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User's Guide to the DCAL System

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ABSTRACT

This report serves as a user's manual for the first release of the Dose and Risk Calculation software, DCAL. DCAL consists of a series of computational modules, driven in either an interactive or a batch mode, for the computation of dose and risk coefficients. The system includes extensive libraries of biokinetic and dosimetric data and models representing the current state of the art. DCAL has unique capability for addressing intakes of radionuclides by non-adults. DCAL runs as 32-bit extended DOS and console application under Windows 95/98/NT/2000/XP. It is intended for users familiar with the basic elements of computational radiation dosimetry. Components of DCAL have been used to prepare EPA *Federal Guidance Reports 12 and 13* and a number of publications of the International Commission on Radiological Protection. The dose and risk values calculated by this first release are consistent with those published in *Federal Guidance Reports 12 and 13*.

1.0 OVERVIEW OF THE DCAL SYSTEM

Under the sponsorship of the U.S. Environmental Protection Agency (EPA), the Dosimetry Research Group (now the Biosystems Modeling Team in the Advanced Biomedical Science and Technology Group) at Oak Ridge National Laboratory (ORNL) has developed a comprehensive software system for the calculation of tissue dose and subsequent health risk from intakes of radionuclides or exposure to radionuclides present in environmental media. This system serves EPA's current needs in radiation dosimetry and risk analysis. The Dose and Risk Calculation software, called DCAL, has been used in the development of two federal guidance reports (*Federal Guidance Reports 12 and 13*) (EPA 1993, 1999) and several publications of the International Commission on Radiological Protection (ICRP), specifically in the computation of age-specific dose coefficients for members of the public (ICRP 1989, 1993, 1995a, 1995b, 1996).

DCAL is designed for use on a personal computer (PC) or scientific work station by users with experience in scientific computing and computational radiation dosimetry. The system consists of a series of computational modules driven by a user interface. DCAL may be used either in an interactive mode designed for evaluation of a specified exposure case or in a batch mode that allows non-interactive, multiple-case calculations on a PC or scientific work-station. Only the PC version of DCAL is being distributed.

DCAL performs biokinetic and dosimetric calculations for the case of acute intake of a radionuclide by inhalation, ingestion, or injection into blood at a user-specified age at intake. The user may compute either equivalent or absorbed (low and high LET) dose rates as a function of time following intake of the radionuclide. The equivalent dose option enables the generation of a table of age-specific dose coefficients, i.e., committed equivalent doses to organs and committed effective doses per unit intake, such as those published in the ICRP documents on doses to the public from intake of radionuclides (ICRP 1989, 1993, 1995a, 1995b, 1996).

If the endpoint the calculation is radiogenic risk, the absorbed dose option must be selected because the radiation risk factors used by DCAL are expressed in terms of absorbed dose. To calculate radiogenic risk, DCAL couples the generated absorbed dose rates with radiation risk factors and mortality data to predict organ-specific risk of radiogenic cancer death from chronic intake of a radionuclide.

DCAL includes a module for the evaluation of dose rate resulting from external exposure to radionuclides present outside the body in environmental media, i.e., distributed in an airborne cloud, in water, on the ground surface, or to various depths in the soil. That module uses the photon and electron dosimetric data tabulated in *Federal Guidance Report 12* (EPA 1993) to generate radionuclide-specific dose rate coefficients. As is the case for intake of radionuclides, if the endpoint of the calculation is radiogenic risk, DCAL couples the generated absorbed dose rates with radiation risk factors and mortality data to predict organ-specific risk of radiogenic cancer death from chronic exposure to the radionuclide in the environmental medium. The discussion below focuses on the dose from internally deposited radionuclides. The reader is referred to Chapter 11 for further discussion of the external dose computations.

For the case of radionuclide intake at a pre-adult age, anatomic and dosimetric parameter values are interpolated in a continuous manner throughout the period of growth. If age dependence is indicated in the biokinetic model, the biokinetic parameter values also are interpolated in a continuous manner throughout growth or throughout life. Age-specific biokinetic models for several radioelements are provided in the ICRP's series on doses to members of the public from intake of radionuclides. The age at intake considered in that series are 100 d, 1 y, 5 y, 10 y, 15 y, and adult. In the ICRP documents as well as in DCAL, biokinetic parameter values for intermediate ages are based on linear interpolation with age. The beginning age of adulthood is defined in the element-specific systemic biokinetic model. That age is 20 y for most elements but is 25 for some bone-seeking elements because of substantial changes in the modeled biokinetics of the element between ages 20 and 25 y.

The dosimetric calculations proceed in three main steps:

Step 1: calculation of time-dependent activity of the parent radionuclide and its radioactive progeny present in anatomical regions (source regions) of the body;

Step 2: calculation of *SEE* values for all combinations of source region *S* and target region *T*, where *SEE(T,S)* is the dose rate in *T* per unit activity present in *S*;

Step 3: calculation of dose rates or equivalent dose rates, based on output generated in Steps 1 and 2.

