External Dose Reconstruction

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
09/25/2018	00	New document initiated to convert ORAUT-PROC-0006, *External Dose Reconstruction*, to a technical information bulletin. Included information on assignment of onsite ambient dose to facilitate cancellation of ORAUT-PROC-0060. Updated to current dose reconstruction approaches. Incorporated responses to the Advisory Board on Radiation and Worker Health Subcommittee on Procedures Reviews comments about ICD-9 codes. Incorporates formal internal and NIOSH review comments. Training is required. Initiated by Mark R. Fishburn.

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ACRONYMS AND ABBREVIATIONS

AWE	atomic weapons employer
CFR	Code of Federal Regulations
DCAS	Division of Compensation Analysis and Support
DCF	dose conversion factor
DOE	U.S. Department of Energy
DOL	U.S. Department of Labor
EALER	elevated ambient levels of external radiation
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
GM	geometric mean
GSD	geometric standard deviation
H(10)*	ambient dose equivalent at 10 millimeters depth in tissue
Hp(d)	personal dose equivalent at depth *d* in millimeters in tissue
hr	hour
HTML	hypertext markup language
ICRP	International Commission on Radiological Protection
IREP	Interactive RadioEpidemiological Program
keV	kiloelectron-volt (1,000 electron-volts)
LOD	limit of detection
MeV	megaelectron-volt (1 million electron-volts)
mrem	millirem
mSv	millisievert
NIOSH	National Institute for Occupational Safety and Health
ORAU	Oak Ridge Associated Universities
POC	probability of causation
SRDB Ref ID	Site Research Database Reference Identification (number)
TIB	technical information bulletin
TLD	thermoluminescent dosimeter
U.S.C.	United States Code
wk	week
w_R	radiation weighting factor
yr	year
§	section or sections

1.0 INTRODUCTION

Technical information bulletins (TIBs) are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historical background information and guidance to assist in the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). TIBs may be used to assist NIOSH staff in the completion of individual dose reconstructions.

In this document, the word "facility" is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an "atomic weapons employer facility" or a "Department of Energy (DOE) facility" as defined in the Energy Employees Occupational Illness Compensation Program Act of 2000 [42 U.S.C. § 7384l(5) and (12)].

1.1 PURPOSE

The purpose of this document is to outline external dose reconstructions under Part B of the Energy Employees Occupational Illness Compensation Program Act of 2000 (EEOICPA). This document incorporates direction from NIOSH on the performance of external dose reconstructions as contained in OCAS-IG-001, *External Dose Reconstruction Implementation Guideline* (NIOSH 2007), TIBs, approved site profiles, and Oak Ridge Associated Universities (ORAU) Team procedures.

1.2 SCOPE

Reconstruction of external dose could involve the calculation and assignment of dose from multiple sources (e.g., photons, neutrons, electrons, ambient dose, X-ray, etc.). This document provides information about the calculation of external dose and how it should be assigned under EEOICPA.

2.0 GENERAL APPROACH

External dose reconstruction represents just one part of the overall dose reconstruction process. Under EEOICPA and Executive Order 13179, dose reconstructions are performed using information from the U.S. Department of Labor (DOL), DOE, atomic weapons employers (AWEs), and claimants, while applying the science-based knowledge and practices of dose reconstruction.

During external dose reconstruction, the dose reconstructor assesses the circumstances of exposure, the completeness of the supporting data in relation to the employment period, and other information relevant to the dose reconstruction approach. The site profiles are reviewed, as necessary, to assist the dose reconstructor. Much of the relevant information from site profiles is captured in site-specific calculational tools (or general calculational tools for cases in which site-specific information is unavailable or unnecessary), and the dose reconstructor uses these tools to assist in the performance of external dose reconstructions.

To provide for efficient throughput in processing claims, overestimating assumptions can be used if a claim is initially deemed likely noncompensable, and underestimating assumptions can be used if a claim is initially deemed likely compensable. These processing options, which are typically available in the calculational tools, are described in ORAUT-PROC-0106, *Roadmap to Reconstructing Dose* (ORAUT 2016). Best-estimate analyses of external doses are possible, using the Vose capability process in the site tools to run Monte Carlo calculations to propagate dose uncertainty, but such analyses are typically more time-consuming because detailed knowledge of specific work locations, job responsibilities, and other claim-specific information is necessary to process the case in this manner. Often a claim determination can be achieved with less detailed knowledge by using claimant favorable assumptions.

The generalized approach is presented in Figure 2-1. This figure illustrates the manner in which progressively more information is analyzed to complete the external dose reconstruction.

As detailed in OCAS-IG-001, dose reconstruction takes into account only dose the worker received at a covered facility (NIOSH 2007). The dose is sorted by radiation type and energy and is reconstructed for a specific target organ, which is determined from the worker's primary cancer verified by DOL (see ORAUT-OTIB-0005, *Internal Dosimetry Organ, External Dosimetry Organ, and IREP Model Selection by ICD-9 Code* (ORAUT 2012). Only doses that were received before the diagnosis of the primary cancer are included in the dose reconstruction. If multiple primary cancers have been verified, doses from covered employment are reconstructed for each associated target organ until the diagnosis date of the considered primary cancer. Radiation dose from medical X-ray examinations for occupational health screening and as a condition of employment is included in the worker's reconstructed dose if the worker received those examinations at a covered site. The following sections summarize key information from OCAS-IG-001 about the external dose reconstruction process.

The dose reconstructor ensures that the records supporting the dose reconstruction are included in the submittal. The following records represent the minimum files that should be included in the submittal:

- Worksheets necessary to recalculate final input parameters for the Interactive RadioEpidemiological Program (IREP),
- IREP Input Spreadsheet,
- IREP HTML Summary Report of estimated POC, and
- Dose reconstruction report.

2.1 RECORDS AND RECONSTRUCTION METHODS PERTAINING TO EXTERNAL RADIATION EXPOSURE

Radiation monitoring records potentially available to the dose reconstructor typically consist of external dosimetry records, internal dosimetry records, diagnostic X-ray records, incident investigation reports, and other monitoring records. Except for internal dosimetry records, these potentially affect the external dose reconstruction.

