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Internal Dosimetry and Monitoring for Special Tritium Compounds (STCs)

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Disclaimer

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C.8 Dosimetry and Monitoring for Special Tritium Compounds (STCs)

Note: Much (but not all) of this section follows the discussion in Appendix E of DOE Handbook 1129-2008, "Tritium Handling and Safe Storage" (DOE 2008). The technical basis for that discussion is found in DOE Handbook 1184-2004 (DOE 2006), "Radiological Control Programs for Special Tritium Compounds", which in turn is based on the "Mound Technical Basis Document for Stable Tritiated Particulate and Organically Bound Tritium" (Mound 2001).

C.8.1 Introduction

Tritium that is adsorbed or contained within particulates (e.g., TiT_2, or tritium gas in glass micro-spheres) presents unique dosimetry problems. Such materials may be referred to as "insoluble" tritium compounds or "special tritium compounds (STCs)." The physical and chemical characteristics of such material will affect not only the uptake, distribution, and retention of the tritium, but will also affect the amount of energy deposited in tissue from each transformation. In addition, other complexities (e.g., production of bremsstrahlung radiation) may have to be considered.

In the last ten or so years, a great deal of effort has gone into understanding the issues affecting bioassay monitoring and internal dosimetry of insoluble tritides. Although this understanding is still evolving, the major technical issues are as follows:

1. In contrast to tritiated water (HTO), which is assumed to be rapidly and uniformly distributed within the body, STCs are assumed to follow the deposition, retention, and absorption of the "carrier" matrix upon intake. Once the carrier material is absorbed into the bloodstream, the tritium is assumed to follow the biokinetic model for HTO.
2. In the case of HTO and OBT, all of the tritium beta particle energy is assumed to be available to contribute to dose. In contrast, in the case of STCs, a significant portion of the beta energy may be absorbed within the carrier matrix particle, and therefore would not contribute to dose. This "self-absorption" must be considered when calculating the doses to the respiratory tract (and also to the GI tract) from intakes of STCs.

The possible dose pathways from inhalation of tritiated particulates are:

- direct irradiation of the surrounding tissue,
- irradiation of the surrounding tissue by bremsstrahlung from the particle,
- uptake of tritium oxide (HTO) contamination from the surface of the particle, and
- absorption of tritium from the particle into the bloodstream.

These issues are discussed in depth in the above-mentioned DOE Handbook (DOE-HDBK-1184-2004). Additional pertinent information may be found in ICRP Publication 88, "Doses to the Embryo and Fetus from Intakes of Radionuclides to the Mother" See "Biokinetic Model for Tritium – A Clarification" on pages 517 – 518, (ICRP 2001).

A more recent review of these issues is found in a review by Charles Potter (Potter 2004).

C.8.2 LLNL Facility Specific Information

Past and current operations at LLNL have used special tritium compounds (STCs). These include the following, organized by facility:

- Rotating Target Neutron Source Target Facilities (RTNS-II)

  Multi-thousand curie titanium-tritide targets were used at the now deactivated Rotating Target Neutron Source Facility (Building B292). Tritium targets have been removed from this facility, however there is known tritium contamination in the target area and it is anticipated that some fraction of this contamination is STCs. Therefore, STCs must be considered during facility maintenance activities and D&D operations.

- Building 331 (The "Tritium Facility"),

  Gram quantities of tritium gas (generally T_2) have been and may be handled in the Tritium Facility, Building 331. Large quantities of tritium have been and may be present in the facility as hydrides on uranium or palladium storage beds, and as HTO in molecular sieve traps. In some of the older containment structures (hoods, glove boxes) tritium was present as a metal tritide (e.g., titanium-tritide) or in other solid compounds. Preparation and handling of TiT_2 targets, tritium recovery and grinder operations are known to have STCs. According to the B331 monitoring plan for grinder operations, ZnO STCs are anticipated.

- Radioactive and Hazardous Waste Management (RHWM) buildings and facilities

  Tritium waste handling from other facilities at LLNL.

- NOVA Facilities

  In the past, several facilities associated with the NOVA laser project handled multi-curie quantities of tritium in small glass micro-spheres. With decontamination and demolition of the NOVA target bay, the source of STC's in this facility no longer exists.

- NIF Facilities

  Tritium target preparation and handling in Building 298, includes palladium storage beds which each contain a maximum of 400 curies. Associated hardware may have HTO contamination of typically less than one curie. Some of this tritium may exchange with organic materials producing small quantities of tritiated organics or metal tritides. Glass capsule targets ("exploding pushers"), which come prefilled with up to approximately 75mCi of Tritium are handled in B298. Also, previously filled targets containing residual amounts of tritium may be worked on in B298.
  The DT generator in B-381 once used titanium tritide targets, containing less than one curie each. While the DT generator itself has been deactivated the internals of the unit remain contaminated. Titanium Tritide targets still remain in the laboratory. The DT generator and associated laboratory space is slated for decommissioning.

  NIF ignition targets are shot in B581 and contain different mixtures of hydrogen isotopes (DT, THD- tritium hydrogen deuterium) depending on the shot. Amounts vary from a few millicuries to tens of curies per shot. After each shot, most of the tritium is recovered to the tritium processing system, although a small residual amount will remain on interior surfaces of the target chamber and other exposed hardware. Most of this tritium is expected to be in the form of HTO. Some may be elemental tritium and a small fraction may be in the form of tritiated organics or metal tritides.

- Other Facilities

  In the past, titanium-tritide compounds have been used in a number of applications, including targets for neutron generators. Compromised targets or other titanium-tritide compounds, can lead to particulate tritides. Low to relatively high levels of tritium still remain in retired experimental facilities and areas pending decontamination and demolition (e.g., B212). For past operations and facilities with legacy tritium contamination, STCs must be considered during facility maintenance activities and D&D operations.

  Several million telephone dials containing tritium were sent to LLNL for H3 recovery. Some dials were intentionally crushed using the B331 grinder (see B331 discussion above), until this effort was abandoned in 2011. H3 bearing phone dials were staged in other buildings across the site (RHWM, B251, etc.) but not involved in any recovery activities, and hence intact phone dials should not pose internal STC exposure concerns.

C.8.3 Biokinetic Models for STC Dosimetry

C.8.3.1 Reference Models

The current foundations for dosimetry of STC compounds are:

- the ICRP-66 Respiratory Tract Model (ICRP 1994a),
- the ICRP-30 Gastro-Intestinal Tract Model,
- the current (ICRP-88) biokinetic model for tritiated water (HTO) (but see also important discussion and clarification in Potter 2004),
- the technical discussion presented in the Mound Technical Basis Document (Mound 2001), and
- the NCRP-156 Wound Model.

The Respiratory Tract and GI Tract models are discussed in Section 3 of the LLNL Technical Basis Manual (Mansfield 2009b). A discussion of the current biokinetic model for HTO is repeated below for the reader's convenience.

C.8.3.2 Dosimetry Modeling for Inhalation Intakes of STCs

The key assumptions used for dosimetry modeling of inhalation intakes of STCs are as follows:

1. The ICRP-66 respiratory tract model is used to calculate the deposition, retention, and absorption of inhaled Type F, Type M, and Type S tritiated particulates,

2. The tritiated particulate is assumed to behave like the substrate (e.g., titanium, in the case of titanium-tritide) until it is absorbed from the respiratory tract and/or the GI tract into the bloodstream,

3. Unless specifically stated otherwise, f1 values for absorption from the GI Tract to the bloodstream are based on the substrate element, and taken from Table B.1. of ICRP-68,

4. Upon absorption into the bloodstream (from either the lungs or GI Tract), the tritium is assumed to follow the biokinetic model of HTO,

5. The beta particle emissions from tritium activity within STC particles in the respiratory tract or GI Tract regions are assumed to be attenuated. The amount of attenuation is described by an energy "Self Absorption Factor" or SAF_e value – that represents the fraction of beta energy *emitted* from the particle. Currently, LLNL is using the methodology used by the Mound Technical Basis Document (Mound 2001) to calculate these SAF_e values.

   (Note that these SAF_e values are different from the "beta particle Self Absorption Factors" SAF_β which are used to convert "observed" LSC activity to "actual" LSC activity (see discussion below in Section C.8.7).)

6. These SAF_e values are used to modify the SEECAL-generated specific effective energy (SEE) values for selected source organs. Specifically, the SAF_e values are applied to any transformations which take place before the tritium activity is absorbed into the bloodstream – that is, transformations which take place in the respiratory tract compartments and GI tract compartments,

7. As stated in ICRP-88: "For dosimetric purposes, however, the [HTO] activity is taken to be distributed throughout the whole body (excluding the lumen of the GI tract) . . ."

8. Per ICRP-68 and the clarification in ICRP-88, the source organ for absorbed HTO is "body tissue", which includes the blood (transfer compartment) and both of the "total body" compartments, but *specifically excludes the contents of the GI tract*, thus, all the HTO transformations which take place in the transfer compartment, total body compartment A, and total body compartment B are summed to represent the number of HTO transformations which take place in "body tissue",

9. The SEECAL-generated HTO SEE value for the "body tissues" source organ to all target organs is 1.323×10^{-17} sieverts per nuclear transformation,

10. Per the ICRP 88 "Errata and Clarifications": "For all tritium compounds, the urinary bladder has not been considered in the biokinetic model." Accordingly, the bladder is not included in the calculations for either excretion pathways or organ doses.

These assumptions and methods are consistent with those in the recent literature (DOE 2004, Mound 2001, ICRP 2001, Potter 2004). LLNL uses custom Mathcad® worksheets to appropriately model intakes of tritiated particulates and to calculate doses from those intakes - making appropriate modifications to selected specific effective energy values.

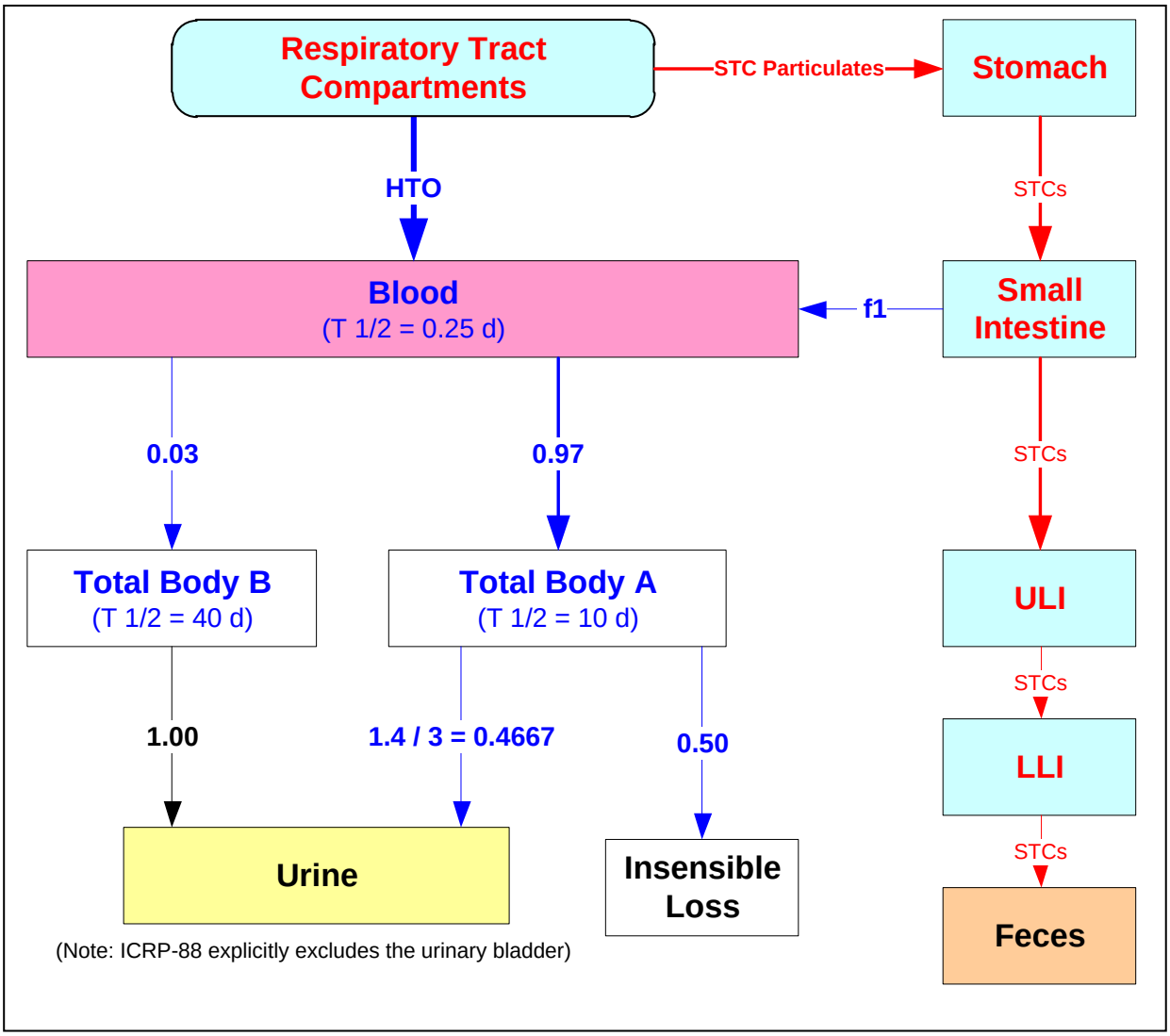
The model for distribution and retention of STCs (and the resulting HTO following absorption to the blood) in the body is presented schematically in Figure C.8.1 below. In this Figure, the pathways for distribution of STC particulates, and the compartments in which STC transformations take place are indicated in red. HTO SEE values for source regions in the respiratory tract and GI tract compartments are weighted with the SAF_e values discussed in Section C.8.3.5 below.

Pathways for distribution of HTO are indicated in blue. Transformations which occur in the "Blood", "OBT" (also called "Total Body B"), and "HTO" (also called "Total Body A") source organs are considered to be distributed throughout the body tissue. Accordingly, the SEE for (All targets ← Body_Tissue) of 1.323×10^{-17} Sv/nt is applied to these transformations (i.e., no energy attenuation correction has been made for these transformations).

Note that the HTO transformations which theoretically take place in the upper large intestine and lower large intestine are ignored – per the ICRP-88 exclusion mentioned in item #7 above.

Figure C.8.1

Biokinetic Model for STC Dosimetry (Inhalation)



C.8.3.3 Inhalation Absorption Types and "f1" Values

The primary route of intake of STCs at LLNL is expected to be inhalation. Although ingestion is possible, it is considered a minor and unlikely route due to workplace controls (e.g., no food or drink in the work areas and washing hands after working in a contaminated area). Absorption of tritium from STCs through the skin is not expected to be a significant route of intake at LLNL because workers will be in protective clothing when entering areas with the most potential for particulate skin contamination. Subsequent discussions will focus on inhalation of STCs.

As discussed in Section 3 of the LLNL Technical Basis Manual, the deposition and retention of inhaled particulates is dictated by the particle size distribution of the inhaled material, and the "absorption type" of the inhaled material. The ICRP recommendations for the deposition and absorption of inhaled tritium compounds are summarized Table C.8.1 (from Tables 5.1.1a and 5.1.1b in ICRP-71, (ICRP 1995).)

Table C.8.1

Summary of ICRP Classification and Absorption Types

Chemical Form	ICRP Vapor Class	Percent Deposited	Absorption Type	Default f1 Value	Biokinetic Model
Tritiated Water (HTO):	SR-2	100	V	n.a.	HTO
Organic Compounds:	SR-2	100	V	n.a.	OBT
Tritium Gas (HT, T2):	SR-1	0.01	V	n.a.	HTO
Tritiated Methane:	SR-1	1.0	V	n.a.	HTO
Particulate Type F:	**n.a.**	**ICRP-66**	**F**	**1.0**	**HTO/STC**
Particulate Type M:	**n.a.**	**ICRP-66**	**M**	**0.1**	**HTO/STC**
Particulate Type S:	**n.a.**	**ICRP-66**	**S**	**0.01**	**HTO/STC**

The "clarification" of tritium dosimetry in ICRP-88, and the clarification of that clarification (Potter 2004) imply that the biokinetic model of the substrate element (e.g., absorption type and f1 values) should be used to model the distribution and retention of STC particulates. Accordingly, the f1 values of Table B.1 of ICRP Publication 68 (ICRP 1994b) as listed below in Table C.8.2, will be used as default values in STC dosimetry calculations.

Table C.8.2

Default f1 Values for Selected STC Materials

STC Material	Default f1 Value
Erbium	**0.0005**
Hafnium	**0.002**
Scandium	**0.0001**
Titanium	**0.01**
Zirconium	**0.002**
Gold	**0.1**
Zinc Oxide	**0.5**

C.8.3.4 Specific Effective Energy Values for STC Dose Calculations

As noted in Section C.3.5.2, the applicable SEE for all target organs (for HTO in the "blood" or "Body_Tis" source organs), for an adult male, is 1.323E-17 sieverts per nuclear transformation, as calculated by the SEECAL module of the DCAL code. This value is calculated using the beta energy spectrum of ICRP-38, a source organ mass of 68.8 kg (see Equation 4 and Table 1 of SEECAL manual, Cristy 1993) and a radiation weighting factor of 1.0 for beta particles. SEECAL-generated SEE values for HTO for other target and source organs are listed in Table C.8.3.

This (All Targets ← Body_Tissue) SEE of 1.323E-17 Sv/nt is applied (without any modifying factors) to all of the HTO transformations which take place in the "Total Body A", "Total Body B", and "Blood" source organs.

As discussed below, energy Self Absorption Factors are applied to tritium transformations which take place in the STC particles within the respiratory tract and GI tract source regions.

Table C.8.3

Uncorrected Specific Effective Energy (SEE) for STC Dosimetry Calculations

Target Organ	SEECAL Source Organ	Adult Male SEE (Sv/nt)	Comment
All	Body_Tis	1.323E-17	Total Body A + Total Body B
All	Blood	1.323E-17	
ET2-bas	ET2-seq	1.088E-17	SEE will be corrected with SAF_e
bbe-sec	bbe-sol	9.853E-18	SEE will be corrected with SAF_e
LNET	LNET	6.069E-14	SEE will be corrected with SAF_e
AI	AI	8.276E-16	SEE will be corrected with SAF_e
AI	LN-Th	4.138E-16	SEE will be corrected with SAF_e
LN-Th	LN-Th	3.035E-14	SEE will be corrected with SAF_e
ST_Wall	ST_Cont	1.821E-15	SEE will be corrected with SAF_e
SI_Wall	SI_Cont	1.138E-15	SEE will be corrected with SAF_e
ULI_Wall	ULI_Cont	2.069E-15	SEE will be corrected with SAF_e
LLI_Wall	LLI_Cont	3.372E-15	SEE will be corrected with SAF_e
BLADWALL	Bladder	n.a.	Ignored in model

C.8.3.5 Energy Self Absorption Factor (SAF_e) Values

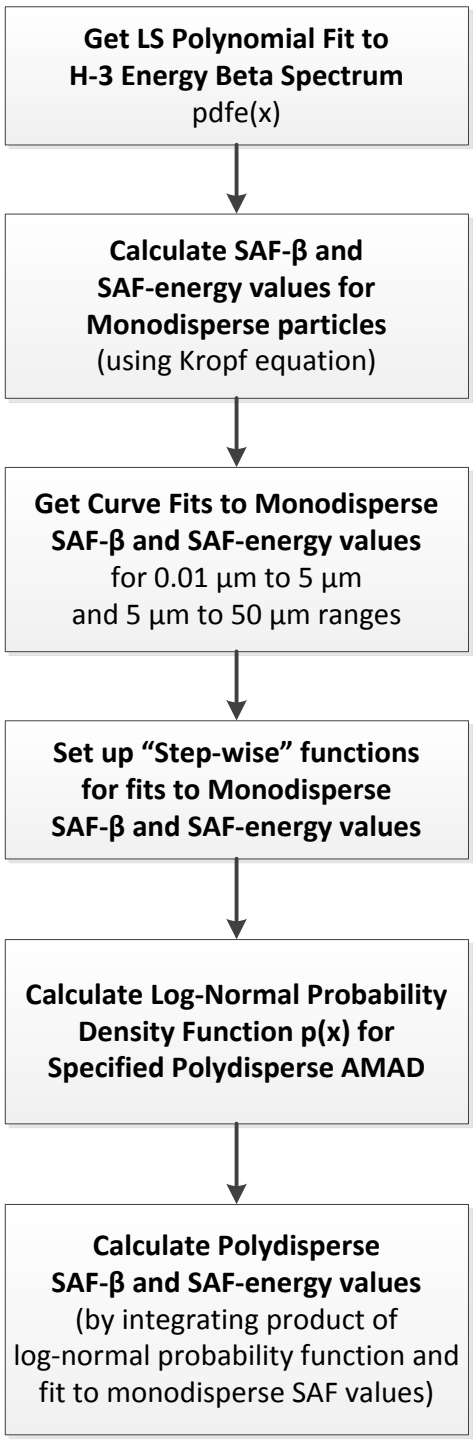
In the case of STCs, where some (or much) of the activity may be imbedded within metal particulates, a significant portion of the beta energy may be attenuated before the beta particle reaches any tissue. Thus, for the source and target organs in which STCs may be present (the compartments of the respiratory tract and GI tract as indicated in red text in the Table above) an energy "Self Absorption Factor" must be applied to the "normal" tritium SEE for that source and target region.

These energy Self Absorption Factors (defined as the fraction of beta energy ***emitted*** from the STC particle) is a complex function of the material density, and the size and shape of the particle. These SAF_e values can range from about 1.0 (100% of energy emitted) for very small, low density materials, down to about 0.1 (10% of energy emitted) for large particle, high density materials.

The calculation of SAF values is complex. Currently, the best documented method of calculation is that implemented in the Mound Technical Basis Document (Mound 2001). The method of calculation used by Mound is outlined below:

Figure C.8.2

Outline of Mound Implementation of Kropf SAF Calculations



This calculation method (as detailed in the Mathcad® worksheet example of Appendices A and B of the Mound TBM) serves as the technical basis for the polydisperse SAF-energy (and SAF-β) values recommended in the DOE Handbook for Radiological Control Programs for Special Tritium Compounds (DOE 2004). Note that the monodisperse SAF values (calculated using the method detailed by Kropf (Kropf 1998) serve as the foundation for the calculation of the polydisperse SAF values.

Table C.8.4 summarizes the SAF-energy values for selected polydisperse particle size distributions as calculated by the above method. These LLNL-calculated values compare favorably with those of Table 5-9 of the DOE Handbook (DOE 2004).

Table C.8.4

Energy Self-Absorption Factors (SAF_e) for Polydisperse Special Tritium Compounds[a]

Material: Density (g/cm^{-3})	**0.01 μm[b] AMAD**	**0.1 μm AMAD**	**1 μm AMAD**	**5 μm AMAD**	**10 μm AMAD**
Sc: 3.10	*1.0*	0.9986	0.7719	**0.3839**	0.2324
Ti: 3.90	*1.0*	1.0	0.7538	**0.3613**	0.2147
Zr: 6.49	*1.0*	1.0	0.7140	**0.3114**	0.1795
Er: 8.56	*1.0*	1.0	0.7047	**0.2945**	0.1667
Hf: 11.68	*1.0*	1.0	0.6802	**0.2585**	0.1407
Au: 19.3	*1.0*	1.0	0.6488	**0.2066**	0.1012
ZnO: 5.6	*1.0*	1.0	0.8026	**0.4211**	0.2605

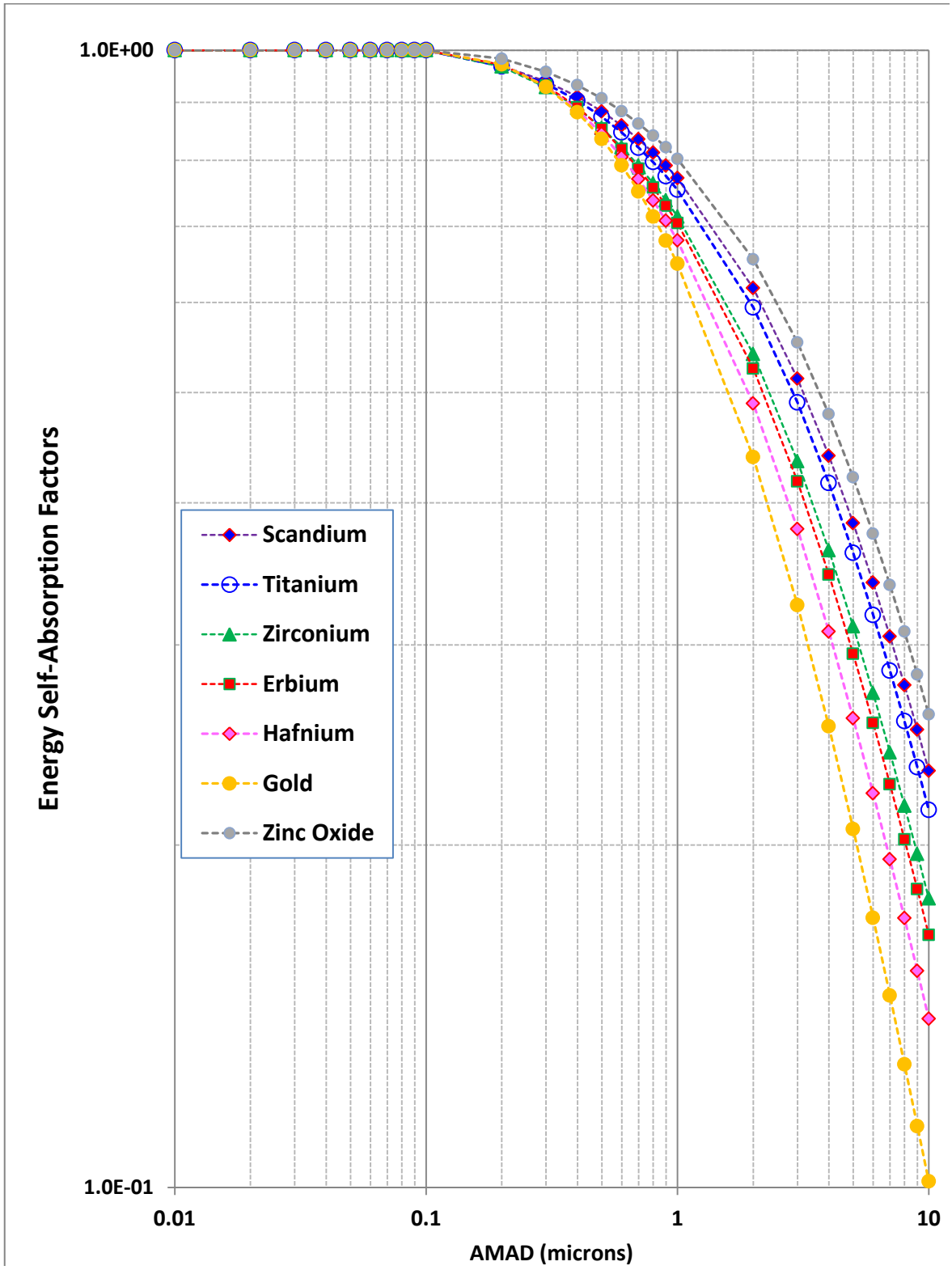
[a] Four-significant figures are displayed for calculated values to aid comparison to other published values. This level of accuracy is not implied.

[b] SAF-energy values for distributions below 0.1 microns, AMAD, are assumed to be 1.0.

The LLNL-calculated SAF_e values are plotted below in Figure C.8.3. As might be expected, the SAF_e value (fraction of energy emitted) drops dramatically as the particle diameter increases. As the AMAD drops below about 0.1 microns, the value of SAF_e asymptotes to 1.0 (100% of the energy is available for deposition in tissue). One can also see a "spread" in values as a function of the material density. This spread is most dramatic at the larger AMAD values.

Figure C.8.3

Fraction of Energy Emitted (SAF_e) vs. STC AMAD



C.8.3.6 Modeling of Wound Intakes of STCs

In the absence of any regulatory guidance regarding the modeling of intakes of STCs via wounds, LLNL internal dosimetry will make the following assumptions:

1. The deposition and retention of STC activity at the wound site can be described by the application of the NCRP-156 wound model,
2. While in the wound, STC activity is assumed to be distributed and retained with the characteristics of the NCRP-156 material types ("soluble", "colloidal", "particles", and "fragments"),
3. Upon transfer from any of the NCRP-156 wound compartments to the blood, the STC activity is assumed to be distributed, retained, and excreted as HTO,
4. Local tissue doses at the wound site (or to any of the NCRP-156 wound compartments) are assumed to be insignificant,
5. The ICRP-88 model is used to predict the concentration of HTO in the urine.

C.8.4 Inhalation Dose Factors for STCs

C.8.4.1 Calculation of Dose Conversion Factors

The key to calculation of dose conversion factors for STCs is the use of the above-discussed energy self-absorption factors to correct for the fraction of tritium beta energy that does not escape from the STC particle, and therefore does not contribute to organ doses. As discussed in Section C.8.3, this correction is applied to doses received by the various regions of the lungs and the GI tract while the STC activity is assumed to be in particulate form. Once the tritium in the STC particulate is "absorbed" (transformed into HTO), it is treated as "normal" tritiated water, and the standard ICRP dosimetry assumptions (and standard SEE values) for tritiated water are used.

The correction for the energy self-absorption factor may be applied prospectively to either the specific effective energy (SEE) values used to calculate the pertinent organ doses, or retrospectively to the organ doses calculated using "standard" SEE values.

C.8.4.1.2 Use of Custom Mathcad Worksheets

LLNL has developed custom Mathcad worksheets that calculate dose conversion factors for inhalation intakes of STCs using the modeling described in Section C.8.3 above. An example of this worksheet is included at the end of this Section. The method of calculation is outlined in Figure C.8.4 below. In this worksheet, the standard SEE values (as calculated by the ORNL DCAL-SEECAL code, ORNL 2006) are multiplied by the fractional SAF-energy values – thus reducing the effective SEE value used in the lung and GI tract organ dose calculations.

The results of these DCF calculations for selected STC materials are summarized in Tables C.8.5 and C.8.6 below. These LLNL-calculated values are similar to those found in Table 5-13 of the DOE Handbook (DOE 2004) but differ for the following reasons:

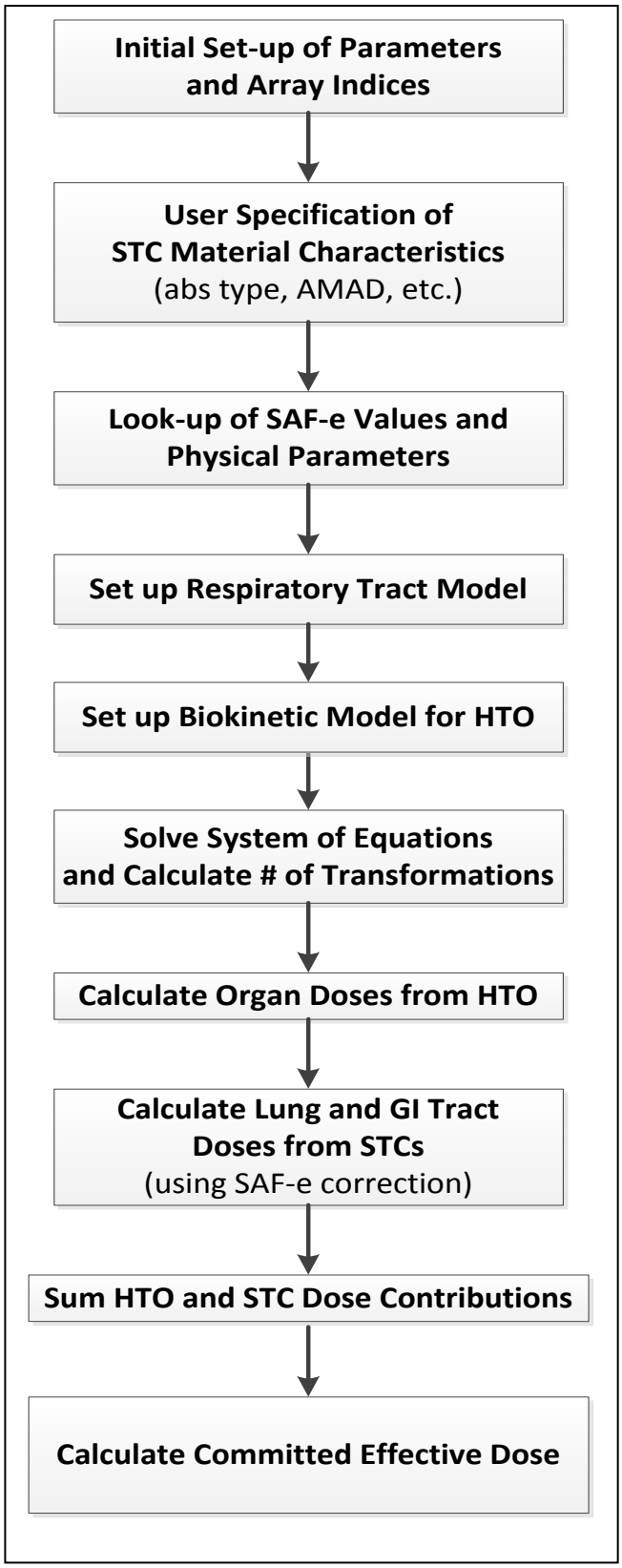
1. The Mound Technical Basis Document (upon which the doses in the DOE Handbook are based) used the now-defunct LUDEP code to calculate organ doses. This difference may result in slightly different organ doses than those calculated using current ICRP models.
2. The Mound Technical Basis Document does not correct the GI Tract doses (received from STCs in the GI Tract contents) for the energy Self Absorption Factor. This modeling choice results in higher doses to the GI Tract walls, which in turn contribute to the calculated committed effective dose.

For these two reasons, the LLNL-calculated doses are believed to be more accurate than those presented in the DOE Handbook. As discussed below, the LLNL-calculated doses agree well with an alternate calculation method developed by La Bone and Potter (La Bone 2010), which

uses the more current dosimetry code IMBA (James 2004) to calculate organ doses (See Section C.8.4.3.)

Figure C.8.4

Outline of LLNL Dose Conversion Factor Calculation Worksheet



C.8.4.2 Reference Inhalation Dose Conversion Factors

Reference dose conversion factors (Committed Effective Dose) for inhalation intakes of 5 micron AMAD STCs are listed in Table C.8.5 below. These DCFs were calculated using custom Mathcad worksheets, and were independently verified against values calculated using the La Bone – Potter spreadsheet method described in Section C.8.4.3.

Table C.8.5

Dose Conversion Factors for Selected STCs (5 microns AMAD)

Form of Tritide	f1 Value (ICRP-68)	CED Sv/Bq	CED rem/μCi
HTO	1.0	1.83E-11	6.77E-5
Erbium	$SAF_e = 0.2945$		
Type F:	0.0005	6.64E-12	2.46E-05
Type M:	0.0005	9.13E-12	3.38E-05
Type S:	0.0005	3.82E-11	1.41E-04
Hafnium	$SAF_e = 0.2585$		
Type F:	0.002	6.48E-12	2.40E-05
Type M:	0.002	8.16E-12	3.02E-05
Type S:	0.002	3.35E-11	1.24E-04
Scandium	$SAF_e = 0.3839$		
Type F:	0.0001	7.05E-12	2.61E-05
Type M:	0.0001	1.16E-11	4.27E-05
Type S:	0.0001	4.97E-11	1.84E-04
Titanium	$SAF_e = 0.3613$		
Type F:	0.01	6.96E-12	2.58E-05
Type M:	0.01	1.10E-11	4.06E-05
Type S:	0.01	4.68E-11	1.73E-04
Zirconium	$SAF_e = 0.3114$		
Type F:	0.002	6.72E-12	2.49E-05
Type M:	0.002	9.59E-12	3.55E-05
Type S:	0.002	4.03E-11	1.49E-04
Gold	$SAF_e = 0.2066$		
Type F:	0.1	6.53E-12	2.42E-05
Type M:	0.1	7.35E-12	2.72E-05
Type S:	0.1	2.75E-11	1.02E-04
Zinc Oxide	$SAF_e = 0.4211$		
Type F:	0.5	8.18E-12	3.03E-05
Type M:	0.5	1.46E-11	5.40E-05
Type S:	0.5	5.68E-11	2.10E-04

These values were calculated using custom Mathcad worksheets using the models and assumptions discussed in Section C.8.3 above, including the use of ICRP-60 tissue weighting factors. HTO value from DCFPAK 2.2 listed for comparison purposes.

Tables C.8.6a and C.8.6b below list reference dose conversion factors for a broad range of particle size distributions.

Table C.8.6a

Reference STC DCFs for Selected Particle Size Distributions

AMAD =	**0.01**	**0.1**	**1**	**2**	**5**	**10**
STC Material	**DCF (Sv/Bq)**	**DCF (Sv/Bq)**	**DCF (Sv/Bq)**	**DCF (Sv/Bq)**	**DCF (Sv/Bq)**	**DCF (Sv/Bq)**
Erbium - Type F	1.48E-11	7.60E-12	6.24E-12	7.30E-12	**6.64E-12**	5.15E-12
Erbium - Type M	1.07E-10	1.04E-10	3.06E-11	2.19E-11	**9.13E-12**	3.49E-12
Erbium - Type S	6.36E-10	6.50E-10	1.72E-10	1.13E-10	**3.82E-11**	1.05E-11
Hafnium – Type F	1.48E-11	7.60E-12	6.18E-12	7.17E-12	**6.48E-12**	5.04E-12
Hafnium – Type M	1.07E-10	1.04E-10	2.96E-11	2.05E-11	**8.16E-12**	3.07E-12
Hafnium – Type S	6.36E-10	6.50E-10	1.66E-10	1.05E-10	**3.35E-11**	8.87E-12
Scandium – Type F	1.48E-11	7.60E-12	6.40E-12	7.64E-12	**7.05E-12**	5.43E-12
Scandium – Type M	1.07E-10	1.04E-10	3.34E-11	2.55E-11	**1.16E-11**	4.58E-12
Scandium – Type S	6.36E-10	6.49E-10	1.88E-10	1.33E-10	**4.97E-11**	1.46E-11
Titanium – Type F	1.48E-11	7.60E-12	6.36E-12	7.56E-12	**6.96E-12**	5.38E-12
Titanium – Type M	1.07E-10	1.04E-10	3.26E-11	2.46E-11	**1.10E-11**	4.34E-12
Titanium – Type S	6.36E-10	6.50E-10	1.84E-10	1.28E-10	**4.68E-11**	1.36E-11
Zirconium – Type F	1.48E-11	7.60E-12	6.26E-12	7.36E-12	**6.72E-12**	5.21E-12
Zirconium – Type M	1.07E-10	1.04E-10	3.10E-11	2.25E-11	**9.59E-12**	3.72E-12
Zirconium – Type S	6.36E-10	6.50E-10	1.74E-10	1.16E-10	**4.03E-11**	1.13E-11
Gold – Type F	1.47E-11	7.60E-12	6.15E-12	7.14E-12	**6.53E-12**	5.18E-12
Gold – Type M	1.07E-10	1.04E-10	2.84E-11	1.89E-11	**7.35E-12**	3.05E-12
Gold – Type S	6.36E-10	6.50E-10	1.58E-10	9.46E-11	**2.75E-11**	7.08E-12
Zinc Oxide – Type F	1.46E-11	7.58E-12	6.54E-12	8.15E-12	**8.18E-12**	6.82E-12
Zinc Oxide – Type M	1.07E-10	1.04E-10	3.48E-11	2.77E-11	**1.46E-11**	7.61E-12
Zinc Oxide – Type S	6.35E-10	6.50E-10	1.96E-10	1.42E-10	**5.68E-11**	1.91E-11

These values were calculated using custom Mathcad worksheets using the models and assumptions discussed in Section C.8.3 above, including the use of ICRP-60 tissue weighting factors.

The values in Table C.8.6b are presented in units of millirem per dpm for convenience in interpreting air sampling results.