Dose coefficients may be computed after Step 3. A dose coefficient is an integrated organ dose or dose equivalent, or an effective dose per unit activity intake. The integration period is 50 y for intake by the adult and from age at intake to age 70 y for intake at a pre-adult age.

Cancer risk coefficients can also be calculated after completion of Step 3 provided the absorbed dose option has been selected. For a given radionuclide and exposure mode, both a mortality risk coefficient and a morbidity risk coefficient are calculated. The mortality risk coefficient is an estimate of the risk, per unit activity inhaled or ingested for internal exposures or per unit time-integrated activity concentration in air or soil for external exposures, of dying from a radiogenic cancer. The morbidity risk coefficient is a comparable estimate of the average total risk of experiencing a radiogenic cancer, whether or not the cancer is fatal. Either risk coefficient applies to an average member of the public, in the sense that estimates of risk are averaged over the age and gender distributions of a hypothetical closed "stationary" population whose survival functions and cancer mortality rates are based on recent data for the U.S. The method of calculation of the risk coefficients is described in Chapter 10.

In its calculations of dose and risk, DCAL relies on data libraries defining the biokinetic models, nuclear decay data, anatomic data, radiation risk models, survival data, cancer mortality and morbidity, and various other miscellaneous data. These libraries enable the user to compute state-of-the-art estimates of radiation dose and risk from intakes of or exposure to radionuclides, with minimal input.

DCAL is designed to allow easy expansion of its library of systemic biokinetic models and gastrointestinal uptake values (f_1 values) with user-supplied models. Such expansions must adhere to DCAL's design considerations. The biokinetic, dosimetric, and risk libraries are considered as permanent files of the DCAL System, although virtually all portions of these libraries are readily accessible and could be modified by users who are familiar with these data and who have acquire an understanding of the organization and structure of the DCAL system.

Two sets of systemic biokinetic models are contained in the DCAL libraries: the models for occupational exposure recommended in ICRP Publication 68 (1994b); and the age-specific models applied in the production of EPA's *Federal Guidance Report 13*. The latter set of models is generally the same as that used in the ICRP's series of documents on doses to members of the public, as summarized in ICRP Publication 72 (1996), although a few of the ICRP's models were modified as described in *Federal Guidance Report 13*. The biokinetic libraries include: the latest ICRP model of the respiratory tract as described in ICRP Publication 66 (1994a); the ICRP's gastrointestinal tract model used in calculations for *Federal Guidance Report 13* (the GI model first used in ICRP Publication 30, 1979); and the urinary bladder voiding model described in ICRP Publication 67 (1993). The nuclear decay library contains nuclear decay data currently used by the ICRP and the Medical Internal Radiation Dose (MIRD) Committee of the Society of Nuclear Medicine (Weber et al. 1989) and information on the energies and intensities of the radiations associated with spontaneous nuclear transformation of 838 radionuclides. The photon specific absorbed fraction library is based on the data of Cristy and Eckerman (1987,

1993) as currently used by the ICRP. Organ masses for adults are taken from ICRP Publication 23 (Reference Man, ICRP 1975) and, for children, the values are taken from the phantoms of Cristy and Eckerman (1987, 1993), which are based on data from ICRP Publication 23. The radiation risk models are based on the EPA's current methodology (EPA 1994), but some parameter values of those models have been modified as described in *Federal Guidance Report 13* (EPA 1999). Gender-specific survival data are from the U. S. Decennial Life Tables for 1989-1991 (NCHS 1997).

Due to a recent movement in radiation protection toward biological realism in the treatment of radionuclides in the body, some of the biokinetic models currently used by the ICRP, and included in the DCAL libraries, are considerably more complex than models traditionally used by the ICRP. For example, some systemic biokinetic models depict continual redistribution of activity among 20 or more compartments at rates that vary with age. The ICRP's current age-specific respiratory tract model (ICRP Publication 66, 1994a) is of similar size and complexity. In the ICRP documents on doses to the public from intake of radionuclides, the systemic models are sometimes used in conjunction with the assumption of independent kinetics of radioactive progeny, which requires the tracking of individual chain members produced in the body by radioactive decay of the parent.

With such models and assumptions, determination of the time-dependent distribution of all chain members may require the solution of a first-order model involving (in effect) several hundred compartments, feedback of activity between compartments, and transfer rates that vary with age and hence time. The corresponding set of coupled differential equations often is too large and complicated to be solved by most conventional solvers, and solution by any conventional solver requires enormous computing space and time.

Rapid solution of these complex models by DCAL with the relatively modest CPUs available on PCs is accomplished by applying an efficient approximation technique developed by the dosimetry team. The technique has no restrictions of practical importance on the number of compartments, the network of flows between compartments, the number of radioactive daughter products, or the paths of movement of chain members. The technique is unconventional in that the problem of solving the model is not viewed as one of solving a set of coupled differential equations representing the model. Instead, the model is viewed as a series of compartments and the time period of interest as a series of time steps, and the contents of each compartment on each time step is approximated as the closed-form solution of a particularly simple linear differential equation. Any specified level of accuracy can be achieved by selecting time steps sufficiently small. For the biokinetic models included in the DCAL libraries, the set of default time steps used in DCAL typically yields relative errors of at most a few tenths of one percent with regard to instantaneous activities in compartments and virtually exact integrated activities. For a specified level of accuracy, computing time and storage requirements increase roughly in proportion to the number of compartments in the model but with current (2006) PCs is at most a few seconds even for the most complex models considered in *Federal Guidance Report 13,* for example. The approximation technique is described in detail in Section 8.

