

# **INTERNAL RADIATION DOSIMETRY**

**Health Physics Society  
1994 Summer School**



**Edited by  
Otto G. Raabe**



**Medical Physics Publishing  
Madison, Wisconsin**

Copyright 1994 by the Health Physics Society

All rights reserved. No part of this publication may be reproduced or distributed in any form or by any means without written permission from the publisher.

ISBN 0-944838-47-2

Library of Congress Catalog Card Number: 94-76682

Medical Physics Publishing  
732 N. Midvale Boulevard  
Madison, WI 53705  
(608) 262-4021

Information in this book is for instructional use only. The editor, authors and publisher take no responsibility for any damage or harm incurred as a result of use of this information.

Printed in the United States of America.

## Chapter 25

# PROGRAMS FOR ASSESSMENT OF DOSES FROM INTAKES OF RADIOACTIVE MATERIALS

Daniel J. Strom

---

## OVERVIEW

As important as the *science* of assessing doses from intakes of radioactive materials is, the *application* of this science in the workplace is equally important. Using the new U.S. Department of Energy (DOE, 1993b) implementation guide for internal dosimetry programs as a basis, the author describes the programmatic elements of the assessment of doses from intakes of radioactive materials. These elements include organization, staffing, training, and facilities; documentation of the technical basis and procedures of the program; design of and participation in the bioassay program; detection and confirmation of intakes; assessment, management, recording, and reporting of doses from intakes of radioactive material; medical response to intakes; quality assurance; and guidance for monitoring in the workplace to support assessment of doses from intakes.

## INTRODUCTION

This chapter is based on the work of many individuals who work or have worked for the U.S. Department of Energy (DOE) or its contractors (see Acknowledgements). Many parts of it are paraphrased from the new DOE implementation guide for internal dosimetry programs (DOE, 1993b). The reader is urged to consult the excellent and well thought-out glossary of that guide. The implementation guide is based on DOE Regulations (DOE, 1993a) and Orders (DOE, 1988, 1992).

In practice, no one *measures* doses from irradiation by radioactive materials inside the body. Such doses are *inferred* from *in vivo* or *in vitro* measurements of radioactive materials, workplace measurements, and/or sometimes from biomarkers such as chromosome aberrations. In this chapter, the process of inference of doses from irradiation by internally retained radionuclides is called *assessment*. Some personnel performing dose assessment first infer a value called the "intake," that is, the activity of the radionuclide(s) taken in (Lessard et al., 1987). Intake assessment has become a central focus of much dose assessment.

The intake-based approach derives from the historical practice of limiting exposures in terms of products of air concentration (either as activity concentration or as potential alpha energy concentration for radon and thoron progeny) and time. The ICRU has never given a name to such products, formerly expressed as MPC-hours (MPC = maximum permissible concentration) or WLM (*working level months*) for radon and thoron progeny, and now expressed as DAC-hours (DAC = *derived air concentration*) or  $\text{J h m}^{-3}$  for radon and thoron progeny. Under the assumption of a constant breathing rate, such as the  $1.2 \text{ m}^3 \text{ h}^{-1}$  of Reference Man (ICRP, 1975), a concentration-time product corresponds to an intake in activity (Bq) or potential alpha energy (J). A *committed effective dose equivalent* (CEDE) can be inferred from an intake by dividing the intake by the appropriate *annual limit on intake* (ALI) and multiplying by 50 mSv (for the ALIs currently in use in the USA).

In a radiation protection system that is based on dose limitation, inference of intake is merely one of several approaches that may be used to assess dose. A dose assessor really only needs to know how much activity is where in the body for how long to assess dose. There is nothing fundamental about the intake assessment approach to internal dosimetry, and by using breathing rates and ALIs assessed for Reference Man, individual differences are suppressed. In a radiation protection system that is based on dose limitation, the dose limits apply to individuals, not to a calculational model like Reference Man.

## PROGRAMS FOR ASSESSMENT OF DOSES FROM INTAKES OF RADIOACTIVE MATERIALS

Monitoring of individuals to assess doses from intakes of radioactive material is usually performed to demonstrate compliance with regulations and to provide assurances that the radiation control program is working. Internal dose assessment programs, including routine bioassay programs, are conducted for certain radiological workers, declared pregnant workers, minors and members of the public. With few exceptions (e.g., exposures to radon and thoron progeny), the assessment of internal dose can and should be based on bioassay data rather than air concentration values of radioactive material(s). Few would argue that worker protection *requires* bioassay data. Adequate radiation protection in mines, and chemical and biological protection in general, are not based on bioassay data, but rather on measurements of workplace conditions. Rather, bioassay data form the basis for more accurate and credible "score-keeping" (in units of absorbed dose or dose equivalent) than do air monitoring data. Also, bioassay data are more persuasive for epidemiologic purposes and for support of litigation than are workplace measurements.

Programs for the assessment of doses from intakes of radionuclides are needed for workers who have the potential for such intakes. This chapter includes guidance for design and

implementation of the bioassay program, and guidance for assessing, recording, reporting, and managing internal doses.

The essential elements of an internal dose assessment program include

- adequate staff with appropriate technical training;
- a *technical basis manual* (TBM) giving scientific information and other rationale explaining each element of the internal dose assessment programs to support dose evaluation methods;
- written policies and procedures covering each step in the activities that determine worker internal dose;
- defined criteria for identifying workers who need to participate in the bioassay program;
- appropriate bioassay measurement methods and frequencies;
- adequate detection capability and quality of bioassay measurements;
- defined criteria and actions for identifying individuals with suspected intakes, based on workplace measurements and bioassay measurements;
- appropriate workplace monitoring programs, including air sampling;
- appropriate action level guidelines;
- methods for control, accountability, and safe handling of samples;
- timely analysis of bioassay samples and measurements, transmission of results, dose evaluation, and recommendations to operations management;
- appropriate dosimetric models and default parameters for assessing internal dose;
- quality assurance program covering all steps in the activities that determine worker internal dose;
- defined program to report internal doses to workers, management, and regulators;

- historical records of bioassay measurement results and dose assessments; and
- historical records of the program, and changes in the program over time.

## **A. Organization, Staffing, Training, and Facilities**

### ***1. Organization***

The internal dose assessment program should be a function of the radiation protection organization at each facility. The manager of radiological protection should have overall responsibility for the internal dose assessment program. Each internal dose assessment program should have a designated leader with demonstrated expertise in internal dose assessment.