Table C.8.6b

Reference STC DCFs for Selected Particle Size Distributions

AMAD =	0.01	0.1	1	2	5	10
STC Material	**DCF (mrem per dpm)**	**DCF (mrem per dpm)**	**DCF (mrem per dpm)**	**DCF (mrem per dpm)**	**DCF (mrem per dpm)**	**DCF (mrem per dpm)**
Erbium - Type F	2.46E-08	1.27E-08	1.04E-08	1.22E-08	1.11E-08	8.58E-09
Erbium - Type M	1.79E-07	1.73E-07	5.10E-08	3.65E-08	1.52E-08	5.82E-09
Erbium - Type S	1.06E-06	1.08E-06	2.87E-07	1.88E-07	6.36E-08	1.75E-08
Hafnium – Type F	2.46E-08	1.27E-08	1.03E-08	1.20E-08	1.08E-08	8.40E-09
Hafnium – Type M	1.79E-07	1.73E-07	4.93E-08	3.42E-08	1.36E-08	5.12E-09
Hafnium – Type S	1.06E-06	1.08E-06	2.77E-07	1.75E-07	5.59E-08	1.48E-08
Scandium – Type F	2.46E-08	1.27E-08	1.07E-08	1.27E-08	1.17E-08	9.05E-09
Scandium – Type M	1.79E-07	1.73E-07	5.56E-08	4.24E-08	1.93E-08	7.64E-09
Scandium – Type S	1.06E-06	1.08E-06	3.14E-07	2.21E-07	8.28E-08	2.43E-08
Titanium – Type F	2.46E-08	1.27E-08	1.06E-08	1.26E-08	1.16E-08	8.97E-09
Titanium – Type M	1.79E-07	1.73E-07	5.44E-08	4.10E-08	1.83E-08	7.24E-09
Titanium – Type S	1.06E-06	1.08E-06	3.07E-07	2.13E-07	7.81E-08	2.26E-08
Zirconium – Type F	2.46E-08	1.27E-08	1.04E-08	1.23E-08	1.12E-08	8.68E-09
Zirconium – Type M	1.79E-07	1.73E-07	5.16E-08	3.75E-08	1.60E-08	6.19E-09
Zirconium – Type S	1.06E-06	1.08E-06	2.90E-07	1.94E-07	6.72E-08	1.88E-08
Gold – Type F	2.46E-08	1.27E-08	1.03E-08	1.19E-08	1.09E-08	8.64E-09
Gold – Type M	1.79E-07	1.73E-07	4.74E-08	3.15E-08	1.22E-08	5.08E-09
Gold – Type S	1.06E-06	1.08E-06	2.64E-07	1.58E-07	4.58E-08	1.18E-08
Zinc Oxide – Type F	2.44E-08	1.26E-08	1.09E-08	1.36E-08	1.36E-08	1.14E-08
Zinc Oxide – Type M	1.78E-07	1.73E-07	5.80E-08	4.62E-08	2.43E-08	1.27E-08
Zinc Oxide – Type S	1.06E-06	1.08E-06	3.27E-07	2.36E-07	9.46E-08	3.19E-08

These values were calculated using custom Mathcad worksheets using the models and assumptions discussed in Section C.8.3 above, including the use of ICRP-60 tissue weighting factors.

C.8.4.3 Alternate Method of Calculating Dose Conversion Factors

An alternate method of calculating dose conversion factors for STCs using standard IMBA-calculated organ doses has been developed by La Bone and Potter (La Bone 2010). The IMBA internal dosimetry program (James 2004) cannot be used to directly calculate STC dose conversion factors – because it has no way to incorporate the energy self absorption factor (SAF_e) values. An EXCEL spreadsheet developed by La Bone and Potter solves this problem by extracting organ dose values from IMBA, and then applying the appropriate SAF_e and other weighting factors.

Figure C.8.5 below illustrates the method of calculation used in the spreadsheet. The example spreadsheet in the Figure is for Type M titanium tritide, with an f1 value of 0.01. Color-coding has been used to facilitate understanding of the method.

The first step in using the spreadsheet is to copy the table of equivalent doses for target organs "Adrenals" to "Uterus" for a Type M tritium (H-3, inorganic) from the IMBA calculation run into the second column of the spreadsheet. *Note that the order of target organs in the spreadsheet is not the same as the order of target organs in the IMBA output table.* Note also that the desired f1 value must be specified using the "GI Tract" module of IMBA.

The SAF_e for titanium tritide has been entered at the top of the second column. Organs to which this SAF_e will be applied (selected respiratory tract and GI tract regions) are high-lighted in pink. For each target organ, the IMBA equivalent dose listed in the second column may include two components: the dose from HTO in body tissue (Total Body A + Total Body B + Blood), and the dose received from tritium within (or near) that target organ. The key to this method is that the SAF_e must be applied to only the later component, and not to the "HTO" tissue dose.

For example, the dose received by the AI lung target region is comprised of the "HTO" body tissue dose, and the dose from two source organs, the LN-th region of the lung, and the AI region itself. In order to accurately calculate the AI dose from STCs, the SAF must be applied only to the doses received from STC activity in the LN-th region and the AI region.

The key to this selective application of the SAF_e is recognition of the fact that ALL target organs receive the same HTO tissue dose. In the case of this example, this HTO dose is 1.70E-13 Sv (per Bq). If this HTO tissue dose is subtracted from the total IMBA Equivalent Dose value (in the second column) the remainder is the dose that would be due to un-attenuated STC activity. Note that the IMBA equivalent dose to any target organ which is not a source organ (e.g., adrenals, brain) may be used as the "HTO tissue" dose. The spreadsheet uses the adrenal dose.

Accordingly, in the third column (labeled "Ht * SAF") this "remainder" dose is multiplied by the SAF, then added back to the HTO tissue dose - to give the total organ dose from both components.

Figure C.8.5

La Bone – Potter Method for Calculating STC DCFs from IMBA Output

Ti-T	Type S	5 microns, AMAD		f1 =	0.01		5 microns AMAD	
Type S				Enter SAF-e =	0.3613			
IMBA Target Organ	IMBA Equivalent Dose (Ht) Sv/Bq	Ht*SAF	Regional Risk Weighting Factor (A)	A x Ht	ICRP-60 Risk Weighting Factor (Wt)	Remainder Organ Mass (g)	Mass Weighted Remainder Organ Dose Ht x Mass	Risk Weighted Equivalent Dose Ht x Wt
Adrenals	1.700E-13	1.700E-13				14	2.38E-12	
UB_Wall	1.700E-13	1.700E-13			0.050			8.50E-15
Bone_Sur	1.700E-13	1.700E-13			0.010			1.70E-15
Brain	1.700E-13	1.700E-13				1400	2.38E-10	
Breasts	1.700E-13	1.700E-13			0.050			8.50E-15
St_Wall	3.250E-12	1.283E-12			0.120			1.54E-13
SI_Wall	7.780E-12	2.919E-12				640	1.87E-09	
ULI_Wall	4.620E-11	1.680E-11	0.570	9.58E-12				
LLI_Wall	1.350E-10	4.888E-11	0.430	2.10E-11				
Kidneys	1.700E-13	1.700E-13				310	5.27E-11	
Liver	1.700E-13	1.700E-13			0.050			8.50E-15
ET1-bas	1.700E-13	1.700E-13	0.001	1.70E-16				
ET2-bas	2.200E-13	1.881E-13	0.998	1.88E-13				
LN-ET	3.260E-09	1.178E-09	0.001	1.18E-12				
BBi-bas	1.700E-13	1.700E-13	0.167	2.83E-14				
BBi-sec	1.700E-13	1.700E-13	0.167	2.83E-14				
bbe-sec	4.750E-13	2.802E-13	0.333	9.33E-14				
AI	2.970E-09	1.073E-09	0.333	3.57E-10				
LN-Th	4.880E-09	1.763E-09	0.001	1.76E-12				
Muscle	1.700E-13	1.700E-13				28000	4.76E-09	
Ovaries	1.700E-13	1.700E-13			0.200			3.40E-14
Pancreas	1.700E-13	1.700E-13				100	1.70E-11	
R_Marrow	1.700E-13	1.700E-13			0.120			2.04E-14
Skin	1.700E-13	1.700E-13			0.010			1.70E-15
Spleen	1.700E-13	1.700E-13				180	3.06E-11	
Testes	1.700E-13	1.700E-13						
Thymus	1.700E-13	1.700E-13				20	3.40E-12	
Thyroid	1.700E-13	1.700E-13			0.050			8.50E-15
Uterus	1.700E-13	1.700E-13				80	1.36E-11	
Composite Organs								
lungs	3.593E-10				0.120			4.31E-11
ET	1.366E-12					15	2.05E-11	
colon	3.060E-11				0.120			3.67E-12
oesophagus	1.700E-13				0.050			8.50E-15
remainder	2.278E-13				0.050			1.14E-14
					1.000	30759	7.01E-09	
					Effective Dose Equivalent =			4.705E-11

The following operation is performed in the third column, labeled "Ht*SAF".

Total Organ Dose = [(IMBA ED – HTO Tissue Dose) * SAF] + HTO Tissue Dose

More specifically:

[Ht * SAF] = [(IMBA ED – IMBA Adrenals ED) * SAF] + IMBA Adrenals ED

where:

IMBA ED = the IMBA Equivalent Dose (Ht) from column 2 and,
SAF_e = the appropriate energy self absorption factor

(Note that target organs which receive only the "normal tissue dose" from HTO distributed throughout the whole body (e.g., adrenals, brain, etc.) are left unchanged by this calculation.)

The subsequent columns in the spreadsheet perform the "standard" regional and risk weighting calculations typical of any effective dose calculation. Regional weighting factors for the lung regions (and for calculation of the dose to the composite organ "colon") are listed in the fourth column, and used in the fifth column. The standard ICRP-60 risk weighting factors are listed in column six, and applied in the last column. The risk-weighted effective organ doses in the last column are then summed to give the total Effective Dose – in this example 4.705E-11 Sv/Bq (which compares favorably with the value of 4.68E-11 Sv/Bq calculated using the LLNL Mathcad worksheet). The target organs that contribute to the total Effective Dose are high-lighted in light yellow.

Effective dose contributions from the "composite" organs (lungs, ET, colon, and esophagus) are calculated (in the second column) per standard ICRP rules. Target organs that contribute to the "lung" dose are high-lighted in light green. Similarly, organs that contribute to the "colon" dose are high-lighted in purple, and organs that contribute to the "ET" dose are high-lighted in light brown.

The ICRP's obtuse "remainder" dose is calculated in the eighth column, using the organ masses listed in column seven. Organs involved in the remainder dose calculation are high-lighted in light blue.

C.8.4.4 Factors Affecting Dose Conversion Factors

Dose conversion factors for intakes of STCs are influenced primarily by the following factors:

- Absorption Type,
- Particle Size Distribution,
- Energy Self Absorption Factor (SAF_e), and
- Fractional Uptake from GI Tract (f1).

The interaction among these factors is complex, and can be difficult to predict. The discussions below may assist the reader in understanding some of these relationships.

The foundation for dose conversion factors used for STCs is the set of "normal" dose conversion factors obtained using standard biokinetic models – without the application of any energy self-absorption factors. These uncorrected "foundation" DCFs for selected STC materials are presented in Figure C.8.6. The highest curve represents Type S materials, the middle curve represents Type M materials, and the lowest curve represents Type F materials.

The most obvious feature of this graph is the great difference among the DCFs for the three absorption types. This difference reflects the fact that the longer residence time in the lungs (for Type M and Type S materials) results in a much larger (uncorrected) effective dose.

An overview of the dose conversion factors (Committed Effective Dose per unit intake of *actual* activity) for Types F, M, and S for selected STC materials is presented in Figures C.8.7, C.8.8, and C.8.9, respectively. The differences in the curves for each material are due to the different SAF_e values and the different (in some cases) f1 values. Factors such as the deposition and retention patterns in the lungs are the same for each of the materials, because, for a given absorption type, these parameters depend only on the particle size distribution.

Figure C.8.6

Comparison of Uncorrected STC Dose Conversion Factors

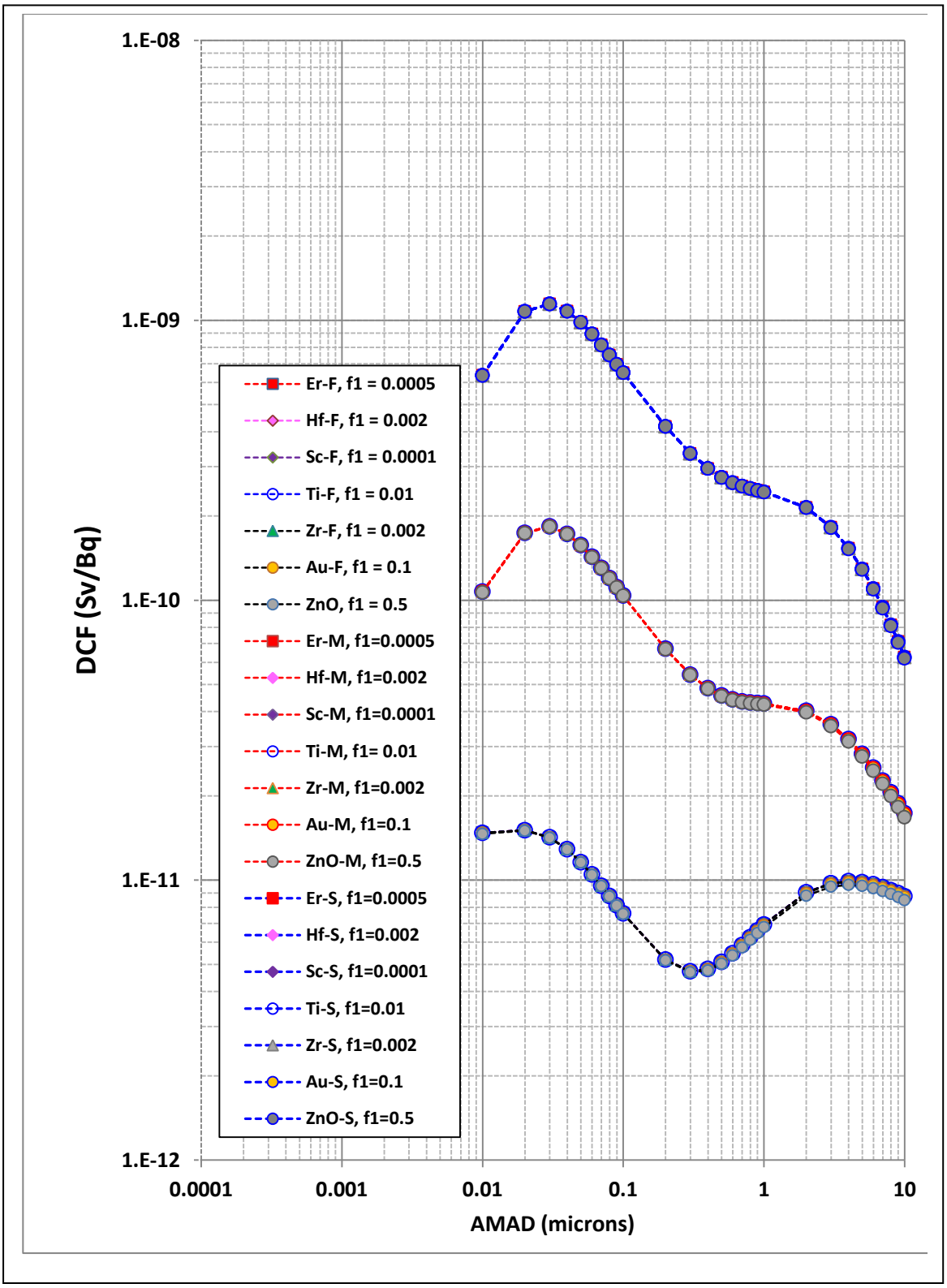


Figure C.8.7

Dose Conversion Factor vs. Particle Size Distribution for Type F STCs

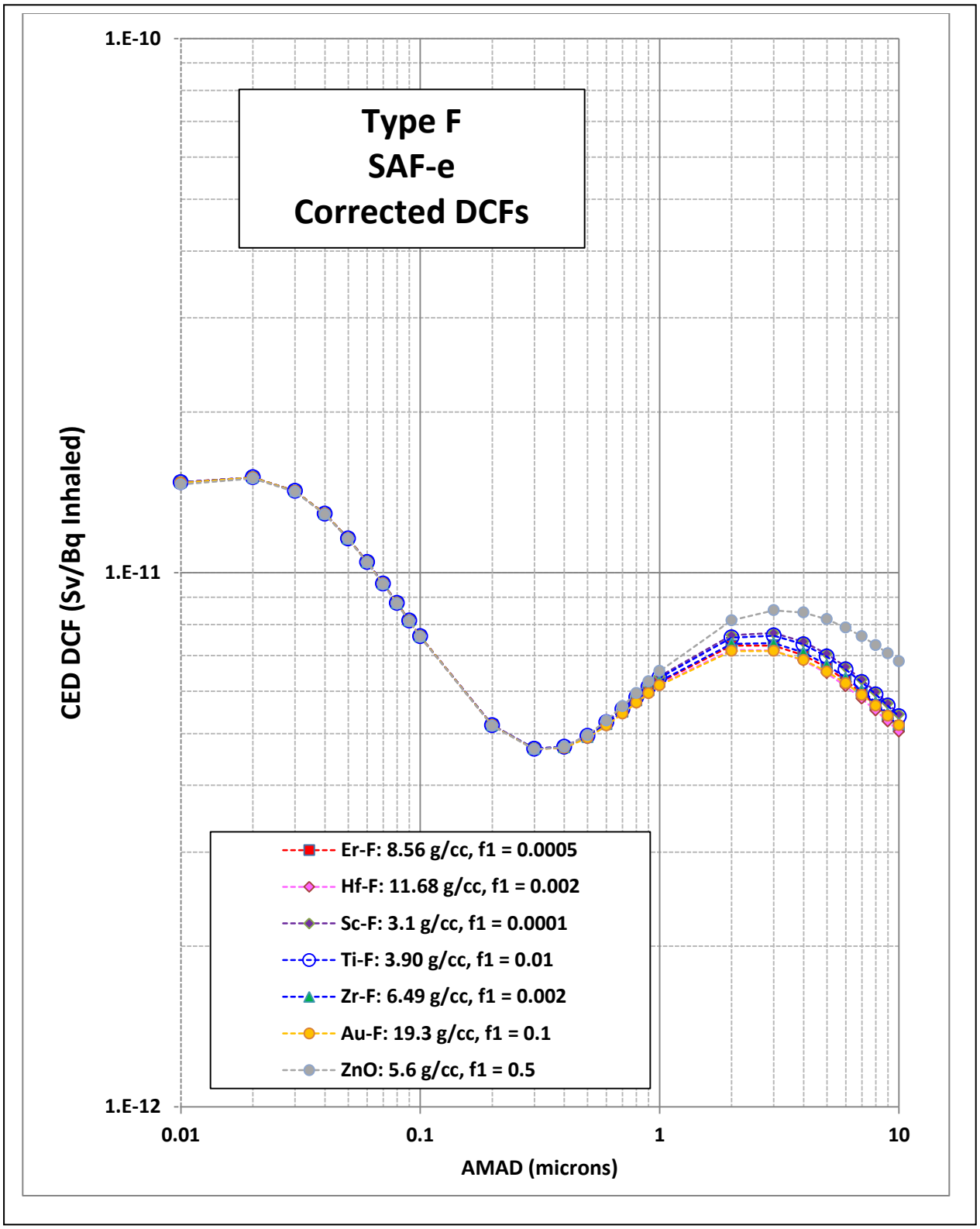


Figure C.8.8

Dose Conversion Factor vs. Particle Size Distribution for Type M STCs

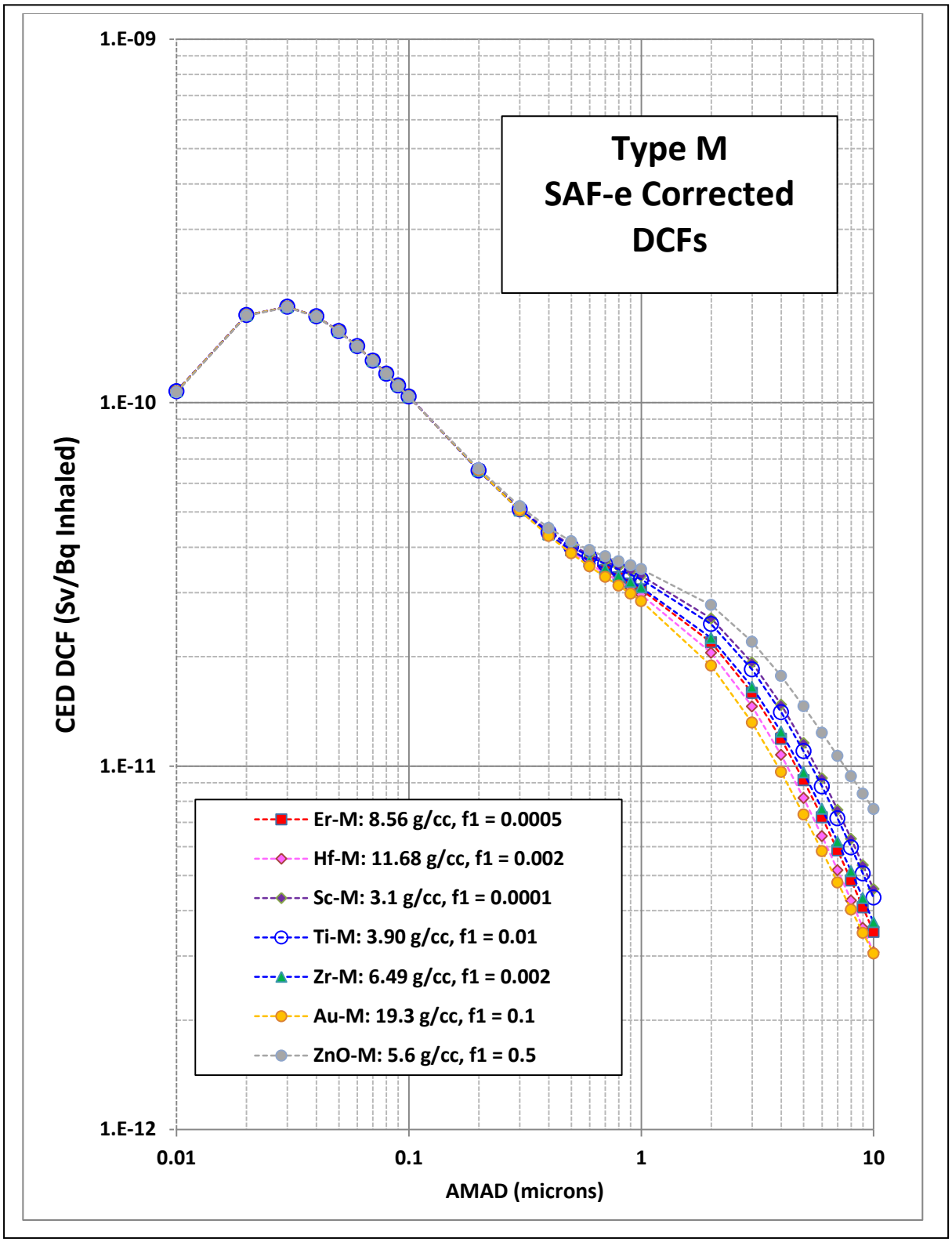
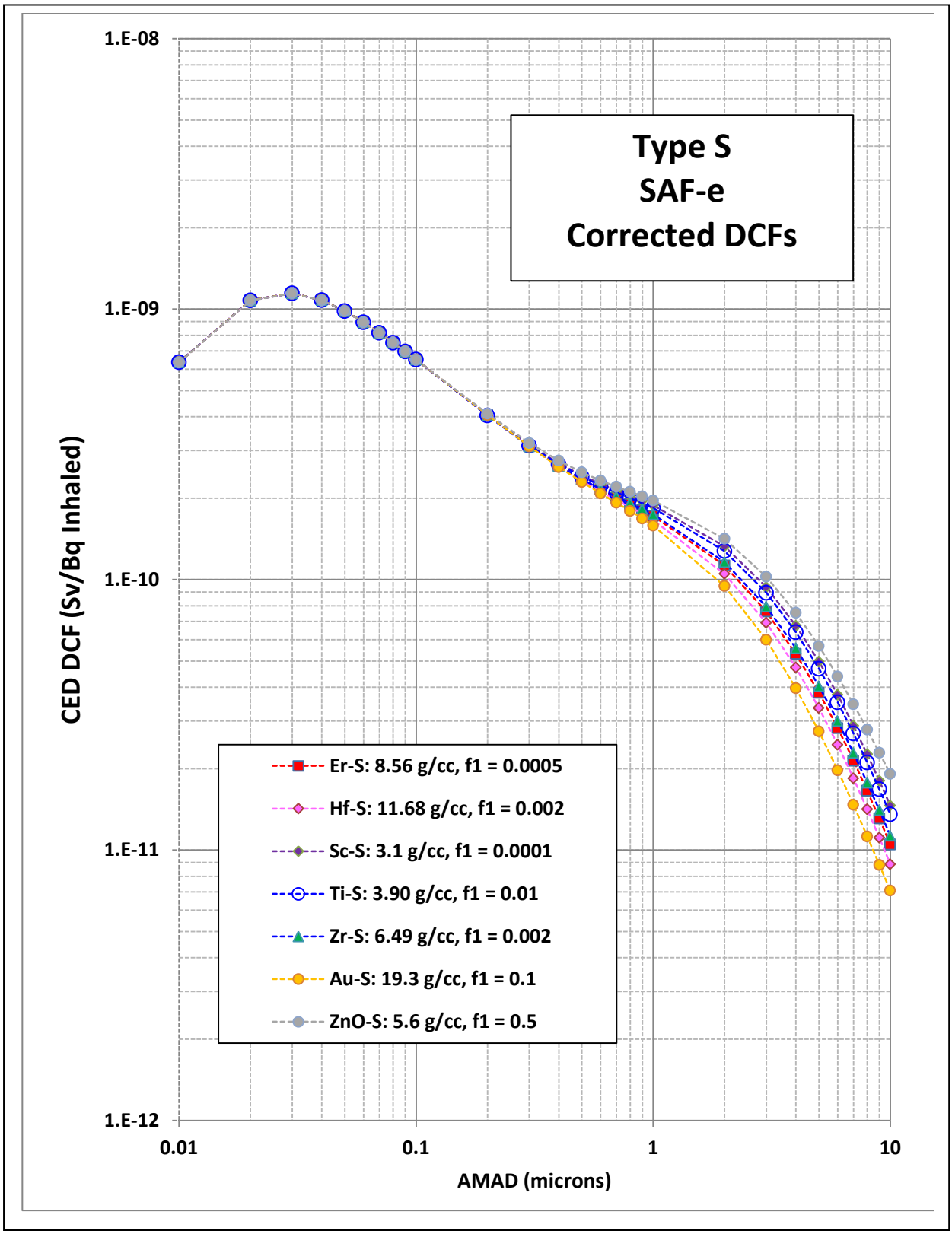


Figure C.8.9

Dose Conversion Factor vs. Particle Size Distribution for Type S STCs



C.8.4.3.1 Effect of Absorption Type

The effect of ICRP-66 absorption type on the DCFs for STCs is complex, because the dose conversion factor depends on deposition and retention in the lungs, energy self absorption factors, and f1 values.

Section to be completed in next revision

C.8.4.3.2 Effect of Particle Size Distribution

The effect of changes in the assumed particle size is also complex, because such changes affect both the pattern of deposition in the lungs, and the self absorption factor applied to lung and GI tract region doses.

Section to be completed in next revision

Placeholder for Figure C.8.10, “Contributions to Uncorrected CED: TiTx”

Placeholder for Figure C.8.11, “Contributions to SAFe Corrected CED: TiTx”

Placeholder for Figure C.8.12, “Percent Contribution to CED – TiTx”

C.8.4.3.3 Effect of Energy Self Absorption Factor

Section to be completed in next revision

Placeholder for Figure C.8.13, “DCF vs. SAFe for Selected STC Material”

C.8.4.3.4 Effect of Fractional Uptake from GI Tract

Section to be completed in next revision

C.8.4.5 Annual Limits of Intake

The Annual Limit of Intake (ALI) is defined in 10 CFR 835 as "the smaller value of intake of a given radionuclide in a year by the reference man (ICRP Publication 23) that would result in a committed effective dose of 5 rem (0.05 sieverts (Sv)) (1 rem = 0.01 Sv) or a committed equivalent dose of 50 rem (0.5 Sv) to any individual organ or tissue." In the case of either HTO or STCs, for any particle size, absorption type, or STC material presented in this Appendix, the limiting ALI will be based on the Committed Effective Dose, not on the committed equivalent dose to the lungs.

ALIs for selected STC materials and particle sizes are presented below in Table C.8.7.

Table C.8.7

Reference STC ALIs for Selected Particle Size Distributions
(*Actual* Activity)

AMAD =	**0.01**	**0.1**	**1**	**2**	**5**	**10**
STC Material	**ALI (μCi)**	**ALI (μCi)**	**ALI (μCi)**	**ALI (μCi)**	**ALI (μCi)**	**ALI (μCi)**
Erbium - Type F	9.15E+04	1.78E+05	2.17E+05	1.85E+05	**2.03E+05**	2.63E+05
Erbium - Type M	1.26E+04	1.30E+04	4.42E+04	6.18E+04	**1.48E+05**	3.87E+05
Erbium - Type S	2.12E+03	2.08E+03	7.86E+03	1.20E+04	**3.54E+04**	1.29E+05
Hafnium – Type F	9.16E+04	1.78E+05	2.19E+05	1.88E+05	**2.08E+05**	2.68E+05
Hafnium – Type M	1.26E+04	1.30E+04	4.57E+04	6.60E+04	**1.66E+05**	4.40E+05
Hafnium – Type S	2.12E+03	2.08E+03	8.14E+03	1.29E+04	**4.03E+04**	1.52E+05
Scandium – Type F	9.15E+04	1.78E+05	2.11E+05	1.77E+05	**1.92E+05**	2.49E+05
Scandium – Type M	1.26E+04	1.30E+04	4.05E+04	5.31E+04	**1.17E+05**	2.95E+05
Scandium – Type S	2.12E+03	2.08E+03	7.18E+03	1.02E+04	**2.72E+04**	9.26E+04
Titanium – Type F	9.16E+04	1.78E+05	2.13E+05	1.79E+05	**1.94E+05**	2.51E+05
Titanium – Type M	1.26E+04	1.30E+04	4.14E+04	5.50E+04	**1.23E+05**	3.11E+05
Titanium – Type S	2.13E+03	2.08E+03	7.35E+03	1.06E+04	**2.89E+04**	9.97E+04
Zirconium – Type F	9.16E+04	1.78E+05	2.16E+05	1.84E+05	**2.01E+05**	2.60E+05
Zirconium – Type M	1.26E+04	1.30E+04	4.36E+04	6.01E+04	**1.41E+05**	3.64E+05
Zirconium – Type S	2.12E+03	2.08E+03	7.76E+03	1.16E+04	**3.35E+04**	1.20E+05
Gold – Type F	9.17E+04	1.78E+05	2.20E+05	1.89E+05	**2.07E+05**	2.61E+05
Gold – Type M	1.26E+04	1.30E+04	4.75E+04	7.16E+04	**1.84E+05**	4.43E+05
Gold – Type S	2.13E+03	2.08E+03	8.53E+03	1.43E+04	**4.92E+04**	1.91E+05
Zinc Oxide – Type F	9.24E+04	1.78E+05	2.07E+05	1.66E+05	**1.65E+05**	1.98E+05
Zinc Oxide – Type M	1.27E+04	1.30E+04	3.88E+04	4.87E+04	**9.26E+04**	1.78E+05
Zinc Oxide – Type S	2.13E+03	2.08E+03	6.89E+03	9.55E+03	**2.38E+04**	7.06E+04

All of these ALI values are based on the intake (of actual activity) that would result in a Committed Effective Dose of -5 rem.

Figures C.8.14 through C.8.15 display the ALI values for selected Types F, M, and S STC materials as a function of particle size. These values are expressed in terms of *actual* activity inhaled.

It will be noted that since the ALI values are proportional to the dose conversion factors, the curves in these Figures are essentially the inverse of those seen in the dose conversion factor curves of Figures C.8.7, C.8.8, and C.8.9.

Figure C.8.14

Annual Limit of Intake vs. Particle Size Distribution (Actual Activity Inhaled)

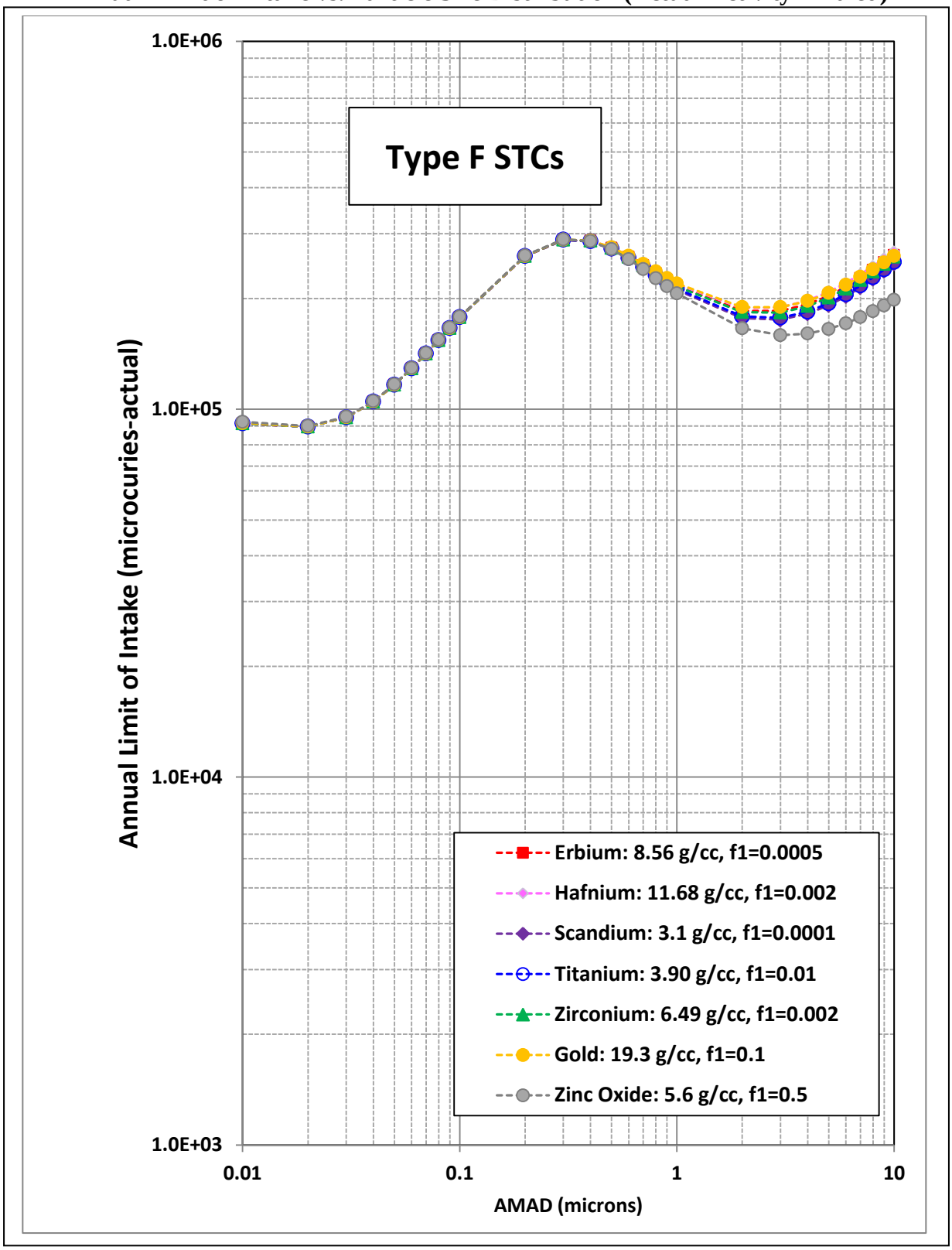


Figure C.8.15

Annual Limit of Intake vs. Particle Size Distribution (Actual Activity Inhaled)

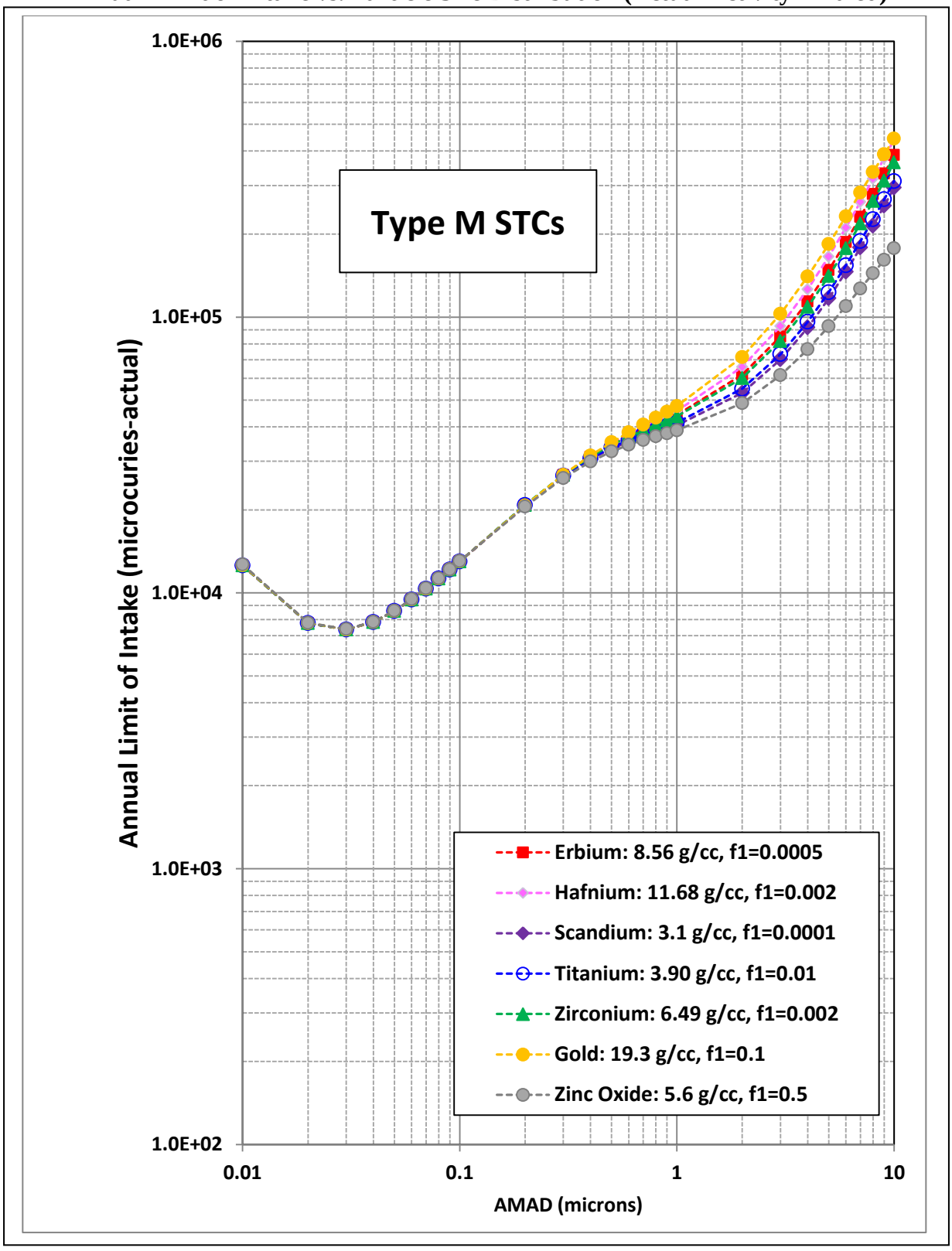
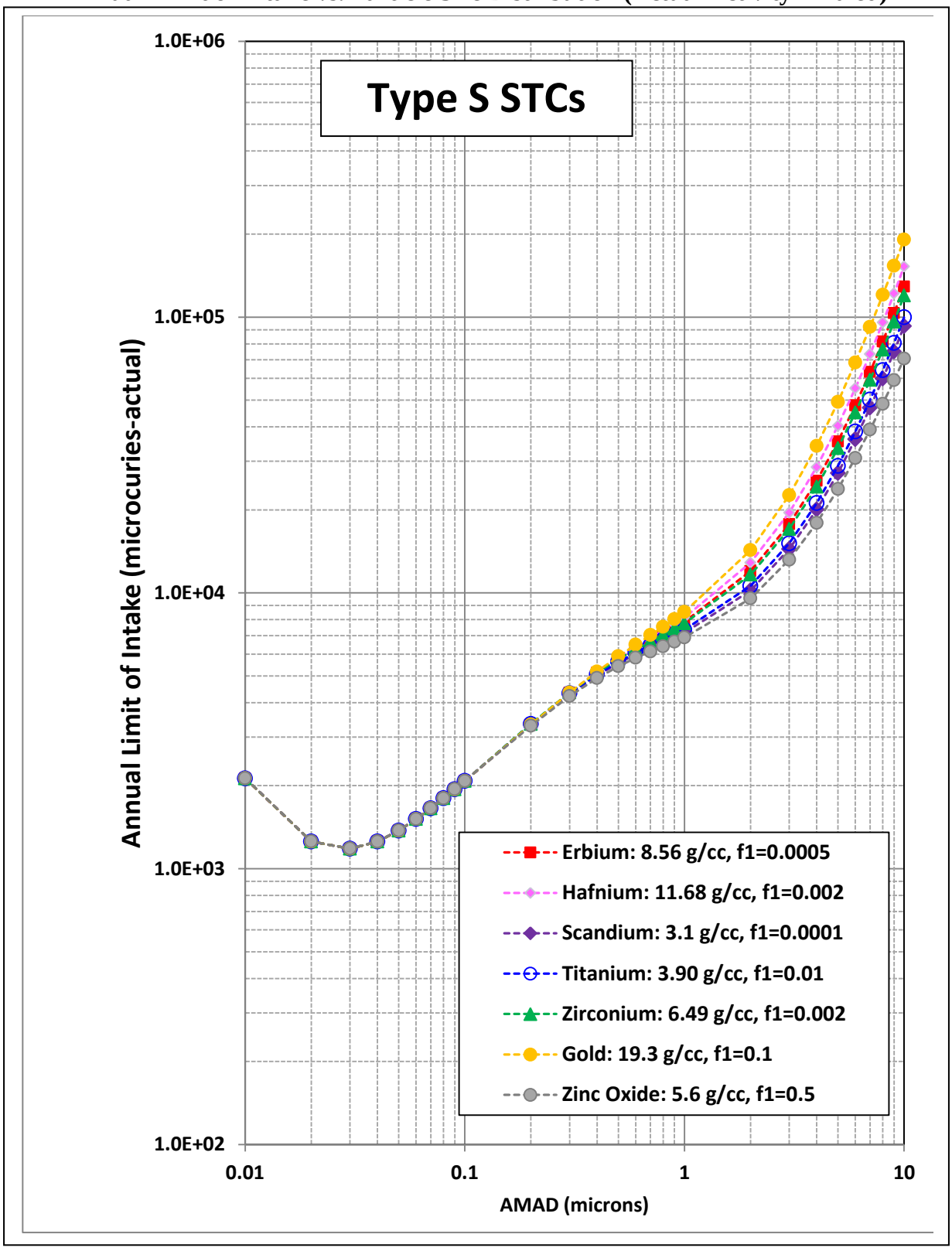


Figure C.8.16

Annual Limit of Intake vs. Particle Size Distribution (Actual Activity Inhaled)



C.8.4.6 Derived Air Concentrations

The Derived Air Concentration (DAC) is defined in 10 CFR 835 (CFR 2012) as "for the radionuclides listed in appendix A of this part, the airborne concentration that equals the ALI divided by the volume of air breathed by an average worker for a working year of 2000 hours (assuming a breathing volume of 2400 m^3)." In the case of either HTO or STCs, for any particle size, absorption type, or STC material presented in this Appendix, the limiting ALI (and therefore the associated DAC value) will be based on the Committed Effective Dose, not on the committed equivalent dose to the lungs.