2.0 INSTALLATION OF DCAL SOFTWARE

2.1 BACKGROUND INFORMATION

DCAL is designed for use on a personal computer (PC) or scientific work station by users with experience in scientific computing and computational radiation dosimetry. The system consists of a series of computational modules driven by a user interface. DCAL may be used either in an interactive mode designed for evaluation of a specified exposure case or in a batch mode that allows non-interactive, multiple-case calculations.

The DCAL system operates as a 32-bit console application on Pentium-class PC with Windows 95/98/NT/2000/XP operating systems. The installation requires about 30 Mbytes of space on the hard drive. Additional space is necessary for files generated during use of DCAL, with the total required space depending on the user's housekeeping practices.

A conventional Windows installation procedure is provided to install the DCAL system. The procedure installs the following three components of the DCAL system:

- computational and utility modules;
- dosimetric data libraries;
- biokinetic data libraries.

The installation procedure creates a folder (or directory) on the hard drive with the default name DCAL within which all subsequent folders and files are installed. Although the installation procedure allows the user to install the software into a folder of his/her choice, it is recommended that DCAL's main folder not be under another folder, such as C:\Program Files. DCAL's data libraries and the computational modules must reside in a folder off the main folder, and the names of these folders cannot be changed.

2.2 INSTALLING THE DCAL SYSTEM

From Windows Explorer click on the DCAL setup executable (DCAL_setup.exe), or from *Start*|*Run* enter *d:\dcal_setup*, where *d:* is the drive with the distribution copy of DCAL. Follow the installer's instructions to complete the installation. Following completion of the installation the user should view the "readme.txt" file for any information that may have been added after this document was prepared. The installation procedure places a shortcut on the desktop that can be used to invoke DCAL. DCAL's computational modules use ANSI device drivers to control the position of the cursor on the screen. If these drivers (ANSI.SYS) are not installed, various strange characters will appear and scroll by on the screen during the computations. Use the Windows FIND utility (*Start*|*Find*) to locate the file ANSI.SYS on the PC; typically it is present in the WINDOWS\COMMAND folder. On Windows 95/98 systems it is necessary to use an ASCII editor (or Windows NotePad) to modify the CONFIG.SYS file located in the root of drive C: to include

```
DEVICE=C:\WINDOWS\HIMEM.SYS
DOS=HIGH,UMB
DEVICEHIGH=C:\WINDOWS\COMMAND\ANSI.SYS
```

On Windows NT/2000/XP machines the CONFIG.NT file should include

```
DEVICE=%SystemRoot%\SYSTEM32\HIMEM.SYS
DOS=HIGH,UMB
DEVICE=%SystemRoot%\SYSTEM32\ANSI.SYS
```

The user should confirm the location of HIMEM.SYS and ANSI.SYS on these systems.

Windows ME does not support the ANSI device drivers, i.e., the CONFIG.SYS file. Windows ME users can download the utility ANSI.COM from www.pcmag.com/article2/0,1759,1556221,00.asp. Users must add the line ANSI.COM > null to the file C:\Windows\Command\CMDINIT.BAT. This BAT files is automatically executed by Windows ME each time a console or DOS application is run.

DCAL's computational modules are written in FORTRAN and compiled as 32-bit extended DOS applications using the Open WATCOM[1] compiler with the PMODE/W DOS extender. The interactive interface module and the various utilities are 32-bit console applications compiled with PowerBasic's Console Compiler[2]. DCAL will not run under DOS 6.2 or Windows 3.1 because of the 32-bit codes.

2.3 INSTALLED FILES

The user should consult the README.TXT file in the DCAL folder for any updated information on the DCAL System that may have been added after this document was prepared. The file DCALFILE.TXT in the DCAL folder lists all the files that were installed with their size and date/time stamp. The following is a summary of the locations and numbers of installed files.

```
Folder: C:\DCAL contains 4 files
Folder: C:\DCAL\BIN contains 23 files
Folder: C:\DCAL\INI contains 8 files
Folder: C:\DCAL\MAN contains 1 files
Folder: C:\DCAL\HLP contains 8 files
Folder: C:\DCAL\DAT\NUC contains 3 files
Folder: C:\DCAL\DAT\SAF contains 23 files
Folder: C:\DCAL\DAT\EXT contains 22 files
Folder: C:\DCAL\DAT\MIS contains 27 files
Folder: C:\DCAL\DAT\RSK contains 8 files
Folder: C:\DCAL\DAT\BIO\I68 contains 281 files
Folder: C:\DCAL\DAT\BIO\F13 contains 333 files
```

The DCAL utility, DCALSYS, invoked from System Help on the DCAL Main Menu (see Sect 2.4), will generate a corresponding snapshot of the files currently residing in the DCAL System. That utility can be run at any time to create a file named DCALSYS.DAT that can be compared to DCALFILE.TXT in the root folder to verify the integrity of the system.