When elements of the internal dose assessment program are performed by one or more subcontractors, the radiation protection organization should assure that subcontractors meet all requirements in applicable regulations and performance standards, and that subcontractors follow written procedures and the TBM. A copy of all relevant subcontractor procedures should be incorporated in the historical records of the contractor.

Where one contractor on a multiple-contractor site conducts the internal dose assessment program, or parts thereof, letters of agreement should detail the responsibilities, authority and communication requirements of the respective parties. A copy of this agreement should be in the TBM and the historical file.

### ***2. Staffing***

The radiation protection organization management should ensure that the internal dose assessment program is adequately staffed to carry out its functions.

The analysis of workplace and bioassay measurement data and the assessment of internal dose involve complex assessment and professional judgment. Personnel with responsibility for internal dose assessment should have the necessary expertise and skill, based on appropriate education and training in conjunction with practical experience, to perform their assigned duties. It is important that internal dose assessment specialists be capable of recognizing conditions warranting follow-up bioassay and dose assessment. Personnel should be familiar with the relevant internal dose assessment literature and the recommendations of national and international scientific organizations with regard to internal dose assessment.

### *3. Training, experience, and continuing education*

Management of the radiological protection organization should establish minimum qualifications for those staff who assess internal doses. The qualifications should include both experience and education requirements. Educational background and formal training needed for internal dose assessment programs are listed below. Members of the dose assessment staff should meet these requirements, or the staff should have access to persons with the required background (perhaps through interdepartmental agreements or contracted services). It is not necessary for all personnel on the staff to have expertise in all of the listed subject areas. The internal dose assessment organization should have or have access to personnel who have education and formal training in advanced mathematical methods, such as calculus, differential equations, and statistical analyses; radiochemistry and radiometric methods and concepts; computer technology and software used for dose assessment; anatomy and physiology of the human body and effects of ionizing radiation on biological systems; nuclear radiation physics; radiochemical behavior of relevant radionuclides; principles of radiation dosimetry including national and international guidance; operational health physics; and technical writing.

New internal dose evaluators should undergo a period of apprenticeship commensurate with their experience and education. In addition, other radiation protection staff should be cross-trained in internal dose assessment to ensure adequate staffing during vacations, absences, and vacancies.

The program should be supported by trained dosimetry technicians, counting system operators, and radiochemistry staff, all of whom should receive training commensurate with job requirements.

Management should establish continuing education requirements for all staff performing internal dose assessments. Retraining and/or continuing education are essential for maintaining an adequate level of expertise and familiarity with current concepts and requirements for internal dose assessment. The same subjects as listed above under the minimum educational qualifications should be considered in establishing continuing education requirements. Retraining and continuing education should include changes in procedures, changes in systems or equipment, changes in guidance and regulations, and significant operating events that occurred in the facility or at other facilities that are relevant to internal dose assessment.

#### 4. Facilities and resources

Computational facilities and software tools used by internal dose assessment personnel should be adequate for performing calculations required for the assessment of dose from radionuclides in the body. A library of handbooks, reference materials, scientific publications, and other resources pertaining to internal dose assessment should be readily available.

##### **B. Internal Dose Assessment Technical Basis Manual (TBM)**

An internal dose assessment *technical basis manual* (TBM) or other organized collection of documents should be developed and should give the scientific and technical foundation for the internal dose assessment program. The TBM should provide the approach to assessing internal doses from bioassay data, and where appropriate, from workplace monitoring data. It should describe: (1) physical and chemical characteristics of radioactive materials encountered in the workplace; (2) methods for calculating internal doses; (3) methods for documenting calculations; (4) dose assessment quality assurance; (5) methods for assessing dose equivalents from specific radionuclides, mixtures of radionuclides, and materials of differing chemical characteristics; (6) recording and reporting practices for internal dose assessment; (7) selection of workers for monitoring; and (8) establishment of the type and frequency of measurements to be used.

The technical basis for assessing dose from both routine and special bioassay, and for evaluating data from personal air samplers and other monitoring equipment should be included in the TBM. Biokinetic models, model parameters, assumptions, and default parameters used in dosimetric modeling and assessment should be clearly identified. Statistical methods for evaluating bioassay data, identifying bioassay results above environmental background values, using appropriate blanks and analyzing trends should be described.

To preclude the "double counting" of intakes and resultant doses, the methodology to account for the portion of a bioassay result that may be due to one or more prior confirmed intakes should be described in the internal dose assessment TBM. The derivation of decision levels should also be documented in the TBM. Default trigger levels and preliminary actions to be taken for exposures to the different radionuclides present at the facility following suspected or confirmed intakes at various levels should be described in the TBM.

The TBM should be reviewed periodically to assure that the scientific bases are current and updated, as necessary. The internal dose assessment TBM should be a controlled document and retained as a radiological protection program record.

## C. Procedures

All elements of the internal dose assessment program should be specified in written procedures. These procedures should be consistent with applicable regulations and the TBM. In summary, the methods and requirements for measurement (bioassay) and assessing and recording internal dose should be specified. The procedures should specify methods for consistent collection of workplace and personnel monitoring data, its assessment, documentation of results, and records maintenance. The components of the internal dose assessment program and the organizational structure to which it reports should be documented in procedures. Responsibilities of line management and members of the dose assessment group should be described. Elements of the workplace and radiological worker monitoring programs that are germane to internal dose assessment should also be included. Guidelines for prompt follow-up of worker intakes to radioactive materials should be carefully defined, and appropriate follow-up response to intakes, including the medical management of workers with excessive intakes, should be described.

The procedures should be reviewed at least once every two years and updated as necessary. The requirements for maintenance of procedures should be specified, including responsibilities for authorship, review, approval, and distribution.

## D. Design of the Bioassay Program

Internal dose assessment programs, including routine bioassay programs, are conducted for certain radiological workers, declared pregnant workers, and minors and members of the public. With few exceptions, the estimation of internal dose should be based on bioassay data rather than air concentration values of radioactive material(s).

The worker bioassay program should (1) provide for investigation of suspected intakes; (2) provide data for assessing internal dose; and (3) provide results that are adequate to demonstrate compliance with applicable radiation dose limits. The primary methods of routine and special worker bioassay are *in vivo* counting (direct bioassay) and *in vitro* excreta analyses (indirect bioassay).