In Appendix A of 10 CFR 835, the DACs listed for "Insoluble" STC materials are presented in terms of *observed* activity, but are based on dose conversion factors that have *not* been corrected for energy self absorption (SAF_e). (The values listed for "insoluble" STCs are actually based on the uncorrected DCFs for hafnium – as presented in the Mound Technical Basis Document.) Thus, the DAC values of 10 CFR 835 represent a conservative upper limit of DAC values.

The DAC values of Appendix A of 10 CFR 835 for insoluble STCs (5 microns, AMAD) are equivalent to:

Type F:	1.0 E+01 $\mu Ci/m^3$
Type M:	6.0 E+00 $\mu Ci/m^3$
Type S:	2.0 E+00 $\mu Ci/m^3$

Calculated DACs for selected STC materials and particle sizes (based on the reference dose conversion factors of Section C.8.4.2) are presented below in Table C.8.7. Note that for convenience, these DACs are presented in terms of *observed* activity (See discussion in Section C.8.7 below).

These calculated, energy absorption-corrected values are likely to be more accurate than the values listed in 10 CFR 835.

Table C.8.8

Reference STC DACs for Selected Particle Size Distributions
(*Observed* Activity)

AMAD =	0.01	0.1	1	2	5	10
STC Material	**DAC ($\mu Ci/m^3$)**	**DAC ($\mu Ci/m^3$)**	**DAC ($\mu Ci/m^3$)**	**DAC ($\mu Ci/m^3$)**	**DAC ($\mu Ci/m^3$)**	**DAC ($\mu Ci/m^3$)**
Erbium - Type F	3.81E+01	6.93E+01	4.98E+01	2.86E+01	**1.52E+01**	1.04E+01
Erbium - Type M	5.24E+00	5.07E+00	1.02E+01	9.55E+00	**1.11E+01**	1.54E+01
Erbium - Type S	8.85E-01	8.10E-01	1.81E+00	1.85E+00	**2.65E+00**	5.12E+00
Hafnium – Type F	3.81E+01	6.92E+01	4.83E+01	2.70E+01	**1.34E+01**	8.58E+00
Hafnium – Type M	5.24E+00	5.06E+00	1.01E+01	9.45E+00	**1.07E+01**	1.41E+01
Hafnium – Type S	8.85E-01	8.09E-01	1.80E+00	1.84E+00	**2.60E+00**	4.88E+00
Scandium – Type F	3.81E+01	6.98E+01	5.36E+01	3.28E+01	**2.00E+01**	1.53E+01
Scandium – Type M	5.24E+00	5.11E+00	1.03E+01	9.85E+00	**1.22E+01**	1.82E+01
Scandium – Type S	8.85E-01	8.17E-01	1.82E+00	1.89E+00	**2.84E+00**	5.70E+00
Titanium – Type F	3.81E+01	6.96E+01	5.24E+01	3.16E+01	**1.87E+01**	1.39E+01
Titanium – Type M	5.24E+00	5.09E+00	1.02E+01	9.73E+00	**1.19E+01**	1.72E+01
Titanium – Type S	8.85E-01	8.13E-01	1.81E+00	1.87E+00	**2.78E+00**	5.53E+00
Zirconium – Type F	3.81E+01	6.92E+01	5.01E+01	2.92E+01	**1.61E+01**	1.14E+01
Zirconium – Type M	5.24E+00	5.06E+00	1.01E+01	9.55E+00	**1.13E+01**	1.59E+01
Zirconium – Type S	8.85E-01	8.09E-01	1.80E+00	1.85E+00	**2.68E+00**	5.24E+00
Gold – Type F	3.82E+01	7.02E+01	4.56E+01	2.39E+01	**1.03E+01**	5.57E+00
Gold – Type M	5.25E+00	5.14E+00	9.87E+00	9.04E+00	**9.15E+00**	9.48E+00
Gold – Type S	8.86E-01	8.20E-01	1.77E+00	1.80E+00	**2.45E+00**	4.08E+00
Zinc Oxide – Type F	3.85E+01	7.09E+01	5.59E+01	3.34E+01	**1.91E+01**	1.35E+01
Zinc Oxide – Type M	5.28E+00	5.18E+00	1.05E+01	9.82E+00	**1.07E+01**	1.21E+01
Zinc Oxide – Type S	8.87E-01	8.27E-01	1.87E+00	1.92E+00	**2.75E+00**	4.81E+00

All of these DAC values are based on the intake (of *observed* activity) that would result in a Committed Effective Dose of 5 rem.

Figures C.8.17, C.8.18, and C.8.19 display the DAC values for selected Types F, M, and S STC materials as a function of particle size. Note that, in contrast to the ALI values, these values are expressed in terms of *OBSERVED* activity inhaled – for convenience in interpreting air sampling results.

Since the DAC values are directly proportional to the dose conversion factors, the curves in these Figures have the same shapes as those seen in the dose conversion factor curves of Figures C.8.7, C.8.8, and C.8.9.

Figure C.8.17

Derived Air Concentration vs. Particle Size Distribution (*Observed* Activity)

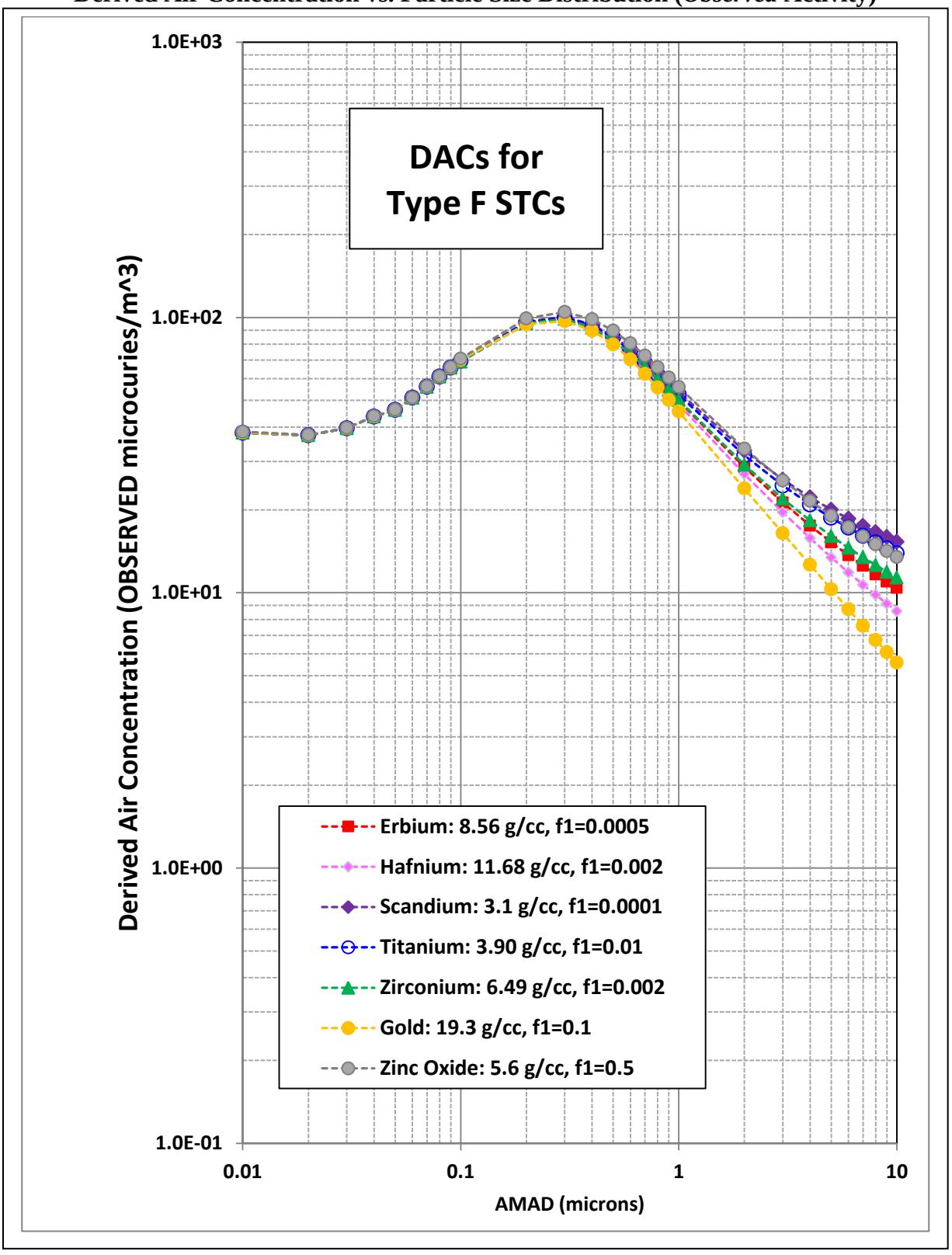


Figure C.8.18

Derived Air Concentration vs. Particle Size Distribution (*Observed* Activity)

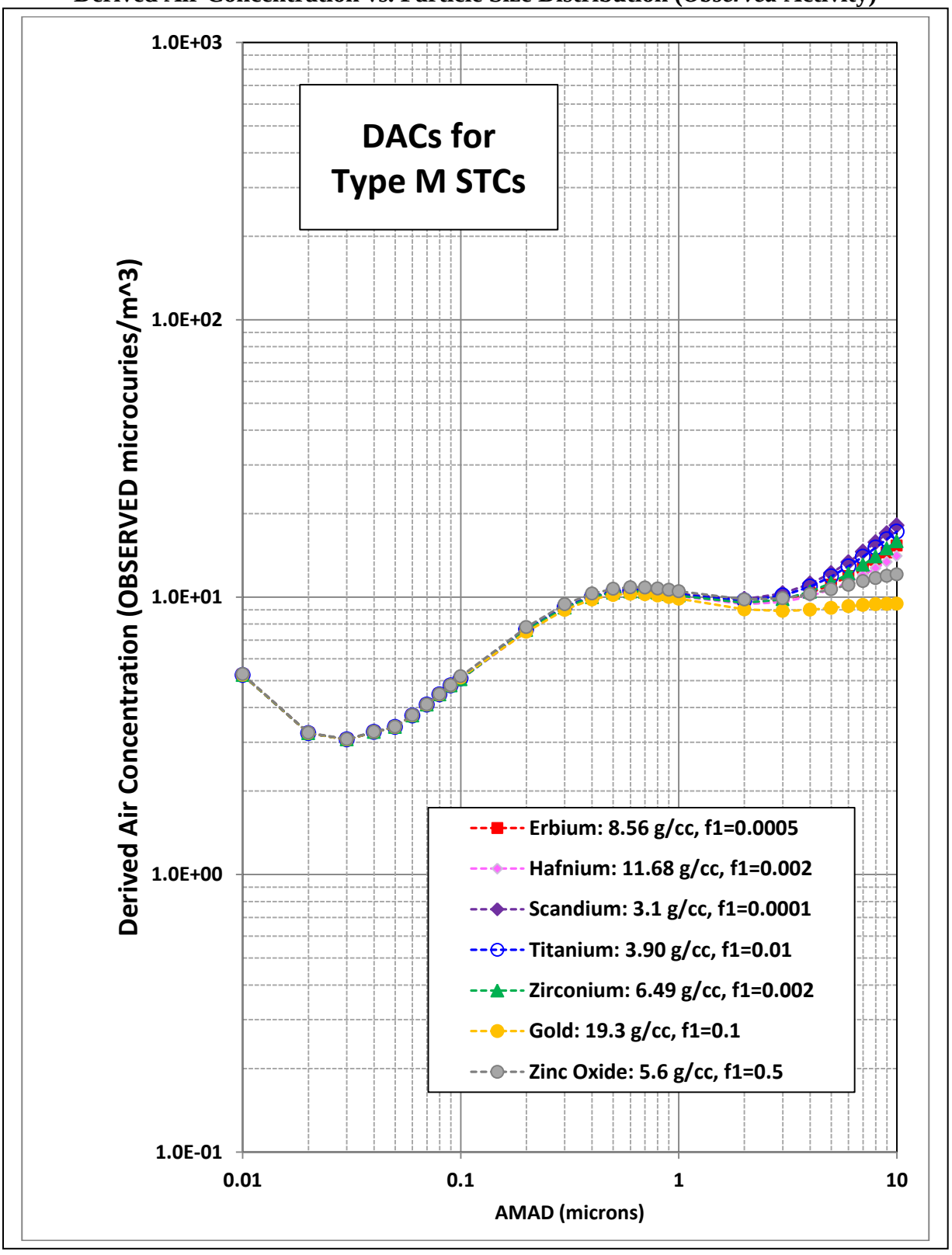
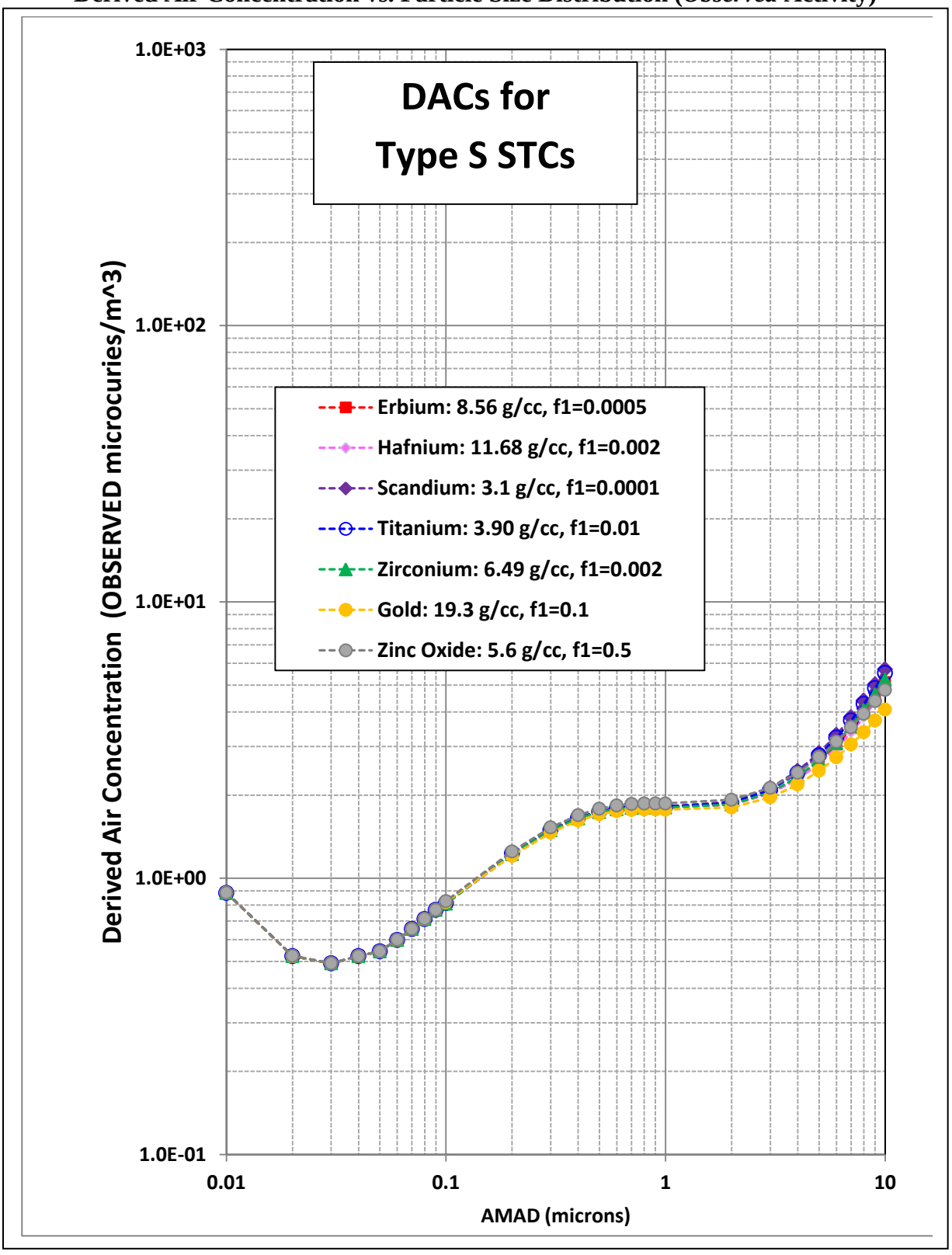


Figure C.8.19

Derived Air Concentration vs. Particle Size Distribution (*Observed* Activity)



C.8.5 Calculation of Intake Excretion Concentrations for Urine

C.8.5.1 ICRP Assumptions

The key assumption used in interpreting tritium urine sample results is the statement in ICRP-88 that: **"For bioassay purposes the activity concentration in urine is calculated by dividing the whole body activity (the activity in blood and both whole body compartments) by the volume of body water, 42 [liters]."** As noted in Potter's clarification (Potter 2004): "Implementation of this model for use in bioassay analysis and internal dosimetry requires generation of intake retention fractions . . ."

For any specified time after intake, this assumption can be expressed as:

$$C_u(t) = \frac{A_{HTO} + A_{OBT} + A_{Blood}}{42} \qquad \text{Eq. C.8.1}$$

Where:

$C_u(t)$ = the "instantaneous" concentration in urine (μCi/liter) at any time t after intake,

A_{HTO} = the activity in the "HTO" compartment at time t (μCi),

A_{OBT} = the activity in the "OBT" compartment at time t (μCi), and

A_{Blood} = the activity in the "Blood" compartment at time t (μCi).

This instantaneous concentration quantity is referred to as an "Intake Excretion Concentration" – to distinguish it from an Intake Excretion Fraction, which more commonly represents a fraction of the intake collected during a particular time increment (e.g., one day.)

The numerator of the right hand side of equation C.8.1 represents the activity that is present in these three model compartments which represent the "tissue" of the whole body. Thus, equation C.8.1 can be re-written as:

$$C_u = \frac{IRF_{Tissue} \times I}{42} \qquad \text{Eq. C.8.2}$$

Where:

IRF_{Tissue} = the total fraction of the intake that is retained in these three "tissue" compartments of the whole body at a reference time t, and

I = the intake activity (μCi).

Solving equation C.8.2 for the intake (I) gives:

$$I = \frac{C_u \times 42}{IRF_{Tissue}} \qquad \text{Eq. C.8.3}$$

which then gives an estimate of the intake that would produce the observed urine concentration.

C.8.5.2 Theoretical STC Intake Urine Excretion Concentrations

Calculation of the Intake Excretion Concentrations (IECs) for the three "tissue" compartments is based on the ICRP-66 Respiratory Tract Model, the ICRP-30 GI Tract Model, and the biokinetic model described in Section C.8.3.2 of this Manual (See Figure C.8.1.) and the key ICRP assumption expressed in equation C.8.1. The IEC value will be a function of the following factors:

- Time after intake,
- Inhalation absorption type,
- Particle size distribution, and
- The value of f1 (fractional absorption from the small intestine).

Note that the energy "self absorption factor" values discussed in Section C.8.3 play no role in the generation of IEC values.

Figures C.8.20 thru C.8.22 below show the IEC (in terms of μCi/liter per μCi inhaled) for Types F, M, and S STCs (5 micron, AMAD) as a function of time after inhalation, for a series of f1 values. (Note that the IEC values are independent of the units of activity used, and therefore could equivalently represent Bq/liter per Bq inhaled.)

As seen in Figure C.8.20, the value of f1 makes very little difference in the shape or magnitude of the IEC curves for Type F materials. This lack of effect comes about due to the very rapid transfer of activity from the lungs to the bloodstream, leaving only a small fraction of the intake to be absorbed from the GI Tract.

In contrast, the family of curves for Type M and Type S IECs show a significant dependence on the assumed f1 value during about the first 100 days after inhalation. This dependence is (presumably) due to the fact that a much larger fraction of the inhaled activity is translocated to the GI Tract, where it can be selectively "operated on" by the differing f1 values.

It is important to note that these curves are for theoretical intakes of "pure" STC materials – unadulterated by any concomitant intake of HTO. As will be seen in the following section, even a small HTO component in the intake will make interpretation of urine results very difficult.

Figure C.8.20

Intake Excretion Concentration – Type F STCs

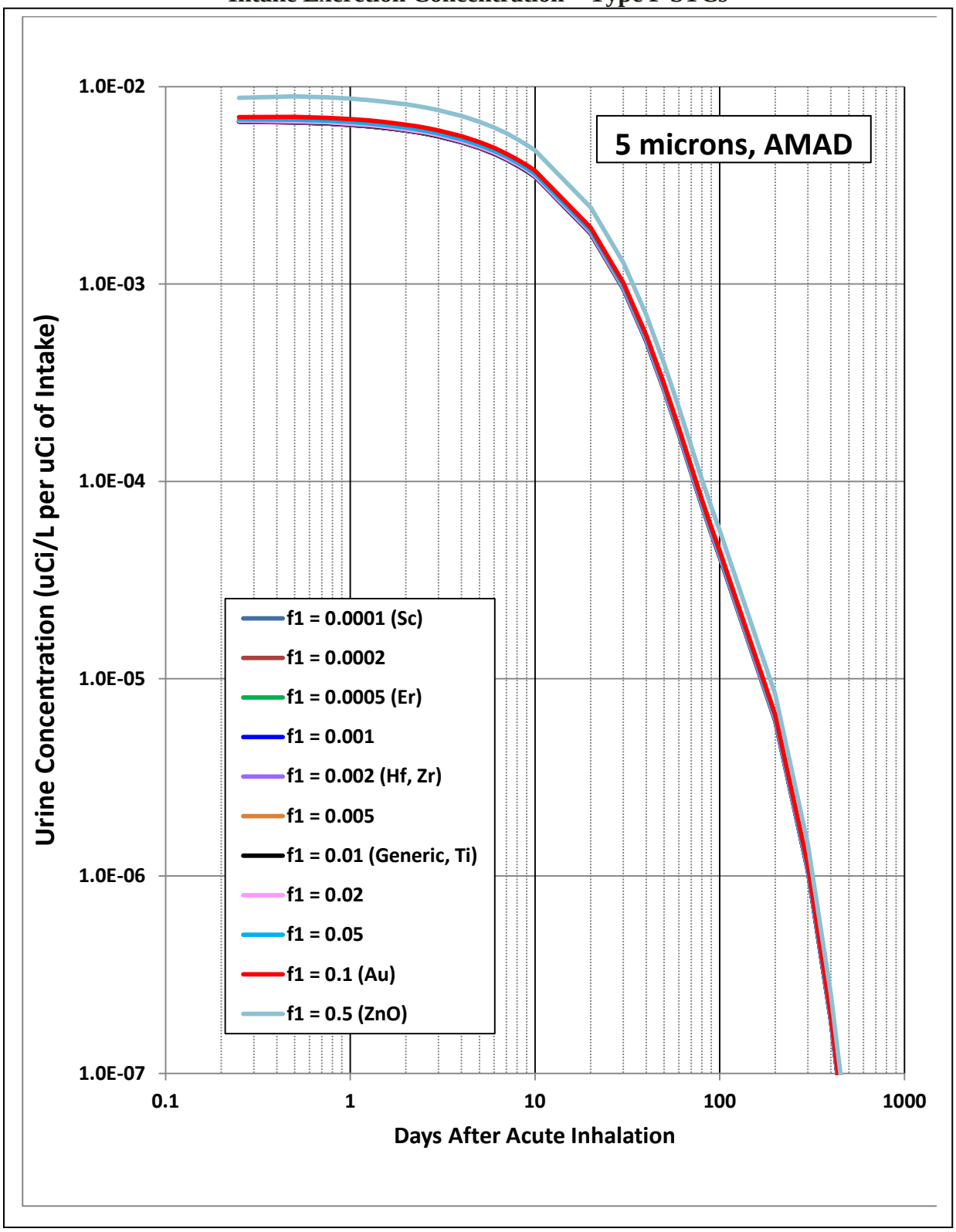


Figure C.8.21

Intake Excretion Concentration – Type M STCs

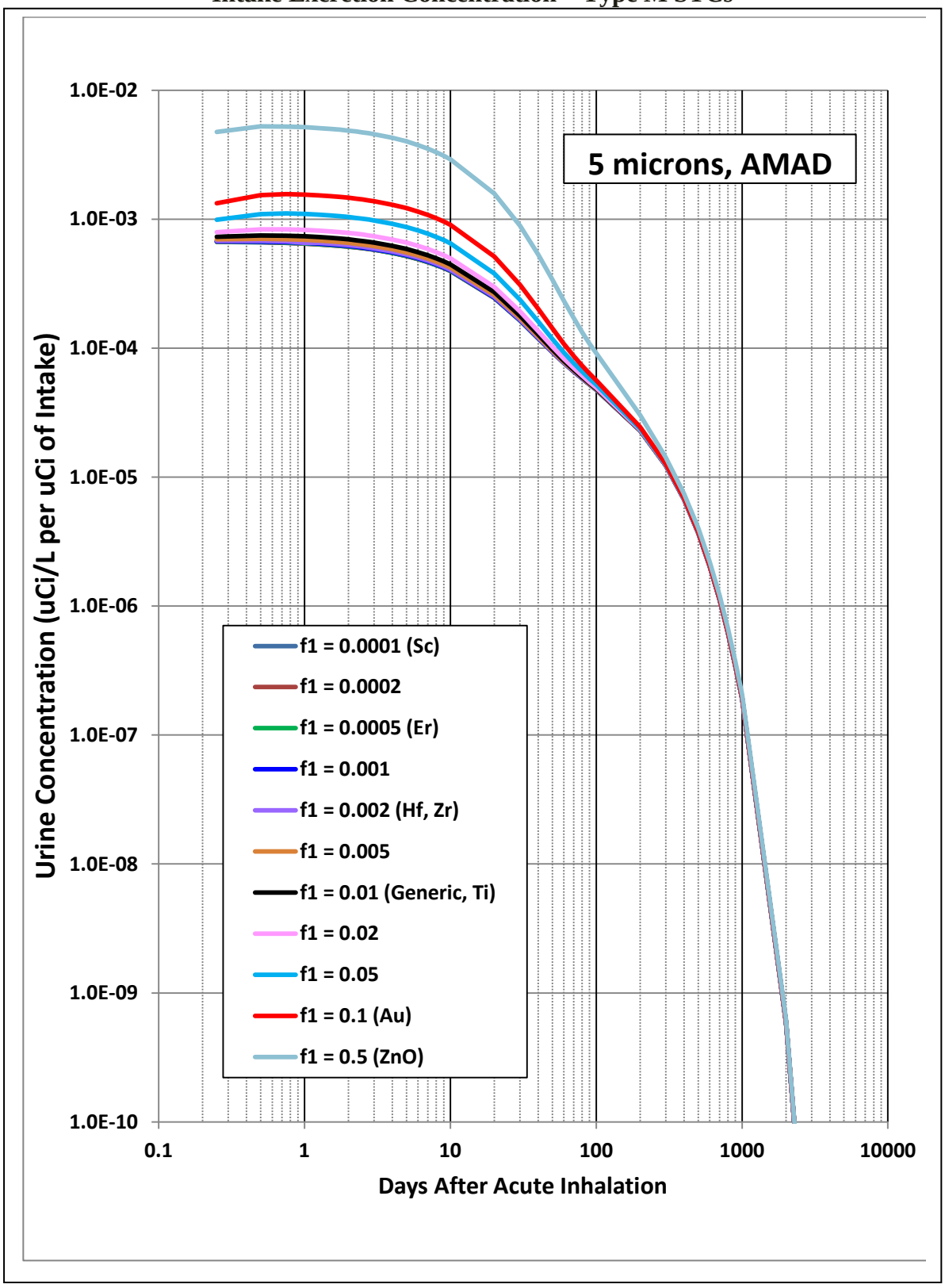
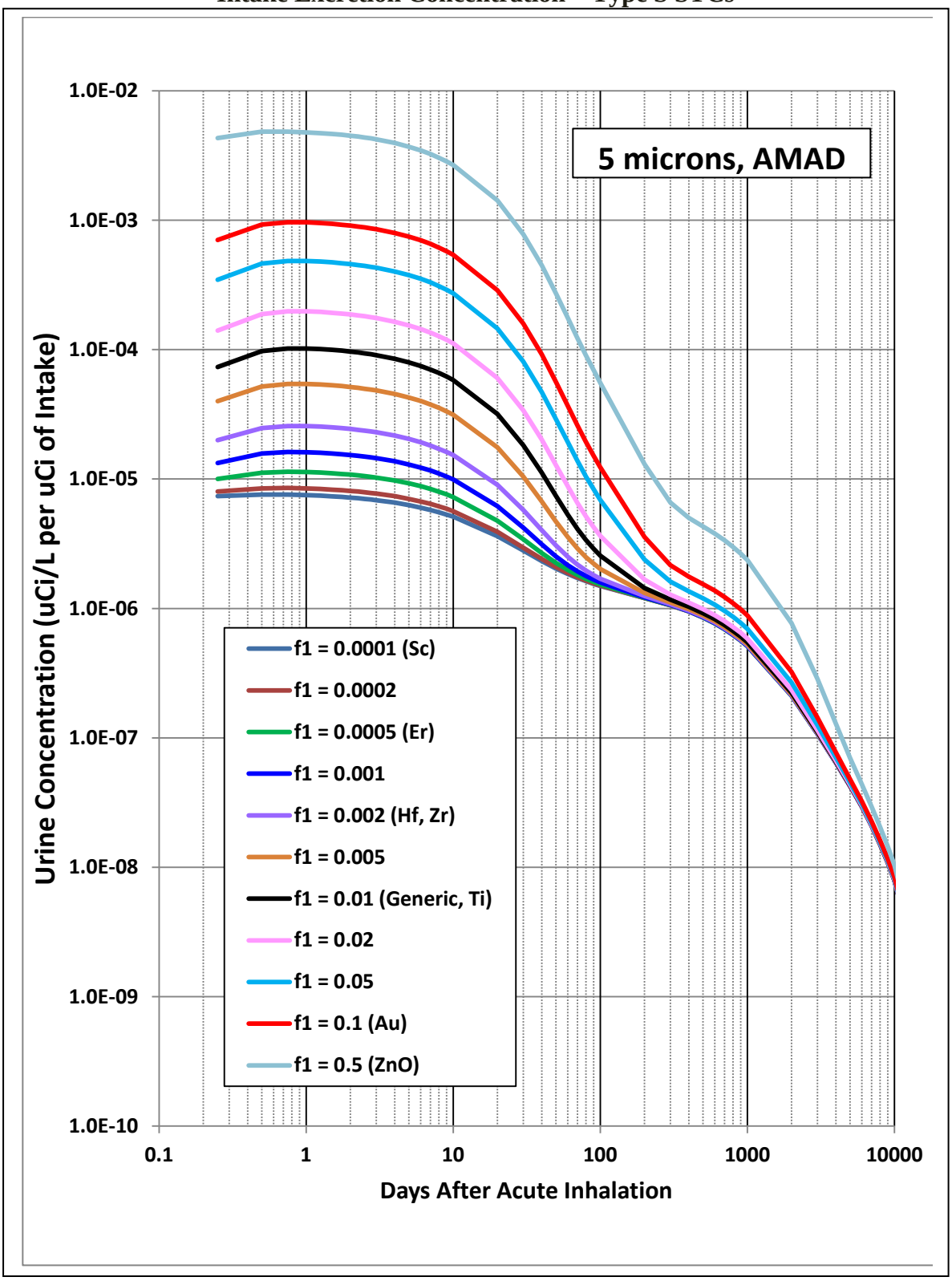


Figure C.8.22

Intake Excretion Concentration – Type S STCs



C.8.5.3 Comparison of Intake Excretion Concentrations – HTO vs STCs

Figure C.8.23 compares the predicted Intake Excretion Concentrations for HTO and Types F, M, and S titanium tritide (f1 assumed to be 0.01). Although the shapes of the curves are generally similar, there are great differences in the absolute IEC values due to the "hold-up" of STCs in the respiratory tract.

Unfortunately, the fact that the IEC curves have very similar shapes during the first 100 days post inhalation prevents one from using urine results to discriminate between intakes of HTO and various types of STCs during this time frame.

In some cases, for some radionuclides, the shape of the urine excretion pattern can be used to determine the absorption type of a material following an intake. However, when the urine excretion patterns for the various absorption types are similar in shape, the specific absorption type can not be determined from the urine excretion pattern. Referring to Figure C.8.23, this discrimination would not be possible until after day 100, and only for Type M or S materials. It would not be possible to distinguish an intake of Type F material from an intake of HTO.

This difficulty is illustrated in Figure C.8.24, which plots the value of the IECs normalized to one unit at day 1 after intake. As expected, the curves for HTO and Type F STCs are essentially indistinguishable. Note also that it would be very difficult to distinguish between the curves for Type M or Type S STCs and HTO until 50 or so days post inhalation. This difficulty is discussed further in Section C.8.8.5 below.

Similar curves would be expected for other common STC materials.