2.1.1 External Dosimetry Records

Table 2-1 lists the general hierarchy of data sources dose reconstructors should employ for external dose reconstruction under EEOICPA. Personal dosimeter results typically represent the most accurate assessment of a worker's dose. In general, recorded dose data from a personal dosimeter should be used whenever possible, and these data are given priority over personal monitors, survey data, or source term data. The adequacy and completeness of the dosimeter data should be described in the site profile in terms of potential limitations in technology, calibration, workplace radiation fields, and administrative practices.

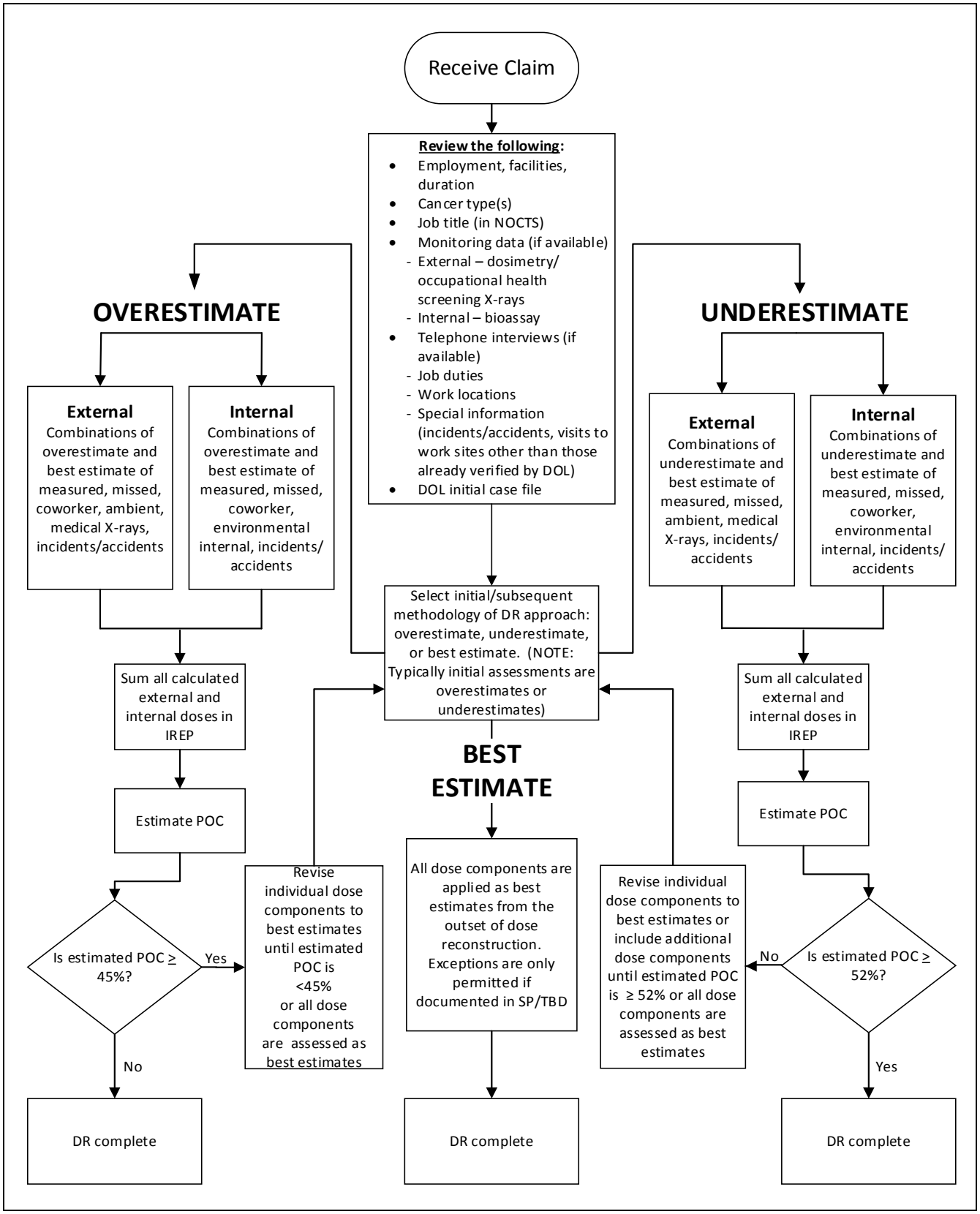

Figure 2-1. Generalized dose reconstruction analysis (modified from ORAUT 2016).

Table 2-1. Hierarchy for accuracy of data sources for external dose reconstruction.

Hierarchy	Data source	Examples
1	Personal dosimeter	Film badge; nuclear track emulsion, type A; TLD
2	Personal monitors	Pocket ionization chambers
3	Coworker data	Film badge, TLD, pocket ionization chambers
4	Area monitoring	Workplace radiation surveys, ambient air room monitors, duration of exposure
5	Source term	Source nuclide, activity, exposure rate, distance from source, duration of exposure, and shielding information
6	Radiation control limits	Generally, workplace posting has been required when the dose rate exceeded 0.025 mSv/hr.

Personal dosimeter records typically include the worker's entire external dose history at the respective covered facilities. These records can represent annual doses or the individual dosimeter processing results for each dosimeter assigned to the worker, or both. If only annual doses are available, the required approach is described in Attachment A and is favorable to claimants.

In relation to the availability of personal monitoring data for each claim, three conditions may apply, each requiring a different approach to reconstruction of external measured, missed, and/or unmonitored doses, as described below.

2.1.1.1 Worker Was Monitored Adequately

Workers are monitored adequately when the site has a robust dosimetry program. A robust dosimetry program involves a demonstrated quality control/assurance program for dosimetry, procedures or policies on who is assigned a dosimeter and the frequency of the monitoring, investigation of anomalous results, investigation of missing results, and retrievable records. The use of dosimetry should be reviewed for the site across the history of the site and will be discussed in the site-specific TBD or site profile.