### 1. Regulatory guidance

Bioassay measurements should be of the appropriate type, frequency, timeliness, and of sufficient accuracy, to demonstrate that dose limits have not been exceeded, and that doses are maintained ALARA. The DOE requires participation in a bioassay program of personnel who are likely to receive intakes resulting in a committed effective dose equivalent (CEDE) of 1 mSv or more. These personnel participate in follow-up bioassay monitoring when their

routine bioassay results indicate an intake in the current year with a CEDE of 1 mSv or more. Personnel whose routine duties may involve exposure to surface or airborne contamination or to radionuclides readily absorbed through the skin, such as tritium, should be considered for participation in the bioassay program. Personnel should submit bioassay samples, such as urine or fecal samples, and participate in bioassay monitoring, such as whole body or lung counting, at the frequency required by the bioassay program. Personnel should be notified promptly of positive bioassay results and the results of dose assessment and subsequent refinements. Dose assessment results should be provided to the individual in units of dose equivalent.

## ***2. Investigation level***

The *investigation level* (IL) is the value of the CEDE from intake(s) of a radioactive material by a worker at or above which, for regulatory purposes, is regarded as sufficiently important to justify further investigation. The DOE has adopted an investigation level of 1 mSv CEDE from intakes occurring in a year for general employees. Each facility should evaluate the need for special ILs for declared pregnant workers, minors, students, and visitors because their dose limits are lower than the limit for general employees. Throughout this document, IL refers to the IL for the appropriate group unless otherwise specified.

To ensure that all dose limitation and dose control requirements are met, the internal dose assessment program should be capable of assessing intakes in a year of radioactive materials that deliver a CEDE at the IL.

## ***3. Derived investigation levels***

*Derived investigation levels* (DILs) are values of routine bioassay results, such as organ or body contents, or excreta concentrations or excretion rates, that indicate an intake resulting in a dose exceeding an IL. Internal dose assessment programs should establish DILs for each bioassay method applied for the analysis of all radionuclides to which workers are likely to be exposed and document the derivation of such DILs in the TBM. The physical and chemical characteristics of the radioactive material which may be taken into the body should be taken into account in establishing DILs. If an internal dose assessment program chooses to use Reference Man (ICRP Publications 23 and 30) default parameters in conjunction with modeling and assumptions recommended in ICRP Publications 30 and 54 in deriving an IL, these choices should be justified in the internal dose assessment TBM.

#### 4. *Factors affecting the DIL*

Factors such as significant clearance of a radionuclide in less than a year (e.g., tritium), the frequency of bioassay monitoring, and the likelihood of multiple exposures during a year (or under chronic intake conditions) should be considered in establishing a DIL. The DIL should be established so that a CEDE of one IL from all intakes in a year is likely to be detected by the monitoring program, i.e., the minimum detectable dose should be less than 1 IL. If a non-routine or an unexpected intake of a radionuclide or group of radionuclides occurs, the minimum detectable dose may be calculated assuming a single intake that occurred on: the date of the intake, if known; or the date that would result in the largest CEDE. If intermittent or chronic intakes are expected, the minimum detectable dose may be calculated assuming a chronic intake during the sample period.

For non-routine or unexpected intakes, the DIL for each independent radionuclide or group of radionuclides should be based on the objective that a CEDE of not more than one IL would be missed in the year from intakes of that radionuclide or group. If it is known or is likely that an individual has or could have intakes during the year from different sources that could result in doses above the IL, appropriately smaller DILs should be determined and the basis for those DILs included in the technical basis document.

#### 5. *Methods of measurement*

The internal dose assessment program staff should determine the minimum detectable amount for each bioassay method for each radionuclide present in a facility to which workers are likely to be exposed. In determining *minimum detectable amounts* (MDAs), the beta (non-detection probability) should be chosen to be 5% or less. The alpha (false positive probability) should be chosen considering the effect on bioassay measurement time, the disruption and inconvenience of false positive results, the costs of improved analytical technology, and handling, analysis, and record-keeping costs associated with the program. The MDAs should be documented in procedures and their statistical bases given in the internal dose assessment TBM. For the MDA to be valid, the false positive probability used for setting the decision level for the bioassay method should be the same as the one used in the calculation of the MDA.

Procedures should describe the method(s) of bioassay measurements (e.g., urinalysis, fecal analysis, or *in vivo* counting), analytical methodology (e.g., chemical separation followed by alpha counting), and measurement parameters (e.g., counting time or instrument efficiency) to be used in each component of the bioassay program.

Several other factors affect the method of bioassay used and its associated *minimum detectable amount* (MDA). They include the possible need for improved detection capability to assess worker dose during the special bioassay following an intake requiring internal dose assessment, due to diminishing amounts of material in bioassay compartments as time goes on; the need for improved precision and accuracy if residual retention and excretion from prior intakes interferes with the detection of additional intakes in subsequent years; timeliness of results needed to manage workers and keep subsequent intakes low enough to avoid exceeding dose limits; convenience to the workers; costs, including lost production time while workers are participating in the bioassay program; and the impact of the method of bioassay on the frequency of bioassay measurements. The method of bioassay, analytical methodology, and measurement parameters should result in an MDA less than the corresponding DIL for all radionuclides to which a worker might be exposed.

The methods of bioassay measurement, their MDAs, and accuracies should be specified in the internal dose assessment TBM, along with a rationale or justification for the methods chosen.

#### *6. Frequency of bioassay measurement*

The routine bioassay measurement frequency depends on the bioassay measurement method and associated MDA. The frequency should be chosen so that it is unlikely that intakes by a worker in a year will result in doses exceeding an IL without detection. Other factors affect the choice of routine bioassay measurement frequency. They include expected frequency, duration and magnitude of elevated airborne radioactive material concentrations; cost of bioassay measurements and the cost of lost production time while workers are participating in the bioassay program; magnitude of a worker's assessed internal dose resulting from prior intakes; convenience to the workers; need to confirm the effectiveness of engineering controls; need to confirm an unexpected bioassay result at or above the DL including time for sampling and analyses; need to assess dose from chronic intakes; and need to confirm the effectiveness of workplace air monitoring and personal controls such as respiratory protection or limitation of exposure time.

Recommendations for selecting the appropriate bioassay frequencies for given work areas have been published by the NCRP (1987) and ICRP (1988). The frequency of the routine bioassay program should be specified in procedures. Justification for the frequencies should be specified in the internal dose assessment TBM, along with an assessment of the largest internal dose (i.e., minimum detectable dose) from an intake (acute or chronic) that could go undetected with the chosen frequency.

### *7. Supplementing routine bioassay programs (where the DIL < the MDA)*

It is recognized that DILs for reasonable and practical routine bioassay programs may be significantly less than the achievable MDA for radionuclides such as plutonium.