Figure C.8.23

Comparison of Intake Excretion Concentrations – Titanium Tritide

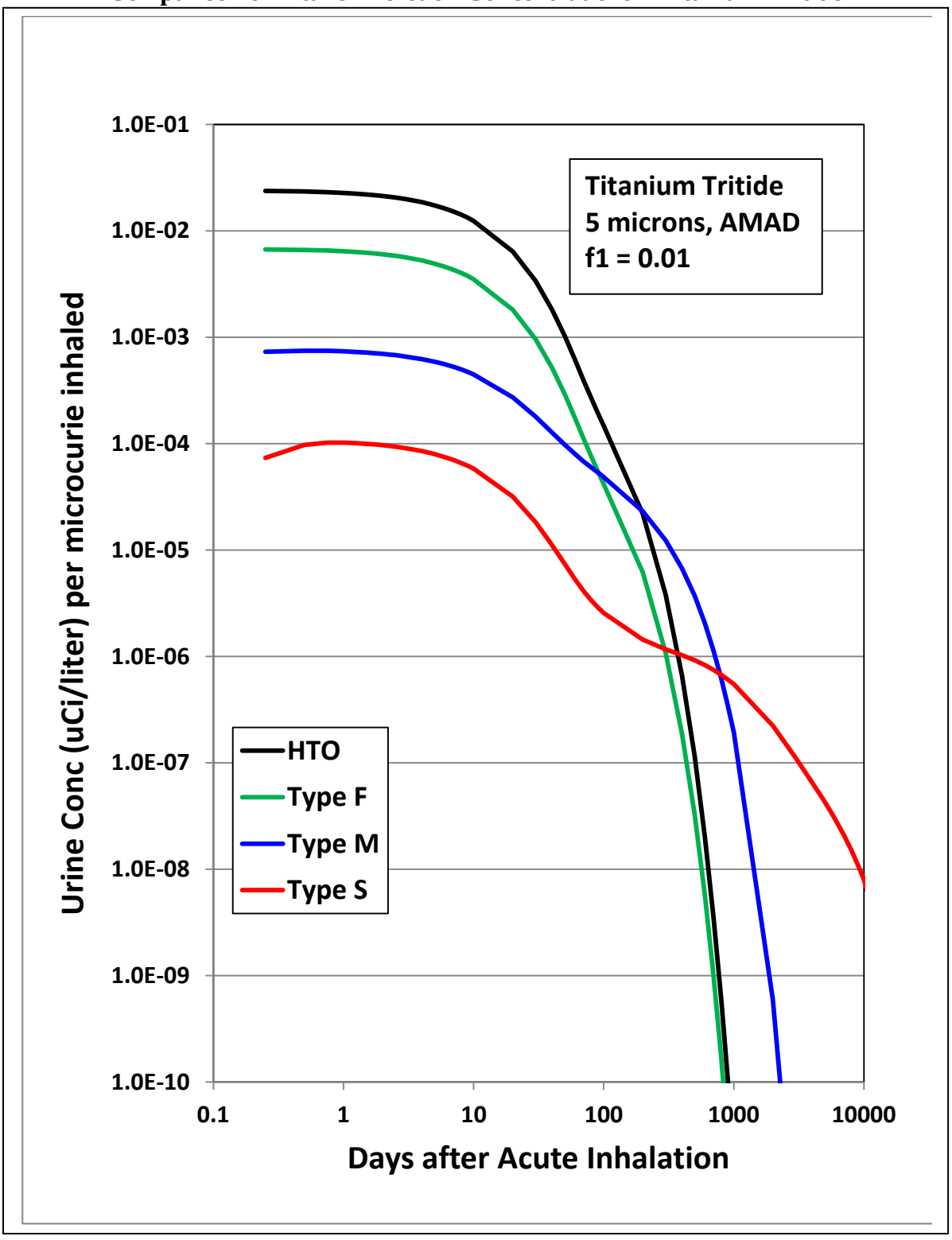
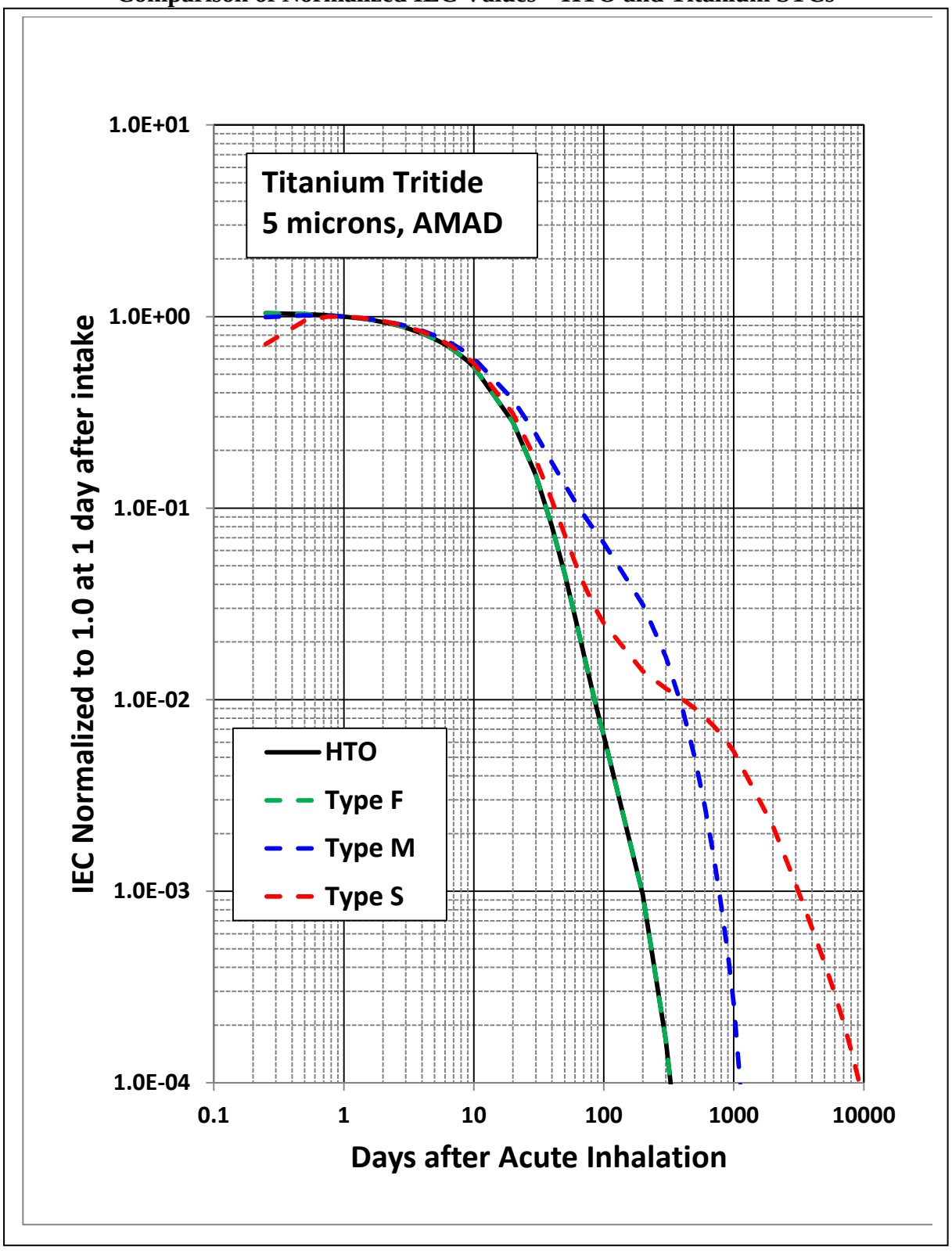


Figure C.8.24

Comparison of Normalized IEC Values – HTO and Titanium STCs



C.8.6 Interpretation of Bioassay Results

C.8.6.1 Intake Estimators

Figures C.8.25 through C.8.31 below show the intake implied by a urine bioassay result of 1 μCi/liter for selected STC materials as a function of absorption type and time after intake. A default occupational particle size distribution of 5 microns, AMAD, is assumed.

As discussed above, the estimate of intake is derived directly from the Intake Excretion Concentration. As such, it is solely a function of absorption type, particle size distribution, and f1 value. Self Absorption Factors play no role in determining intake excretion fractions. Accordingly, these curves are not element-specific. Thus for example, the "Hafnium" curves may be used for any element with an f1 factor of 0.002.

The following general observations can be made for all STC compounds:

a) Since these curves are essentially the reciprocals of the IEC curves, one sees a great difference in the implied intakes between Types F, M and S materials.
b) After about 10 days post-inhalation, the curves for all three types of materials begin to turn up sharply.
c) The curves for the various materials are generally similar, but reflect the different f1 values assumed for the material in question.

The effect of different f1 values is most pronounced in Type S materials, as seen in Figure C.8.32. The curves in this figure (essentially the reciprocals of IEC curves of Figure C.8.22) reflect the fact that at very low f1 values, a much smaller fraction of the intake is absorbed from the GI Tract into systemic distribution (and thence to the urine) – so the IEC value is very low, and the corresponding implied intake (per unit activity concentration) is very high.

Figure C.8.25

Intake Estimator – Erbium STCs – 5 microns, AMAD, f1 = 0.0005

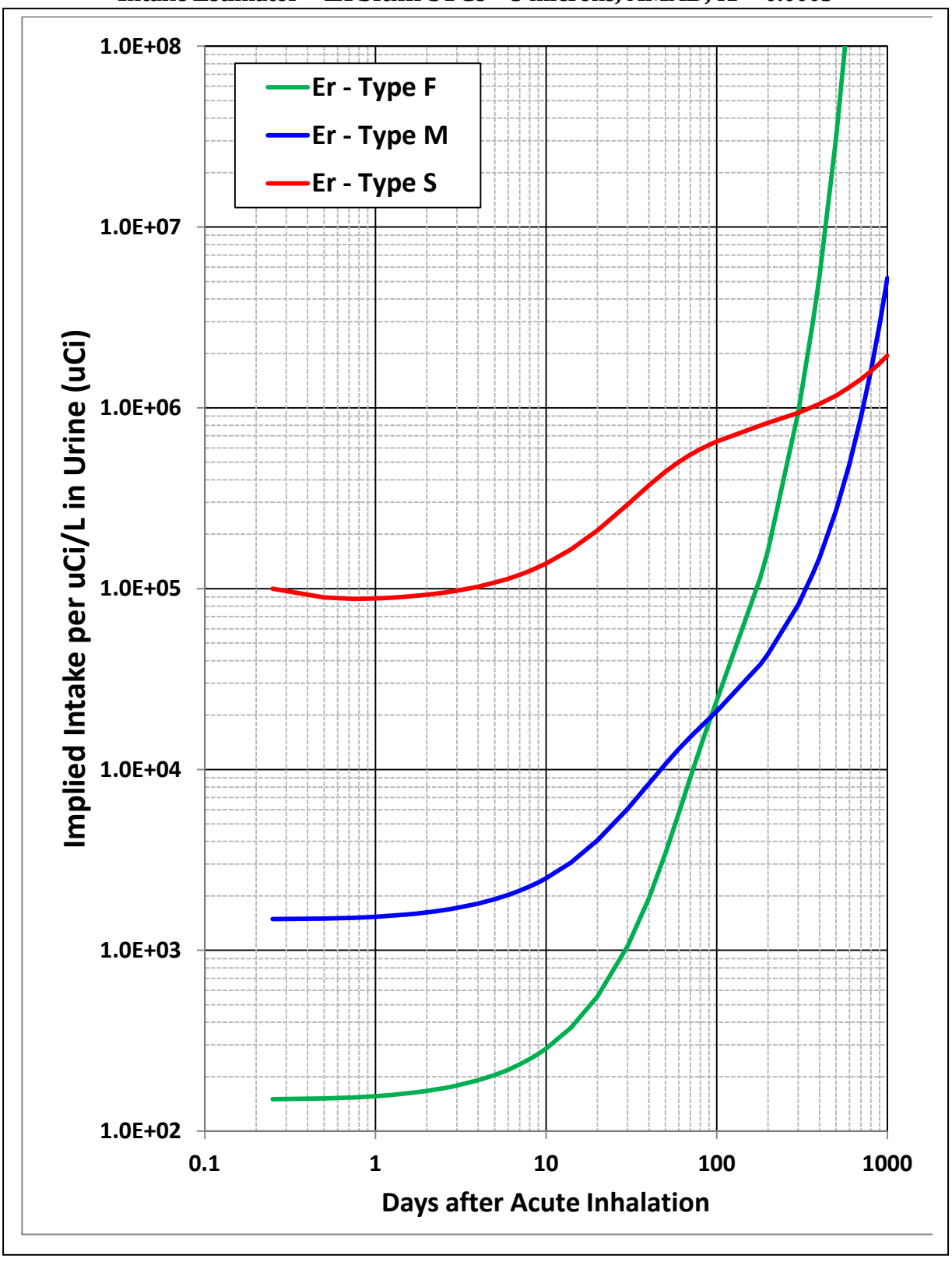


Figure C.8.26

Intake Estimator – Hafnium STCs – 5 microns, AMAD, f1 = 0.002

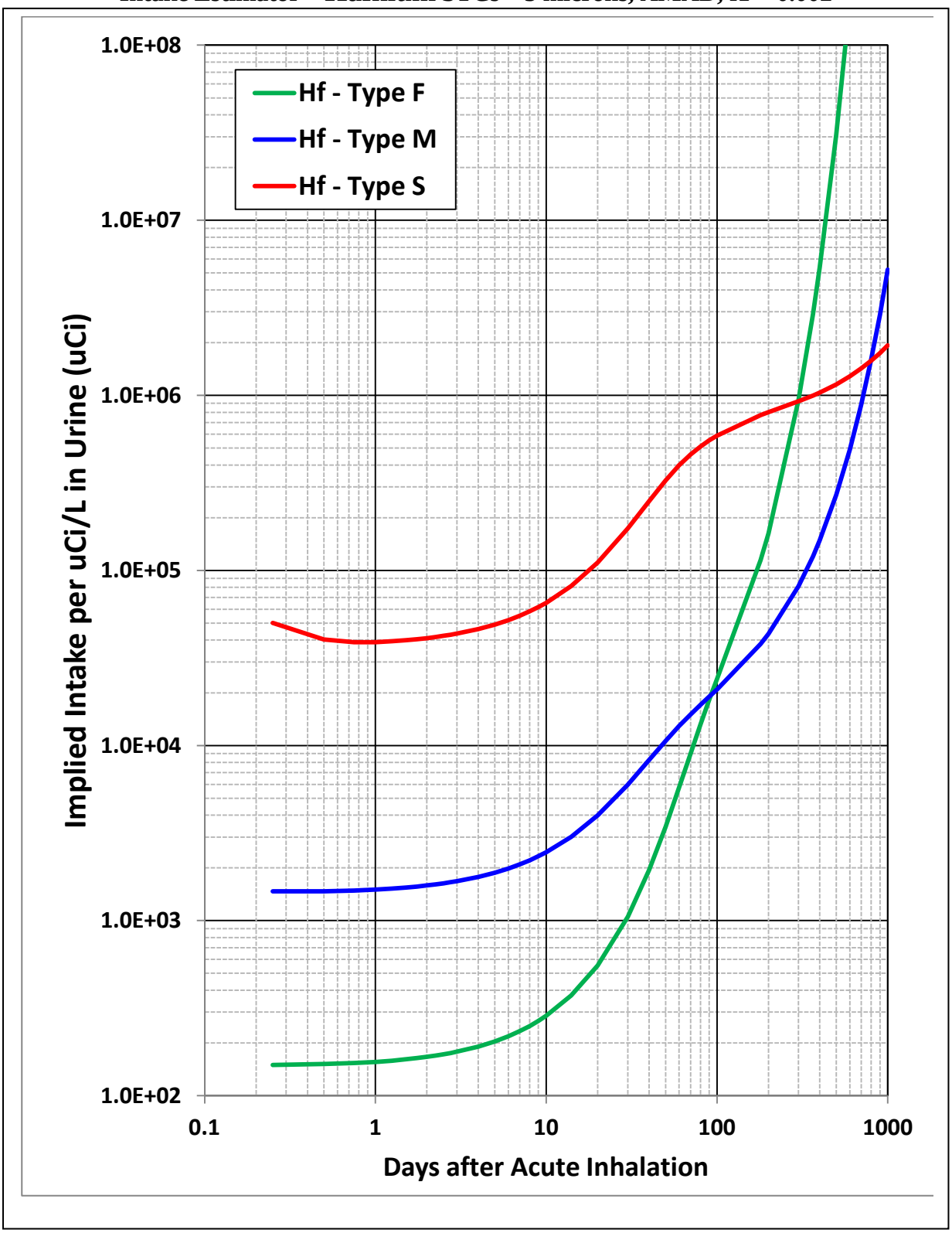


Figure C.8.27

Intake Estimator – Scandium STCs – 5 microns, AMAD, f1 = 0.0001

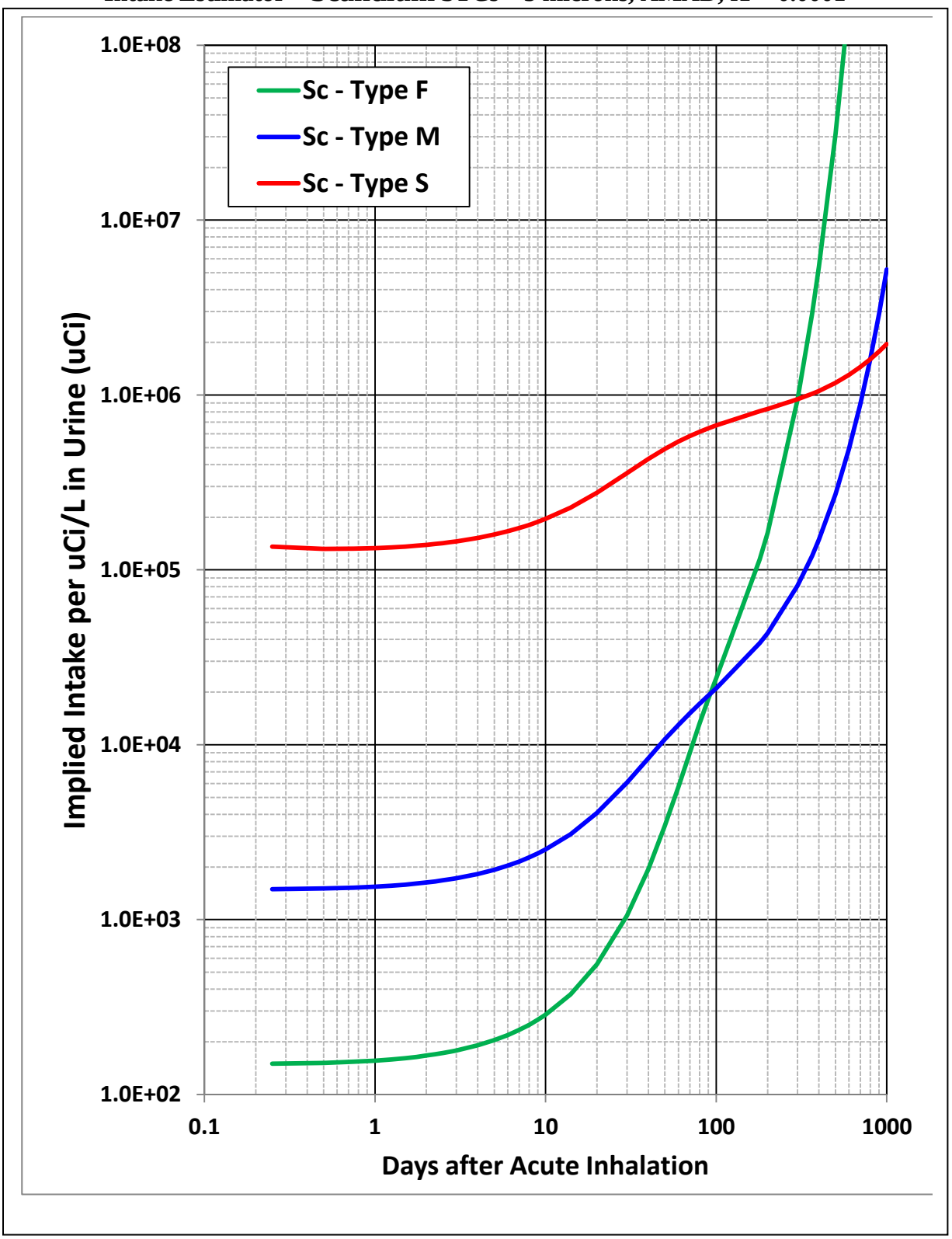


Figure C.8.28

Intake Estimator – Titanium STCs – 5 microns, AMAD, f1 = 0.01

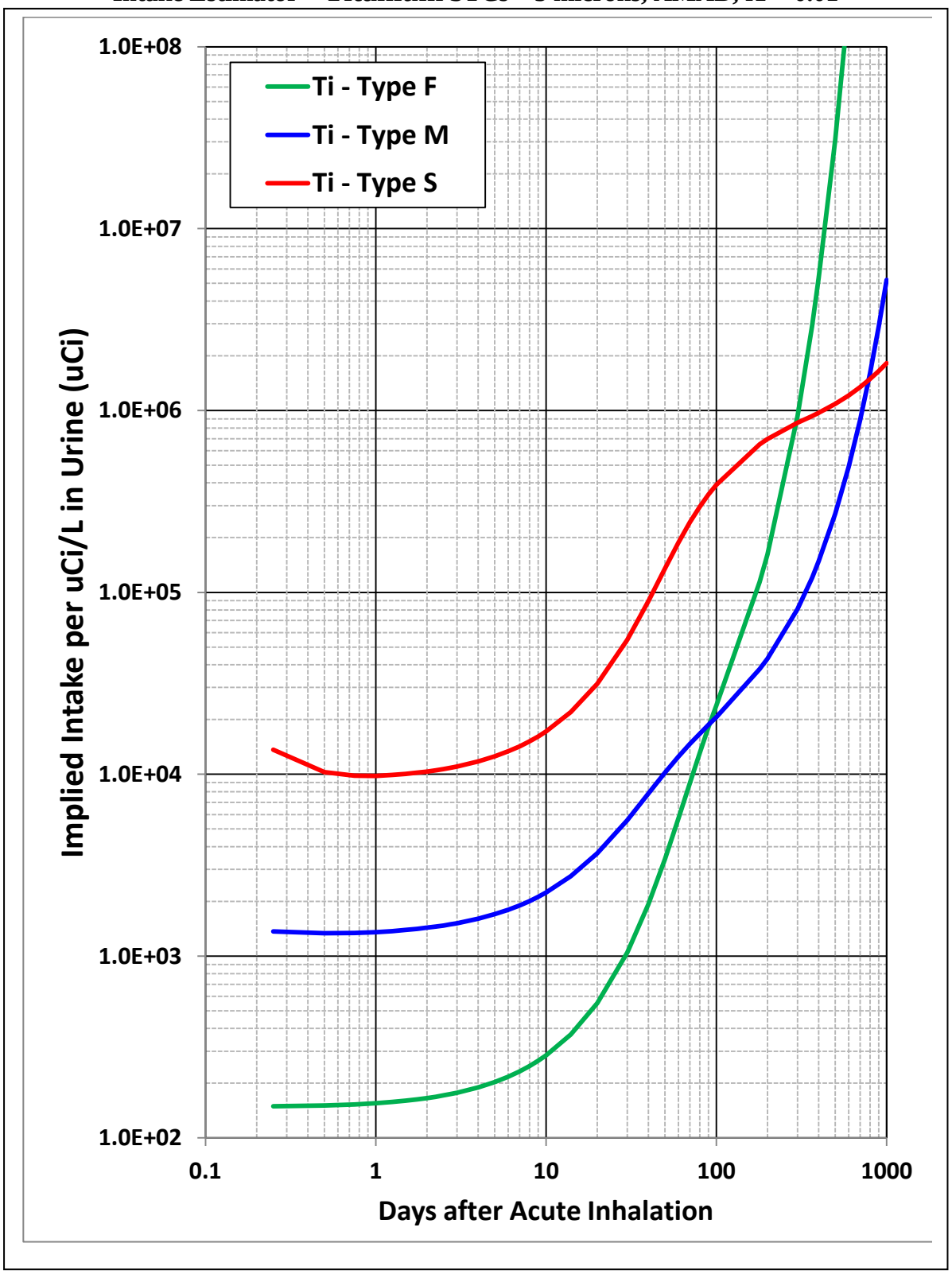


Figure C.8.29

Intake Estimator – Zirconium STCs – 5 microns, AMAD, f1 = 0.002

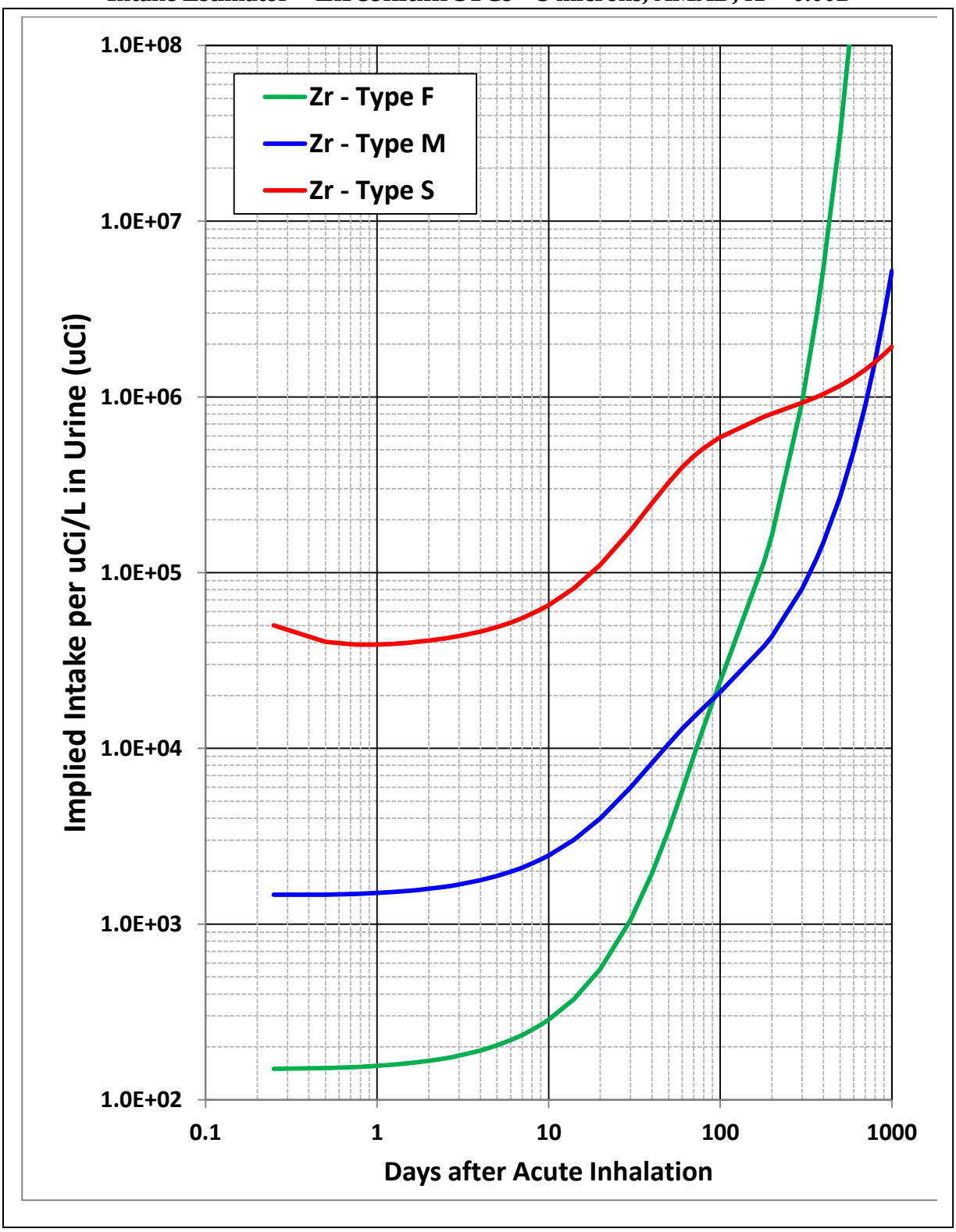


Figure C.8.30

Intake Estimator – Gold STCs - 5 microns AMAD, f1 = 0.1

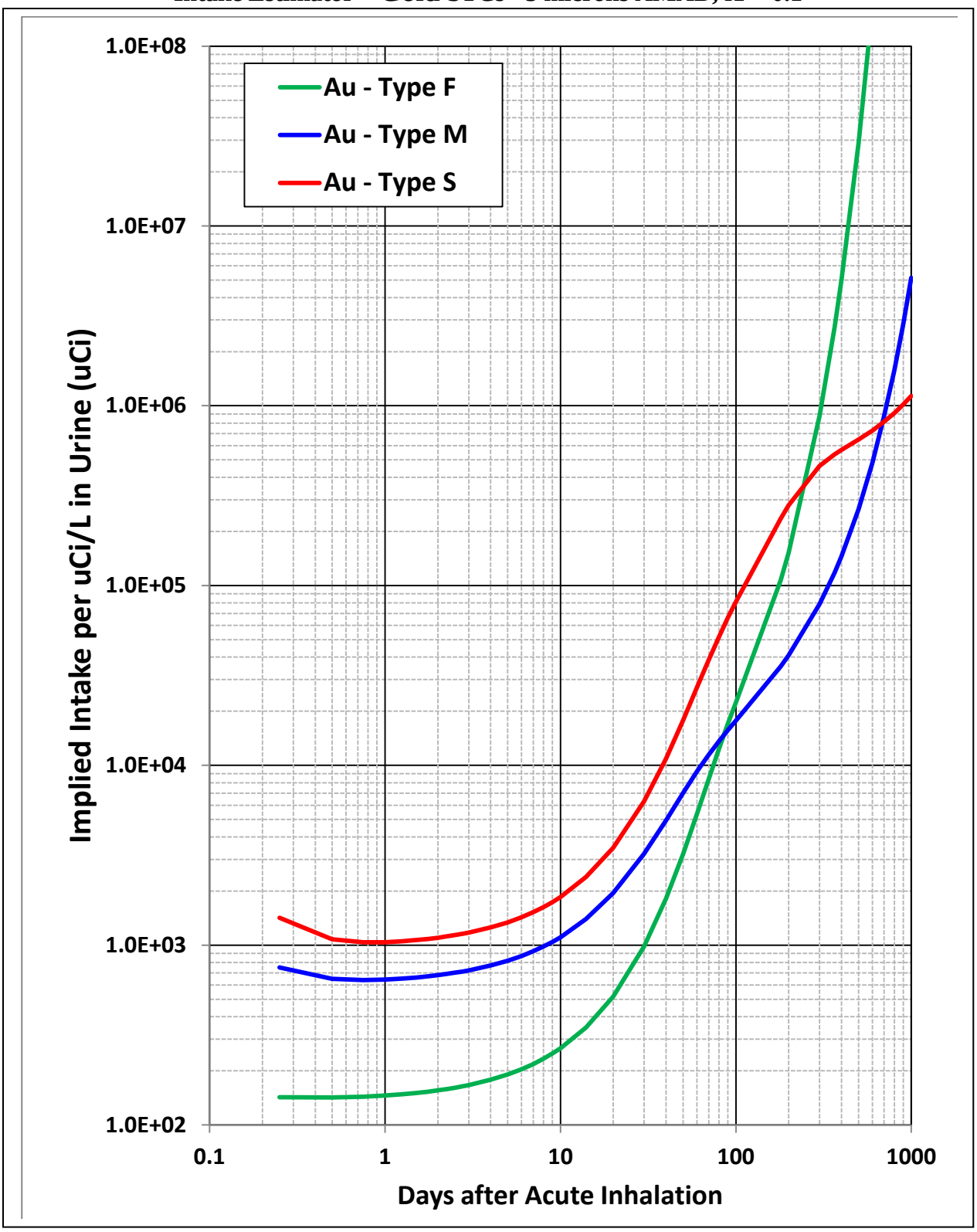


Figure C.8.31

Intake Estimator – Zinc Oxide STCs - 5 microns AMAD, f1 = 0.5

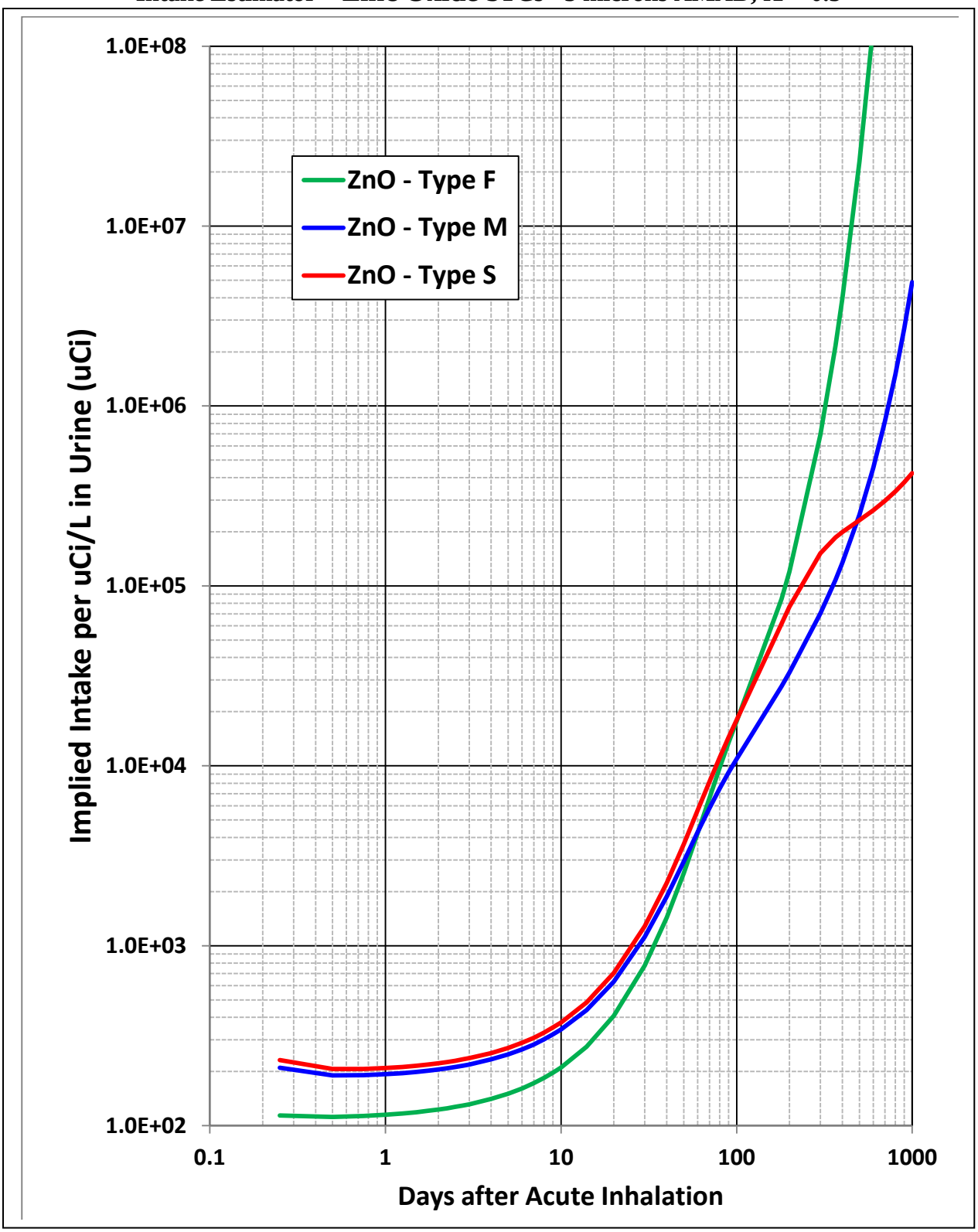
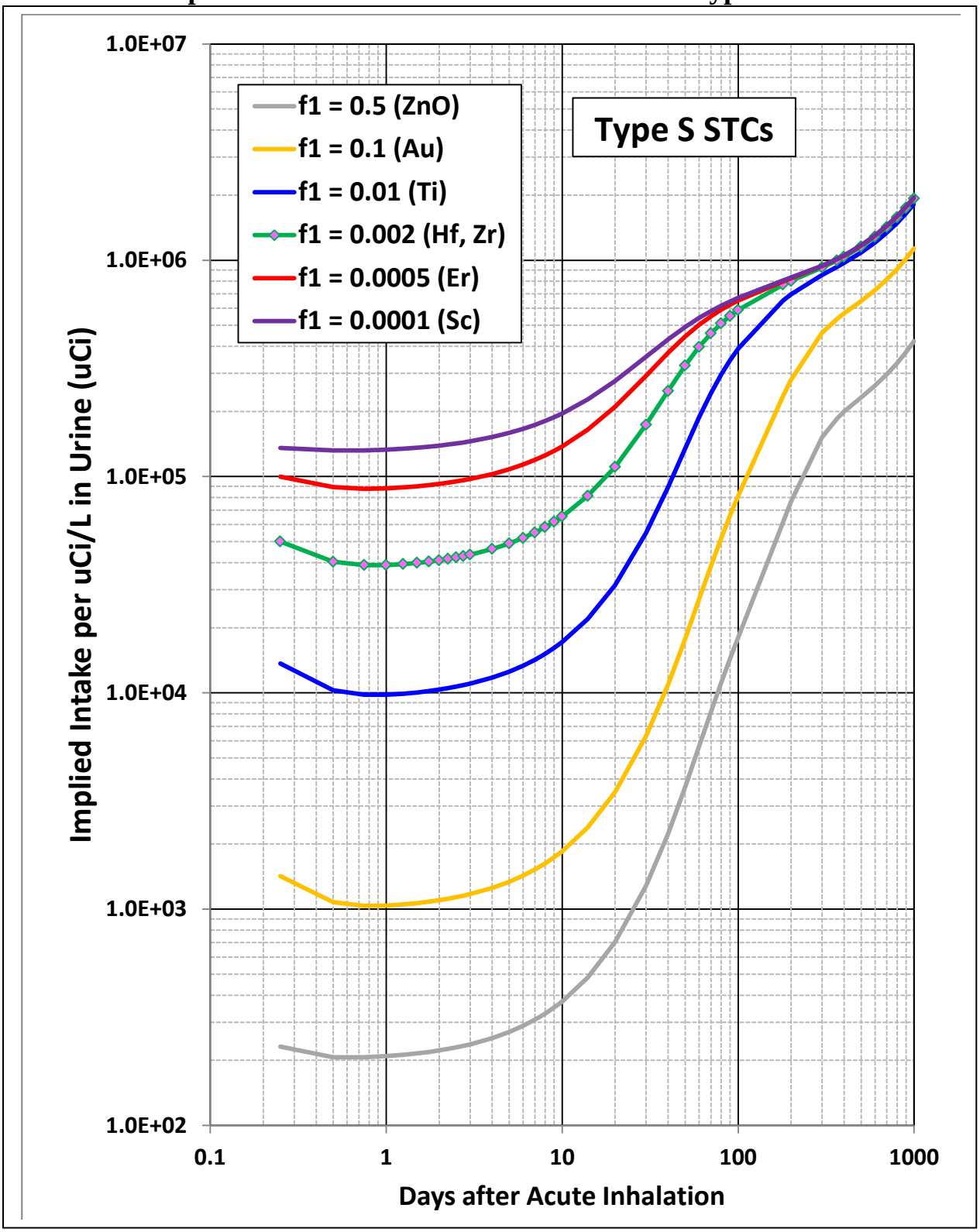


Figure C.8.32

Comparison of Intake Estimation Curves for Type S STCs



C.8.6.2 Dose Estimators

Figures C.8.33 through C.8.39 below show the dose (committed effective dose, in rem) implied by a urine bioassay result of 1 μCi/liter for selected STC materials as a function of absorption type and time after intake. These curves are derived by multiplying the implied intake by the appropriate dose conversion factors. These theoretical curves are applicable only to intakes of STC materials that are unadulterated by intakes of HTO.

These families of curves are very similar to the intake estimator curves seen above – but they have been scaled by the appropriate absorption type, f1, and SAF_e-specific dose conversion factors (from Table C.8.5). Accordingly, these estimated doses are not only a function of the estimated intake, but are also a function of the assumed self-absorption factors – which are element, density, and particle-size specific (see Section C.8.3.5 for discussion).

The following general observations can be made:

a) For all elements, the dose implied for Type S materials is far higher than for Type M or Type F materials – due to the much higher implied intake (lower IEC values), and the somewhat higher dose conversion factors.

b) After about ten days post-inhalation, all the curves begin to turn up rapidly. This rapid increase is most pronounced for Type F materials since it reflects the rapid (roughly 10 day halftime) clearance of systemic HTO. The Type M and Type S curves reflect the delayed clearance of tritium activity from the lungs into systemic distribution.

The implied dose curves for selected Type S materials are compared in Figure C.8.40. These curves reflect not only the different IEC values (driven largely by the differing f1 values) but also the differences in SAF_e values, which lower the contributions from the lung and GI Tract doses.

Thus, for example, the lowest curve is that for ZnO, which has the highest f1 value (0.5), resulting in the highest IEC and the correspondingly lowest estimated intake. These low estimated intake values dominate the position of the curve – despite the relatively high SAF_e value for ZnO.