In general, external monitoring data that has been collected since the implementation of 10CFR835, "Occupational Radiation Protection" (issued in 1993 and implemented in the following few years) represent adequate monitoring. Monitoring in the "835" era is generally considered adequate because the regulations and implementing standards and guides for 10CFR835 established a consistent, DOE-complex wide program in line with what NIOSH considers a robust dosimetry program.

Accreditation of a site dosimetry program in accordance with the DOE Laboratory Accreditation Program or the National Voluntary Laboratory Accreditation Program indicates that the site program has been reviewed for and demonstrated quality control and quality assurance for the measurement of dose by the dosimeters. In these situations, the dosimetry data likely can be used as the basis for external radiation dose reconstruction (i.e., to compute the annual dose for the worker for each year of covered employment); that is, no adjustments are required other than incorporation of missed dose and conversion to organ dose.

For adequately monitored workers, the associated uncertainty should be assumed to be normally distributed unless indicated otherwise in the site profile. For overestimate or underestimate reconstructions, the dose distribution can be considered a constant (point estimate) which results in an IREP input of only one parameter. For conservatism, a multiplicative factor may be applied to the assigned dose in lieu of uncertainty for an overestimate and not accounted for in an underestimate.

2.1.1.2 Worker Was Not Monitored

Determine if worker should have been monitored. Some non-monitored workers were not exposed so ambient dose would be assigned. Other non-monitored workers may have been exposed and dose needs to be assigned by evaluating other sources of dose data (i.e., Table 2-1 data sources).

Most AWE workers and some DOE workers were not individually monitored for external radiation exposure using assigned personal dosimeters, including some who would have been classified as radiation workers by today's radiation protection standards. Similarly, less-exposed workers who were not expected to exceed a significant percentage (e.g., 10% to 30%) of radiation protection standards lacked monitoring; a practice that continues at some sites today and is consistent with current regulations. If there was a significant potential for radiation exposure, recorded doses for monitored coworkers can be used as surrogates (see ORAUT-OTIB-0020, *Use of Coworker Dosimetry Data for External Dose Assignment*; ORAUT 2011). However, in the absence of such information, workplace radiation measurements (for example, area monitoring data) could exist that can be used to estimate dose. For workers with no significant exposure potential, external radiation dose reconstruction is based on ambient dose (see Attachment B). In general, it is expected that reconstructed dose to unmonitored workers will be less than dose to monitored workers.

At some facilities, only a small sample of the workforce, or only workers who met certain criteria, were monitored to ensure compliance with radiation exposure limits. As an example, although construction workers were often unmonitored, it is possible in some instances to use data from representative coworkers who received similar exposures, such as radiological control technicians who monitored the work activities, to estimate a realistic maximum external dose. When assigning dose to construction trade workers use the guidance in ORAUT-OTIB-0052, *Parameters to Consider When Processing Claims for Construction Trade Workers* (ORAUT 2014).

When no radiation monitoring data are available for a worker or representative coworkers, scientifically reasonable estimates of exposure should be developed based on survey data or the source term or quantity of radioactive material at the facility. Often a claim determination can be achieved with less detailed knowledge by using claimant favorable assumptions. It should be recognized that dose reconstructions based on survey data will probably be biased because monitoring data tended to be recorded at the highest level to ensure compliance; however, this is an acceptable bias in this compensation program. If no survey data are available, the dose should be estimated based on the activity of the source term, engineering and administrative controls, and work history at the same facility.

2.1.1.3 Worker Monitored Inadequately

Early workers at Manhattan Engineer District, U.S. Atomic Energy Commission, or AWE facilities were typically monitored inadequately in comparison with current practices. This was due to less capable dosimetry technology, higher control limits, more frequent dosimeter exchanges, and/or monitoring records are incomplete, missing, or unclear. Often, routine monitoring of worker neutron exposure was not performed in the 1940s and 1950s for some facilities.

Monitoring data before 1960 must be evaluated cautiously due to technological shortcomings and because monitoring programs were designed to ensure compliance with historically higher radiation safety limits. In such cases, external radiation dose reconstruction is based on available dosimetry data together with available site profile information about site processes, radioactivity, radiation fields, and other pertinent information.

When workers are monitored inadequately, it may be due to monitoring records that are incomplete, missing, or unclear. When this occurs external dose reconstruction must consider options to estimate all or a portion of a worker's dose and the associated uncertainty.

If the individual has sufficient monitoring records before and after the missing records, the dose to assign can be interpolated. The interpolation, or gap fill, which could be a simple average between the monitoring periods, is considered reasonable provided the work practices, radiological protection measures, and administrative and engineering controls did not change. Gap fill can be conducted only if there is no indication, whether from the claimant, worker, site radiological, or DOL records, that a radiological incident resulting in a higher exposure occurred during the period of missing records or that the worker's job duties or the exposure potential changed during the gap period. All documents associated with the claim should be reviewed to determine that there were no significant changes in the worker's job duties or exposure. Examples of information that could indicate significant changes in a worker's job duties or exposure include:

- Information (e.g., from telephone interviews, DOL records, etc.) that the worker changed jobs during the period in question.
- Significant changes in the recorded dose in the covered periods surrounding the missing dosimeter records.
- Information about incidents occurring during the period in question.

The length of the gap fill period is dependent on the surrounding dosimetry exchange frequency, whether it was weekly, monthly, quarterly, or semiannually. The gap period must be bounded on both ends with reported dosimetry information and should only be used to address a gap equal to an exchange period that is bounded on both sides by provided dosimetry data. An example would be a worker with first and third quarter dosimeter results, but no dosimeter results in the second quarter. If the claim information (e.g., the worker site records, telephone interview, etc.) do not indicate a change in employment and there is no indication that a higher exposure occurred during the period of missing records (as discussed in the previous paragraph), then dose may be assigned for the second quarter that aligns with the dose assigned in the first and third quarters.