By definition, a technology shortfall exists when the bioassay program's derived investigation level is less than the minimum detectable amount of the routine monitoring method (DIL less than MDA). A technology shortfall occurs when a performance objective (expressed as a DIL) cannot be achieved with current or state-of-the-art methods and equipment.

The assessment of dose equivalent from intakes of radionuclides should be based on bioassay data rather than air concentration values. Air concentration values may be used for this purpose only if bioassay data are unavailable, inadequate, or result in a less accurate dose estimate, such as in the case of exposure to the short-lived progeny of  $^{222}\text{Rn}$  and  $^{220}\text{Rn}$ .

In the case of a technology shortfall, the facility should enhance workplace monitoring and the use of indicators (e.g., unexpected glove or surface contamination, increase in airborne radioactive material contamination) to trigger early special bioassay monitoring; enhance personal contamination monitoring (e.g., clothing, skin, nasal smears) to trigger special bioassay monitoring; use the best practical state-of-the-art bioassay monitoring methods; implement enhanced design, operation, controls, and personnel protection equipment and procedures to minimize intakes; consider supplementary air monitoring; and document and justify the planned supplementary approach in the internal dose assessment TBM.

When air monitoring data are used, each worker's stay times (in hours) and the average concentration (in DACs) to which the worker is exposed should be multiplied to yield exposures to airborne radioactive materials in units of DAC-hours. Forty (40) DAC-hours corresponds to 1 mSv CEDE when the stochastic DAC is used.

A technology shortfall is not sufficient cause for failing to place workers on a minimum or best-available bioassay program.

Alternative approaches and assumptions used in dose calculations and the level of intake or CEDE detection achieved should be described and documented in the facility's internal dose assessment TBM. If DAC-hour calculations are used to assess exposures to airborne radioactive materials, any permitted adjustment to such calculations to account for the use of respiratory protection should be documented in the TBM.

## **E. Participation in the Bioassay Program**

Workers may be selected to participate in either routine or special bioassay programs. The routine bioassay program is generally used to monitor workers to detect the occurrence of an intake of radioactive materials, and special bioassay sampling is generally used to obtain follow-up data from suspected or confirmed intakes.

### ***1. Routine bioassay program***

Routine bioassay monitoring should be performed for radiological workers exposed to surface or airborne radioactive contamination where the worker is likely to receive 1 mSv CEDE from all occupational intakes of radionuclides during a year.

The routine bioassay program also should include baseline bioassay measurements for workers (if appropriate based on work history) before initiating a period of work assignment at a facility and a final termination bioassay measurement upon termination of work at a facility. Such measurements should be made before and after any potential for exposure, respectively.

Workers should continue to participate in the bioassay program even when the DIL is less than the *minimum detectable amount* (MDA). While it may not be possible, in these circumstances, to detect intakes resulting in one IL, it is important to detect and assess intakes that are larger than those leading to one IL.

### ***2. Special bioassay program***

Workers should participate in a special bioassay program to confirm or rule out radionuclide intakes when routine bioassay program results are unexpectedly above the appropriate DIL, or when workplace monitoring program results, knowledge of facility operating conditions, or other information indicate that it is likely that a worker may have had an intake resulting in a dose in excess of an IL.

Special bioassay analyses shall also be performed when any of the following occur: (1) Facial or nasal contamination is detected that could indicate a potential for internal contamination; (2) airborne monitoring indicates the potential for intakes leading to a CEDE exceeding one IL; or (3) when an intake is suspected for any reason.

Reasons for suspecting an intake may include detection of contamination on the head or neck, hands or forearms, or inside of respirator; detection of extensive or extended personal

skin or personal clothing contamination; loss of containment; or failure of ventilation system or respiratory protection equipment.

Special bioassay sampling should be performed for workers following exposure to radionuclides in air when the potential intake leads to a dose that exceeds one IL during an incident or over a short period of time, and for workers with confirmed intakes.

### *3. Exception to routine bioassay requirement*

A minimal internal dose assessment program should suffice if the probability of a measurable intake of radioactive material at a facility is low or negligible. The minimal program should consist of workplace monitoring and periodic review of operations involving radioactive materials to ensure that intake probability remains low. However, if an intake in a year for any worker at a facility would result in a CEDE greater than an IL projected from air monitoring results, special bioassay and dose assessment should be performed.

Facilities with no routine bioassay program should have written contingency plans detailing air monitoring result action level guidelines, bioassay sample collection procedures, and arrangements with other qualified organizations for *in vivo* counting, excreta measurements, and internal dose assessment, as appropriate.

### *4. Timely receipt of bioassay results*

Results of bioassay measurements should be provided to dose evaluators in a short enough time to provide an adequate degree of worker protection. Consideration of timeliness should include the following: the need to support decisions on implementing and/or continuing medical intervention; the need to support rapid reporting to the worker, management, and regulators and subsequent follow-up for significant intakes; the need to confirm a suspected intake based on a high routine measurement before the detection capability is lost due to rapid clearance from the bioassay compartment; the need to support the ALARA program with timely information; and the need to provide records of exposures within 90 days of the termination of an employee, if requested by that employee.

The internal dose assessment program should establish with the bioassay measurements laboratory an agreement of needed turnaround times, MDAs for special and routine samples, and priorities for classification of samples (e.g., routine, special, emergency).

Following suspected intakes, consideration should be given to performing additional sampling while awaiting initial results to ensure an adequate amount of data at early times

after intake for dose assessment purposes. Additional sampling may include the evaluation of air sample media, source terms, contamination surveys, respirator filters, nasal or mouth swabs, irrigation fluids from personal decontamination, and wound debris.

#### **F. Detection and Confirmation of Intakes**

The decision level (DL) should be set by considering the acceptable rate of false positives, the cost and consequences of false positives, and the dosimetric consequences of false negatives. Bioassay results above the DL may be expected in the absence of a new intake due to normal statistical fluctuations, non-occupational or environmental sources, or if there have been prior confirmed intakes. The analytical laboratory decision level should be based on a reagent blank. The occupational intake decision level should be based on both the analytical laboratory DL and considerations of expected levels of activity in unexposed workers due to environmental exposures.

If a bioassay result above the DL is unexpectedly observed, follow-up bioassay measurements should be promptly made to either confirm the result as a true intake or identify it as a false positive result. An intake should be considered confirmed when a bioassay result exceeding the decision level is associated with a known incident; or a bioassay result exceeding the DL is shown not to be a false positive by investigation or by appropriate statistical analysis of follow-up measurements.