Figure C.8.33

Dose Estimator – Erbium STCs, f1 = 0.0005, 5 microns AMAD, SAF_e = 0.2945

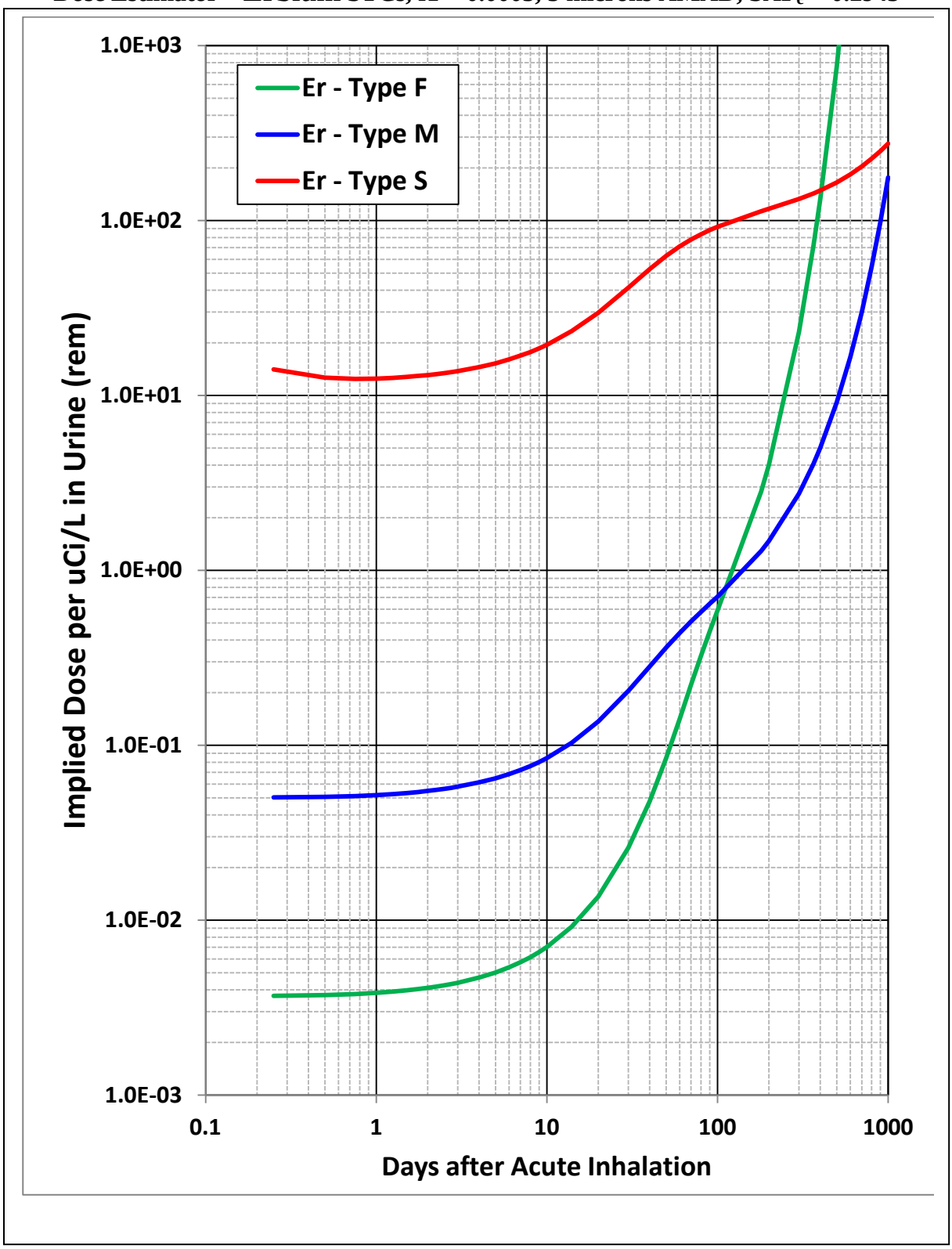


Figure C.8.34

Dose Estimator – Hafnium STCs, f1 = 0.002, 5 microns AMAD, SAF_e = 0.2585

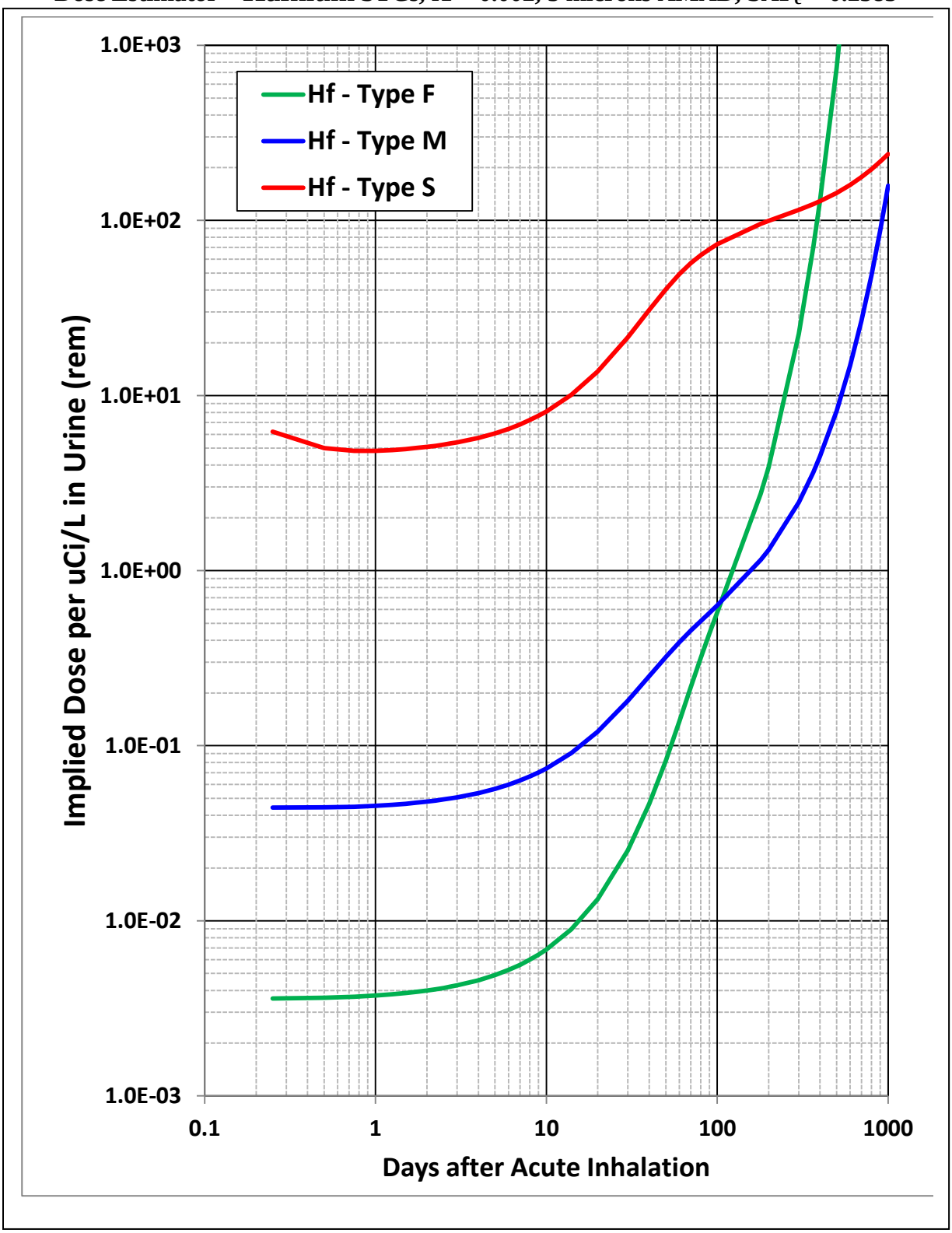


Figure C.8.35

Dose Estimator – Scandium STCs, f1 = 0.0001, 5 microns AMAD, SAF_e = 0.3839

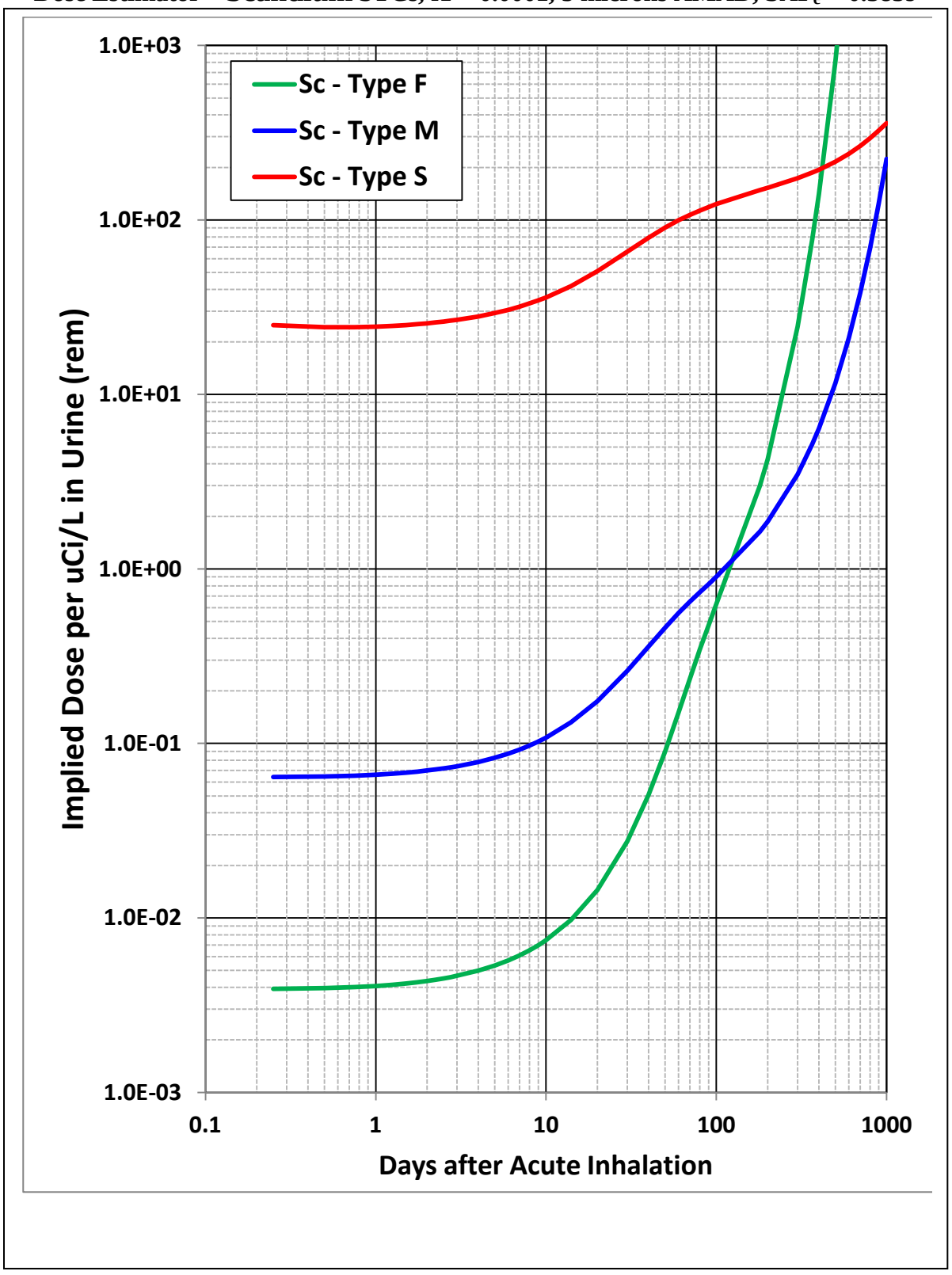


Figure C.8.36

Dose Estimator – Titanium STCs, f1 = 0.01, 5 microns AMAD, SAFe = 0.3613

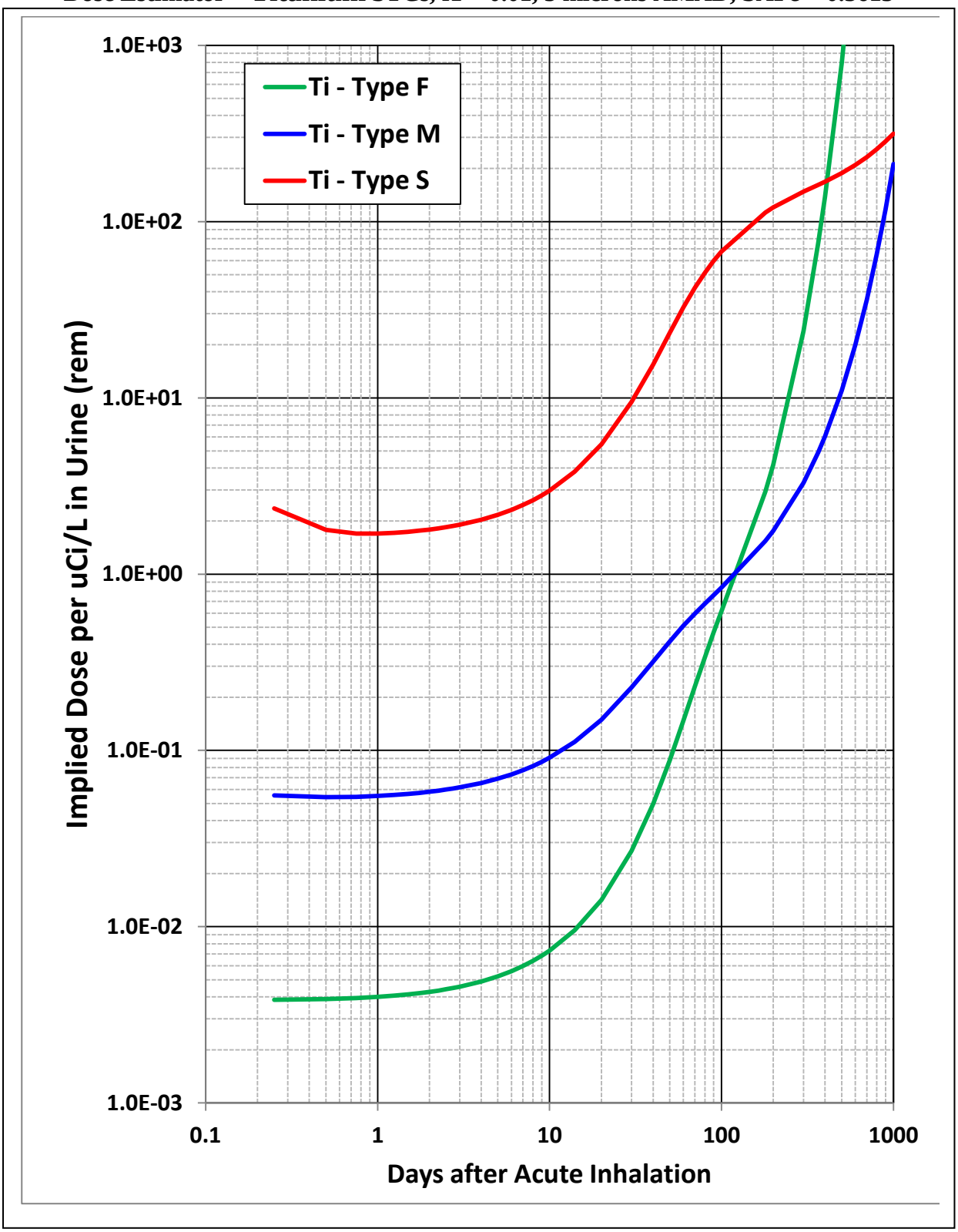


Figure C.8.37

Dose Estimator – Zirconium STCs, f1 = 0.002, 5 microns AMAD, SAF_e = 0.3114

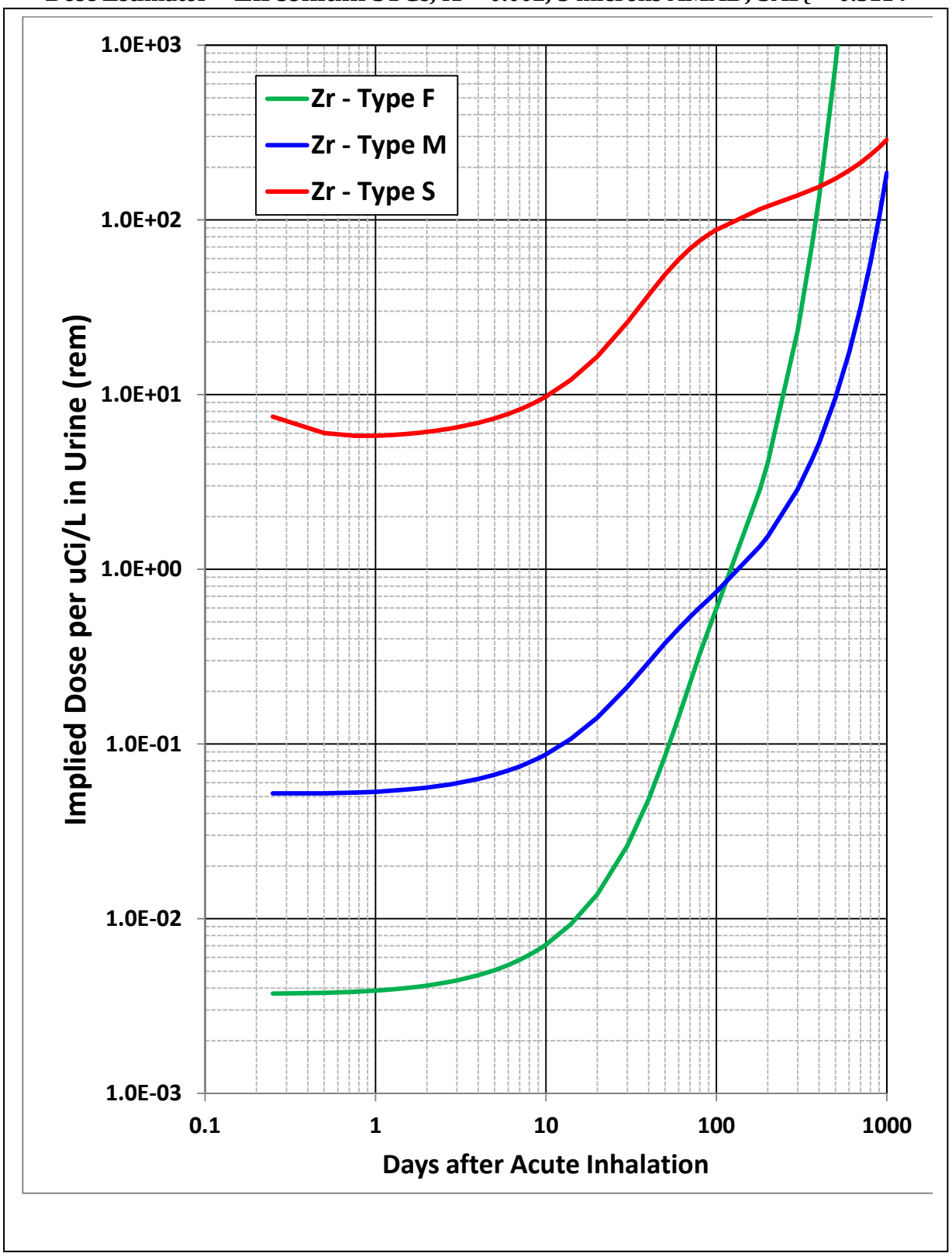


Figure C.8.38

Dose Estimator – Gold STCs, f1 = 0.1, 5 microns AMAD, SAF_e = 0.2066

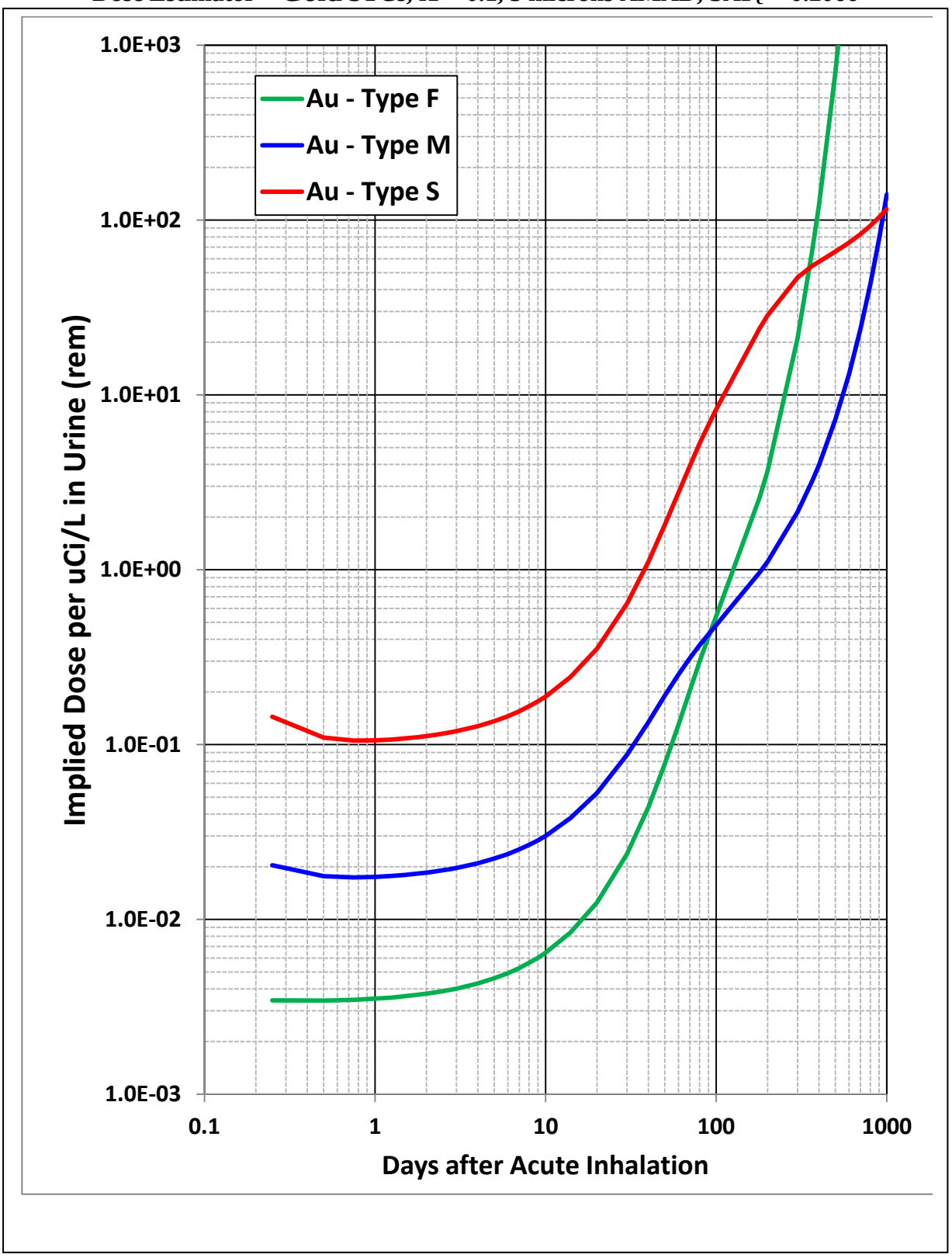


Figure C.8.39

Dose Estimator – Zinc Oxide STCs, f1 = 0.5, 5 microns AMAD, SAF_e = 0.4211

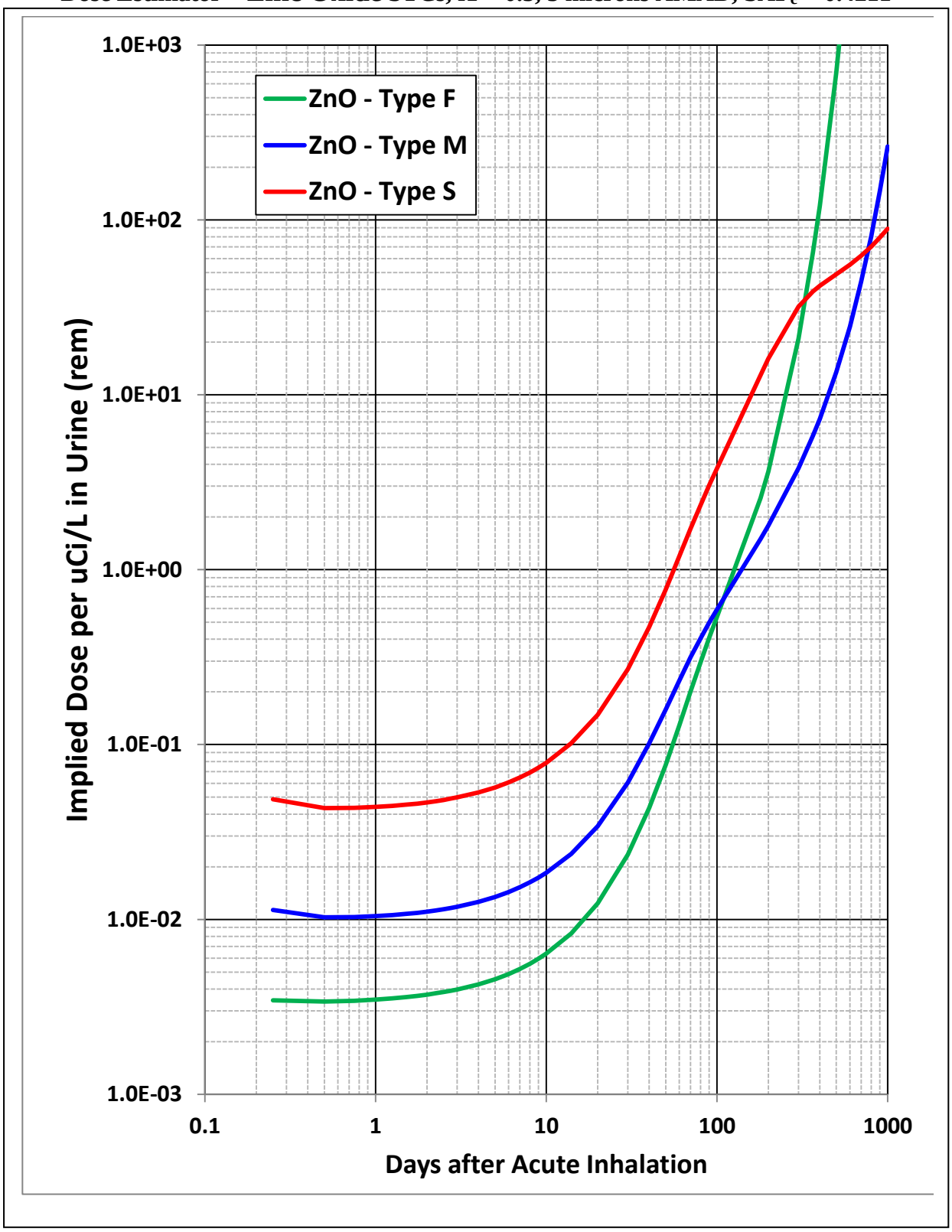
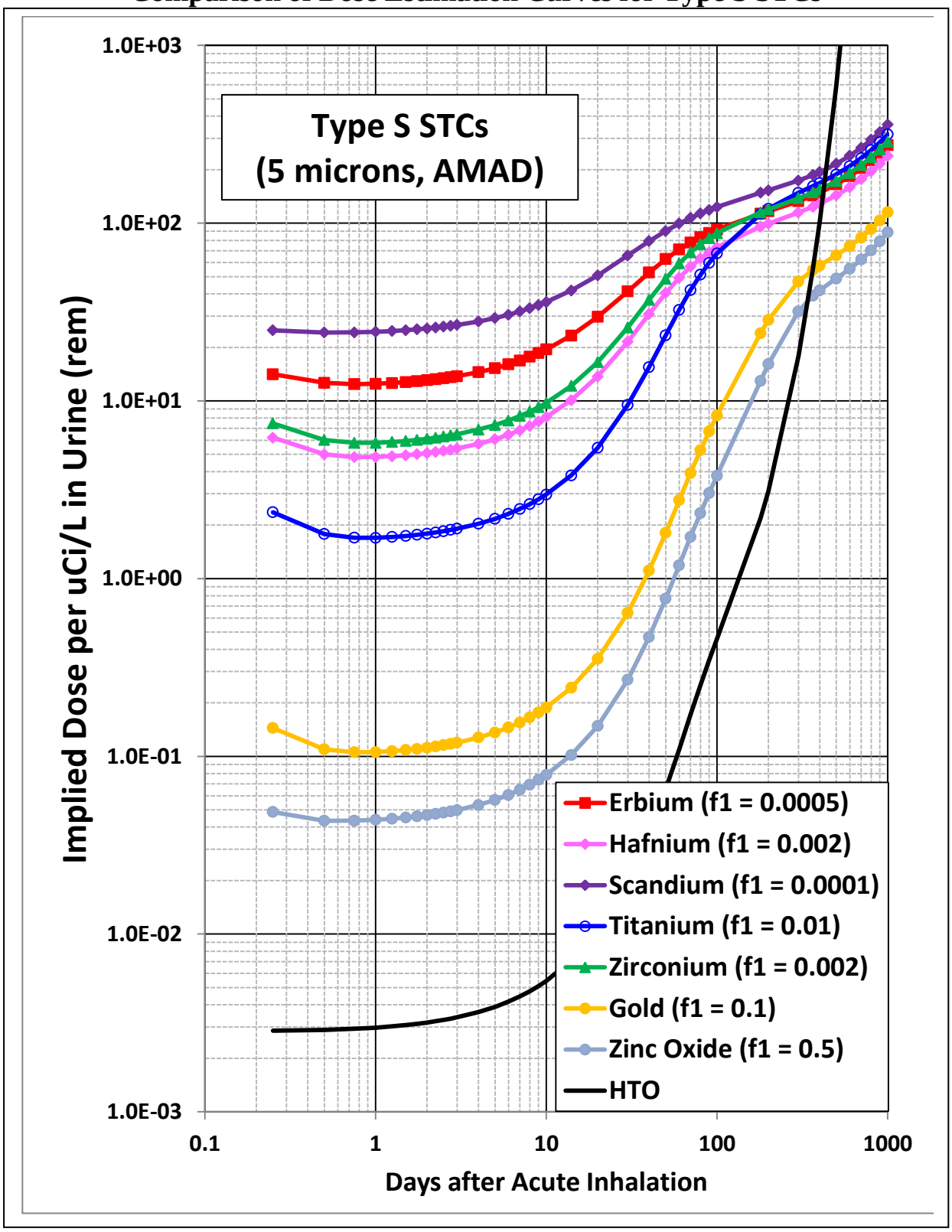


Figure C.8.40

Comparison of Dose Estimation Curves for Type S STCs



C.8.6.3 Urine Bioassay Factors (MDDs and DILs)

C.8.6.3.1 Minimum Detectable Doses for Urine Sampling for STCs

In the case of urine monitoring for STCs, the MDD is simply the dose implied by 1.0 μCi per liter (as presented in Section C.8.6.2) multiplied by the Minimum Detectable Concentration for tritium in urine (conservatively assumed to be 0.01 μCi/liter). It is important to recall that these MDD values are for intakes of "pure" STCs, unadulterated by concomitant intakes of HTO.

Table C.8.9

Summary of Urine Sampling MDD Values for Selected STCs
(Inhalation, 5 microns, AMAD, MDC = 0.01 μCi/liter)

Sample Interval	7 days	14 days	30 days	60 days	90 days
STC Material	MDD (rem)	MDD (rem)	MDD (rem)	MDD (rem)	MDD (rem)
Erbium - Type F	5.75E-05	9.17E-05	2.59E-04	1.41E-03	4.49E-03
Erbium - Type M	7.22E-04	1.03E-03	2.05E-03	4.39E-03	6.44E-03
Erbium - Type S	1.69E-01	2.33E-01	4.13E-01	7.11E-01	8.81E-01
Hafnium – Type F	5.60E-05	8.94E-05	2.52E-04	1.38E-03	4.37E-03
Hafnium – Type M	6.33E-04	9.08E-04	1.81E-03	3.90E-03	5.74E-03
Hafnium – Type S	6.83E-02	1.01E-01	2.15E-01	4.93E-01	6.85E-01
Scandium – Type F	6.10E-05	9.74E-05	2.75E-04	1.50E-03	4.77E-03
Scandium – Type M	9.22E-04	1.32E-03	2.61E-03	5.58E-03	8.19E-03
Scandium – Type S	3.19E-01	4.18E-01	6.58E-01	9.95E-01	1.19E+00
Titanium – Type F	5.98E-05	9.55E-05	2.70E-04	1.47E-03	4.67E-03
Titanium – Type M	7.73E-04	1.12E-03	2.27E-03	5.09E-03	7.60E-03
Titanium – Type S	2.46E-02	3.81E-02	9.49E-02	3.25E-01	5.98E-01
Zirconium – Type F	5.81E-05	9.27E-05	2.62E-04	1.43E-03	4.54E-03
Zirconium – Type M	7.43E-04	1.07E-03	2.12E-03	4.58E-03	6.74E-03
Zirconium – Type S	8.22E-02	1.21E-01	2.59E-01	5.93E-01	8.24E-01
Gold – Type F	5.27E-05	8.42E-05	2.38E-04	1.30E-03	4.12E-03
Gold – Type M	2.51E-04	3.79E-04	8.76E-04	2.51E-03	4.27E-03
Gold – Type S	1.55E-03	2.43E-03	6.42E-03	2.76E-02	6.73E-02
Zinc Oxide – Type F	5.21E-05	8.32E-05	2.35E-04	1.28E-03	4.08E-03
Zinc Oxide – Type M	1.53E-04	2.37E-04	6.05E-04	2.32E-03	4.97E-03
Zinc Oxide – Type S	6.48E-04	1.02E-03	2.70E-03	1.19E-02	3.03E-02

Values in red are greater than 0.1 rem.

Figures C.8.41 through C.8.43 present MDD value for inhalation of selected Type F, M, and S STC materials with a particle size distribution of 5 microns, AMAD.

As expected, urine sampling for Type F STCs (Figure C.8.41) provides a good deal of sensitivity until about 100 days post inhalation. The material and f1 value make essentially no difference to the MDD values. The rapid increase in MDD values after about 10 days reflects the rapid clearance of HTO from systemic distribution.

In the case of Type M STCs (Figure C.8.42), one begins to see a differentiation in MDD values in the first 100 days post inhalation – due to differences in f1 values, IEC values, and dose conversion factors. However, the sensitivity of urine sampling for Type M STC materials is still quite good up to about 100 days post inhalation.

For Type S STCs (Figure C.8.43) the great difference in IEC values, coupled with differences in dose conversion factors, produce widely separated MDD curves – all of which are much higher than the corresponding Type M or S curves. The high f1 values (leading to high IEC values) for gold and zinc oxide give reasonably good sensitivity up until about 60 days post inhalation. The sensitivity for materials with lower f1 values (higher IEC values) is relatively poor.

Figure C.8.41

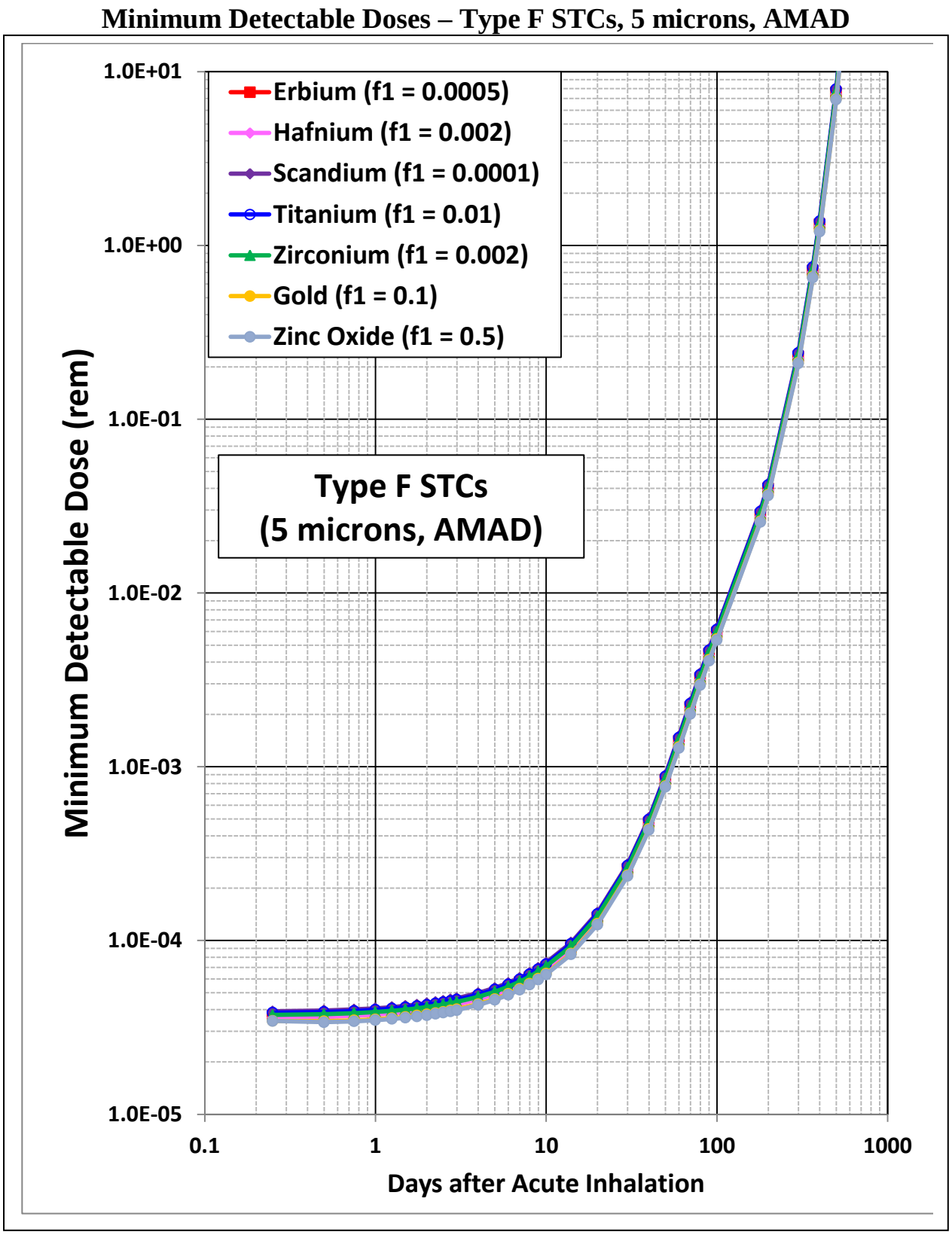

Minimum Detectable Doses – Type F STCs, 5 microns, AMAD
Erbium (f1 = 0.0005)
Hafnium (f1 = 0.002)
Scandium (f1 = 0.0001)
Titanium (f1 = 0.01)
Zirconium (f1 = 0.002)
Gold (f1 = 0.1)
Zinc Oxide (f1 = 0.5)
Type F STCs
(5 microns, AMAD)
Minimum Detectable Dose (rem)
1.0E+01
1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
0.1
1
10
100
1000
Days after Acute Inhalation

Figure C.8.42

Minimum Detectable Doses – Type M STCs, 5 microns, AMAD

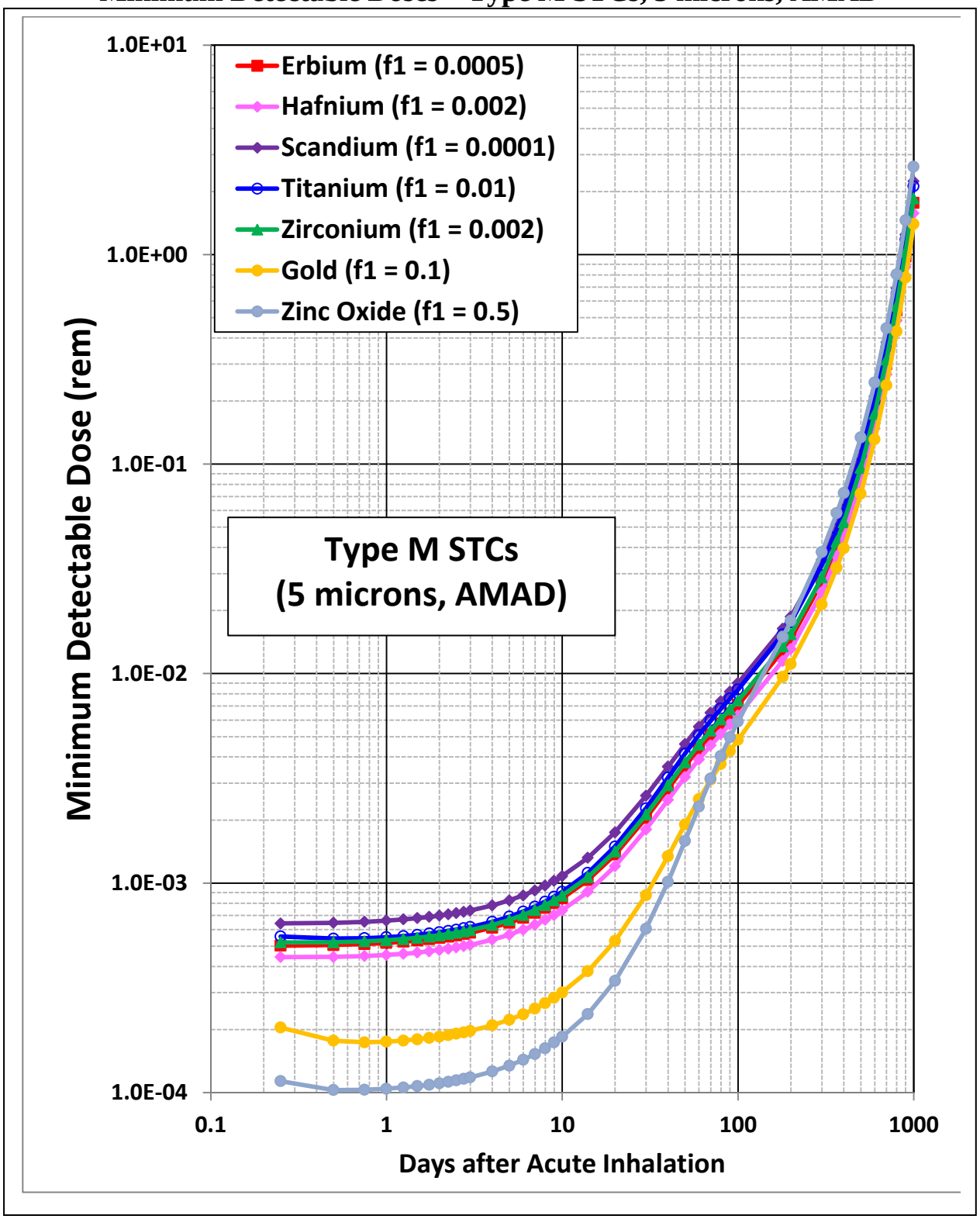
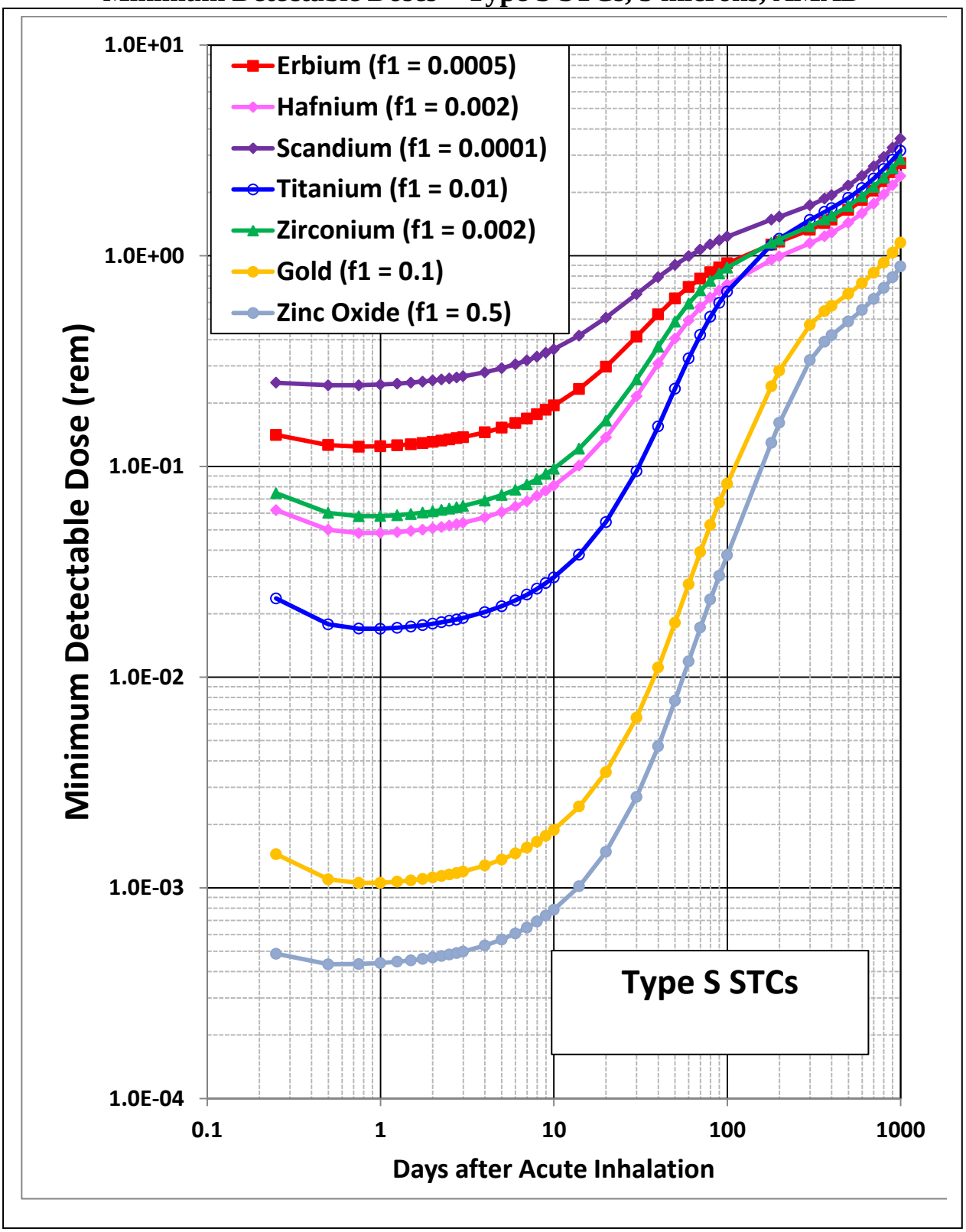


Figure C.8.43

Minimum Detectable Doses – Type S STCs, 5 microns, AMAD



C.8.6.3.2 Derived Investigation Levels for Urine Sampling for STCs

The Derived Investigation Level (DIL), as defined in Section 2.5, is that result (for a particular radioactive material, analysis method, and route of intake) which implies a committed effective dose equal to the Investigation Level dose of 0.1 rem CED. The DIL is inversely related to the concept of "Minimum Detectable Activity".