Site-specific guidance about dosimetry practices should also be reviewed because some site guidance documents are more prescriptive in their methods for gap fill based on site-specific dosimetry practices. In addition, the dose reconstructor should ensure that all dosimetry records are evaluated and that any gap fill that is used aligns with them as appropriate (e.g., if an annual result is available ensure the amount of recorded and gap fill dose does not exceed the annual dose).

The assignment of dose using adjacent dosimetry information as described above should be the first method for assigning dose for a missing dosimetry exchange period. If monitoring data is not available, coworker data might represent a good option in cases involving missing or incomplete records. For records that are unclear, dose reconstruction management should be notified so an acceptable approach can be determined, which could involve requesting additional information from DOE.

2.1.2 Occupational Medical X-Ray Dose

Diagnostic records from medical X-ray examinations are often available identifying the date and clinical summary for each examination. The site profile or TBD is where information regarding X-ray frequency and type is provided and should be the initial document to review when evaluating site X-rays. Use the approach detailed in ORAUT-OTIB-0006, *Dose Reconstruction from Occupational*

Medical X-Ray Procedures (ORAUT 2018b) for assignment of dose and determining if off-site examinations are covered.

2.1.3 Incident Investigation Reports

Reports about incidents that might have involved the worker are often provided in the DOE records, either in separate files or embedded in the external, or internal, dosimetry records. The dose reconstructor should request records if they may exist, but are not available in the file (e.g., on reading the claimant interview in which a reportable incident involving external dose is described). The dose reconstructor needs to determine if the dose from the incident was captured by the dosimetry records of the worker and are already included in the dose reconstruction. If not, the dose reconstructor will need to assign the dose from the incident (this may involve the dose reconstructor performing a calculation to determine the dose to assign) in addition to other dose the worker is assigned.

2.1.4 Other Monitoring Records

Other monitoring records (e.g., area dosimetry results, survey results, etc.) that potentially pertain to reconstruction of external dose might be available in the DOE files. The dose reconstructor needs to determine if the dose from area dosimeter results, radiation surveys, etc. needs to be included because dosimetry monitoring was not performed or was inadequate. If monitoring was not performed or was inadequate, the dose reconstructor will need to assign dose in addition to other dose the worker is assigned. An example of this approach which used survey data to calculate and assign neutron dose is available in Section 6.4 of ORAUT-TKBS-0006-6, *Hanford Site – Occupational External Dose* (ORAUT 2010).

2.2 EXTERNAL RADIATION EXPOSURE TYPES

Dose reconstructions generally address the potential for recorded external and internal dose, missed dose, occupational medical exposures, and onsite ambient radiation exposures to arrive at an overall estimate of worker dose and uncertainty, applying assumptions that are favorable to the claimant as necessary to minimize the likelihood that dose is underestimated. External radiation includes three types of radiation, as described below.

2.2.1 Photon (Gamma and X-Ray) Radiation

There are four basic components of photon radiation dose. The sum of the dose components in each calendar year comprises a worker's annual occupational photon radiation dose D_γ. This is expressed as follows:

$$D_\gamma = D_D + D_M + D_{OM} + D_{EN} \quad (2\text{-}1)$$

where

D_γ = total annual photon radiation dose
D_D = recorded worker occupational dose typically based on personal dosimeter measurements
D_M = missed dose (unrecorded or unmeasured due to dosimeter limitations)
D_{OM} = occupational medical monitoring X-ray examination dose
D_{EN} = environmental (onsite ambient) dose, which might or might not have been included in the dosimeter dose reported by the site

In addition to the above, unmonitored photon dose can be assigned if a worker was not monitored for radiation exposure and the dose reconstructor determines that doses exceeding D_{EN} might have been received. Unmonitored photon doses can be estimated based on adjacent monitoring records, coworker doses, applicable dose limits, or area measurement data.

Recorded photon doses D_D are adjusted, if appropriate, based on site profile information. If a relevant site profile does not exist for a particular case, dose reconstructors should consult ORAUT-OTIB-0008, *A Standard Methodology for Overestimating External Doses Measured with Thermoluminescent Dosimeters* (ORAUT 2006a) or ORAUT-OTIB-0010, *A Standard Complex-Wide Methodology for Overestimating External Doses Measured with Film Badge Dosimeters* (ORAUT 2006b), depending on whether the measurements were from thermoluminescent dosimeters (TLDs) or film badges, respectively.

As discussed in OCAS-IG-001, the prescribed method for evaluating missed photon dose D_M is to assign a dose equal to the limit of detection (LOD) divided by 2 for each dosimetry measurement that is recorded as zero except for cases in which multiple badges are issued for a particular monitoring period. In these cases, only one zero measurement should be assigned per monitoring period. These doses are then summed for a given year. The LOD/2 method results in a slightly positive bias (overestimate) of the true dose in most cases (NIOSH 2007).

Missed doses calculated in this manner are represented by a lognormal distribution for the purpose of calculating probability of causation (POC). Specifically, the photon LOD/2 times the number of zero monitoring badges is the central estimate or geometric mean (GM) of a lognormal distribution, and the upper 95th-percentile estimate is the LOD times the number of zero monitoring badges, which equates to a geometric standard deviation (GSD) of 1.52 (NIOSH 2007).

Additionally, OCAS-IG-001 also provides guidance on how to assign dose from non-zero dosimetry results that are less than the LOD. Dose should be assigned equal to the LOD divided by 2 for each dosimetry measurement (film badge, pocket ionization chamber, or TLD) that is recorded as zero or if it is below the LOD divided by 2. Readings greater than or equal to LOD divided by 2 are to be used as recorded.

When the number of zero measurements cannot be determined, the missed dose becomes more complicated. When the records provide only an annual dose, the number of zero doses should be estimated based on that dose, the monthly, quarterly, or annual limits for that year, and the maximum number of possible zero monitoring intervals (see Attachment A).

External ambient doses D_{EN} are determined using Attachment B of this document. Occupational medical X-ray doses D_{OM} are determined using ORAUT-PROC-0061, *Occupational X-Ray Dose Reconstruction* (ORAUT2017a) and ORAUT (2018b).