[1] Open Watcom is an effort of the Open Source development community to maintain and enhance the Watcom C/C++ and Fortran compilers. See http://www.openwatcom.org/ for further information.

[2] **PowerBASIC, Inc.;** 1978 Tamiami Trail S. #200; Venice, FL 34293. See http://www.powerbasic.com/ for further information.

2.4 DCAL Main Menu Module

All DCAL computations are invoked from DCAL's Main Menu, shown in Fig. 2.1. The install procedure places a shortcut for this module on the desktop. Clicking on the shortcut invokes the module DCAL2005.EXE, which is present in the folder DCAL.

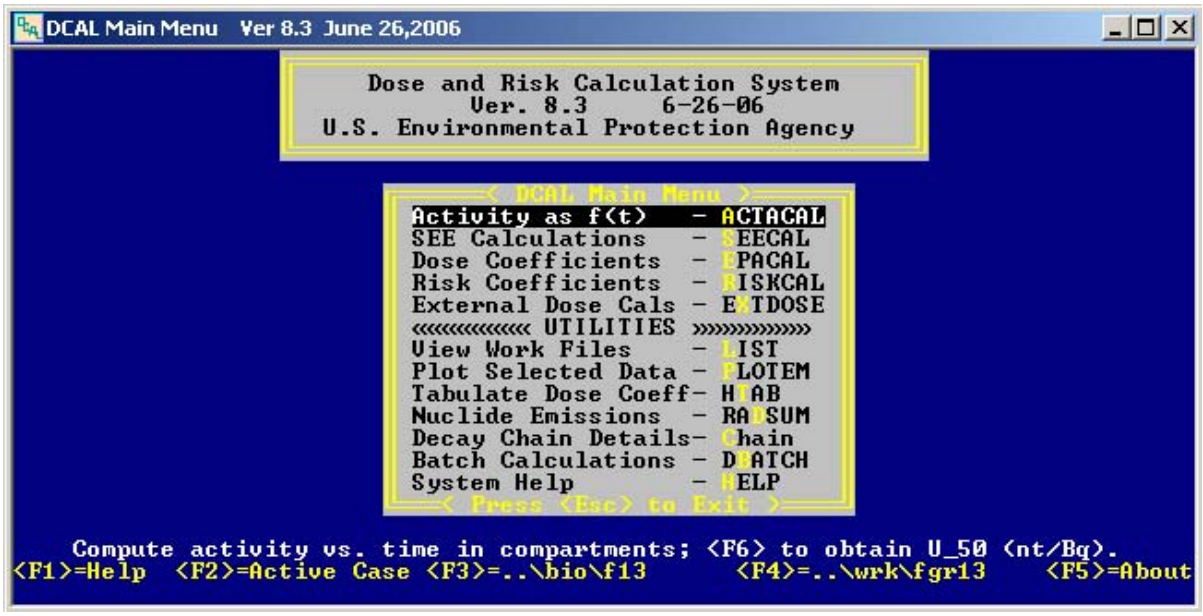


Fig. 2.1. DCAL's main menu.

3.0 DESIGN OF THE DCAL SYSTEM

3.1 INTENDED USERS

DCAL is a menu-driven scientific software system designed for users who have experience in scientific computing and a working knowledge of computational radiation dosimetry. The discussions in this user's guide assume fundamental knowledge in:

- computer programming;
- compartmental modeling;
- radiation physics.

3.2 FUNCTION AND ORGANIZATION OF DCAL'S MODULES

DCAL consists of a series of computational modules driven by the interactive-menu interface shown in Fig. 2.1. A schematic of the DCAL system is shown in Fig. 3.1.

The dosimetric calculations for intake of a radionuclide proceed in three main steps:

Step 1: Activity module (ACTACAL): calculation of time-dependent activity of the parent radionuclide and its radioactive progeny present in anatomical regions (source regions) of the body;

Step 2: SEE module (SEECAL): calculation of *SEE* values for all combinations of source region *S* and target region *T*, where *SEE(T,S)* is the dose rate in *T* per unit activity present in *S*;

Step 3: Dose rate module (EPACAL): calculation of dose rates or equivalent dose rates, based on output generated in Steps 1 and 2.

If the absorbed dose option has been selected, risk calculations can then be undertaken after completion of Step 3. Risk calculations are carried out by the RISKCAL module and, in the case of inhalation or ingestion, are based on an assumed intake of 1 Bq of the parent radionuclide per day, throughout life. The calculations are based on best available age-specific risk coefficients and mortality data.