Table C.8.10

Summary of Urine Sampling DIL Values for Selected STCs

Sample Interval	7 days	14 days	30 days	60 days	90 days
STC Material	DIL (μCi/liter)	DIL (μCi/liter)	DIL (μCi/liter)	DIL (μCi/liter)	DIL (μCi/liter)
Erbium - Type F	1.74E+01	1.09E+01	3.86E+00	7.08E-01	2.23E-01
Erbium - Type M	1.39E+00	9.67E-01	4.89E-01	2.28E-01	1.55E-01
Erbium - Type S	5.93E-03	4.29E-03	2.42E-03	1.41E-03	1.14E-03
Hafnium – Type F	1.79E+01	1.12E+01	3.96E+00	7.26E-01	2.29E-01
Hafnium – Type M	1.58E+00	1.10E+00	5.54E-01	2.57E-01	1.74E-01
Hafnium – Type S	1.46E-02	9.91E-03	4.65E-03	2.03E-03	1.46E-03
Scandium – Type F	1.64E+01	1.03E+01	3.64E+00	6.67E-01	2.10E-01
Scandium – Type M	1.08E+00	7.57E-01	3.83E-01	1.79E-01	1.22E-01
Scandium – Type S	3.14E-03	2.39E-03	1.52E-03	1.00E-03	8.43E-04
Titanium – Type F	1.67E+01	1.05E+01	3.71E+00	6.80E-01	2.14E-01
Titanium – Type M	1.29E+00	8.94E-01	4.40E-01	1.97E-01	1.32E-01
Titanium – Type S	4.06E-02	2.63E-02	1.05E-02	3.07E-03	1.67E-03
Zirconium – Type F	1.72E+01	1.08E+01	3.82E+00	7.00E-01	2.20E-01
Zirconium – Type M	1.35E+00	9.37E-01	4.71E-01	2.18E-01	1.48E-01
Zirconium – Type S	1.22E-02	8.24E-03	3.86E-03	1.69E-03	1.21E-03
Gold – Type F	1.90E+01	1.19E+01	4.21E+00	7.71E-01	2.43E-01
Gold – Type M	3.98E+00	2.64E+00	1.14E+00	3.98E-01	2.34E-01
Gold – Type S	6.45E-01	4.11E-01	1.56E-01	3.63E-02	1.49E-02
Zinc Oxide – Type F	1.92E+01	1.20E+01	4.26E+00	7.80E-01	2.45E-01
Zinc Oxide – Type M	6.54E+00	4.21E+00	1.65E+00	4.32E-01	2.01E-01
Zinc Oxide – Type S	1.54E+00	9.84E-01	3.71E-01	8.41E-02	3.30E-02

Values in red are less than the MDA of 0.01 μCi/liter.

Figures C.8.44 through C.8.46 present DIL value for inhalation of selected Type F, M, and S STC materials with a particle size distribution of 5 microns, AMAD. As with the above MDD figures, these curves represent DILs for intakes of "pure" STCs – unadulterated by any concomitant intake of HTO.

For all Type F STC materials, the DIL value is well above the Minimum Detectable Concentration (nominally assumed to be 0.01 μCi/liter) for sampling intervals up to about 200 days. As with the Type F MDD curves, the rapid decrease in Type F DIL values is due to the rapid systemic clearance of HTO.

The DIL values for Type M STC materials begin to reflect the different intake excretion curves and, to a lesser extent, the differing dose conversion factors (due to the different SAF_e values.) Type M DIL values remain above the Minimum Detectable Concentration for sampling intervals up to about 400 days. (This "extension" is due to the hold-up of STCs in the lungs, thereby delaying clearance of activity from the body.)

The DIL curves for Type S materials reflect the great difference in predicted intake excretion concentrations – along with the differing dose conversion factors. Note that the respective DIL values are all significantly lower than those for Type M materials. Note also that the DIL curves for erbium and scandium STCs never exceed the Minimum Detectable Concentration of 0.01 μCi/liter.

C.8.6.3.3 Influence of Concomitant Intakes of HTO

In practice, workplaces that present the potential for exposures to STCs also present the potential for concomitant or associated exposures to HTO. Such associated intakes of HTO make the use of routine urine sampling for STC problematic – as illustrated in Figure C.8.24 above. As seen in this figure, in the first month or so after intake, the pattern of urine excretion for intakes of either HTO or STCs is very similar. And, because of the absolute difference in the magnitudes of the intake excretion fraction values, insignificant intakes of HTO can mimic significant intakes of STCs (particularly for Type S STCs.)

This problem is further illustrated in Figure C.8.47 below, which compares the urine bioassay Derived Investigation Levels (DILs) for HTO against those for Type F, Type M, and Type S Zirconium STCs. Each curve represents the concentration in urine that implies an intake that would result in a CED of 0.1 rem, as a function of the number of days after intake at which the sample was collected.

As expected, the curves for HTO and Type F zirconium STC are essentially identical. However, the values for Type M zirconium STCs are significantly lower than those for HTO, and the values for Type S zirconium STCs are (in the first 100 days) several orders of magnitude lower than those for HTO. Thus, the urinary excretion from very small concomitant intakes of HTO (if assumed to be all from a Type M or Type S STC) can lead to significant over-estimation of actual doses. Accordingly, urine sampling alone would not allow one to discriminate between intakes of HTO and STCs and accurately assess doses from those intakes.

(One could choose to interpret the urine results based on a "worst case" assumption of a 100% STC intake – however, since this approach may vastly over-estimate actual doses, it is not recommended in cases where the doses appear to be significant.)

Figure C.8.44

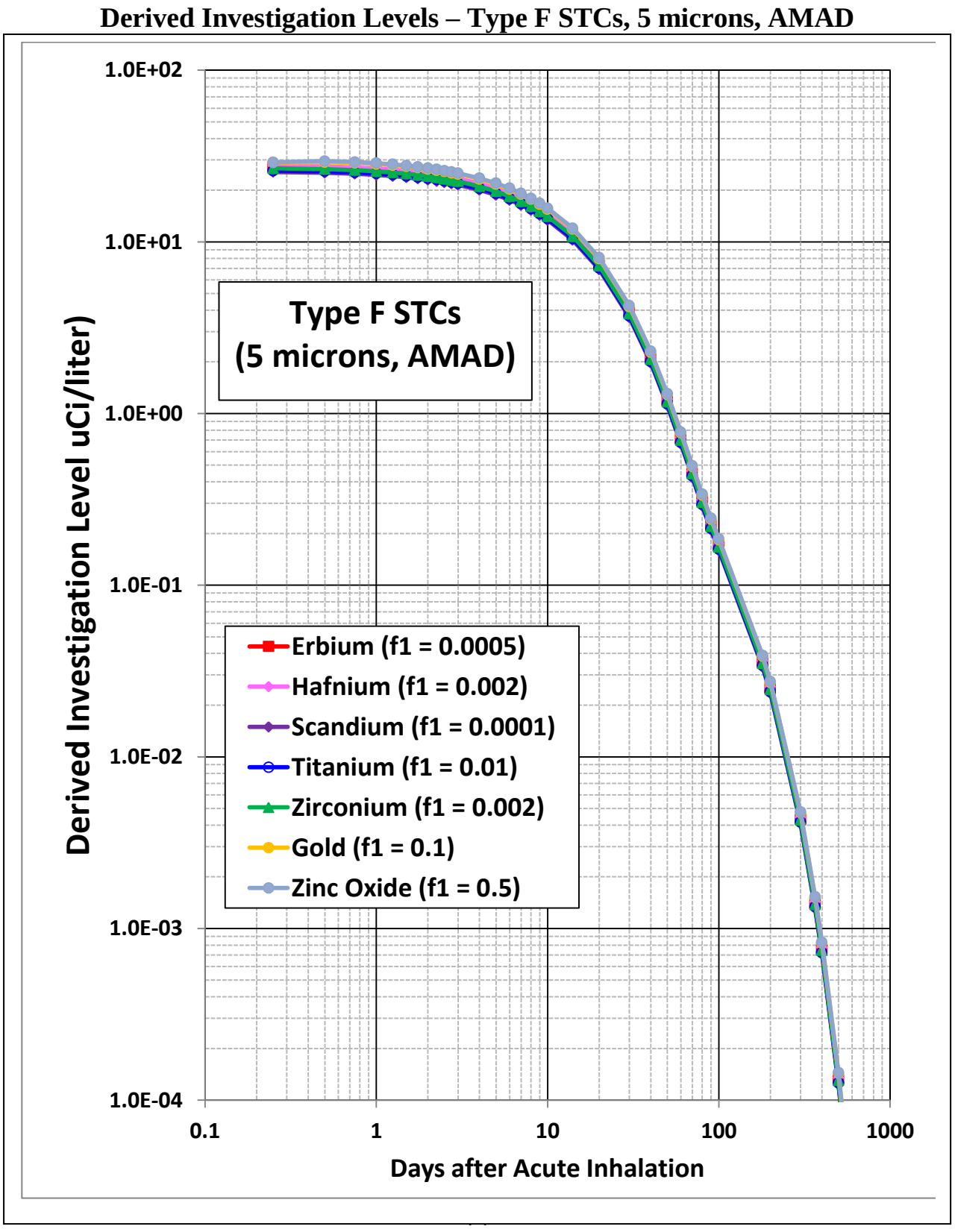

Derived Investigation Levels – Type F STCs, 5 microns, AMAD
Type F STCs
(5 microns, AMAD)
Derived Investigation Level uCi/liter)
1.0E+02
1.0E+01
1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
0.1
1
10
100
1000
Days after Acute Inhalation
Erbium (f1 = 0.0005)
Hafnium (f1 = 0.002)
Scandium (f1 = 0.0001)
Titanium (f1 = 0.01)
Zirconium (f1 = 0.002)
Gold (f1 = 0.1)
Zinc Oxide (f1 = 0.5)

Figure C.8.45

Derived Investigation Levels – Type M STCs, 5 microns, AMAD

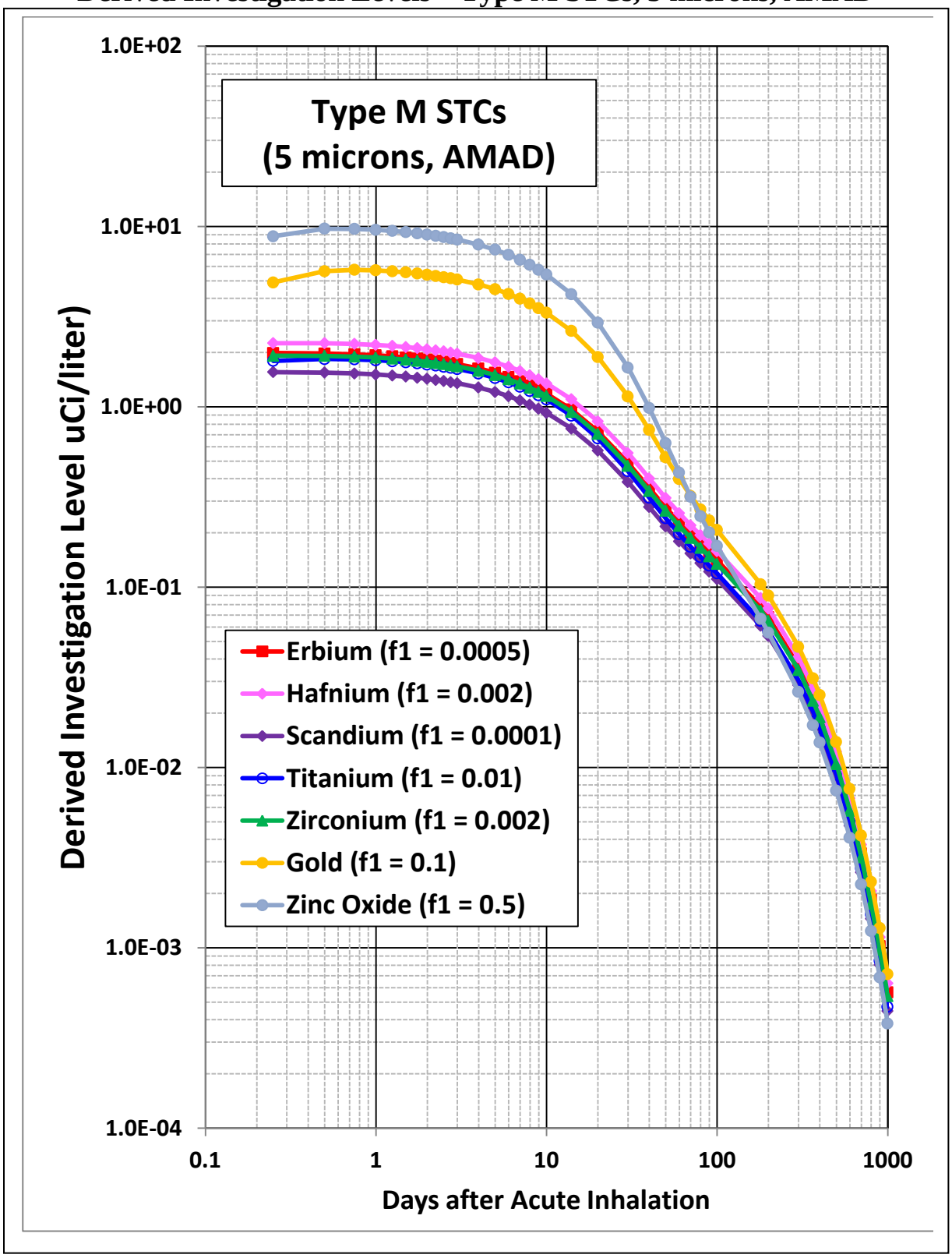


Figure C.8.46

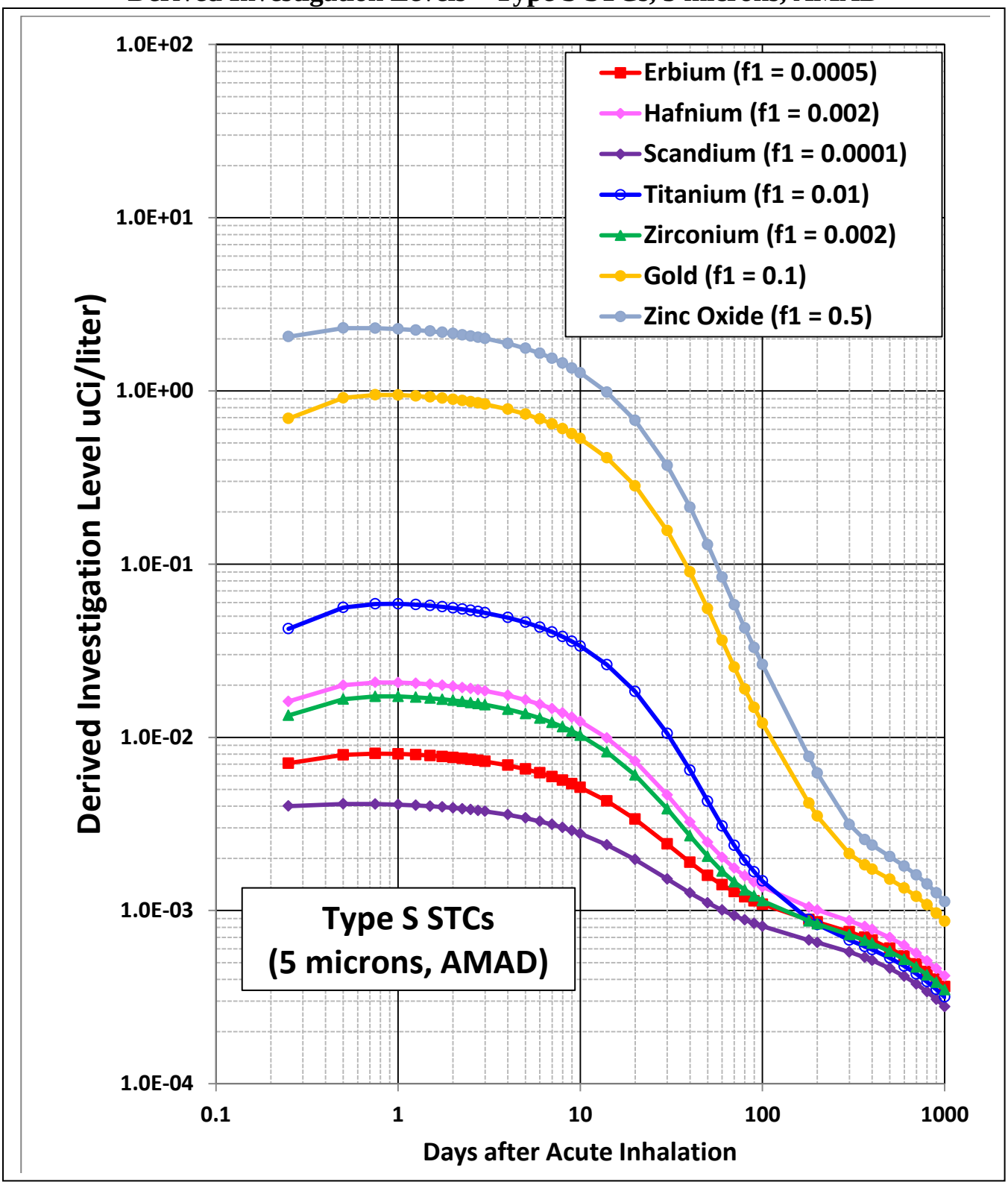
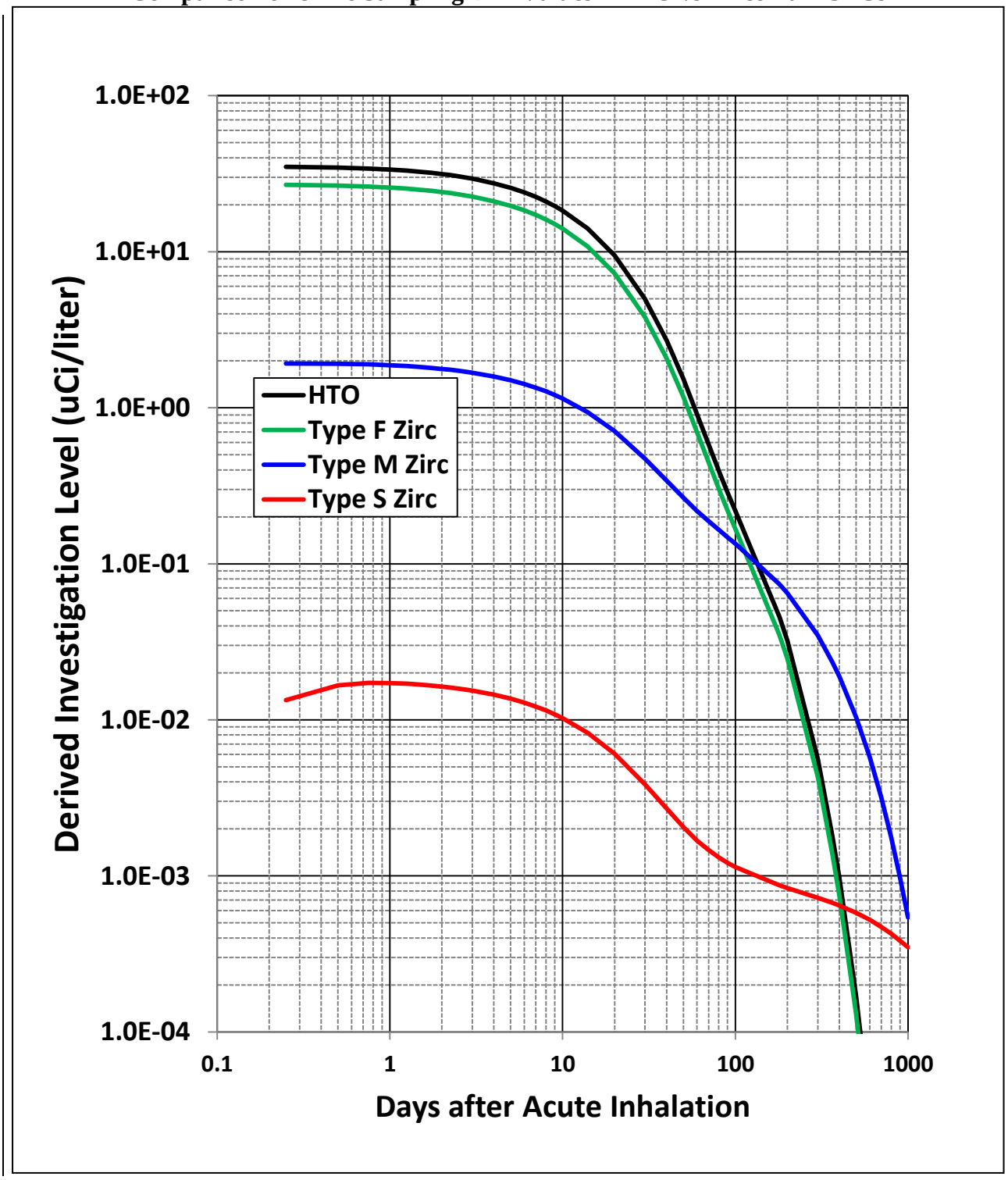

Derived Investigation Levels – Type S STCs, 5 microns, AMAD
1.0E+02
1.0E+01
1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
Derived Investigation Level uCi/liter)
0.1
1
10
100
1000
Days after Acute Inhalation
Erbium (f1 = 0.0005)
Hafnium (f1 = 0.002)
Scandium (f1 = 0.0001)
Titanium (f1 = 0.01)
Zirconium (f1 = 0.002)
Gold (f1 = 0.1)
Zinc Oxide (f1 = 0.5)
Type S STCs
(5 microns, AMAD)

Figure C.8.47

Comparison of Urine Sampling DIL Values – HTO vs Zirconium STCs



C.8.7 Interpretation of Breathing Zone Air (BZA) Monitoring Results

C.8.7.1 Introduction

As discussed in Sections C.8.5 and C.8.6, urine sampling for intakes of STCs is problematic due to the likely presence of HTO in the workplace. As discussed in DOE-HDBK-1184-2004 (DOE 2006), air sampling can be an effective means of monitoring for, and assessing intakes from, airborne STCs. If the STC material is adequately characterized, BZA sample results can be used for calculation of doses from such intakes. The technical basis for such monitoring and assessment is presented below.

C.8.7.2 Correction for Beta Particle Self Absorption Factor (SAF_β) during LSC counting

Breathing Zone Air (BZA) can be an effective means of both monitoring for, and assessing intakes of, STCs. Typically, such samples are counted by liquid scintillation counting (LSC). As discussed in the DOE Handbook (DOE 2006) LSC counting results for such samples must be corrected for the self-absorption of beta particles within the STC particles.

Application of this beta particle self-absorption factor (SAF_β) will convert the "observed" (counted) activity on a filter or swipe into "actual" (true) activity. Use of "observed" activity is discussed in detail in Section C.8.7.3.

As discussed in Section 5.2.3 of the DOE Handbook (DOE 2006), liquid scintillation counting (LSC) measurements of STC activity on air and swipe filters must be corrected for the self absorption of beta particles that may take place within the STC particle. LSC counting registers the discrete number of "counts" observed within the specified energy window. Accordingly, the Self Absorption Factor for Beta Particles (SAF_β) is defined as the fraction of beta particles (as opposed to the fraction of beta particle *energy*) that escapes the STC particulate.

As described in Section C.8.3.5, SAF_β values are calculated using the method described in the Mound Technical Basis Document (Mound 2001). This calculation method (as detailed in the Mathcad® worksheet example of Appendices A and B of the Mound TBM) serves as the technical basis for the polydisperse SAF_β) values recommended in the DOE Handbook for Radiological Control Programs for Special Tritium Compounds (DOE 2006).

Table C.8.11 summarizes the SAF_β values for selected polydisperse particle size distributions as calculated by the above method. These LLNL-calculated values may be compared to those of Table 5-10 of the DOE Handbook (DOE 2006). These calculated SAF_β values may then be used to convert "observed" activity to actual activity.

Table C.8.11

Beta Particle Self-Absorption Factors (SAF_β) for Polydisperse Special Tritium Compounds[1]

Material: Density (g/cm^{-3})	**0.01 μm[2] AMAD**	**0.1 μm AMAD**	**1 μm AMAD**	**5 μm AMAD**	**10 μm AMAD**
Sc: 3.10	*1.0*	0.9416	0.6088	**0.2507**	0.1478
Ti: 3.90	*1.0*	0.9392	0.5918	**0.2316**	0.1330
Zr: 6.49	*1.0*	0.9340	0.5576	**0.1919**	0.1050
Er: 8.56	*1.0*	0.9352	0.5520	**0.1798**	0.0953
Hf: 11.68	*1.0*	0.9346	0.5306	**0.1548**	0.0768
Au: 19.3	*1.0*	0.9467	0.4984	**0.1194**	0.0513
ZnO: 5.6	*1.0*	0.9537	0.6493	**0.2769**	0.1633

[1] Four-significant figures are displayed for calculated values to aid comparison to other published values. This level of accuracy is not implied.

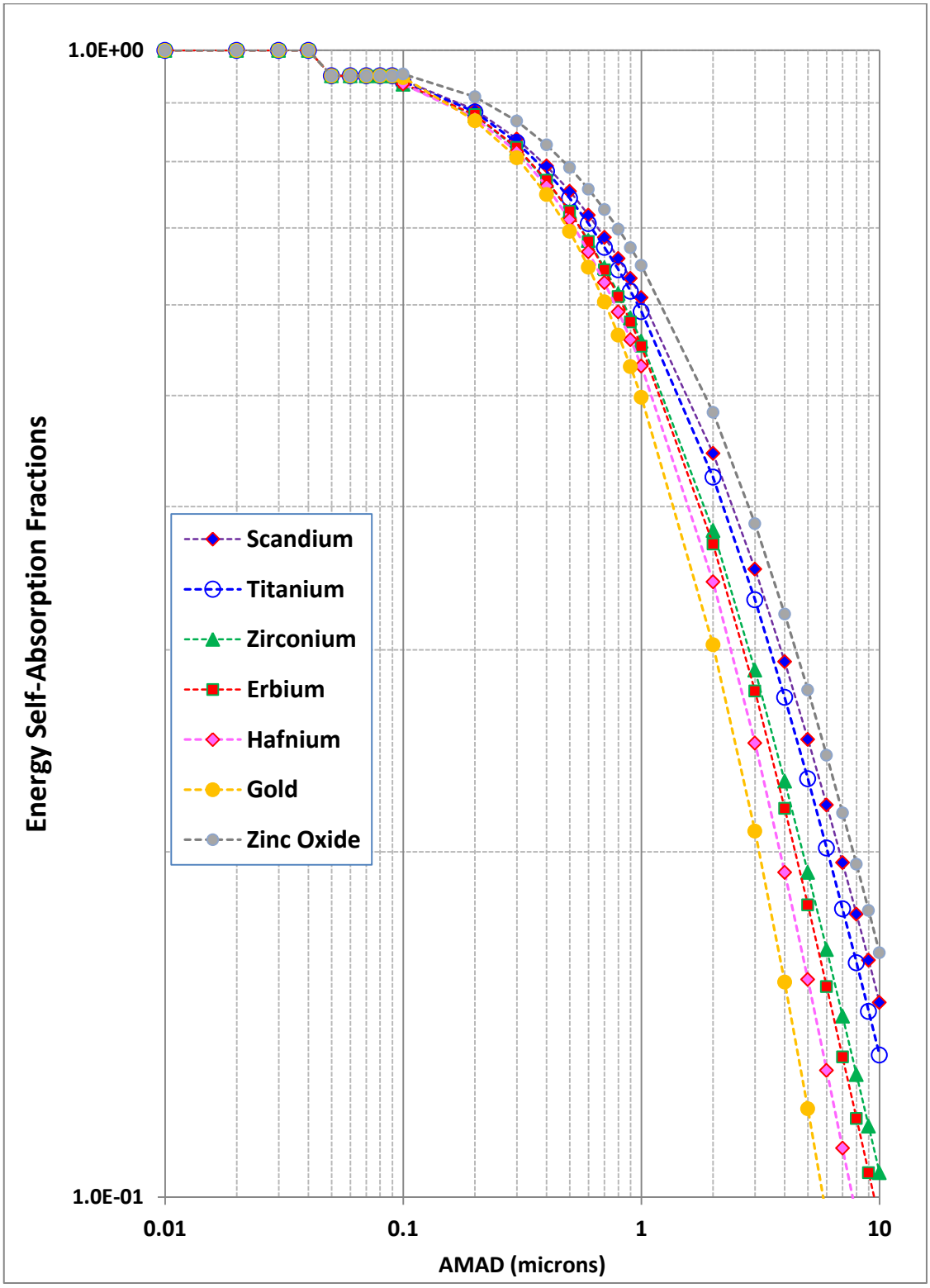
[2] SAF-Beta values for distributions below 0.05 microns, AMAD, are assumed to be 1.0.

The LLNL-calculated SAF_β values are plotted below in Figure C.8.48. As might be expected, the SAF_β value (fraction of beta particles emitted) drops dramatically as the particle diameter increases. One can also see a "spread" in values as a function of the material density.

As the AMAD drops below about 0.1 microns, the value of SAF_β asymptotes to a value of 1.0 (100% of beta particles escape the STC particle and are counted.) Unfortunately, the Mathcad log-normal function used to calculate SAF_β values fails at AMAD values less than 0.1. In order to conservatively "work around" this problem, SAF_β values from 0.09 microns to 0.05 microns AMAD are assumed to be 0.95 for all materials, and SAF_β values below 0.05 microns AMAD are assumed to be equal to 1.0 for all materials. These assumptions produce the step-function like appearance seen at small particle size distributions in Figure C.8.48.

Figure C.8.48

Fraction of Beta Particles Emitted (SAF_β) vs. STC AMAD



C.8.7.3 Use of "Observed" Activity vs. "Actual" Activity as a Basis for BZA Dose Calculations

"Observed Activity" is defined in the DOE Handbook - Radiological Control Programs for Special Tritium Compounds, DOE-HDBK-1184 (DOE 2006) as: "The *apparent* [author's emphasis] 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." In theory, the observed activity would have to be corrected for all three of the above mentioned factors. In practice, although the self absorption factor can be estimated (see Section C.8.3.5 above) the contribution from activity due to bremsstrahlung and/or due to the presence of non-STC tritium (e.g., HTO) on the filter is typically unknown. In general, it is sufficiently conservative to assume that all the observed activity on the filter is due to STC beta emissions, in which case, the above discussed SAF_{β} values may be used to convert the "observed" activity to actual activity.

Ideally, if the nature of the STC material is well-characterized (chemical form, particle size distribution, etc.), the "observed" activity on an air filter or swipe can be converted to "actual" activity using the appropriate SAF_{β} factor, and then material-specific dose conversion factors can be applied to the estimate of "actual" activity inhaled.

As discussed in the Mound Technical Basis Document (Mound 2001) and the DOE Handbook (DOE 2006), it may not be possible or practicable to completely characterize the STC material(s) in the workplace. In such circumstances, the options are to:

1. Make conservative assumptions about the nature of the STC material (which may lead to unacceptably large over-estimations of actual doses, or
2. Reduce the uncertainty in dose estimation via the use of "observed" activity and "observed" dose conversion factors as described below.

The DOE Handbook recommends option 2 above, and "adopts the concept of observed activity (discussed above) as an appropriate surrogate for the actual activity for STCs." The Handbook further states that: ". . . when tritiated particulate intake is defined in terms of observed activity (and when [the] DCF is correspondingly defined in terms of observed activity intake) the uncertainty in the observed intake essentially disappears, since the self-absorption is accounted for."

As discussed below, this generalization is true for Type F, M, and S materials with small particle size distributions (e.g., less than about 1 micron, AMAD), and Type S materials with particle size distributions up to about 5 microns, AMAD. However, the generalization may not be true in the case of Type F and Type M STC materials with particle size distributions larger than 1 micron, AMAD. Accordingly, the concept of "observed activity" as presented in the DOE Handbook, needs to be used with some circumspection.

[Section to be completed in next revision.]

Placeholder for Figure C.8.49, "Sequential Correction of DCFs for Type F STCs"
Placeholder for Figure C.8.50, "Sequential Correction of DCFs for Type M STCs"
Placeholder for Figure C.8.51, "Sequential Correction of DCFs for Type S STCs"

C.8.7.4 Factors Which May Affect BZA Air Sampling

A number of factors may affect the representativeness and accuracy of using BZA filter results for assignment of internal doses from STCs. These factors are discussed in some detail in the DOE Handbook for Radiological Control Programs for Special Tritium Compounds (DOE 2006) and are listed below:

1. Representativeness of BZA sampling location,
2. Representativeness of BZA sampling period to exposure period,
3. BZA sampler flow rate,
4. Collection (and counting) of non-respirable particles,
5. "Cross-contamination" of filter during handling,
6. Loss of activity from filter during handling,
7. Filter collection efficiency,
8. "Active" filter collection area vs. "counted" filter area,
9. LSC counting efficiency for filters,
10. Correction for Beta Particle Self Absorption Factor (SAF_β) during LSC counting,
11. Presence of non-STP tritium activity on filters during counting, and
12. Possible attenuation of emitted beta particles due to dust loading on filters.

Each of these factors will be briefly discussed:

- Representativeness of BZA Sample Location

  In order for the BZA filter sample to be representative of the air inhaled by the worker, the sampler must be located reasonably near the worker's nose and/or mouth (recall that some workers will be "mouth-breathers"). As noted in the DOE Handbook (DOE 2006), NRC Reg Guide 8.25 (NRC 1992) states that ". . . samplers located within about 1 foot of the worker's head may be accepted as representative . . ."

  Considering the other uncertainties involved in BZA monitoring, and the generally conservative assumptions made (as discussed below) it is considered sufficiently accurate if the BZA sampler is worn somewhere between upper chest level and the top-of-the-head.

- Sampling Period vs. Exposure Period

  To the extent practicable, the sampling period should match the exposure period. This factor becomes very important in situations where the air activity is expected to be non-uniform with time. As discussed below in Section C.8.7.5, the total sample volume does not need to be known.

- BZA Sampler Flow Rate

  As discussed below, the ratio of the sampling rate to the breathing rate gives an effective "Sampling Intake Retention Fraction", or S-IRF. The higher this ratio, the more sensitive the monitoring method will be. In most sampling situations, the application of an assumed average or effective sampling flow rate to the entire monitoring period will be sufficiently accurate.

- Collection (and counting) of non-respirable particles

  As discussed in the DOE Handbook (DOE 2006) it is possible that relatively large "non-respirable" particles will be collected on the BZA filter, counted, and be included in the estimate of intake and associated dose. This inclusion will lead to a somewhat conservative estimate of intake and dose.

- "Cross-contamination" of filter during handling

  Obviously, erroneously high results will occur if filters are inadvertently contaminated during handling. Care should be taken to avoid such contamination.

- Loss of activity from filter during handling

  Care should be taken to avoid loss of particulate activity from the surface of the filter during handling. Filters should be handled by the edges (preferably with tweezers).

- Filter collection efficiency

  As discussed in the DOE Handbook (DOE 2006) filter collection efficiencies have been observed to range from about 0.981 to essentially 1.00 for 0.3 to 10 micron sized particles. Since the lower value here represents only about a 2% loss, filter collection efficiencies can be assumed to be 100% for routine monitoring.