As described in OCAS-IG-001, photon doses are categorized into three input categories for IREP as follows (NIOSH 2007):

- <30 keV,
- 30–250 keV, and
- >250 keV.

Considering both organ dose conversion factor (DCF), and the risk associated with photon dose as represented in IREP, the 30-250 keV energy range typically represents the photon energy most favorable to the claimant if a dose reconstructor is faced with (1) an unknown energy distribution or (2) a desire to process a likely noncompensable case using an overestimating approach. One notable exception is dose to the skin from work with or near isotopes of plutonium because the DCF for the

skin is considered to be 1 for all energies [ORAUT-OTIB-0017, *Interpretation of Dosimetry Data For Assignment of Shallow Dose* (ORAUT 2005)], and because <30-keV photons have a higher risk factor in IREP than do 30–250 keV photons (NIOSH 2002). A photon energy division of 25% 30–250 keV and 75% >250-keV photons can be assumed to represent a reasonable minimum approach to process a likely compensable case because radiation scattering reasonably precludes the existence of exclusively high-energy photons in a workplace environment. Unless there is information to the contrary, external ambient (D_{EN}) and medical X-ray doses (D_{OM}) are always classified as 30–250 keV photons as favorable to claimants (Attachment B and ORAUT-PROC-0061; ORAUT 2017a).

In accordance with OCAS-IG-001, all external photon doses may be assigned as acute or chronic; however, they are typically assigned as acute (NIOSH 2002); except for external onsite ambient doses that are always considered chronic (NIOSH 2007).

2.2.2 Neutron Radiation

There are two basic components of neutron radiation dose. The sum of the dose components in each calendar year comprises a worker's annual occupational neutron radiation dose D_N. This is expressed as follows:

$$D_N = D_D + D_M \tag{2-2}$$

where

- D_N = total annual neutron radiation dose
- D_D = recorded worker occupational neutron dose, typically based on personal neutron dosimeter measurements
- D_M = missed neutron dose (unrecorded or unmeasured neutron dose due to dosimeter limitations)

Because neutron exposures from manmade sources do not generally exist in the environment, and because neutrons are not used in most diagnostic or occupational medical procedures, ambient and medical dose categories are not included in the external neutron dose reconstruction.

As is the case with photons, unmonitored neutron dose can be assigned if a worker was not monitored or was monitored inadequately for neutron exposure. Unmonitored neutron doses are typically determined based on neutron-to-photon ratios from the site profiles or using a quantile regression approach. However, many workers would not have received a significant neutron dose, and evaluation of the neutron dose component might be unnecessary in such cases (see ORAUT-OTIB-0023, *Assignment of Missed Neutron Doses Based on Dosimeter Records;* ORAUT 2008). Accordingly, photon dose might often represent the only type of external radiation dose a dose reconstructor evaluates.

Recorded neutron doses D_D are adjusted, if appropriate, based on site profile information. When using film dosimetry, track fading and angular dependence might be an issue. If needed, the site profile or technical basis document should provide guidance. The neutron dose for each energy category is adjusted to the International Commission on Radiological Protection (ICRP) Publication 60 weighting factors as described generally in OCAS-IG-001 (NIOSH 2007). For example, since the 1950s a quality factor of 10 has generally been applied to fast neutron exposures; however, it has varied from 5 to 20 across facilities and times. Table 2-2 lists the ICRP Publication 60 weighting factors for specific energy ranges.

Table 2-2. Neutron energy intervals and associated ICRP Publication 60 weighting factor and some examples of exposures or facilities where the specific neutron energy might be encountered.

Neutron energy (MeV)	Publication 60 radiation weighting factor (w_R)[a]	Typical exposure scenario
<0.01	5	Low-energy neutron exposures include thermal neutrons commonly found around nuclear reactors or moderated neutron sources. More prevalent around heavy-water reactors.
0.01–0.10	10	Intermediate-energy neutron exposures can also result from operation around nuclear reactors as high-energy neutrons are moderated to thermal energies.
0.10–2.00	20	Commonly called fission spectrum neutrons, this is the most typical energy range from operation of light-water or graphite-moderated reactors.
2.0–20.0	10	Reactions between alpha particles from materials such as plutonium or polonium and light materials such as beryllium can result in the production of neutrons. These reactions are commonly called alpha-neutron (α,n) reactions. This neutron energy interval also includes 14 MeV neutrons from fusion reactions.
>20.0	5	Exposures to neutrons greater than 20 MeV can result from work around accelerators.

a. Source: ICRP (1991).

Neutron monitoring was not fully implemented until the late 1950s or was generally inadequate. As a result, missed or unmonitored neutron doses D_M have the potential to contribute significantly to the annual occupational dose, especially in the early years of the DOE weapons complex.

If the monitoring data and methods were considered adequate according to site profile information, a neutron missed dose should be evaluated using the same method discussed for photons. Specifically, the neutron LOD/2 times the number of zero monitoring badges is the central estimate of a lognormal distribution, and the upper 95th-percentile estimate is the LOD times the number of zero monitoring badges. However, a zero in the records for neutron dose does not necessarily imply that there was a potential for neutron exposure, so exceptions apply (see ORAUT-OTIB-0023; ORAUT 2008). Use the site profile information to reconstruct unmonitored neutron dose for workers exposed without monitoring being performed. This dose is generally reconstructed using neutron-to-photon ratios based on the reconstructed measured and missed photon doses. An additional method involving quantile regression, described in ORAUT-RPRT-0087, *Applications of Regression in External Dose Reconstruction* (ORAUT 2018a), can also be used which uses monitoring results from dosimeters which are sensitive to both photons and neutrons and models that relationship to determine possible neutron dose when only a photon result is available.

As described in OCAS-IG-001, neutron doses are categorized into five IREP input categories as follows (NIOSH 2007):

- <10 keV,
- 10–100 keV,
- 0.1–2 MeV,
- 2–20 MeV, and
- >20 MeV.

Considering the neutron weighting factor adjustment, organ DCF, and the risk associated with neutron dose as represented in IREP, the 0.1–2 MeV energy range is typically most favorable to the claimant, but the dose reconstructor should use the guidance in the site profile for neutron dose distribution.