Investigations for the purpose of confirming an intake should consider many factors, including evaluation of radionuclides detected versus those expected (e.g., to rule out an unreported medical administration of radioactive materials); evaluation of area survey results versus radionuclide types and quantities detected; evaluation of skin or clothing contamination contribution to bioassay indications; evaluation of co-workers' bioassay results; and verification of results through measurements of radionuclide transport within and out of the body.

In the absence of other confirming data, one acceptable decision rule for confirming an intake is the observation that 2 out of the first 3 measurements in a bioassay series are above the decision level. Follow-up bioassay samples should be scheduled and obtained in response to an initial positive bioassay result exceeding the decision level.

If appropriate confirmatory follow-up measurements to an unexpected bioassay measurement above the decision level are not obtained, two options should be considered depending on the magnitude of the bioassay measurements. The first option is to simply presume an intake has occurred if the CEDE from the intake is projected to be less than one IL. This

option minimizes costly and disruptive investigations that wouldn't be performed for comparable external doses.

The second option is to perform an investigation if the CEDE from the intake is projected to equal one IL or more. If an investigation is performed, and fails to provide sufficient evidence to establish that an intake did not occur, then an intake should be presumed to have occurred. The basis for projecting a CEDE of one IL from bioassay results should be documented in the TBM.

Both the need for promptness of the follow-up or confirmatory bioassay measurement and the determination of the MDA used for the analysis depend on a variety of factors. These include the clearance time of the particular radionuclide, its chemical and physical form, the mode of intake, the CEDE corresponding to the suspected intake, the usefulness of the confirming measurement in assessing the internal dose, the possibility of elevated bioassay results from non-occupational sources (e.g., medical applications, diet, or radon progeny), and the likelihood of the worker receiving additional intakes between the first and second bioassay measurement. These factors should be considered by the internal dose assessment staff in determining the follow-up or confirmatory actions to be taken in response to positive bioassay results.

These actions should be addressed in formal procedures. The internal dose assessment TBM should contain the rationale for the formal action procedures. The procedures should also address who will establish confirmatory bioassay requirements in cases not covered by the procedures.

## **G. Internal Dose Assessment**

### ***1. Guidance***

Internal doses should be assessed for all confirmed intakes, as defined above. For intakes confirmed with bioassay results below the DIL, no further investigation or follow-up bioassay are indicated. For intakes confirmed with bioassay results above the DIL, follow-up bioassay and investigation should be performed.

Bioassay data are the primary input for internal dose assessments. The extent of the investigation and the number and frequency of special bioassay measurements following a suspected or confirmed intake should be determined on an individual, case-specific basis, taking into account the potential magnitude of the intake, the effective clearance half-time, the health of the worker, and the number of measurements needed to evaluate the internal dose.

The schedule and frequency of long-term special bioassay measurements to evaluate the CEDE to an individual who has had an intake resulting in a dose in excess of an IL should depend on the expected magnitude of the CEDE and the likelihood of the individual receiving additional intakes.

While the investigation should be tailored to the specific individual and exposure circumstances, there should be in place, documented in the TBM, the trigger levels and preliminary actions to be taken for exposures to the different radionuclides encountered at the facility.

Methods of assessing the committed dose equivalent from internal sources of radiation should be appropriate to the workplace conditions. The methods should be consistent to the extent possible with EPA, NCRP, and ICRP recommendations and good practices.

## *2. Interpretation of bioassay data*

Biokinetic models should be used to interpret bioassay data and assess initial radionuclide intake. The particular biokinetic models used for internal dose assessment should relate well to the available bioassay data and should account specifically (when possible and if known) for the chemical and physical characteristics of the material taken into the body. When the available data are lacking or are contradictory, professional judgment will be needed to make a dose assessment.

Since the assessments of internal dose depend on knowing the intake profile with respect to time, the dose assessment staff should base the time course of intake on known incidents, air monitoring data, records of perturbations in facility operations, and/or discussions with the worker by radiation protection staff. If the time course of intake cannot be plausibly established, then the procedure for assessing doses based on the internal dose assessment TBM should be used.

Assessments of CEDE from a specific intake should account for expected values of bioassay measurements from prior confirmed intakes.

## *3. Assessment of internal dose from bioassay data*

Internal dose assessment program staff should evaluate the CEDE from the intake. The data necessary to calculate committed effective doses to tissues or organs of concern should be maintained for possible future reassessment.

Methods for assessing the various doses from intakes should be specified in the internal dose assessment TBM. The methods should be based on recommendations given in ICRP Publications 30, 48, and 54, and other reports of the ICRP and NCRP which embody improvements and updates of the science of internal dose assessment. Other methods may be used provided they are documented and justified in the procedures and/or internal dose assessment TBM.

In the calculation of internal doses less than the IL, default parameters may be used. These parameters (e.g., intake date, deposition probabilities, retention functions, organ masses, absorption fractions) should be based on regulatory requirements (e.g., Appendix B of 10 CFR 835), the recommendations of the ICRP, NCRP, or facility-specific factors as documented in the internal dose assessment TBM.

If the initial assessment of an intake indicates a worker dose in excess of 10 times an IL, individual-specific and facility-specific factors should be used when more appropriate parameters are expected to change the dose calculations by a factor of 1.5 or more (ICRP, 1988). The basis for determining which individual-specific and facility-specific factors are expected to change the dose calculations by a factor of 1.5 or more should be documented in the internal dose assessment TBM. Determination of individual retention patterns for a worker requires participation in the special bioassay program and may require temporary work restriction or reassignment to prevent subsequent intakes from confounding the dose assessment.

#### *4. Periodic reassessment of internal dose*

In the case of certain well-retained radionuclides (e.g., plutonium), long-term follow-up and reassessment of doses may be required. The internal contribution to lifetime dose should continue to be reassessed as further bioassay results and improved methods for assessing internal dose become available.

Assessments for active workers with prior confirmed intakes should be revised when information demonstrates a change in the currently assessed CEDE of 5 mSv or a factor of 1.5 of the previously assigned dose for that intake, whichever is higher. In cases where intakes are detected or confirmed in a year subsequent to the year of the intake, the CEDE should be attributed to the known or assumed year of the intake, and all records and reports for that year should be amended as appropriate.

## H. Dose Management

DOE requires internal dose assessment programs for assessing intakes to radionuclides and for maintaining adequate worker exposure records. The effective assessment of intakes of radioactive materials is highly dependent on individuals (staff, management, radiation protection, medical, etc.) taking appropriate action.