- "Active" filter collection area vs. "counted" filter area

  Typically, the entire BZA filter is placed in the LSC vial and counted. If, for some reason, only a fraction of the filter is counted in the LSC vial – a correction should be made for the difference between the total collection area (in which the activity is assumed to reside) and the actual area of filter counted.

- LSC counting efficiency for filters

  Counting efficiency factors (i.e., cpm per dpm) are applied by the RML.

- Correction for Beta Particle Self Absorption Factor (SAF_{β}) during LSC counting,

  See discussion in Section C.8.7.2.

- Presence of non-STP tritium activity on filters during counting

  LSC counting of air filters does not distinguish between activity from non-STC activity (e.g., HTO, OBT) and STC activity. Unless otherwise specified, it is assumed that all of the activity counted via LSC on an air filter specifically used to monitor for STCs is due to STCs.

- Possible attenuation of emitted beta particles due to dust loading on filters.

  Significant dust loading on air filters may attenuate the beta radiation during LSC counting. Such dust loading is not expected to be a significant problem in normal working environments. However, in very dusty/dirty work environments, filters should be examined for obvious dust loading, and appropriate correction factors considered.

C.8.7.5 Calculation of Intake and Doses from BZA Samples

The calculation of intake and associated dose will depend upon a number of known or assumed factors, and will generally follow these steps:

1. Collect the air sample at a particular flow rate, for a specified time period.
2. Count the air filter (typically using liquid scintillation counting) to determine the apparent ("observed") activity on the filter.
3. Determine the actual activity on the filter by dividing the observed activity by the Self Absorption Factor (SAF_{β}) for the STC material of interest. (See Section C.8.3.5 for discussion of SAF factors.)
4. Calculate the "Sampling Intake Retention Fraction" by dividing the BZA sampling rate by the assumed breathing rate.
5. Calculate the intake by dividing the actual activity on the filter by this Sampling Intake Retention Fraction.
6. Calculate the dose by multiplying the intake activity by the material-specific dose conversion factor.

C.8.7.5.1 Intake and Dose Calculations Based on Actual (SAF_{β}-corrected) Activity

For BZA sample results, the most direct method of calculating the implied intake and associated dose is as follows:

$$I = \frac{A_{filt}}{\left(FR_{filt}/BR\right)} \qquad \text{Eq. C.8.4}$$

Where:

I	=	the intake (dpm),
A_{filt}	=	actual (SAF_{β}-corrected) activity measured on the filter (dpm),
BR	=	assumed breathing rate (liters per minute), and
FR_{filt}	=	the sampling flow rate (liters per minute).

The ratio of the sampling flow rate (FR_{filt}) to the breathing rate (BR) may be thought of as a "Sampling Intake Retention Fraction" (S-IRF) since it represents the fraction of the intake that is present on the filter. Thus:

$$S\text{–}IRF = \frac{FR_{filt}}{BR} \qquad \text{Eq. C.8.5}$$

Once the intake is calculated, the associated dose (committed effective dose) is simply:

$$CED = I * DCF \qquad \text{Eq. C.8.6}$$

Where:

CED	=	the committed effective dose (millirem),
I	=	the above calculated intake (dpm), and
DCF	=	the appropriate dose conversion factor for the STC material of interest (millirem per dpm inhaled).

Equations C.8.x and C.8.y above may be combined to give:

$$CED = \frac{A_{filt}}{\left(FR_{filt}/BR\right)} * DCF \qquad \text{Eq. C.8.7}$$

or,

$$CED = \frac{A_{filt}}{S-IRF} * DCF \qquad \text{Eq. C.8.8}$$

BZA filter results are typically reported in terms of concentration (i.e., microcuries per cubic centimeter), along with the associated sample volume. In that case, the implied dose is calculated as follows:

The intake (activity inhaled) implied by a BZA filter result is:

$$I = \frac{Conc_{sample} * 2.22E6 * Vol_{sample} * 1.0E3}{SAF_{\beta} * S{-}IRF} \qquad \text{Eq. C.8.9}$$

Where:

I	=	the intake (dpm),
$Conc_{sample}$	=	the reported sample concentration ($\mu Ci/cm^3$),
2.22E6	=	conversion from $\mu Ci/cm^3$ to dpm/cm^3,
Vol_{sample}	=	the associated sample volume (liters),
1.0E3	=	conversion from dpm/cm^3 to dpm/liter,
SAF_{β}	=	the Beta Self Absorption Factor for the STC material of interest, and,
S-IRF	=	the sampling "Intake Retention Fraction" (the ratio of the filter sampling rate to the assumed breathing rate).

As above, the associated dose (committed effective dose) is then:

$$CED = I * DCF \qquad \text{Eq. C.8.10}$$

Where:

CED	=	the committed effective dose (millirem),
I	=	the above calculated intake (dpm), and
DCF	=	the appropriate dose conversion factor for the STC material of interest (millirem per dpm inhaled).

For convenience, the reference dose conversion factors of Table C.8.6b are repeated here in units of millrem per *actual* (SAF_{β}-corrected) dpm inhaled:

Table C.8.6b

Reference STC DCFs for Selected Particle Size Distributions – ACTUAL Activity

AMAD =	**0.01**	**0.1**	**1**	**2**	**5**	**10**
STC Material	**DCF (mrem per dpm)**	**DCF (mrem per dpm)**	**DCF (mrem per dpm)**	**DCF (mrem per dpm)**	**DCF (mrem per dpm)**	**DCF (mrem per dpm)**
Erbium - Type F	2.46E-08	1.27E-08	1.04E-08	1.22E-08	1.11E-08	8.58E-09
Erbium - Type M	1.79E-07	1.73E-07	5.10E-08	3.65E-08	1.52E-08	5.82E-09
Erbium - Type S	1.06E-06	1.08E-06	2.87E-07	1.88E-07	6.36E-08	1.75E-08
Hafnium – Type F	2.46E-08	1.27E-08	1.03E-08	1.20E-08	1.08E-08	8.40E-09
Hafnium – Type M	1.79E-07	1.73E-07	4.93E-08	3.42E-08	1.36E-08	5.12E-09
Hafnium – Type S	1.06E-06	1.08E-06	2.77E-07	1.75E-07	5.59E-08	1.48E-08
Scandium – Type F	2.46E-08	1.27E-08	1.07E-08	1.27E-08	1.17E-08	9.05E-09
Scandium – Type M	1.79E-07	1.73E-07	5.56E-08	4.24E-08	1.93E-08	7.64E-09
Scandium – Type S	1.06E-06	1.08E-06	3.14E-07	2.21E-07	8.28E-08	2.43E-08
Titanium – Type F	2.46E-08	1.27E-08	1.06E-08	1.26E-08	1.16E-08	8.97E-09
Titanium – Type M	1.79E-07	1.73E-07	5.44E-08	4.10E-08	1.83E-08	7.24E-09
Titanium – Type S	1.06E-06	1.08E-06	3.07E-07	2.13E-07	7.81E-08	2.26E-08
Zirconium – Type F	2.46E-08	1.27E-08	1.04E-08	1.23E-08	1.12E-08	8.68E-09
Zirconium – Type M	1.79E-07	1.73E-07	5.16E-08	3.75E-08	1.60E-08	6.19E-09
Zirconium – Type S	1.06E-06	1.08E-06	2.90E-07	1.94E-07	6.72E-08	1.88E-08
Gold – Type F	2.46E-08	1.27E-08	1.03E-08	1.19E-08	1.09E-08	8.64E-09
Gold – Type M	1.79E-07	1.73E-07	4.74E-08	3.15E-08	1.22E-08	5.08E-09
Gold – Type S	1.06E-06	1.08E-06	2.64E-07	1.58E-07	4.58E-08	1.18E-08
Zinc Oxide – Type F	2.44E-08	1.26E-08	1.09E-08	1.36E-08	1.36E-08	1.14E-08
Zinc Oxide – Type M	1.78E-07	1.73E-07	5.80E-08	4.62E-08	2.43E-08	1.27E-08
Zinc Oxide – Type S	1.06E-06	1.08E-06	3.27E-07	2.36E-07	9.46E-08	3.19E-08

These values were calculated using custom Mathcad worksheets using the models and assumptions discussed in Section C.8.3 above, including the use of ICRP-60 tissue weighting factors.

C.8.7.5.2 Use of "Observed" vs. Actual BZA Results

The use of "observed" air filter activity (in conjunction with "observed" dose conversion factors) is discussed in Section C.8.7.3 above. As noted in that Section, the DOE Handbook (DOE 2006) "adopts the concept of observed activity (discussed above) as an appropriate surrogate for the actual activity for STCs."

In the case of small particle size distributions, and Type S materials, the use of the "observed" activity concept, in conjunction with appropriate "observed" dose conversion factors, can reduce some of the uncertainty associated with the estimates of intake and dose from such STCs. Since the use of the "observed" BZA filter results provides a more accurate and convenient method of intake and dose estimation for these conditions, LLNL will use this concept for the following types of STC materials:

- Type S - all assumed or known particle size distributions,
- Type M - assumed or known particle size distributions from 0.01 to ~5 microns, AMAD,
- Type F - assumed or known particle size distributions from 0.01 to ~5 microns, AMAD.

Use of the "observed" activity concept for other types of materials should be approved on a case-by-case basis.

C.8.7.6 Representative BZA Dose Estimators

Figures C.8.52 thru C.8.54 below display the dose implied by observed activity on a BZA filter for selected Type F, Type M, and Type S STC materials as a function of particle size distribution. All of these figures are based on an assumed BZA sampler flow rate of 4 liters per minute, and an assumed breathing rate of 20 liters per minute.

The "observed" dose conversion factors are calculated using the actual dose conversion factors of Table C.8.6b and the corresponding SAF_{β} values. Note that the relative shapes of these BZA observed DCF curves are the same as the "OBSERVED" curves presented in Section C.8.7.3, where the SAF_e and SAF_{β} corrections were sequentially applied to the uncorrected DCFs.

One of the most notable features of these figures is the significant difference among the Type F, Type M, and Type S DCFs for any particular material at any particular particle size distribution. Although the DCFs for Type F materials start much lower than those for Type M or S materials (as a function of particle size distribution) the rapid increase in Type F DCFs after about 1 micron, AMAD, bring the Type F DCFs into the range of those for Type M and Type S materials.

Note also that assumption of Type S materials will always result in the most conservative estimate of doses – regardless of the assumed particle size distribution.

Figure C.8.52

Dose Implied by OBSERVED BZA Filter Activity – Type F STCs

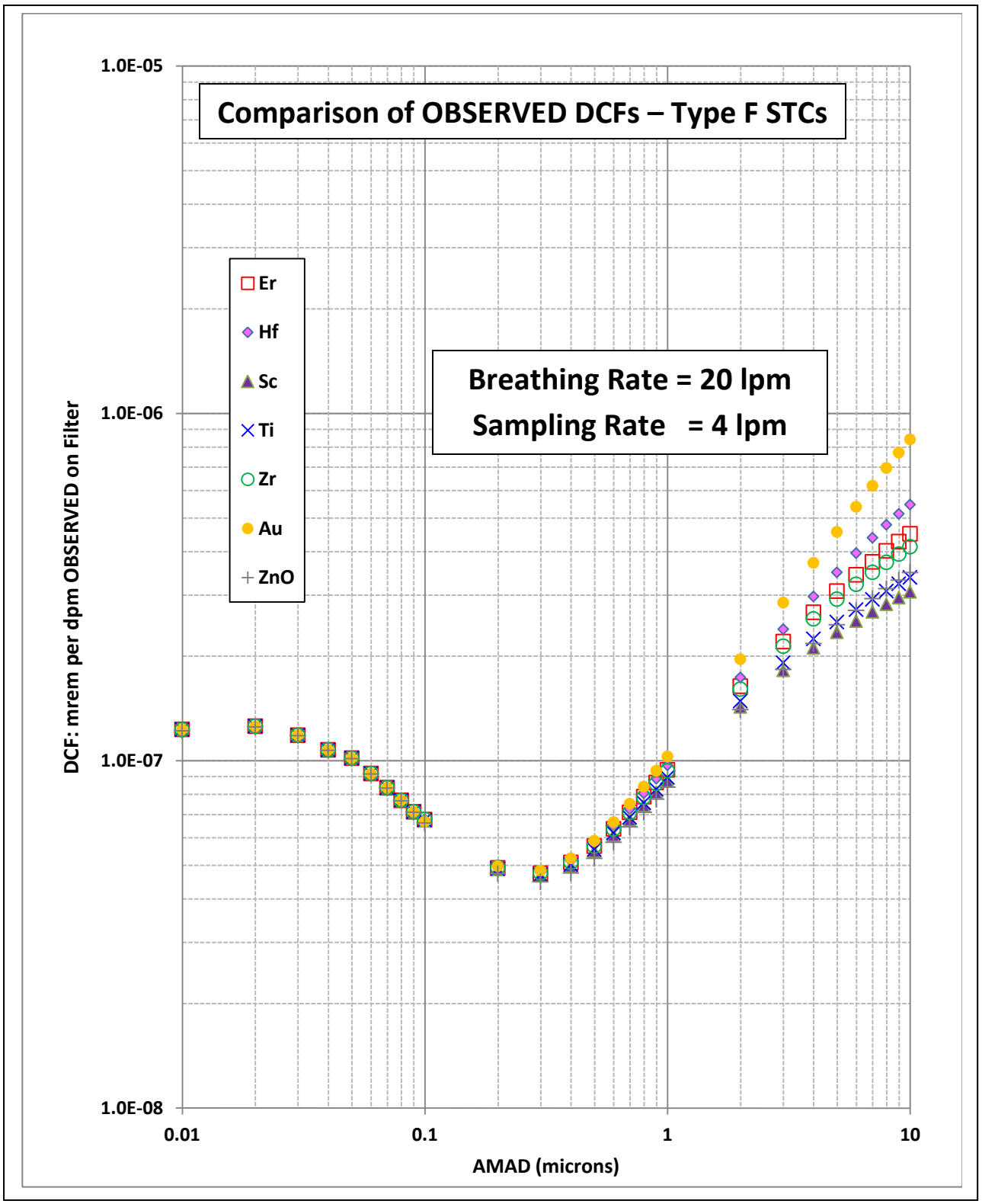


Figure C.8.53

Dose Implied by OBSERVED BZA Filter Activity – Type M STCs

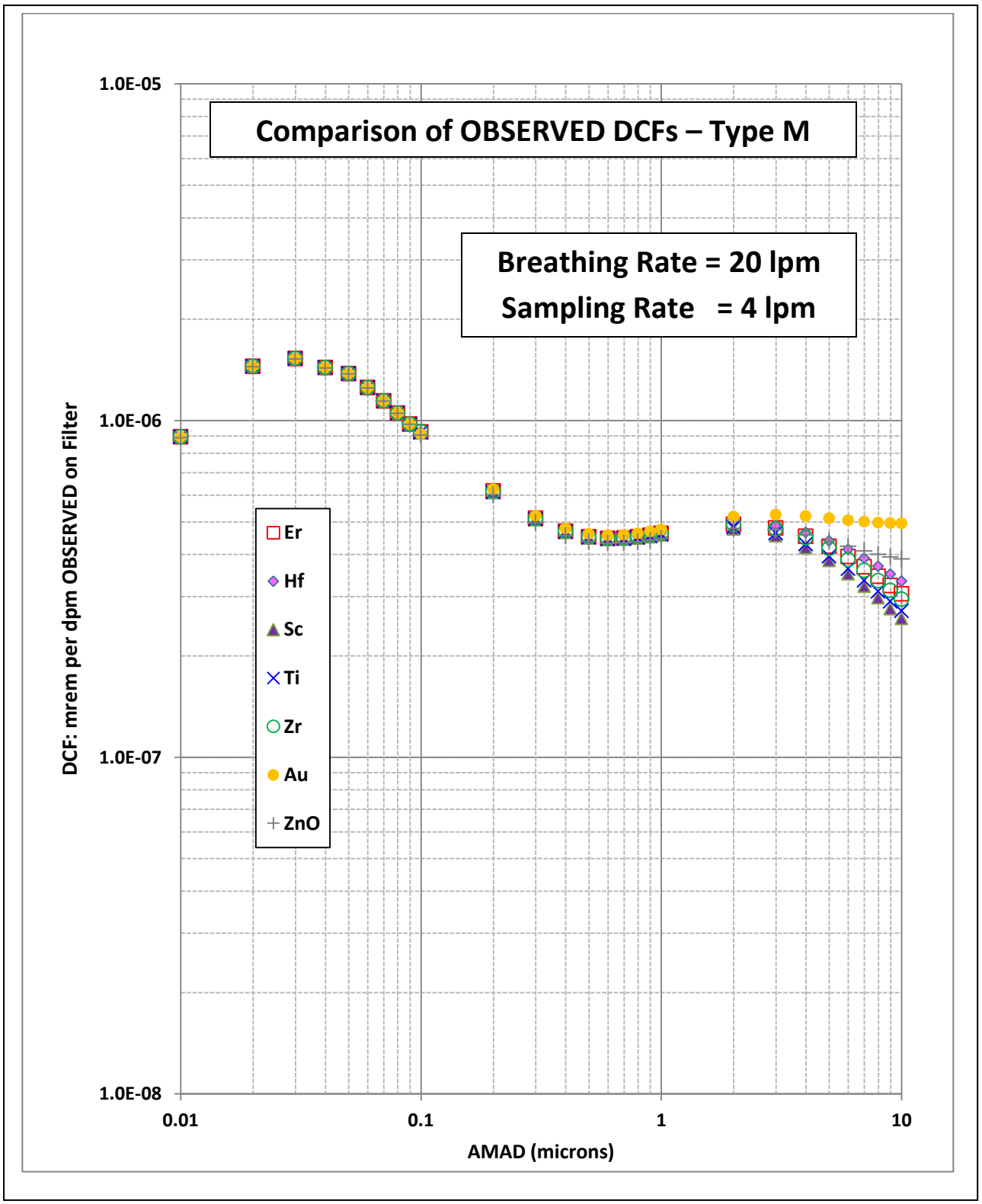
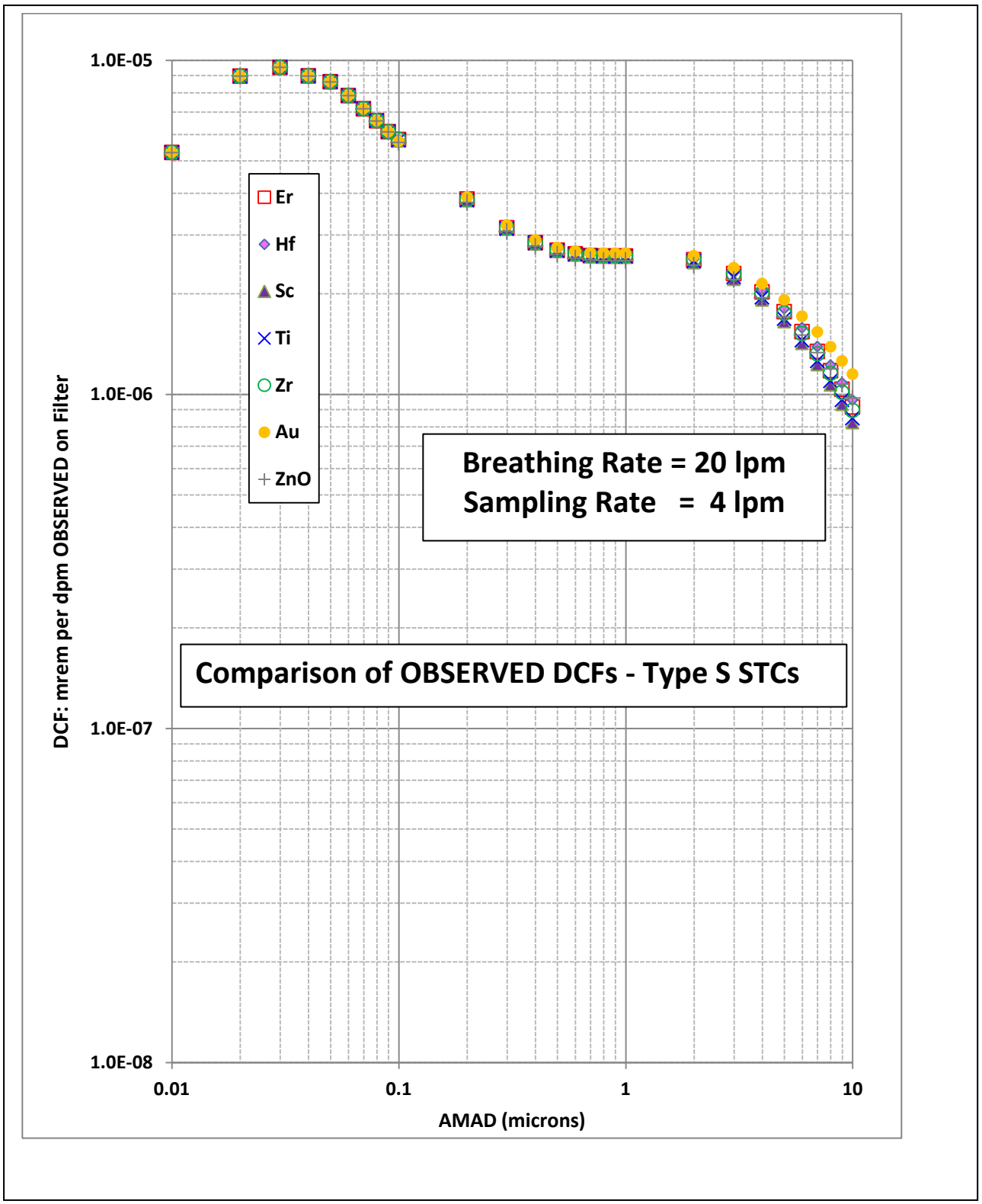


Figure C.8.54

Dose Implied by OBSERVED BZA Filter Activity – Type S STCs



C.8.7.7 BZA Monitoring Factors (MDDs and DILs)

C.8.7.7.1 Minimum Detectable Doses for BZA Monitoring

The Minimum Detectable Dose (MDD) for BZA monitoring for STCs is a function of the MDA for activity on the air filter, the assumed breathing rate, the BZA sampling rate, and the appropriate dose conversion factor.

The Minimum Detectable Dose (MDD, as defined in Section 2.6), is the smallest dose (CED) that would be expected to be reliably detected by a particular routine monitoring method alone. The MDD will be a function of the absorption type, time after inhalation, particle size distribution, and dose conversion factor.

The Minimum Detectable Dose for a specific STC material may be calculated using the equation below:

$$MDD = \frac{MDA_{filt}}{\left(FR_{filt}/BR\right)} * DCF \qquad \text{Eq. C.8.11}$$

Where:

MDD	=	the minimum detectable dose (mrem),
MDA_{filt}	=	the minimum detectable actual (SAF_{β}-corrected) activity (dpm),
FR_{filt}	=	the sampling flow rate (liters per minute),
BR	=	the assumed breathing rate (liters per minute), and
DCF	=	the appropriate dose conversion factor for the STC material of interest (millirem per dpm inhaled).

As seen in the equation above, the MDD is directly proportional to the assumed MDA and DCF, and is inversely proportional to the sampling flow rate. Note that the MDD is independent of the total sample volume or sampling time.

MDD value for selected STC materials for sampling flow rates from 1 to 5 liters per minute are summarized in Table C.8.12 below. For convenience, the MDD values in this table and following figures are presented in terms of *observed* activity (See footnote on Table C.8.12).

Table C.8.12

Reference STC BZA Minimum Detectable Doses
MDA = 20 *observed* dpm (prior to SAF correction), DCFs for 5 micron AMAD material

Sampling Flow Rate (LPM) =	**1**	**2**	**3**	**4**	**5**
STC Material	**MDD (mrem)**	**MDD (mrem)**	**MDD (mrem)**	**MDD (mrem)**	**MDD (mrem)**
Erbium - Type F	2.46E-05	1.23E-05	8.21E-06	6.16E-06	4.92E-06
Erbium - Type M	3.38E-05	1.69E-05	1.13E-05	8.46E-06	6.77E-06
Erbium - Type S	1.41E-04	7.07E-05	4.72E-05	3.54E-05	2.83E-05
Hafnium – Type F	2.79E-05	1.40E-05	9.31E-06	6.98E-06	5.58E-06
Hafnium – Type M	3.51E-05	1.76E-05	1.17E-05	8.79E-06	7.03E-06
Hafnium – Type S	1.44E-04	7.22E-05	4.81E-05	3.61E-05	2.89E-05
Scandium – Type F	1.87E-05	9.37E-06	6.24E-06	4.68E-06	3.75E-06
Scandium – Type M	3.07E-05	1.54E-05	1.02E-05	7.68E-06	6.14E-06
Scandium – Type S	1.32E-04	6.61E-05	4.41E-05	3.30E-05	2.64E-05
Titanium – Type F	2.00E-05	1.00E-05	6.68E-06	5.01E-06	4.01E-06
Titanium – Type M	3.16E-05	1.58E-05	1.05E-05	7.90E-06	6.32E-06
Titanium – Type S	1.35E-04	6.74E-05	4.49E-05	3.37E-05	2.70E-05
Zirconium – Type F	2.33E-05	1.17E-05	7.78E-06	5.84E-06	4.67E-06
Zirconium – Type M	3.33E-05	1.67E-05	1.11E-05	8.33E-06	6.67E-06
Zirconium – Type S	1.40E-04	7.01E-05	4.67E-05	3.50E-05	2.80E-05
Gold – Type F	3.65E-05	1.82E-05	1.22E-05	9.11E-06	7.29E-06
Gold – Type M	4.10E-05	2.05E-05	1.37E-05	1.03E-05	8.20E-06
Gold – Type S	1.53E-04	7.67E-05	5.11E-05	3.83E-05	3.07E-05
Zinc Oxide – Type F	1.97E-05	9.85E-06	6.57E-06	4.92E-06	3.94E-06
Zinc Oxide – Type M	3.51E-05	1.76E-05	1.17E-05	8.78E-06	7.03E-06
Zinc Oxide – Type S	1.37E-04	6.84E-05	4.56E-05	3.42E-05	2.73E-05

MDD values based on an assumed "raw" MDA (uncorrected for SAF) of 20 dpm, which is then corrected using the material-specific SAF-beta factor. This SAF-corrected MDA is then multiplied by the appropriate material-specific (i.e., SAF-energy corrected) DCF.

Minimum Detectable Doses for BZA sampling are presented below in Figures C.8.55 through C.8.57 for Types F, M, and S STCs. The MDD values in these curves are based on a typical BZA sampler flow rate of 4 liters per minute, and an assumed Minimum Detectable Activity of 20 dpm (*observed* activity.) As seen in these figures, the theoretical monitoring sensitivity of BZA sampling is very good – even for Type S materials with small particle size distributions (the "worst case."

Figure C.8.55

MDD for BZA Monitoring for Type F STCs

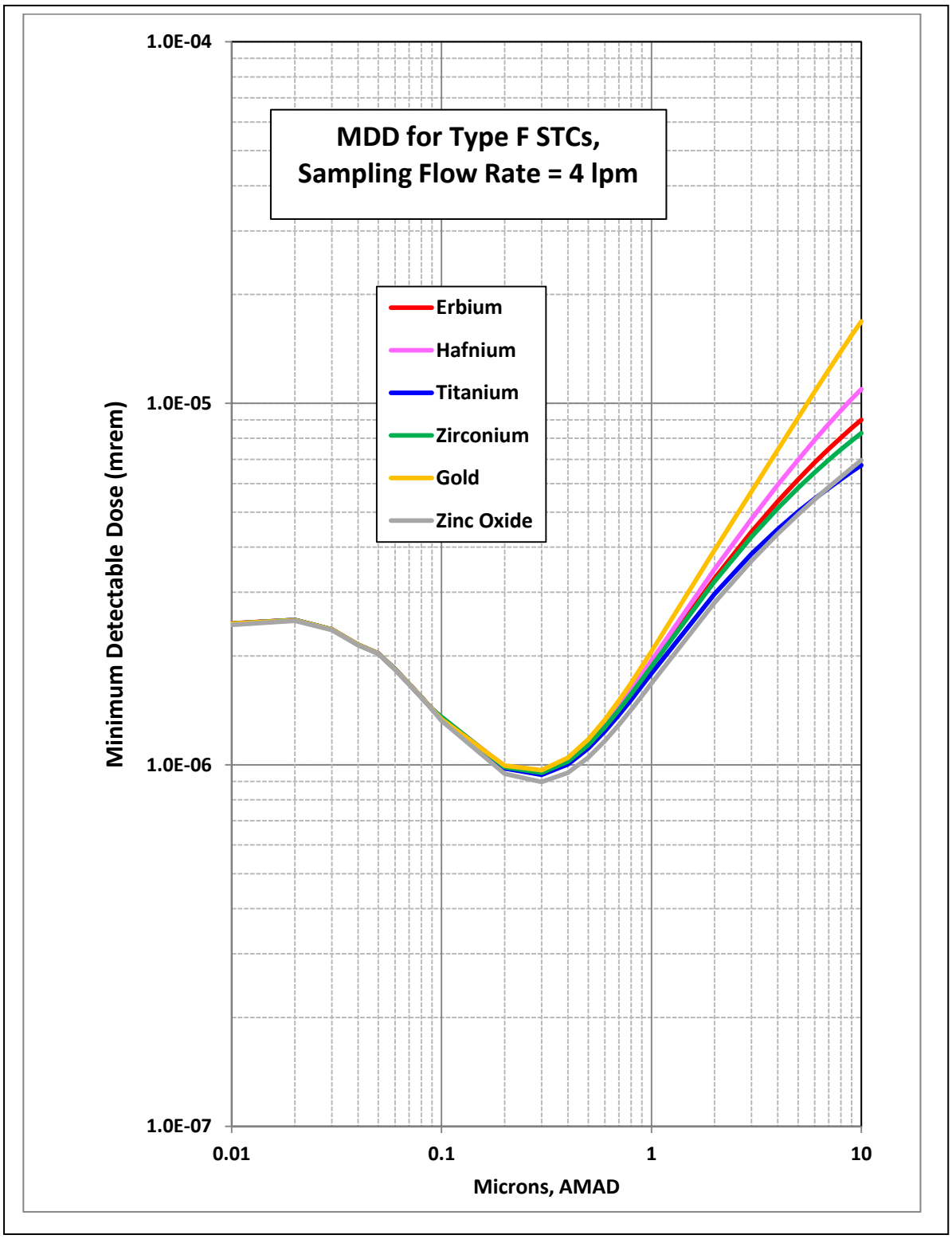


Figure C.8.56

MDD for BZA Monitoring for Type M STCs

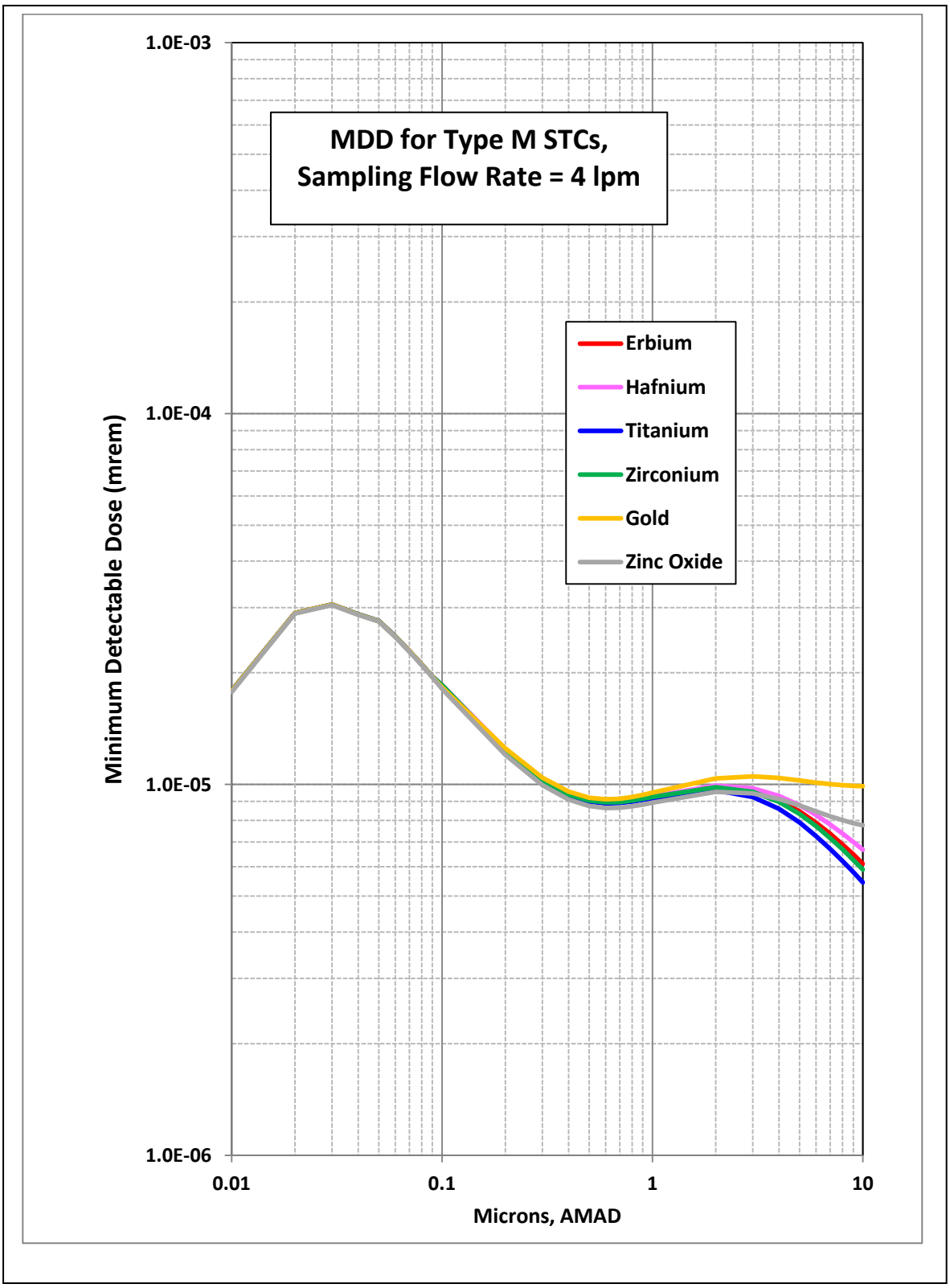
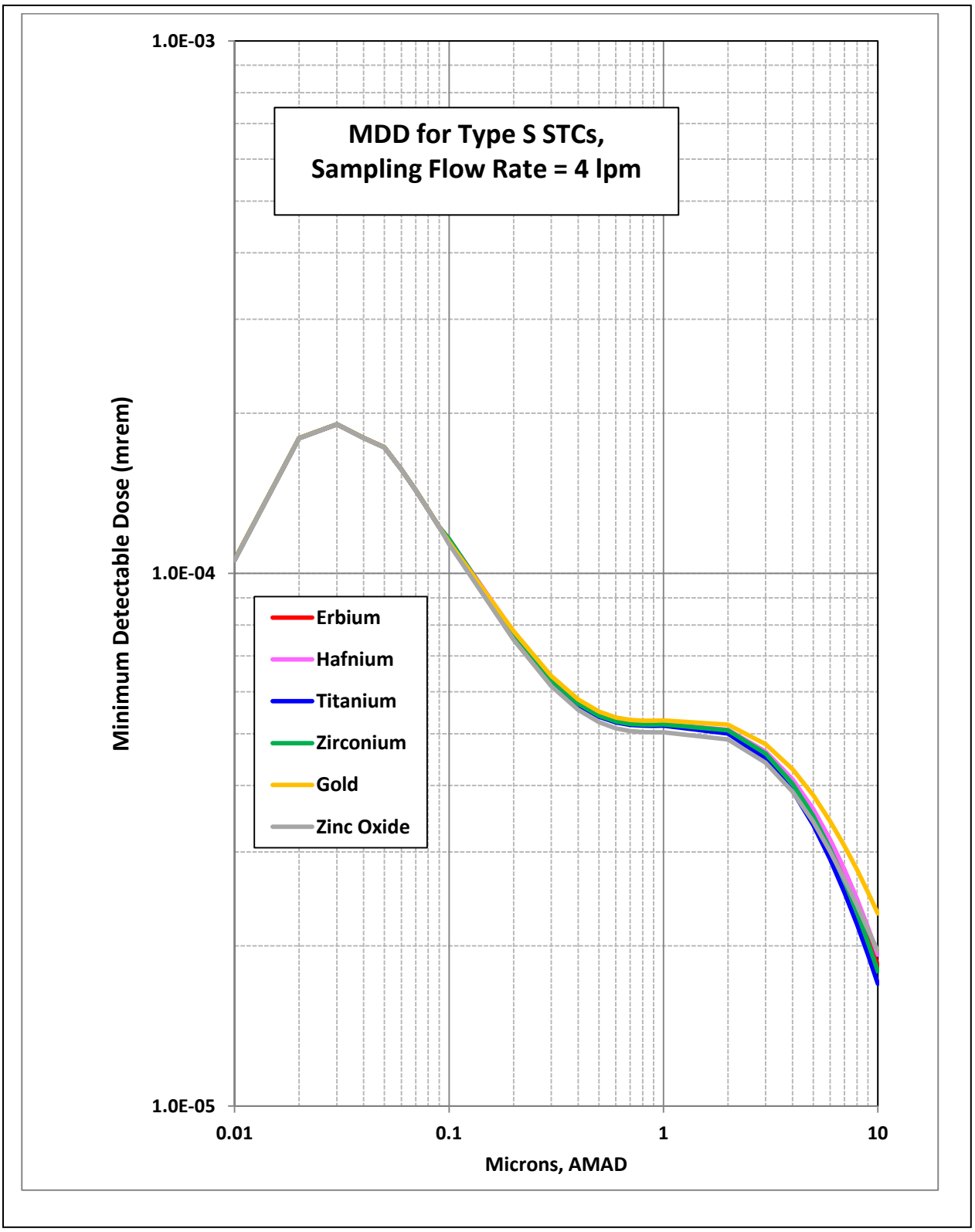


Figure C.8.57

MDD for BZA Monitoring for Type S STCs



C.8.7.7.2 Derived Investigation Levels (DILs) for BZA Monitoring

The Derived Investigation Level (DIL), as defined in Section 2.5, is that result (for a particular radioactive material, analysis method, and route of intake) which implies a committed effective dose equal to the Investigation Level dose of 0.1 rem CED.

For convenience, DIL values are expressed in terms of *observed* activity on the BZA filter. Accordingly, the DIL value will be a function of the beta self absorption factor (SAF_{β}, the sampling flow rate, and the energy self absorption factor (SAF_e) corrected dose conversion factor.

The BZA DIL for a specific STC material may be calculated using the equation below:

$$DIL = \frac{100}{DCF_{obs}} \qquad \text{Eq. C.8.12}$$

Where:

DIL	=	the Derived Investigation Level (dpm),
100	=	the Investigation Level CED of 100 millirem,
DCF_{obs}	=	the appropriate dose conversion factor for the STC material of interest (millirem per OBSERVED dpm inhaled).

$$DCF_{obs} = \frac{DCF_{actual}}{SAF_{\beta} * \left(\frac{FR_{filt}}{BR}\right)} \qquad \text{Eq. C.8.13}$$

Where:

DCF_{obs}	=	the appropriate dose conversion factor for the STC material of interest (millirem per OBSERVED dpm inhaled),
DCF_{actual}	=	the appropriate dose conversion factor for the STC material of interest (millirem per ACTUAL dpm inhaled),
SAF_{β}	=	the beta self-absorption factor,
FR_{filt}	=	the sampling flow rate (liters per minute),
BR	=	the assumed breathing rate (liters per minute).