In accordance with OCAS-IG-001, all neutron doses should be entered as chronic in IREP (NIOSH 2007).

2.2.3 Electron (Beta) Radiation

In general, external electron radiation dose is significant only for exposures to the surface skin tissue of the body. The exposure to skin can originate from an unshielded electron source, such as $^{90}Sr/^{90}Y$ or uranium decay products, or from skin contamination with beta/gamma emitters. Other organs for which external electron exposure is relevant include the breast, testes, and lip; see ORAUT-OTIB-0017, *Interpretation of Dosimetry Data for Assignment of Shallow Dose* for detailed information (ORAUT 2005).

There are three basic components of skin radiation dose. The sum of these components in each calendar year is a worker's annual occupational electron radiation dose D_E. This is expressed as follows:

$$D_E = D_D + D_M + D_S \quad (2\text{-}3)$$

where

D_E = total annual electron radiation dose
D_D = recorded worker occupational electron skin dose typically based on personal dosimeter measurements
D_M = unrecorded or unmeasured electron dose commonly referred to as the missed electron or skin dose
D_S = dose from skin contamination by beta/gamma-emitting nuclides; this dose poses a unique exposure scenario that should be evaluated in skin cancer cases

As is the case with photons, unmonitored electron dose can be assigned if a worker was not monitored or was monitored inadequately for electron exposure.

All components of electron dose (D_D, D_M, and D_S) must be calculated based on the guidance in ORAUT-OTIB-0017 (ORAUT 2005). This involves an understanding of the open window result values (e.g., electron or low energy photon), site dosimetry reporting schemes, limit of detection issues, and dosimetry shielding by security credentials and personnel protective equipment. Recognizing these confounding factors and using the approach provided in ORAUT (2005) is necessary to determine the dose to assign. When calculating the electron dose, separate the non-penetrating doses and determine if they represent >15 keV electrons (corrected for attenuation, if applicable) or <30 keV photons and include any applicable missed dose. As discussed in ORAUT (2005), a DCF of 1 is assumed for determining dose to the skin.

As described in OCAS-IG-001, electron doses are categorized into two IREP input categories as follows (NIOSH 2007):

- ≤15 keV, and
- >15 keV.

However, only the >15-keV category is considered to be a source of external radiation. Electrons ≤15 keV do not have sufficient energy to penetrate the epidermal layer of the skin and are therefore not considered an external radiation hazard.

In accordance with OCAS-IG-001, external electron doses should be entered as acute in IREP (NIOSH 2007).

2.3 CONVERSION OF RECONSTRUCTED EXTERNAL DOSE TO ORGAN DOSE

For external dose reconstruction under EEOICPA, the organ or tissue that developed the cancer is the primary organ of interest. Detailed information on ICD-9 codes and the appropriate external organ is provided in ORAUT-OTIB-0005 (ORAUT 2012).

Film badges and TLDs were typically worn on the upper front torso of the worker's body. Depending on the monitoring era, workplace radiation fields, and site, these devices were calibrated to a selected radiation quantity as follows:

- Exposure,[1]
- Absorbed dose in air,
- Ambient dose equivalent, or
- Penetrating dose at a selected depth in tissue (i.e., similar to current personal dose equivalent, *Hp(d)*, where *d* = 0.07 millimeter for shallow dose and *d* = 10 millimeters for deep dose.

The precise radiation quantity a site used to measure and record dose to workers historically is difficult to evaluate retrospectively. Under most circumstances, it is known that calibration of early film dosimeters using comparatively high-energy radium or ^{137}Cs gamma sources generally resulted in an overestimation of the dose received by a worker in the comparatively lower energy photon radiation fields typical of the workplace because of the film overresponse to lower energy photons caused by shielding and scattering of the radiation. In view of these considerations, the corresponding uncertainties, and the desire to conduct consistent evaluations, organ DCFs are selected from OCAS-IG-001 based on the geometry that is most favorable (NIOSH 2007). For most organs this is an anterior-posterior exposure, but for some organs (i.e., lung, esophagus, red bone marrow, bone surfaces) both anterior-posterior and rotational geometries must be evaluated and the geometry that results in the highest POC should be selected. When evaluating claims with multiple cancers, to be consistent, whichever geometry is determined to have the highest overall POC should be applied to all cancers.

Certain exceptions exist in the use of the DCFs in OCAS-IG-001 (NIOSH 2007). For likely noncompensable cases, the calculation of measured doses involves rounding organ DCFs up to 1 unless the DCF exceeds 1, in which case the actual DCF is applied. This practice was established (1) to help ensure favorability to claimants and (2) to avoid, if possible, reporting a reconstructed organ dose less than the dose of record.

Other exceptions include:

- Reconstruction of dose to the skin, where a DCF of 1 is assumed in accordance with ORAUT-OTIB-0017 (ORAUT 2005),
- Reconstruction of external ambient dose (ambient dose equivalent [*H*(10)*] DCF in OCAS-IG-001 (NIOSH 2007) for an isotropic exposure geometry as indicated in Attachment B), and

[1] *Exposure* is used to measure gamma and X-ray radiation interaction only with air and was historically measured in roentgens: 1 R = 2.58 × 10^{-4} coulombs per kilogram. It is a measure of the ionizations of the molecules in a mass of air. The quantity is easy to measure directly and was used historically to calibrate radiation protection instruments and dosimeters.

- Reconstruction of organ doses from occupational X-rays. Organ-specific doses are presented in the respective site profiles as described in ORAUT-PROC-0061 (ORAUT 2017a).

2.4 UNCERTAINTY

The uncertainties in the measured dosimeter dose and the occupational medical dose are assumed to be represented by a normal distribution, while the uncertainties in the missed dose and the ambient onsite dose are assumed to be represented by a lognormal distribution. The uncertainty in the organ DCF is assumed to be represented by a triangular distribution as provided in NIOSH (2007).