Each site should have a plan that documents the dose management practices. The plan should include procedures for managing workers with retained radionuclides so that: (1) monitoring is appropriate; (2) additional exposures may be averted; (3) workers may receive adequate medical care (including decorporation therapy), if necessary; (4) internal doses can be appropriately assessed and recorded; (5) total dose (external and internal) may be assessed against appropriate administrative controls and annual and lifetime dose limits; (6) workers are informed of the states of follow-up investigations and dose assessment; and (7) consideration is given to temporary work restrictions to avoid exposures to radionuclides similar to those being assessed in the ongoing investigation.

Additional dose management criteria apply to the embryo/fetus of a declared pregnant worker. Internal and external exposures to declared pregnant workers should be controlled so that, if the dose equivalent to the embryo/fetus is determined to have already exceeded 5 mSv by the time a worker declares her pregnancy, the declared pregnant worker is not assigned to tasks where additional occupational exposure is likely during the remaining gestation period; and so that substantial variation above a uniform exposure rate that would satisfy the limit of 5 mSv from conception to birth for the embryo/fetus of a declared pregnant worker should be avoided.

### *1. Baseline bioassay for new employees or workers initiating or resuming work with radioactive materials*

Each new general employee should be assessed for internally retained radionuclides before the worker begins any work with radioactive materials or resumes such work if he or she is likely to receive intakes resulting in a CEDE greater than 1 mSv. Similarly, students, minors, visitors, and declared pregnant workers should receive a baseline bioassay before they begin any work with radioactive materials or resume such work if they are likely to receive intakes resulting in a CEDE greater than one IL.

Efforts should be made to obtain records of prior years occupational internal and external exposure. Baseline bioassay measurements should be requested if he or she has had previous intakes of radioactive materials. If a worker is going to work with radioactive material for which the presence of naturally occurring radioactive materials (e.g., uranium in urine) is

detectable in bioassay measurements, baseline bioassay should be considered regardless of prior occupational exposure.

If a worker has retained radioactive material from prior intakes, the effect of those levels on the ability of the program to detect new exposures must be assessed. Special monitoring procedures may be required for such cases.

## 2. Dose limitation

Both DOE and NRC regulations require the combining of internal and external dose equivalents. The *total effective dose equivalent* (TEDE) should be determined by summing the CEDE from internally deposited radionuclides and the effective dose equivalent (or deep dose equivalent) from external exposures. The sum of the CEDE from intakes during the year along with the contribution of the total dose equivalent from external sources should be compared to the 50 mSv annual limit.

In addition, occupational exposure to general employees should be limited such that the sum of the dose equivalent for external exposures and the committed dose equivalent to any organ or tissue other than the lens of the eye does not exceed 500 mSv.

Committed dose equivalents and CEDEs should be calculated for intakes of radioactive materials that take place during a year, and should not include intakes from prior years. These doses should be recorded and reported to the worker and management in the year of intake.

## 3. Lifetime dose control

According to the NCRP, a worker's lifetime occupational radiation exposure should not exceed  $N \times 10$  mSv, where  $N$  is the age of the individual in years (NCRP, 1987, 1993). DOE terms this product the "Lifetime Control Level." "Special Control Levels" (that is, individual dose limits less than normal limits) should be established for individuals who have doses exceeding  $N \times 10$  mSv.

In the DOE, the lifetime occupational dose is the sum of all TEDE values for each year since January 1, 1989, plus the sum of external dose equivalent values recorded prior to January 1, 1989. Internal doses due to intakes prior to January 1, 1989, that is, prior to DOE's adoption of CEDE, should be reassessed in terms of CEDE if sufficient data is available or if available data indicates a need for a reassessment.

A reassessment of intakes occurring prior to January 1, 1989, should be conducted for single intakes resulting in CEDEs greater than or equal to 1 mSv or total annual intakes resulting in CEDEs greater than or equal to 10 mSv.

Each facility should document in the internal dose assessment TBM the method for assessing intakes occurring prior to January 1, 1993, and the rationale for deciding that an intake need not be reassessed. For compliance purposes in the DOE, the lifetime occupational dose is to be compared to the Lifetime Control Level.

#### **4. Accidental dose controls**

Action levels for administrative response to intakes of radionuclides by workers should be detailed in the internal dose assessment program procedures manual.

### **I. Recording Internal Doses and Related Information**

#### **1. Requirements**

Records should be kept of the results of individual external and internal dose monitoring; the results of individual external and internal dose measurements that are performed, but are not required; the following quantities for internal dose: CEDE; committed dose equivalent to any organ or tissue of concern; and estimated intake and identity of radionuclides. In the DOE, records include the quantities for the summation of the external and internal dose: TEDE in a year; for any organ or tissue assigned an internal dose during the year, the sum of the dose equivalent from external exposure and the committed dose equivalent to that organ or tissue; and cumulative TEDE received from external and internal sources while employed at the site or facility, since January 1, 1989. The records also include the dose equivalent to the embryo/fetus of a declared pregnant worker. The dose equivalent for the embryo/fetus may be determined to be the summation of the deep dose equivalent to the mother for external exposure and the dose equivalent due to intakes of radioactive materials by the mother which may be calculated using the methods described by Sikov et al. (1992). For minors, students, and members of the public entering a controlled area, records should be kept, as applicable, of the TEDE. Data necessary to allow at a later date the verification, correction, or recalculation of recorded doses should be generated and recorded. Records should be retained for a very long time. Documentation of all occupational exposure received during the current year should be obtained. In the absence of formal records of previous occupational exposure during the year, a written estimate signed by the individual may be accepted.

Records should be readily available to the monitored individual. Records may have to be transferred if a site is closed. Results of surveys, measurements, and calculations used to determine individual occupational exposure from external and internal sources should be documented and maintained. When dose assessment records are stored on easily corruptible media such as magnetic discs or tape, a back-up system for data and computational results should be available for record keeping. The data necessary to support or re-calculate doses at a later date should be maintained pursuant to Section 4 of ANSI N13.6 (ANSI, 1972). Records should be kept to document the appropriateness, quality, and accuracy of monitoring methods, techniques, and procedures in use during any given period pursuant to Section 6 of ANSI N13.6.

## *2. Individual information*

All records about individuals should be identified by name and Social Security Number or Passport Number and country. The following personal identifiers should be retrievable along with individual exposure data: full name and former names; Social Security Number or Passport Number and country; date of birth; sex; employment status; occupation code (i.e., job title); principal facility type and building number; and organization code. When the above personal identifiers change during the year, records should be kept of the change and the date, where possible.