If the equivalent dose option has been selected, then dose coefficients may be calculated after completion of Step 3. Dose coefficients include integrated organ dose equivalents as well as the effective dose per unit intake. Dose coefficients are derived by integrating the equivalent dose rates generated in Step 3. The integration is performed by fitting a spline function to the equivalent dose rates and then evaluating the exact integral of the function. The spline-fitting method used in DCAL does not exhibit the undesirable oscillations between adjacent points that often occur with spline fits (de Boor 1978, Fritsch and Carlson 1980, Fritsch and Butland 1982).

In its calculations of dose and risk, DCAL relies on libraries of biokinetic and dosimetric models, nuclear decay data, anatomic data, radiation risk models, survival data, cancer mortality and morbidity data, and other miscellaneous data. These libraries of state-of-the-art models and data allow best available estimates of dose and risk from internally deposited radionuclides, with minimal input by the user. As described later, DCAL allows expansion of portions of its library of biokinetic data with user-supplied files.

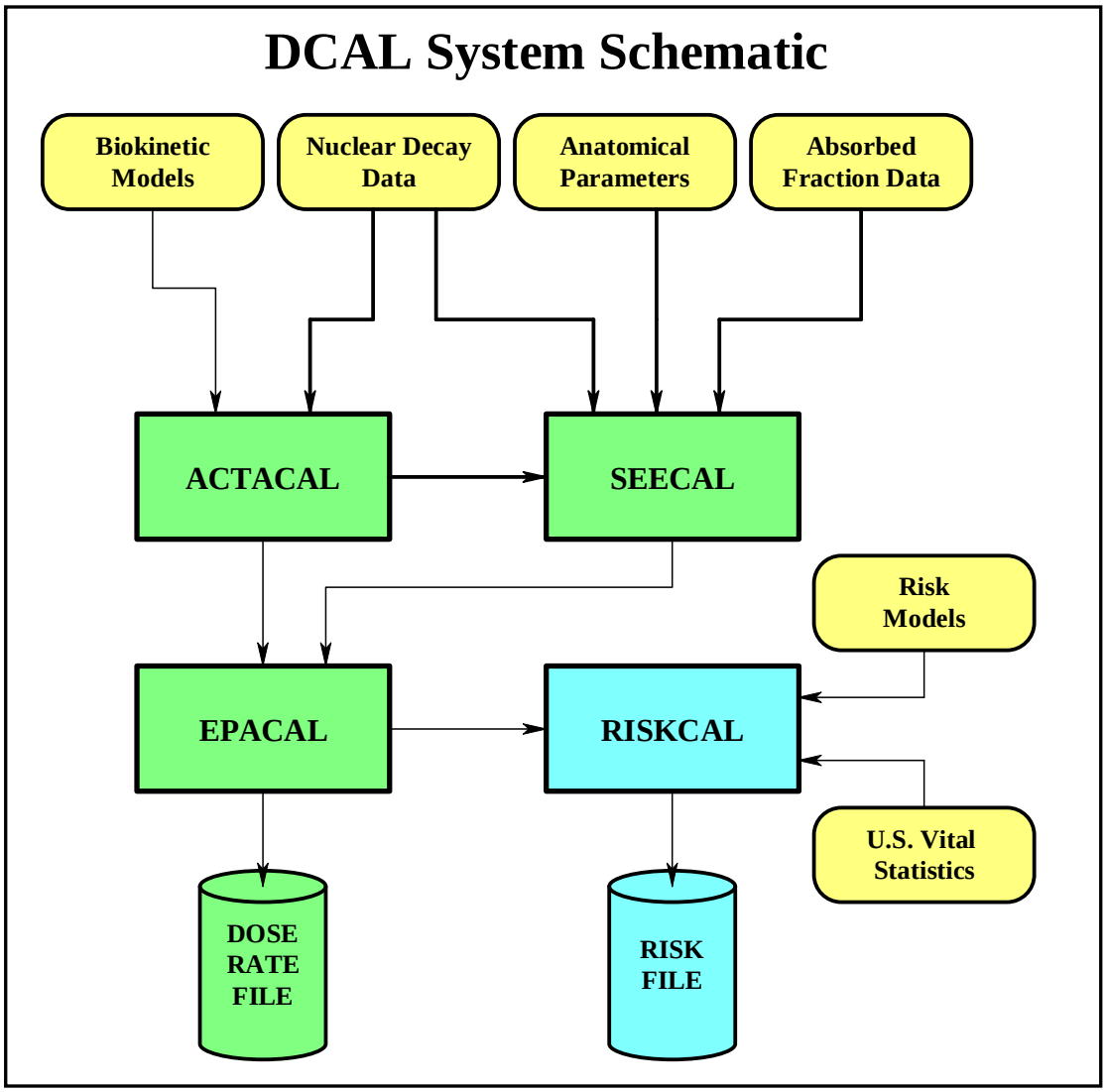


Fig. 3.1. Schematic of the DCAL System

Calculations performed using DCAL inherit a pedigree from the computational modules and the various permanent data files (libraries) used in the calculations. All computational modules access the appropriate libraries for their common information needs. For example, ACTACAL and SEECAL both call upon the same data libraries for the numerical values of organ masses and the energies of emitted radiations. This adds a level of assurance to the computations and minimizes the information requested of the user. For example, the half-life of the radionuclide taken into the body and a description of subsequent radioactive decay chain, if any, are obtained from the library rather than from user input.

