16	0.0032	CMD=3.8 s_g=2.8 AMD~20 AMAD~19	Cool (1983) [Sample KMS2] (d)
Glass	0.27	0.23	0.027	0.03	Same as above	Cool (1983) [Sample KMS1] (e)
Luminous Paint	0.12	~10	0.88	0.019	----	Rudran (1988)

(a) An additional slow component (F~0.1 and R<0.01) is apparent from Fig 2 in reference.
(b) Represent each of two separate data sets within this study.
(c) An additional fast component of F=0.00015 and R=100 occurred for this HfT_X sample.
(d) Parameters are recalculated from Fig 1 of reference. An additional slow component of F=0.61 and unspecified R^2 is apparent. Particle sizes are from Cool (1984).
(e) Parameters are recalculated from Table 2 of reference, assuming 30% dissolution at day 100. An additional slow component of F=0.70 and unspecified R^2 is apparent. Particle sizes are from Cool (1984).

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CONCLUDING MATERIAL

Review Activities:

DOE	Ops Offices	Field Offices
DP	AL	RFSO
EH	CH	OH
EM	ID	GFO
ER	NV	
FM	OR	
LM	RL	
NE	SR	
NS		
PR		
SA		

Area Offices	National Laboratories
Amarillo	BNL
Ashtabula	LANL
Carlsbad	LLNL
Columbus	PNNL
Fernald	Sandia
Kansas City	FNL
Kirtland	
Los Alamos	
Miamisburg	
Pinellas	
West Valley	

Preparing Activity:

DOE EH-52 Joel Rabovsky

Project Number:

OCSH-0002