## *3. Intake records*

For each confirmed intake, information recorded should include the magnitude of intake in terms of activity or mass for each radionuclide; time course of intake including date(s) and time(s) and whether known or assumed; intake route (inhalation, ingestion, skin puncture, etc.) and whether known or assumed; radionuclides involved and their physical and chemical forms whether known or assumed; bioassay information pertinent to assessment of the intake; and methods and assumptions used for dose assessment.

## *4. Dose assessment records*

All information that is necessary to review or recalculate each assessed dose should be recorded including uncensored bioassay data, models, assumptions, parameters, and additional bioassay data as appropriate. The names of the evaluator and reviewer and the outcome of the review should be recorded.

Recording a bioassay result as "less than DL" rather than recording a numerical value is called censoring data. No censoring of data should be done, that is, actual numerical results should be recorded whether negative, zero, positive below the DL, or positive at or above

the DL. Reassessments of internal doses should be documented such that a complete historical record of preliminary and final CEDE estimates is retained. Future refinements in radiation risk assessment and dosimetric modeling may require reconsideration of the actual time course and organ distribution of doses. The internal dose assessment records should therefore include as much information as is available to reconstruct the organ or tissue absorbed dose.

## **J. Reporting Requirements**

The records should be readily available to the monitored individual. On an annual basis, each individual monitored should be provided a radiation dose report. Individuals who terminate employment shall be provided a record of their exposure if they so request. Exposure reports to individuals should include CEDE; committed dose equivalent to any organ or tissue of concern; and estimated intake and identity of radionuclides.

For situations in which there is no detectable internal dose or intake of radionuclides, it is preferable to state in the report that there was no internal dose component and that no radionuclides were detected as a result of the internal dose monitoring program.

Terminating employees should be provided records of their dose within 90 days of termination of employment. The termination report should include the TEDE for the year in which they terminate, the cumulative TEDE, and the lifetime occupational dose. A written estimate should be provided at the time of termination if requested.

If an internal dose assessment is still in progress at the 90-day limit, the worker should be notified, and provided with an interim report and later with the final dose record as soon as the assessment is completed.

The site should report on an annual basis the CEDEs by radionuclide or groups of radionuclides, and TEDE for the year, and lifetime occupational dose. Amended reports of CEDE by radionuclide or group of radionuclides for intakes in prior years, if reassessments are performed, should be entered in the individual's records as well as reflected in the TEDE, cumulative TEDE, and lifetime occupational dose reported to regulators.

## **K. Medical Response**

Facilities with potential for intakes approaching dose limits should be prepared to follow an action plan for medical response to any potential or accidental intake of radioactive material. The plan should be developed as a cooperative effort between medical and radiation protection organizations and should include activation of key response functions

(internal dose assessment, analytical laboratory, *in vivo* counting, medical assistance, etc.), training, and action levels for response. The elements of this plan should include action levels for medical response; responsibilities of the affected worker, radiation protection staff, internal dose assessment staff, physicist, medical staff, and management; guides for immediate medical care, decontamination, monitoring, and long-term assessment; and provisions for periodically reviewing, updating, and rehearsing the action plan.

Since there is no consensus on the decision levels for medical treatment of workers, action levels should be established in the TBM based on decisions reached among medical, management, and radiation protection staff. Planning for such emergency actions should include the provision of facilities and materials that will be required.

## L. Quality Assurance

### 1. General requirement

The internal dose assessment program should meet regulatory requirements for quality assurance. Internal audits of all functional elements of the radiation protection program should be conducted no less than every 3 years and should include program content and implementation. From the initial step (such as urine sample collection or reporting for an *in vivo* count) through sample analysis and dose assessment to recording of the results, every step in an internal dose assessment program is important in protecting workers and demonstrating compliance with regulations. All steps in the activities that control or assess worker internal doses should be covered by written procedures that provide appropriate quality control and quality assurance. Quality assurance practices, such as having supervisors ensure that bioassay samples are submitted on an appropriate frequency, will enable corrective action when necessary. Quality control will provide the needed documents and records for demonstrating compliance.

Computer software is normally used to perform internal dose assessments. Procedures for software quality assurance should be developed and implemented to address software documentation per ANSI/ANS 10.3 (ANSI, 1986); validation and verification of models, data, assumptions, and algorithms per ANSI/ANS 10.4 (ANSI, 1987); software security; configuration management; periodic testing to assure proper function; and actions to be taken in the event that software errors are detected. Hand calculations should be independently verified by a second qualified internal dose evaluator. This review should be documented.

## ***2. Independent review***

The internal dose assessment program should receive periodic assessment by the site radiation protection organization to review technical basis documentation, dose assessment procedures, instrumentation and analytical methods, qualifications of personnel, quality assurance program elements, and other elements of the program, as necessary to insure that the program maintains the capability to stay abreast of scientific developments in internal dose assessment and provides a quality radiation protection service to workers. External peer-review by qualified individuals, on a periodic basis, is also recommended.

Appraisals of the internal dose assessment program should be included as part of the contractor radiation protection program. These appraisals should be conducted as often as necessary but no less frequently than every three years.

Internal dose assessment program accreditation, when it becomes available, should provide formal external review and testing of program capabilities. Each site should work toward and plan for eventual accreditation. Radiochemical laboratories and in vivo counting facilities whose measurements are used by internal dose assessment programs are expected to have quality assurance programs, documented regular equipment calibration programs, National Institute of Standards and Testing traceable standards, and written procedures that can be referenced by internal dose assessment programs.

## **M. Guidance for Monitoring in the Workplace**

The objectives of the workplace monitoring program are to verify the integrity of radioactive material containment, detect the release of radioactive materials from some routine operations, detect inadvertent releases of those materials in the workplace, evaluate and provide the basis for modification to containment systems, and provide a basis for design of bioassay programs.

### ***1. Performance requirements***

Area monitoring in the workplace should be routinely performed, as necessary, to identify and control potential sources of personnel exposure to radiation and/or radioactive material. Measurements of radioactivity concentrations in the ambient air of the workplace include air sampling and real-time air monitoring. The derived air concentration should be used as a reference level in the control of occupational exposures to airborne radioactive material. For situations where the particle size is known to differ significantly from 1  $\mu\text{m}$ , appropriate corrections can be made to both the estimated dose to workers and the DACs.

For the purpose of workplace monitoring, air samplers positioned in the breathing zone of workers may be used to complement fixed-station and portable air samplers, as necessary to ensure that representative air samples are obtained. Bioassay measurements may be used to help verify the adequacy of the workplace air monitoring program, but should not provide the primary basis for monitoring for loss of radionuclide control in the workplace.