When DCAL is installed on a PC, the folder DCAL (or user-selected name) is created, along with several folders that contain executable files, permanent data files, system help files, and output files generated by the user. The locations of different types of files within the DCAL folder are indicated in Fig. 3.2.

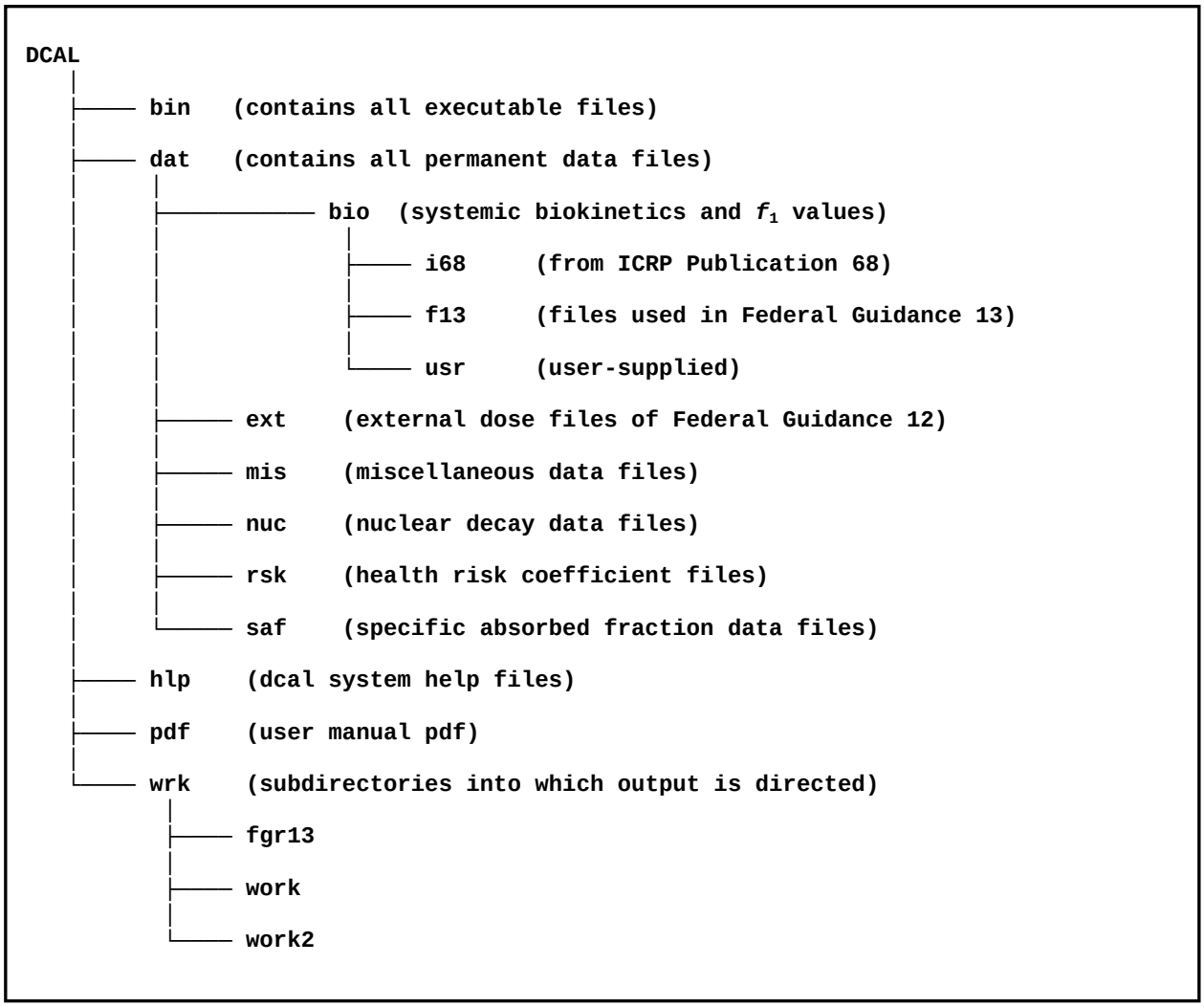


Fig. 3.2 Organization of DCAL files by folder. Names of folders off the main folder not be changed.

The folder DCAL contains the executable file DCAL2005.exe that serves as the Main Menu for the DCAL System. All other executable files (*.exe) of the system are located in the folder BIN and are thus isolated from other files as a housekeeping aid. The folder HLP contains system help files that can be accessed from the DCAL Main Menu.

Permanent data files are contained in folders that branch from the folder \DCAL\DAT. Two of the folders, \DCAL\DAT\EXT and \DCAL\DAT\RSK, contain permanent data files used in risk computations. The other folders off \DCAL\DAT contain files representing biokinetic and dosimetric models or data.