Assessment of the overall external dose uncertainty is dependent on the methodology of the dose reconstruction approach. For likely compensable claims (underestimates), uncertainty may not be applied. For likely noncompensable claims (overestimates), the uncertainty may be incorporated by increasing the assigned dose components and assigning them as a constant. For claims where the a priori compensability is unknown (best estimates), each dose component is treated as a distribution and Monte Carlo sampling of the distributions is employed to calculate the overall uncertainty of the dose estimate.

Attachment B and ORAU (2017a) provide details on the assessment of uncertainties for external ambient and occupational X-ray doses, respectively.

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ATTACHMENT A
METHOD FOR ASSIGNING MISSED DOSE WHEN THE NUMBER OF NULL RESULTS IS UNKNOWN

The basis for these instructions is Section 2.1.2.3 of OCAS-IG-001, *External Dose Reconstruction Implementation Guideline* (NIOSH 2007).

Overestimating Approach (Appropriate for Likely Noncompensable Cases)

Instruction: Calculate the maximum number of potential zeroes N_{max}, taking into consideration the published exchange frequency and applicable dose limits. This number multiplied by the LOD (i.e., $N_{max} \times LOD$) is considered the 95th percentile of a lognormal distribution. Multiply by LOD/2 (i.e., $N_{max} \times LOD/2$) to determine the GM. These values are represented by a lognormal distribution with a GSD of 1.52.

Example: Assume the case and site profile information has provided a 1-rem reported annual dose, weekly exchanges, LOD of 40 mrem, 300-mrem/wk dose limit for the era, and a 52-week work year:

- The maximum number of zeroes is 48 (e.g., 300 mrem/wk for 3 weeks, 100 mrem in 4th week, zero the rest).
- The missed dose assigned is 48 × 0.040 rem/2 = 0.960 rem (lognormal, 1.52 in IREP Parameter 2).

Underestimating Approach (Appropriate for Likely Compensable Cases)

Instruction: Calculate the median between the maximum and minimum number of potential zeros N_{med} taking into consideration the published exchange frequency, applicable dose limits, and LOD. When multiplied by the LOD (i.e., $N_{med} \times LOD$), the resultant value is considered the 95th percentile of a lognormal distribution and $N_{med} \times LOD/2$ is the GM. This is considered an underestimating approach in comparison with the guidance in OCAS-IG-001 (NIOSH 2007).

Example: Using the same assumptions as above:

- The maximum number of zeroes is 48.
- The minimum number of zeroes is 27 (e.g., 40 mrem in 25 weeks, zero the rest).
- The median is 37.5.
- The missed dose assigned is 37.5 × 0.040 rem/2 = 0.750 rem (lognormal, 1.52 in IREP Parameter 2).

Best-Estimate Approach (Appropriate for Cases in Which Overestimating Approach Results in POC >45% and Underestimating Approach Results in POC <52%)

Instruction: Calculate the median between the maximum and minimum number of potential zeros N_{med} taking into consideration the published exchange frequency, applicable dose limits, and LOD. When multiplied by LOD/2 (i.e., $N_{med} \times LOD/2$), the resultant value is considered the GM of a lognormal distribution. Then calculate the maximum number of potential zeroes N_{max} taking into consideration the published exchange frequency and applicable dose limits. When multiplied by the LOD (i.e., $N_{max} \times LOD$), the resultant value is considered the 95th percentile of a lognormal

ATTACHMENT A
METHOD FOR ASSIGNING MISSED DOSE WHEN THE NUMBER OF NULL RESULTS IS UNKNOWN (continued)

distribution, and the GSD must be calculated accordingly using the 95th- and 50th-percentile dose. The GSD is calculated as:

$$GSD = \left(\frac{95th\ percentile}{50th\ percentile} \right)^{\left(\frac{1}{1.64485} \right)} \quad \text{(A-1)}$$

Example: Assumptions the same as above.

- The maximum number of zeroes is 48.
- The minimum number of zeroes is 27.
- The median is 37.5.
- The missed dose is 37.5 × 0.040/2 = 0.750 rem (lognormal).
- 95th percentile dose is 48 × 0.040/2 = 0.960 rem; $GSD = \left(\frac{0.960}{0.750} \right)^{\left(\frac{1}{1.64485} \right)} = 1.162$
- The missed dose assigned = 0.750 rem (calculated in previous bullet), lognormal, 1.162 in IREP parameter 2.

ATTACHMENT B
ONSITE AMBIENT DOSE ASSIGNMENT

This attachment provides guidance for the assignment of external onsite ambient dose. This attachment is intended to provide general information about the assignment of external onsite ambient dose during the dose reconstruction process. Site-specific guidance might be provided in the site profile.

B.1 GENERAL

As described in OCAS-IG-001, *External Dose Reconstruction Implementation Guideline* (NIOSH 2007), doses from elevated background radiation as a result of DOE or AWE activities must be included in dose reconstructions. This requirement is complicated by site reporting practices, fallout from atmospheric weapons testing, and worker location in relation to site monitoring data. Because these exposures are a concern for workers who were not monitored or who worked at a site where elevated background radiation from DOE or AWE activities might have been subtracted from dosimeter results, reconstruction of doses must rely on information in site-specific site profiles and other published health physics resources.

External film dosimeters or TLDs have been used for occupational radiation monitoring since the 1940s. To account for background radiation levels that are not traditionally included in occupational radiation dose records, control dosimeters have been used from the outset. Good radiation protection practice dictates that during shipment a control dosimeter accompanies each batch of dosimeters issued to workers. Between manufacture or annealing and issuance, and between retrieval and processing, each shipment of dosimeters is irradiated by natural cosmic and terrestrial radiation sources and potentially inadvertently irradiated by other sources. The function of the control dosimeter is to measure all nonoccupational radiation exposure to the batch of dosimeters. On processing, the reading from the control dosimeter is subtracted from the reading of each of the other dosimeters in the batch, which yields a result for each dosimeter that is solely due to occupational radiation exposure. Note that the subtraction could occur with raw data, such as optical density readings for film or glow curves, or with transformed data, such as exposures in roentgens, absorbed doses in rad or grays, or dose equivalents in rem or sieverts.