Real-time monitoring using continuous air monitors [CAMs] should be performed in normally occupied areas where an individual is likely to be exposed to a concentration of radioactivity in air exceeding one DAC, or where there is a need to alert potentially exposed individuals to unexpected increases in airborne radioactivity levels.

Air monitors should be calibrated at least once per year, and shall be capable of measuring one DAC when averaged over 8 hours (8 DAC-hours) under laboratory conditions. For the airborne radioactive material that could be encountered, real-time air monitors should have alarm capability and sufficient sensitivity to alert potentially exposed personnel that immediate action is necessary in order to minimize or terminate inhalation exposures. Should there be a need to use a higher alarm level in the actual workplace, the need should be justified and documented. The establishment of CAM alarm levels above 8 DAC-hours should be justified and documented in the internal dose assessment TBM.

## *2. Allowance for physical and chemical form*

The specific physical and chemical characteristics of the materials potentially involved should be determined and taken into account in the design of the monitoring program. These include radionuclide composition, mode of intake, activity median aerodynamic diameter and particle-size distribution, solubility and transportability from the lung to other organs, and gastrointestinal absorption into the systemic circulation. Accounting for physical and chemical characteristics may necessitate a different set of secondary protection limits applied to specific work locations. The basis for revised secondary limits should be documented in the internal dose assessment TBM.

## *3. Recourse for technology shortfall for monitoring in the workplace*

The technology needed to perform workplace measurements for some radioactive materials at levels indicative of a CEDE of 1 mSv may not be available. If the performance requirement cannot be achieved for this reason, the facility should: (1) continue to use the best practicable (state-of-the-art) monitoring methods; (2) document the level of intake detection achieved; and (3) implement enhanced design, operation, controls, and personnel protection equipment and procedures to minimize intakes of radioactive materials.

## ACKNOWLEDGEMENTS

The author wishes to recognize the contributions over the past decade of many persons to this work. The implementation guide from which this chapter was largely drawn is the product of the combined wisdom and experience of the DOE expert group on internal dosimetry. That group has had a varied membership over the years, led by the late Roscoe Hall and later by Rick Brake. Members and contributors included Don Bihl, Jim Bogard, Liz Brackett, Rick Brake, Gene Carbaugh, Bill Fairman, Roger Falk, Darrell Fisher, Judy Foulke, Roscoe Hall, Ken Heid, Bill King, Tom La Bone, Jim Lawrence, Ed Lessard, Bob Loesch, DeVaughn Nelson, Jack Selby, Dan Strom, Monte Sula and Al Tschaeche. This group was initiated by Ed Vallario, and supported by Ken Ferlic and Rick Jones of DOE.

## DISCLAIMER

While much of the technical content of this chapter derives from the DOE implementation guide for internal dosimetry programs (DOE, 1993b), the opinions in this chapter are the sole responsibility of the author and not of the DOE or of Battelle. No government funds were used to prepare this chapter.

## REFERENCES

- American National Standards Institute. *Practice for Occupational Radiation Exposure Records System*. ANSI N13.6-1972. New York: American National Standards Institute; 1972.
- American National Standards Institute. *Guidelines for the Documentation of Digital Computer Programs*. ANSI/ANS 10.3-1986. LaGrange Park, Illinois: American Nuclear Society; 1986.
- American National Standards Institute. *Verification and Validation of Scientific and Engineering Computer Programs for the Nuclear Industry*. LaGrange Park, Illinois: American Nuclear Society; ANSI/ANS 10.4-1986; 1987.
- American National Standards Institute. *Internal Dosimetry Programs for Tritium Exposure--Minimum Requirements*. New York: American National Standards Institute; ANSI N13.14-1983; 1983.
- International Commission on Radiological Protection. *Report of the Task Group on Reference Man*. New York: Pergamon Press; ICRP Publication 23; 1975.

- International Commission on Radiological Protection. *Recommendations of the International Commission on Radiological Protection*. New York: Pergamon Press; ICRP Publication 26; 1977.
- International Commission on Radiological Protection. *Limits for Intakes of Radionuclides by Workers: Design and Interpretation*. New York: Pergamon Press; ICRP Publication 30; 1979.
- International Commission on Radiological Protection. *The Metabolism of Plutonium and Related Elements*. New York: Pergamon Press; ICRP Publication 48; 1986.
- International Commission on Radiological Protection. *Individual Monitoring for Intakes of Radionuclides by Workers: Design and Interpretation*. New York: Pergamon Press; ICRP Publication 54; 1988.
- Lessard, E. T., et al. *Interpretation of Bioassay Measurements*. Upton, New York: Brookhaven National Laboratory; NUREG/CR-4884; 1987.
- National Council on Radiation Protection and Measurements. *General Concepts for the Dosimetry of Internally Deposited Radionuclides*. Bethesda, Maryland: NCRP Publications; NCRP Report No. 84; 1985.
- National Council on Radiation Protection and Measurements. *Recommendations on Limits for Exposure to Ionizing Radiation*. Bethesda, Maryland: NCRP Publications; NCRP Report No. 91; 1987.
- National Council on Radiation Protection and Measurements. *Limitation of Exposure to Ionizing Radiation*. Bethesda, Maryland: NCRP Publications; NCRP Report No. 116; 1993.
- Sikov, M. R., et al. 1992. *Contribution of Maternal Radionuclide Burdens to Prenatal Radiation Doses*. Bethesda, Maryland: U.S. Nuclear Regulatory Commission; NUREG/CR-5631, Rev.1; 1992.
- U.S. Department of Energy. *Radiological Protection for Occupational Workers*. Washington, D.C.: U.S. Department of Energy; DOE Order 5480.11; 1988.
- U.S. Department of Energy. *Radiological Control Manual*. Washington, D.C.: U.S. Department of Energy; DOE/EH-0256T; 1992.

- U.S. Department of Energy. Occupational radiation protection. *Federal Register*, Vol. 58(236):65458-; 10 CFR Part 835; December 14, 1993a.
- U.S. Department of Energy (DOE). *Internal Dosimetry Programs*. Washington, DC: U.S. DOE; Implementation Guide for use with Title 10, Code of Federal Regulations, Part 835; G-10 CFR 835/C1 - Rev. 0; Dec. 1993b.
- U.S. Environmental Protection Agency. *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion*. Washington, D.C.: U.S. E. P. A.; Federal Guidance Report No. 11; EPA-520/1-88-020; 1988.