3.3 LIBRARIES OF BIOKINETIC, DOSIMETRIC, AND RISK MODELS OR DATA

3.3.1 Library of Biokinetic Models

With exceptions described below, the biokinetic files included in the DCAL library represent biokinetic models recommended in recent publications of the ICRP. The following biokinetic models are available:

- Respiratory tract kinetics:
  - model of ICRP Publication 66 (1994a).
- Transfer kinetics through segments of the gastrointestinal (GI) tract:
  - model of ICRP Publication 30 (1979).
- Clearance from urinary bladder contents via urinary excretion:
  - urinary bladder voiding model described in ICRP Publication 67 (1993).
- Systemic biokinetics and GI absorption fraction (f_1 value):
  - biokinetic models and f_1 values from ICRP Publication 68 (1994b);
  - biokinetic models and f_1 values used in *Federal Guidance Report 13* (EPA 1999).

With a few exceptions, the biokinetic models and f_1 values used in *Federal Guidance Report 13* (EPA 1999) are the same as those used in ICRP Publication 72 (1996), which is a compilation of age-dependent dose coefficients for members of the public. The exceptional cases are as follows: the systemic biokinetic models for radioisotopes of actinium and protactinium are updates of models recommended by the ICRP; multiple f_1 values for chromium are given in ICRP Publication 72, but only the value that applies to hexavalent chromium is used for ingestion cases in *Federal Guidance Report 13*; and the f_1 value for polonium used in ICRP Publication 72 (0.5) is applied to polonium in diet, but a smaller value (0.1) is applied to polonium in tap water. The files in folder \DCAL\DAT\BIO\I68 represent the systemic biokinetic models recommended in ICRP Publication 68 (1994b) on occupational exposures. The files in folder \DCAL\DAT\BIO\F13 represent the systemic biokinetic models used in *Federal Guidance Report 13* (EPA 1999).

The DCAL system is designed to accept user-supplied systemic biokinetic models and f_1 values for elements but is not designed to allow expansion of the libraries containing respiratory, gastrointestinal, or urinary bladder voiding models.

Biokinetic data other than the systemic biokinetics and f_1 values are contained in the folder \DCAL\DAT\BIO\MIS. For example, this folder contains files of transfer rates required to implement the respiratory tract model of ICRP Publication 66 (1994a).

The biokinetic files are read by the ACTACAL module. This calculates activity as a function of time in the compartments specified in the biokinetic data files.

3.3.2 Library of Nuclear Decay Data

Information on the energies and intensities of the various radiations emitted by 838 radionuclides are contained in the file ICRP38.RAD found in the folder \DCAL\DAT\NUC. This includes 825 radionuclides whose decay data were evaluated during the preparation of ICRP Publications 30 and 38 (ICRP 1983) and 13 additional radionuclides whose decay data were evaluated more recently by the Medical Internal Radiation Dose (MIRD) Committee of the Society of Nuclear Medicine (Weber et al. 1989). Abridged tabulations of these data have been published by the ICRP in Publication 38 (1983). The index file ICRP38.NDX contains pointers to the initial record of each radionuclide in the RAD file and other data, such as the half-life and fraction of the nuclear transformation forming a radioactive daughter nucleus. The file ICRP38.BET contains the beta spectra for beta emitters.

3.3.3 Library of Data on Specific Absorbed Fractions

Age-dependent *SEE* values are used to convert the time-dependent distribution of activity in the body, as predicted by a biokinetic model, to absorbed dose rates or equivalent dose rates to organs. For a given target organ *T* and a given source organ *S*, the quantity *SEE(T,S)* reflects the yield and average energy (and, for calculation of equivalent dose rates, a radiation weighting factor) for each type of radiation emitted from *S* as well as the specific absorbed fraction *SAF(T,S)* for that radiation type. *SAF(T,S)* is the fraction of emitted energy from source organ *S* that is absorbed by target organ *T*, per unit mass of *T*.

For the parent radionuclide and each decay chain member considered in the ACTACAL calculation, the SEECAL module calculates age-dependent *SEE* values for each source and target organ pair indicated in the SEECAL request file generated by ACTACAL. These *SEE* calculations are based on (1) nuclear decay data contained in the file ICRP38.RAD in the folder \DCAL\DAT\NUC; (2) a library of specific absorbed fractions for non-penetrating radiations contained in folder \DCAL\DAT\SAF; (3) a library of specific absorbed fractions for photons contained in folder \DCAL\DAT\SAF; and (4) age-specific organ masses contained in folder \DCAL\DAT\SAF. The specific absorbed fractions are those currently used by the ICRP (Cristy and Eckerman 1987, 1993). Organ masses for adults are taken from ICRP Publication 23 (1975) (Reference Man). For children, age-specific organ masses are taken from the phantoms of Cristy and Eckerman (1987), which are based on data from ICRP Publication 23.

3.3.4 Library of Risk Models and Mortality Data

Radiogenic cancer risk models are used to convert estimates of radiation dose to estimates of excess force of mortality attributable to that dose. The risk calculations performed by DCAL are for attributable risk. Attributable risk is defined as the likelihood (according to the risk model) of death from cancer or development of cancer due to a radiation exposure.