Determination as to whether control dosimeters were exposed to elevated ambient levels of external radiation (EALER) is generally associated with where the control dosimeters were stored. From the intended use of control dosimeters, it is clear that controls should be subjected to exactly the same nonoccupational radiation exposure as the issued dosimeters and differ only in the occupational component. The implementation of this intention, that is, procedures for issuance and retrieval of dosimeters, likely differed over time at a given facility and certainly differed among DOE and AWE sites. For example, at large facilities, controls might have been kept at a central dosimeter location or distributed with batches of dosimeters to remote identification (ID) badge or dosimeter exchange buildings such as guard stations near reactors, reprocessing facilities, or manufacturing facilities. During some periods, dosimeters were incorporated into ID badges to ensure that no one entered without a dosimeter, and these ID badges were picked up at the entrance station at the beginning of each shift and returned there at the end of each shift. If control dosimeters were kept at remote exchange facilities, they would have recorded EALER at those facilities. Such doses from EALER recorded by the controls would subsequently have been subtracted from each worker's dosimeter reading. However, if control dosimeters were kept at a distant central badging facility where ambient radiation levels were lower than in the work areas, each worker's dosimeter would have recorded not only his or her occupational exposure, but also his or her exposure to EALER. In the latter case, no adjustment for occupational environmental radiation levels is needed because it would have been included in the worker's occupational measurements.

ATTACHMENT B
ONSITE AMBIENT DOSE ASSIGNMENT (continued)

For the early days of reactor operation, one important component of external environmental dose arises from submersion in, or irradiation at a distance from, a plume of ^{41}Ar (with a radiological half-life of 1.83 hours), which formed when naturally occurring ^{40}Ar nuclei absorbed neutrons near operating reactors. The emissions from ^{41}Ar are primarily a 1.2-MeV (maximum) beta particle and a 1.3-MeV photon. A wooden badge exchange building would likely provide very little shielding or attenuation of the photons and, if air exchange rates at the control dosimeter storage point were high, even the beta component could have approached outdoor levels. In addition to radiation from airborne releases of radioactive materials, other components of EALER could arise from:

- Scattered radiation from waste trenches, storage facilities, etc.;
- Terrestrial contamination; and
- Skyshine (radiation scattered to the ground from air over nuclear or high-energy accelerator facilities).

However, these components are unlikely to have been the same at dosimeter exchange facilities as they were on the rest of the site, so control dosimeters that were stored at remote exchange facilities would not have recorded this component.

Processes with potential for significant EALER include:

- Operating production reactors,
- Fuel reprocessing,
- Other radiochemical processing facilities,
- Atmospheric nuclear weapons testing,
- Underground nuclear weapons testing with significant venting of fission gasses,
- Accidental airborne releases of radioactive materials, and
- Certain high-energy accelerators (in the early years).

Large sites might have had inhomogeneous EALER, and control dosimeters that were distributed with batches intended for particular areas might have been able to measure significant EALER that the workers' dosimeters might have missed.

In general, there is a point in time at a particular site after which there is no need to assess specific EALER to add to the worker's dose because (1) levels were so low they would not significantly affect the POC, and (2) control dosimeters were kept under controlled conditions and EALER would not have been subtracted. As environmental monitoring programs matured, environmental TLD measurements ruled out significant EALER values. This point in time can only be established for a particular site by reviewing site and worker monitoring practices.

External dosimetry results account for both occupational and environmental penetrating radiation exposures if control dosimeters were not exposed to elevated environmental radiation due to operations. Not all DOE and AWE sites might have experienced the problem of missed EALER.

All external ambient doses are assigned in IREP as follows:

- Exposure rate: Chronic; and
- Radiation type: Photons E = 30–250 keV.

ATTACHMENT B
ONSITE AMBIENT DOSE ASSIGNMENT (continued)

Due to the variations in site geography, monitoring practices, reporting practices, facilities, and operations, a best estimate cannot be generated for a site that does not have a completed site profile. To assess doses in recent years that might not be covered in the site profiles, the most recent onsite ambient doses can be assumed to apply.

B.2 BEST-ESTIMATE METHOD

Most dose reconstructions for which data are provided in the site profile use a Monte Carlo method in which the external environmental dose with its uncertainty distribution is multiplied by the appropriate organ DCF distribution to calculate the best-estimate ambient dose. A best estimate must take into account all available records pertinent to determination of work location. For workers who worked in multiple areas of the site, if the worker's records and claimant interview do not provide enough information to determine specific work locations, values representing a site average are appropriate as a best estimate.

Dose reconstructors should use site-specific guidance on the calculation of environmental dose when provided (e.g., number of hours, area dose rates, etc. for calculation of the ambient dose assignment). If site-specific guidance is not available, the assumption should be made that the worker worked 50 hr/wk and 50 wk/yr (to reasonably account for holiday and/or vacation time) or a total of 2,500 work hours per year when assigning ambient dose as a best estimate. Partial years of employment should be scaled accordingly. In addition, if the claimant interview indicates that fewer or more hours were worked, then this information should be used. For example, if the worker was off the site half of the time where only natural background radiation levels existed, only 25 hours of exposure per week should be assumed.

The calculated annual dose using site information is multiplied by the appropriate *exposure*-(R)-to-organ DCF in OCAS-IG-001 (NIOSH 2007) for an isotropic exposure geometry for most sites to determine the dose to be assigned for each year. Some sites provide environmental data based on survey measurements or calculations rather than film or TLD dosimeter results. For sites that provide data based on survey measurements or calculations, the calculated annual dose should be multiplied by the appropriate ambient dose equivalent [$H^*(10)$] DCF in OCAS-IG-001 for an isotropic exposure geometry. A DCF of 1 for onsite ambient dose is applied for cancers where the skin is used to calculate external dose.

If the supporting documentation for all of the elements necessary for a best-estimate dose reconstruction does not exist, conservative assumptions should be applied in relation to work location and area conditions, erring in favor of the claimant.