Substituting equation C.8.13 into C.8.12 gives:

$$\mathrm{DIL} = \frac{100}{\frac{\mathrm{DCF_{actual}}}{\mathrm{SAF_{\beta}} * \left(\frac{\mathrm{FR_{filt}}}{\mathrm{BR}}\right)}} \qquad \text{Eq. C.8.14}$$

Which is equivalent to:

$$\mathrm{DIL} = \frac{100 * \mathrm{SAF_{\beta}} * \left(\frac{\mathrm{FR_{filt}}}{\mathrm{BR}}\right)}{\mathrm{DCF_{actual}}} \qquad \text{Eq. C.8.15}$$

As seen in the equation above, the DIL is directly proportional to the beta self-absorption factor and the sampling IRF (ratio of sampling flow rate to breathing rate) and inversely proportional to the dose conversion factor (mrem per *actual* dpm inhaled.)

DIL value (in terms of observed activity) for selected STC materials for sampling flow rates from 1 to 5 liters per minute are summarized in Table C.8.13 below

Table C.8.13

Reference STC BZA Derived Investigation Levels
DCFs for 5 micron AMAD material

Sampling Flow Rate (LPM) =	**1**	**2**	**3**	**4**	**5**
Sampling IRF =	0.05	0.1	0.15	0.2	0.25
STC Material	**DIL (dpm) observed**	**DIL (dpm) observed**	**DIL (dpm) observed**	**DIL (dpm) observed**	**DIL (dpm) observed**
Erbium - Type F	8.12E+07	1.62E+08	2.44E+08	3.25E+08	4.06E+08
Erbium - Type M	5.91E+07	1.18E+08	1.77E+08	2.36E+08	2.95E+08
Erbium - Type S	1.41E+07	2.83E+07	4.24E+07	5.66E+07	7.07E+07
Hafnium – Type F	7.16E+07	1.43E+08	2.15E+08	2.87E+08	3.58E+08
Hafnium – Type M	5.69E+07	1.14E+08	1.71E+08	2.28E+08	2.85E+08
Hafnium – Type S	1.39E+07	2.77E+07	4.16E+07	5.54E+07	6.93E+07
Scandium – Type F	1.07E+08	2.14E+08	3.20E+08	4.27E+08	5.34E+08
Scandium – Type M	6.51E+07	1.30E+08	1.95E+08	2.60E+08	3.26E+08
Scandium – Type S	1.51E+07	3.03E+07	4.54E+07	6.05E+07	7.57E+07
Titanium – Type F	9.98E+07	2.00E+08	2.99E+08	3.99E+08	4.99E+08
Titanium – Type M	6.33E+07	1.27E+08	1.90E+08	2.53E+08	3.16E+08
Titanium – Type S	1.48E+07	2.97E+07	4.45E+07	5.93E+07	7.42E+07
Zirconium – Type F	8.57E+07	1.71E+08	2.57E+08	3.43E+08	4.28E+08
Zirconium – Type M	6.00E+07	1.20E+08	1.80E+08	2.40E+08	3.00E+08
Zirconium – Type S	1.43E+07	2.85E+07	4.28E+07	5.71E+07	7.14E+07
Gold – Type F	5.49E+07	1.10E+08	1.65E+08	2.19E+08	2.74E+08
Gold – Type M	4.88E+07	9.75E+07	1.46E+08	1.95E+08	2.44E+08
Gold – Type S	1.30E+07	2.61E+07	3.91E+07	5.22E+07	6.52E+07
Zinc Oxide – Type F	1.02E+08	2.03E+08	3.05E+08	4.06E+08	5.08E+08
Zinc Oxide – Type M	5.69E+07	1.14E+08	1.71E+08	2.28E+08	2.85E+08
Zinc Oxide – Type S	1.46E+07	2.93E+07	4.39E+07	5.85E+07	7.32E+07

Derived Investigation Levels for BZA sampling are presented below in Figures C.8.58 through C.8.60 for Types F, M, and S STCs. The DIL values in these curves are in terms of observed activity, and are based on a typical BZA sampler flow rate of 4 liters per minute. As seen in these figures, the theoretical monitoring sensitivity of BZA sampling is very good – even for Type S materials with small particle size distributions (the "worst case.")

Figure C.8.58

DIL for BZA Monitoring for Type F STCs

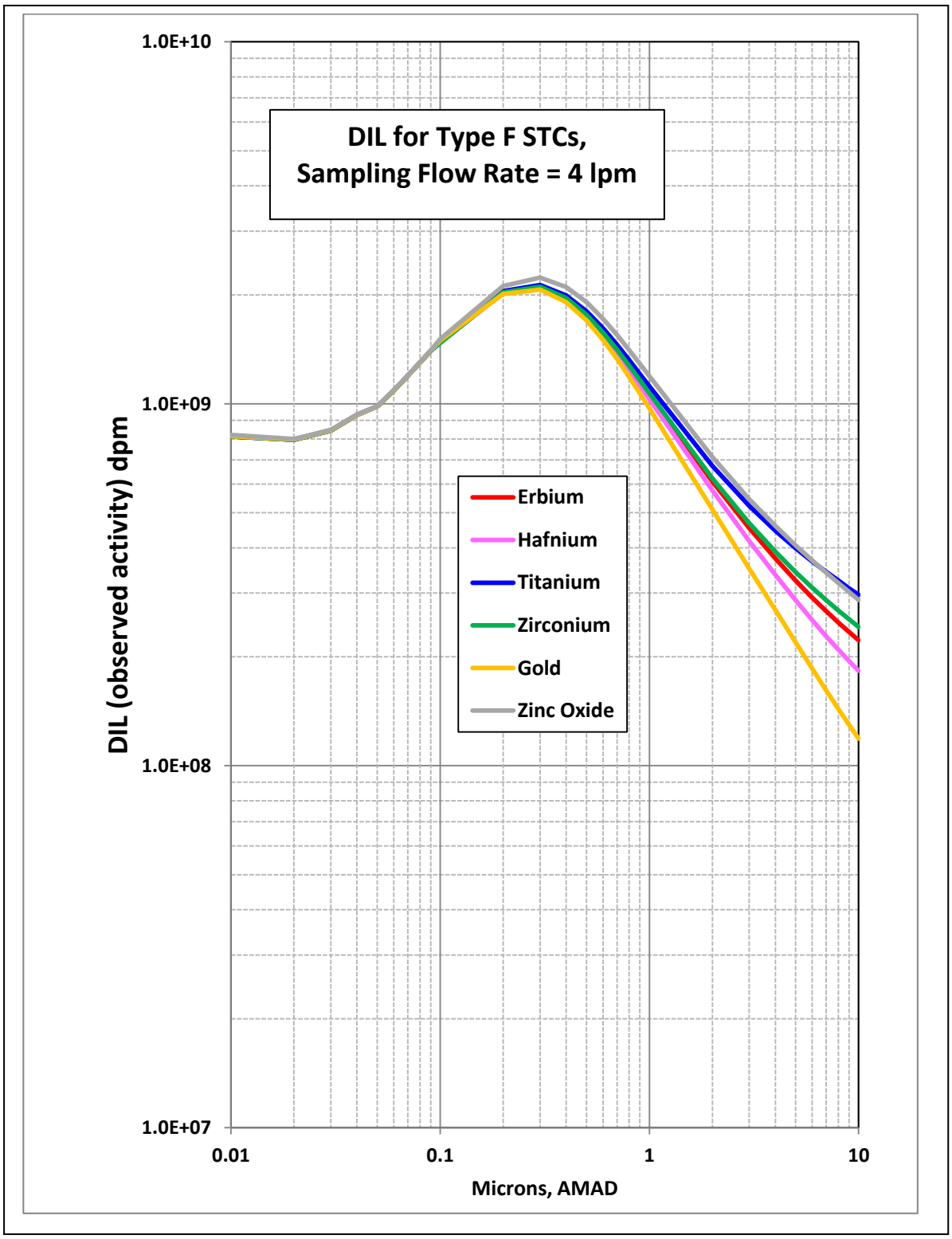


Figure C.8.59

DIL for BZA Monitoring for Type M STCs

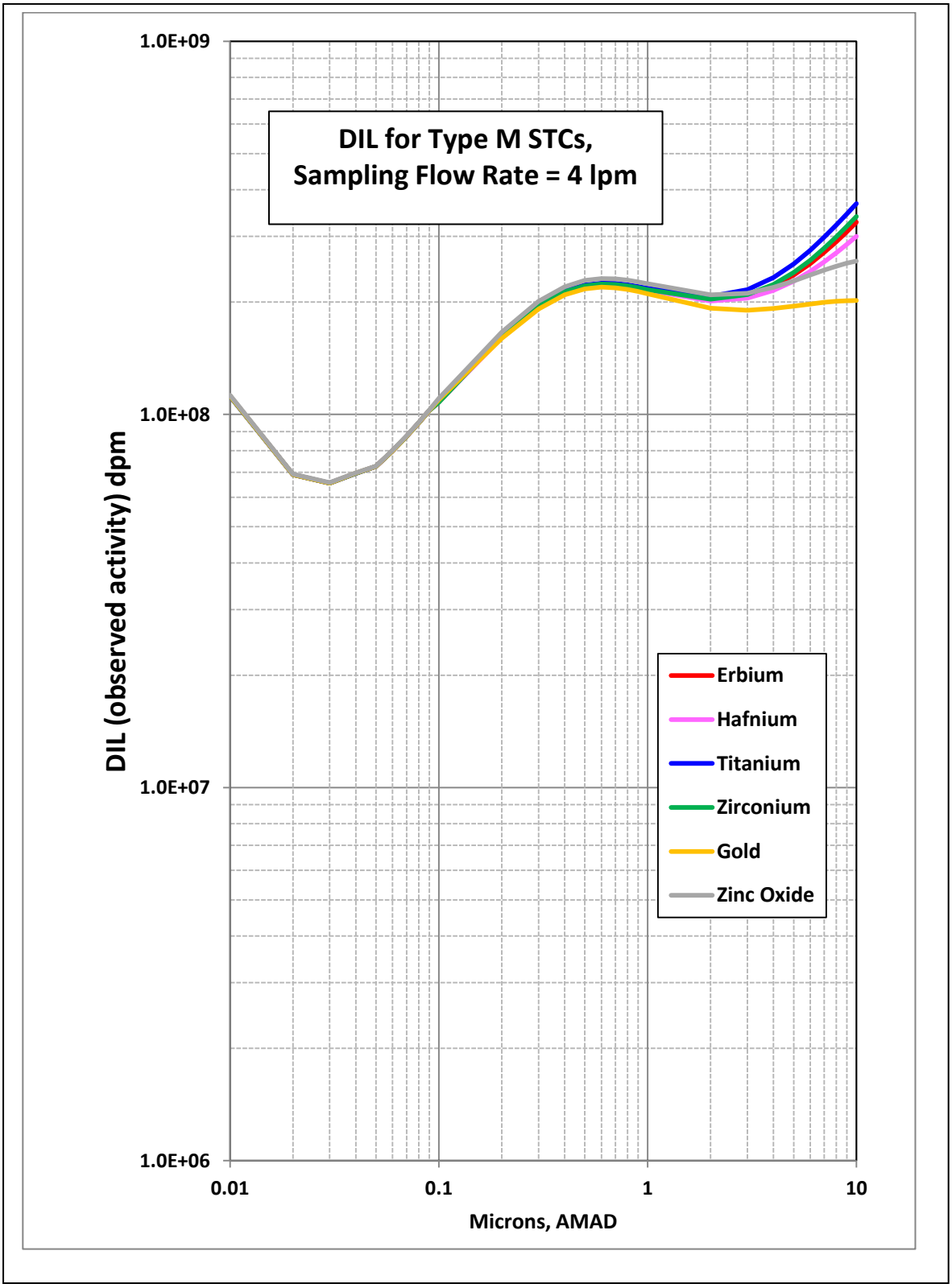
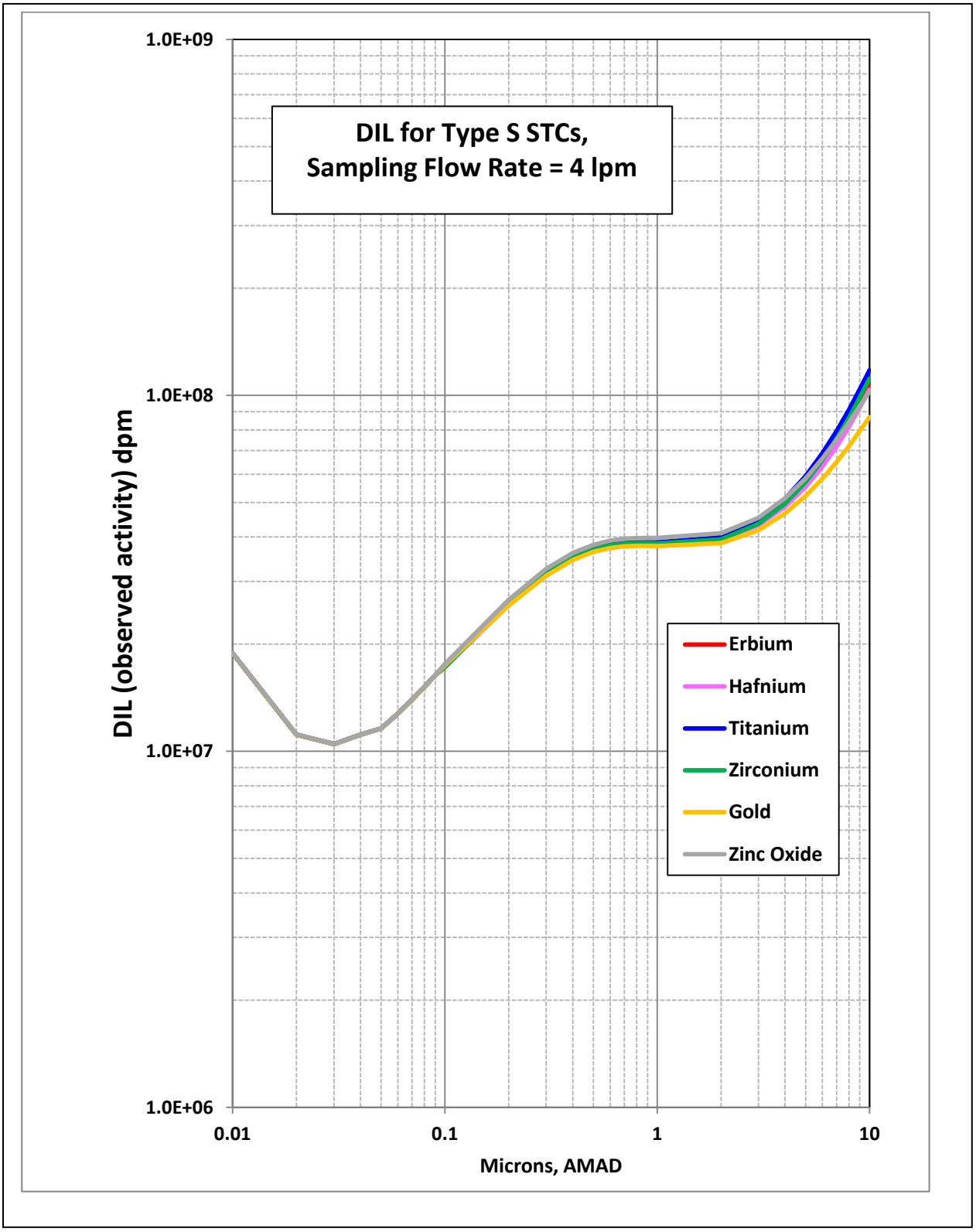


Figure C.8.60

DIL for BZA Monitoring for Type S STCs



C.8.8 Workplace Monitoring for STCs

Workplace monitoring results (e.g., area air sampling and swipe sampling) may be used as general indicators of the potential for internal intakes of STCs. As recommended in Section 3.1 of the DOE Handbook (DOE 2006) (and as discussed in Section C.8.7 of this Manual) the concept of "observed" activity will generally be used for interpretation of workplace monitoring results.

C.8.8.1 Area Air Sampling

The guidelines of Section 3.2.2 of the DOE Handbook should be used for area air monitoring or sampling for STCs.

Section 835.403 of 10 CFR 835 requires that monitoring of airborne radioactivity be performed where:

1) An individual is likely to receive an exposure of 40 or more DAC-hours in a year, or
2) As necessary to characterize the airborne radioactivity hazard where respiratory protective devices for protection against airborne radionuclides have been prescribed.

Note that any extrapolation of air concentrations from the monitoring location to the worker's breathing zone must be done with care.

Workplace (area) sampling is subject to the same considerations and constraints as discussed above. Note that, while the calculated Derived Air Concentration (DAC) values based on SAF_e-corrected DCFs and "observed" air activity (as presented in Section C.8.4.6) may be used as reference points, the DACs of 10 CFR 835 (Appendix A) shall be used for workplace controls (e.g., posting, monitoring) unless otherwise specified and approved.

C.8.8.2 Swipe (Surface) Sampling Results

Guidelines of Section 3.2.1 of the DOE Handbook (DOE 2006) should be used for surface contamination monitoring for STC contamination.

Liquid scintillation counting of swipe samples is subject to the same beta self absorption factor (SAF_β) discussed in Section C.8.7.2. For the same reasons discussed in Section C.8.7.3, use of "observed" swipe activity may reduce the uncertainty in interpretation of swipe results. (However, see caveat below.)

LLNL is required to use the surface contamination levels listed in Appendix D of 10 CFR 835 for workplace posting and controls. In Appendix D, a single value of 10,000 dpm/100 cm^2 is listed for "Removable" tritium and STCs. As noted in footnote 2 of that Table:

"As used in this table, dpm (disintegrations per minute) means 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."

It is clear from that footnote that the value of 10,000 dpm/100 cm^2 listed for STCs is for *actual* (SAF_{β}-corrected) activity on the swipe.

In a master-stroke of clarity, footnote 6 of the Surface Contamination Limit table further states that: "In certain cases, a 'Total' value of 10,000 dpm/100 cm^2 may be applicable either to metals, of the types which form insoluble special tritium compounds that have been exposed to tritium; or to bulk materials to which particles of special tritium compounds are fixed to a surface."

The reader is referred to Section 3.2.1 of the DOE Handbook (DOE 2006) for further discussion of surface contamination monitoring for STCs.

C.8.9 Individual Monitoring Programs

C.8.9.1 General Information

Routine individual monitoring programs for possible internal intakes of STCs should be tailored to the workplace and the potential for worker exposure. The guidelines of Sections 5, 6, and 7 of the LLNL Internal Dosimetry Program Manual (IDPM), (Mansfield 2009a) and those of Section 4 (specifically Section 4.2.1) of the DOE Handbook (DOE 2006) shall be used in establishing routine monitoring programs for STCs. The selection of appropriate monitoring methods and intervals depends on a variety of factors, including:

- the potential presence of HTO (along with the STC),
- the type of STC, and
- other operational concerns (e.g., new operation.)

Unless demonstrated otherwise, it should be assumed that workplaces with the potential for exposures to STCs also have some potential for concomitant intakes of HTO. Accordingly, the default monitoring program (if monitoring is desired or necessary) will typically be a combination of urine sampling and BZA sampling.

The guidelines of Section 6 and 7 of the LLNL IDPM shall be used to establish routine monitoring programs for possible intakes of STCs. To the extent practicable, the nature of the potential internal hazard (i.e., types of materials) shall be characterized as discussed in Section 6.2 of the IDPM. If an adequate characterization is not practicable, conservative assumptions (including the use of the "observed" activity concept), may be used to monitor for and assess doses from STCs.

The guidelines of Section 7.3 of the IDPM shall be used to determine whether "baseline" urine samples for tritium are required or recommended.

C.8.9.2 Selection of Workers for Routine STC Monitoring Program

Identification and selection of workers for a routine STC monitoring program should be consistent with the guidelines of Section 4.1 of the DOE Handbook (DOE 2006). As noted in that Section: "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."

The guidelines of Section 6.3 of the IDPM (Mansfield 2009a) shall be used to determine the need for participation in a routine monitoring program. Guidelines for selection of workers ("Requirements for Participation") for monitoring and the associated monitoring category (mandatory, confirmatory, or discretionary) are outlined in Table 6.1 of the IDPM. Note that the applicable dose values used for this categorization should be the sum of projected STC *and* HTO doses.

C.8.9.3 Special Monitoring Situations

New operations and inadequately characterized operations may warrant enhanced monitoring (e.g., more frequent urine samples.)

Monitoring of special cases (e.g., Declared Pregnant Workers, nursing mothers) shall be determined on a case-by-case basis by Internal Dosimetry, in conjunction with the ES&H Team Health Physicist.

C.8.9.4 Management and Follow-up of Elevated Results

As described in Section 5.8 of the LLNL IDPM (Mansfield 2009a), Program Notification Levels will be established for both urine and BZA monitoring results. Section 7.11 of the IDPM ("Management of Results" outlines the procedures to be used to follow-up on urine bioassay and BZA monitoring results. BZA sample results should be managed in a manner that is analogous to that used for urine sample results.

The guidelines of Section 7.12 of the IDPM shall be used to manage detection and confirmation of intakes. Follow-up monitoring shall be conducted according to the guidelines of Section 7.13 of the IDPM (Mansfield 2009a).

In the case of suspected significant intakes of STCs, concomitant intakes of HTO can significantly perturb urine sample results (see discussion in Section C.8.6.) In such cases, it may be desirable or necessary to temporarily remove the worker from further possible exposures to either STCs or HTO, in order to better interpret urine sample results. Such temporary work restrictions shall be handled on a case-by-case basis per Section 7.13.3 of the IDPM.

C.8.9.5 Assessment of Doses from Intakes of STCs

Assessment and reporting of doses from intakes of STCs shall be performed using the guidelines of Section 9 of the LLNL IDPM (Mansfield 2009a) and the general recommendations of Section 5 of the DOE Handbook (DOE 2006).

C.8.9.5.1 "Dual" Assignment of Doses from STCs

The difficulty of monitoring for, and assessing doses from concomitant intakes of both HTO and STCs has been discussed above. LLNL has chosen to adopt a realistic, yet conservative method of dealing with such dose assignments, using the method described below:

1. If practicable, doses from intakes of STCs will be assigned based on BZA filter results, as described in Section C.8.7.4 above,
2. Doses from possible (or likely) concomitant intakes of HTO will be assigned based on urine sample results, as described in Section C.8.6.2.

Use of BZA results is the preferred method for assessment of doses from STCs. However, as noted in Section 4.2.1 of the DOE Handbook (DOE 2006): "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))."

This dual, independent assignment of doses will result in an over-estimation of the actual total dose received by the worker. As seen in the figures below, the degree of over-estimation will be a function of the assumed absorption type, and the interval between intake and urine sampling. Note these data and graphs represent only STC intakes, not concomitant intakes of HTO and STCs.

For Type F STCs, the assigned "HTO" dose will be from about 75% to 85% of the actual Type F STC dose – regardless of the sampling interval or material involved. This nearly constant relationship comes about due to the rapid transfer of Type F materials to the bloodstream.

The picture is more complex for Type M STCs – as seen in Figure C.8.62. If the interval between intake and sampling is less than about 30 days, the assigned "HTO" dose is generally less than 30% of the actual Type M STC dose – even for the "high f1 value" materials. However, the percent over-estimation rapidly increases to unacceptable levels after about 100 days.

The over-estimation of dose for Type S STCs is quite acceptable (generally less than 1% and in any case less than 12% for all STC materials up until an interval of about 90 days.

Figure C.8.61

Assigned HTO Dose as Percent of Actual STC Dose – Type F

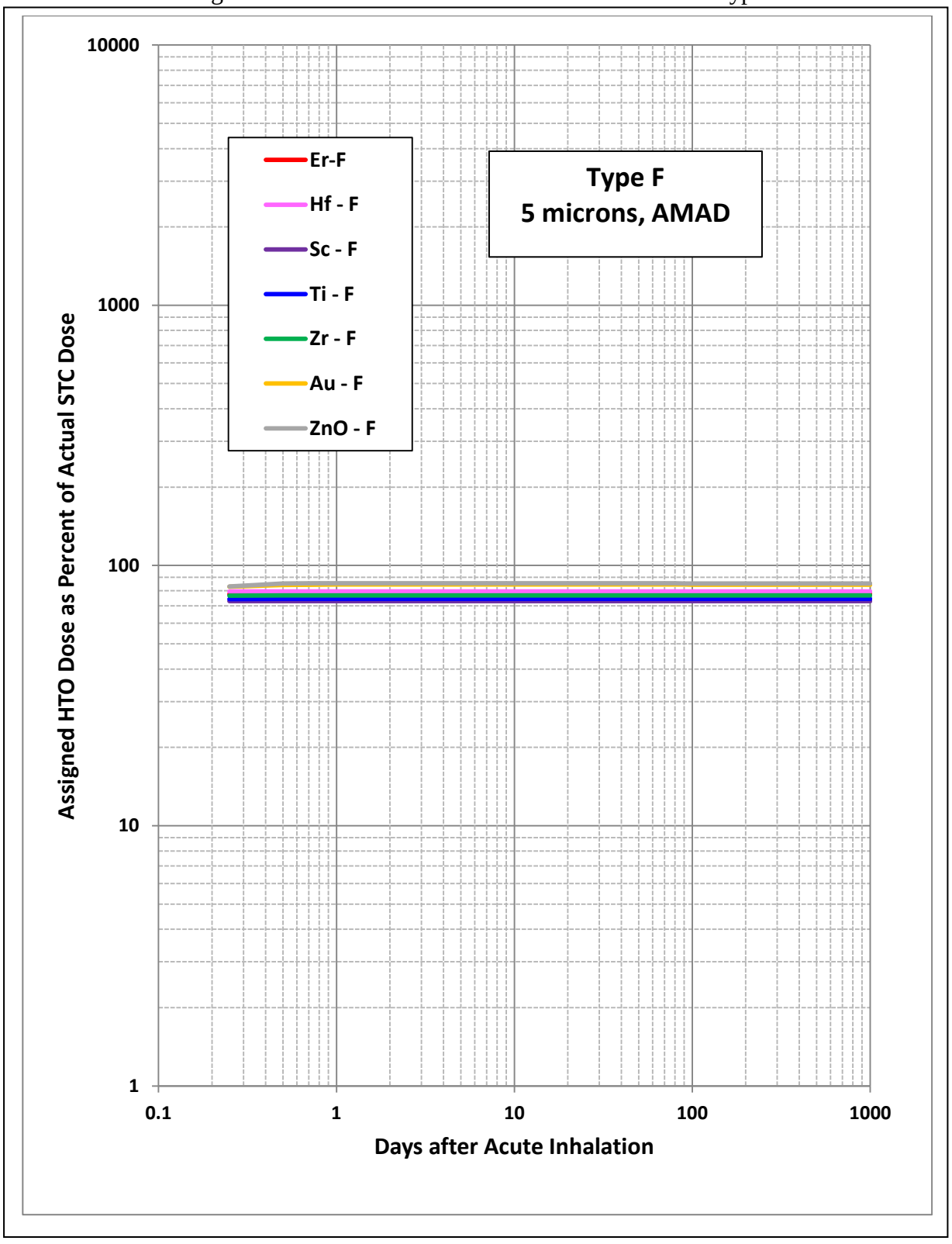


Figure C.8.62

Assigned HTO Dose as Percent of Actual STC Dose – Type M

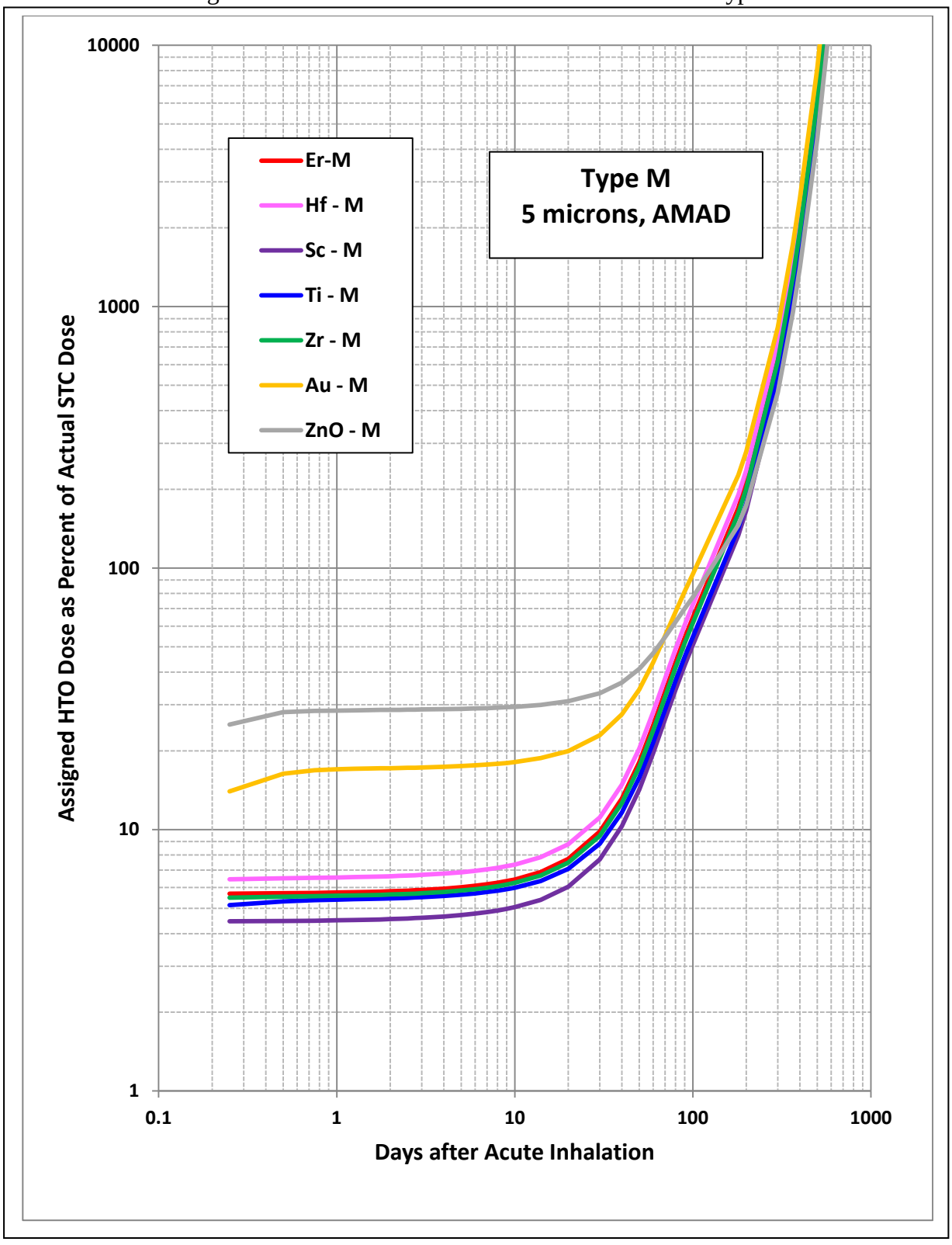
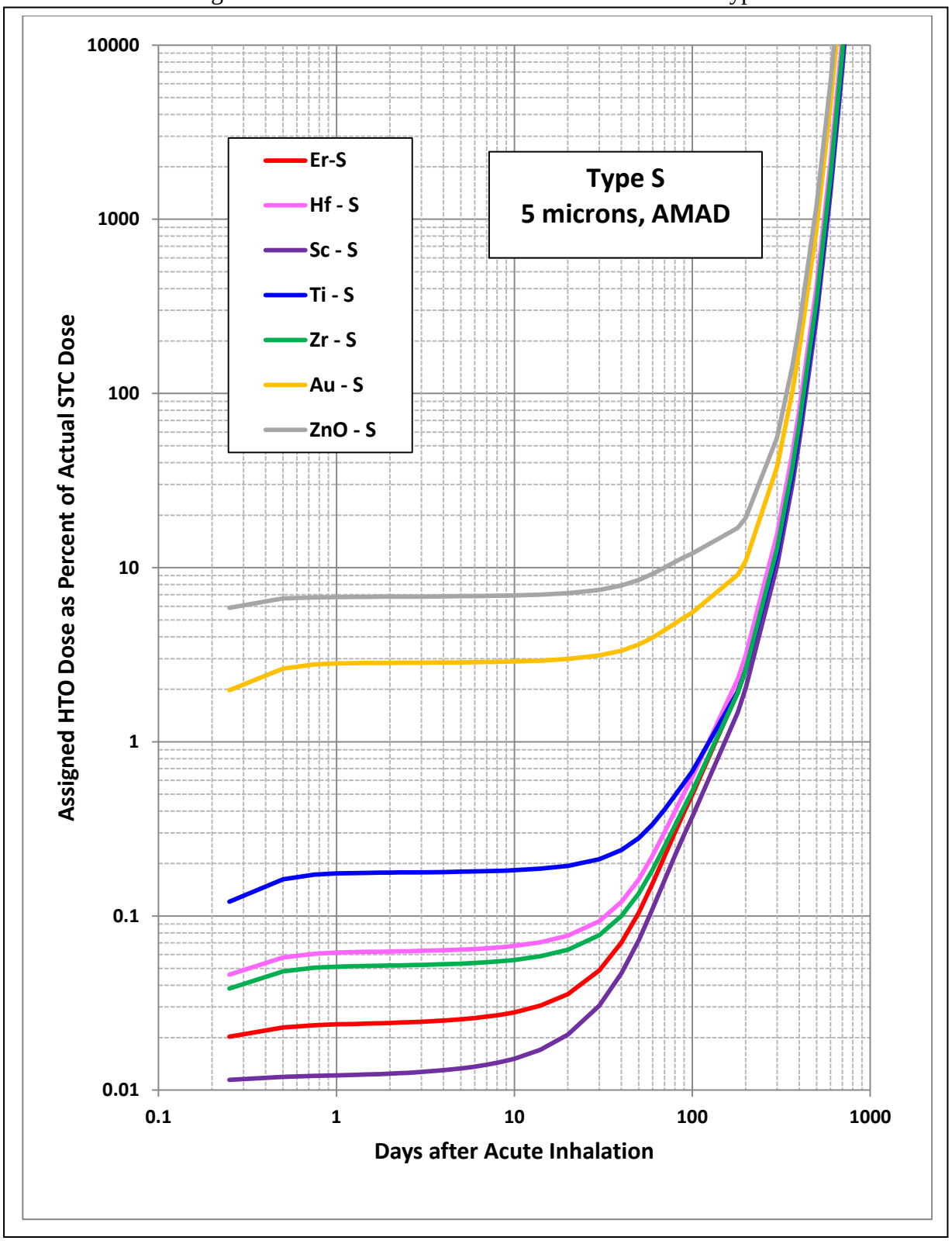


Figure C.8.63

Assigned HTO Dose as Percent of Actual STC Dose – Type S



C.8.9.5.2 Models and Assumptions Used for Dose Assessments

Although some workplace control parameters (e.g., the DAC values of 10 CFR 835) represent conservative upper-bound values, LLNL will use the most accurate, reasonably conservative assumptions in assessing doses from intakes of STCs. Thus, for example, LLNL will use the reference dose conversion factors of Section C.8.4.2, which have been corrected for the material and particle size-dependent the energy self-absorption factors, along with calculated beta counting self absorption factors discussed in Section C.8.7.2.

C.8.9.6 Reporting and Recording of Doses

Doses from intakes of STCs should be assessed and recorded per the guidelines of Section 9 of the IDPM (Mansfield 2009), as summarized in Table 9.1 of that Section.

C.8.9.57 Bioassay Laboratory Capabilities

As discussed in Section C.5.2, for purposes of planning bioassay programs, the Minimum Detectable Concentration (MDC) for HTO in urine is assumed to be 0.01 μCi per liter. The Minimum Detectable Activity for analysis of BZA filters is assumed to be 20 dpm.

C.8.10 Incident Response

The general guidelines of Section 11 of the IDPM should be used for response to suspected intakes of STCs.

C.8.10.1 A Perspective on Potential Doses

Some perspective on the risks of accidental inhalation intakes of STCs may be gained by comparing the quantity of *observed* activity necessary to produce a given dose. (In the event of an accident or incident, it is likely that most of the early activity and contamination information will be in terms of *observed* activity.) Table C.8.13 compares doses from STCs with those from HTO and other selected radionuclides.

Table C.8.13

Comparison of Inhalation Dose Conversion Factors

Material (Assumed to be 5 microns, AMAD unless specified otherwise)	**Dose Conversion Factor (CED) OBSERVED ACTIVITY inhaled (mrem/dpm)**	**ALI Intake Required to Result in 5 rem OBSERVED ACTIVITY (dpm)**	**CED Resulting from inhalation of 1.0E6 dpm OBSERVED ACTIVITY (mrem)**
HTO	3.05E-08	1.64E+11	0.03
Pu-239 (Type M)	5.33E-02	9.38E+04	5.33E+04
Pu-239 (Type S)	1.38E-02	3.61E+05	1.38E+04
U-235 (Type M)	3.00E-03	1.67E+06	3.00E+03
U-235 (Type S)	1.02E-02	4.92E+05	1.02E+04
Cs-137 (Type F)	1.12E-05	4.48E+08	1.12E+01
Sr-90 (Type S)	1.28E-04	3.90E+07	1.28E+02
STC: Au (Type M)	1.03E-07	4.88E+10	0.1
STC: Au (Type S)	3.83E-07	1.30E+10	0.4
STC: ZnO (Type M)	8.78E-08	5.69E+10	0.09
STC: ZnO (Type S)	3.42E-07	1.46E+10	0.34
STC: Au, Type S, 0.1 microns AMAD	1.14E-06	4.37E+09	1.1
STC: ZnO, Type S, 0.1 microns AMAD	1.14E-06	4.40E+09	1.1
Worst Case STC: any material, Type S:	**1.9E-6**	**2.6E+09**	**2.0**

As indicated in this table, an intake of 1,000,000 dpm (observed), assuming the "worst case" STC dose conversion factor (any material, Type S, ~0.03 microns AMAD) would result in a CED of less than 2 millirem. An intake of about 2.6 *billion* dpm (observed) would be required to produce a CED of 5 rem.

C.8.10.2 Suspected Exposure to Airborne STCs

As with any intake of radioactive materials, among the first priorities will be to:

- Characterize the nature of the material, and
- Estimate the magnitude of the intake and associated doses.

As discussed in Section C.8.8.6, it is likely that any intake of STCs will involve a concomitant intake of HTO. Accordingly, potential intakes of STCs should be treated as having two components; an intake of STCs and an intake of HTO. Follow-up and monitoring efforts should address both of these possible intake components.

As with any suspected intake of tritium, urine samples should be collected, per the guidelines in Section C.6.7 of this Technical Basis Manual. As a first approximation, these urine sample results may be interpreted as indicative of the HTO component of the intake (but not necessarily of the STC component of the intake.)

Nasal swabs may be of some use in the event of suspected inhalation of STCs. The guidelines of Appendix A.6.1 of the LLNL TBM shall be used for collection of such nasal swab samples.

In addition, in the event of a suspected serious exposure to tritiated particulates, collection of early (first few days) fecal samples should be *considered*, since inhaled particulates would be expected to be eliminated via that route. Cases involving inhalation of metal tritides have occurred which produced no significant tritium in the urine, but obvious tritium in the feces (De Ras 1980.) Collection and analysis of fecal samples would allow confirmation of intake, and may give information regarding the fractional uptake.

If necessary, the biokinetic model for STCs presented in Figure C.8.1 may be used to predict the quantity of STC particulate activity in the feces.

C.8.10.3 Follow-up Sampling for Suspected Intakes of STCs

The guidelines of Section 11.10 of the LLNL IDPM shall be used to establish appropriate follow-up sampling for suspected intakes of STCs.

C.8.10.4 Medical Intervention for Intakes of STCs

Referring to the dose and intake values of Table C.8.13, it is considered unlikely that an intake of STCs which would warrant medical intervention would occur at LLNL. However, should such an intake occur, the following intervention actions could be considered:

1. Nasal irrigation

   Careful nasal irrigation may remove some STC particulates deposited in the nasal passages.

2. Increased fluid intake

   As discussed in Section C.6.8 of this Technical Basis Manual, doses from uptakes of HTO can be relatively simply and effectively reduced by increasing the person's fluid intake, thereby decreasing the effective half-time of water in the body. Accordingly, this intervention method may be useful in reducing the dose from the HTO component of the intake.

Note that any such medical interventions shall be coordinated and administered through Health Services. Note also the special considerations discussed in Section C.8.9 of this Technical Basis Manual.

C.8.11 References for Special Tritium Compounds

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