The radiation risk models used in DCAL are based on the U.S. EPA's radiation risk methodology (EPA 1994) but have been updated in some cases as described in *Federal Guidance Report 13* (EPA, 1999). The EPA's risk models are embodied in libraries of age- and gender-specific risk coefficients, survival data, and force of mortality data for specific cancers. These libraries are found in the folder \DCAL\DAT\RSK.

The risk coefficients used in DCAL are age specific and for most sites represent compromise values based on different but equally plausible methods of transporting risk across populations (EPA 1994; EPA 1999). Gender-specific survival data are from the *U. S. Decennial Life Tables for 1989-1991* (NCHS 1997). Mortality data are from 1989-1991 vital statistics mortality data (NCHS 1992, 1993a, 1993b).

3.4 DCAL OUTPUT FILES

Each computational module of DCAL generates several output files, with the precise number of files depending on the options selected during the interactive session. The output files are "self-documenting" in the sense that they contain information that identifies input data files, such as names, dates of creation, and file size. This information defines the pedigree of the results. In addition, each module generates, or contributes to, a log file (extension LOG) that records general information concerning the input data sets (e.g., name and date when created), plus relatively detailed information on the decay chain, source and target organs, biokinetic compartments, biokinetic parameter values, and organ masses. The user can request that ACTACAL generate an output file (extension CPT) of the time-dependent activities in all compartments in the model, in addition to the standard file of activities within the source regions of the model. Other DCAL modules are not affected by ACTACAL's option to generate the CPT file.

The names of all DCAL files follow the 8.3 DOS file name convention, that is, long file names are not permitted. With the exception of files of SEE values, a DCAL output file is assigned a name of the form XXZZZUVW.[extension], where:

The first five characters (XXZZZ) are formed from the radionuclide name (e.g., H-3, Ra-226, Am-244m, etc.). If the nuclide name contains more than six characters, then the dash and the least significant digit in the mass number are not used; for example, the characters AM44M represent Am-244m. If the nuclide name involves six characters then the dash is deleted, for example RA226 denotes Ra-226. For names of length five or less the full name is retained with the underscore character used to fill in any unused positions. For example, H-3__ , C-14_, and I-131 appear in the name of the files associated with intakes of H-3, C-14, and I-131, respectively.

The sixth position (U) is a letter that identifies the age at intake, with *A* being the youngest age, *B* the next age, and so forth. If only one age at intake is considered, e.g., the adult, the identifying letter is *A*. If the intake ages considered are those of the ICRP's series on doses to members of the public, they are identified as follows:

A **= infant (100 d)**
B **= age 1 y (365 d)**
C **= age 5 y (1825 d)**
D **= age 10 y (3650 d)**
E **= age 15 y (5475 d)**
F **= adult; age 20y (7300 d) or 25 y (9125 d) (for certain bone seekers)**

The seventh position (V) in the file name identifies the intake mode. *G* and *J* denote intakes by ingestion and injection into blood, respectively. Inhalation intakes are noted by the absorption type assigned to the aerosol, i.e., absorption type *F*, *M*, or *S* of the ICRP Publication 66 (1994a) model. For inhalation of vapor or gases the seventh and eighth places are assigned the letters *AG*.

The eighth position (W) identifies the size of the inhaled aerosol (e.g., 5 for an activity median aerodynamic diameter or AMAD of 5 μm) and contains the underscore character for the other intake modes. If the particle size is not an integer then W may not be unique and meaningful.

Specific file extensions are used to identify different types of output. For intake case XXZZZUVW, some or all of the following files are generated, depending on the options selected during the interactive session:

XXZZZUVW.LOG, created by the ACTACAL module, with contributions from other modules,

is a master log file containing general identifying information on all data files used in the calculation and relatively detailed information on decay chains, source and target organs, biokinetic compartments, biokinetic parameter values, and organ masses.

XXZZZUVW.ACT, created by ACTACAL, is the file of age- and time-dependent activities of parent and decay chain members in source organs;

XXZZZUVW.CPT, created by ACTACAL if requested by the user, contains age- and time-dependent activities of parent and decay chain members in each compartment of the biokinetic model;

XXZZZUVW.REQ, created by ACTACAL, contains the information needed by the SEECAL module to generate the necessary SEE values (e.g., parent and decay chain members, age(s) at intake, and source and target regions);

XXZZZUVW.DRT or XXZZZUVW.HRT, created by the EPACAL module, is the file of absorbed or equivalent dose rates, respectively, depending on the user's selected option;

XXZZZUVW.HEF, created by HTAB utility, is a table of age-specific dose coefficients (committed equivalent doses and effective doses per unit intake), similar to tables given in the ICRP's series on doses to members of the public. If the absorbed dose option is selected, then the low and high LET absorbed dose committed organ doses will be tabulated.

XXZZZUVW.RSK, created by RISKCAL module, records the gender-specific cancer risk, by cancer site, resulting from unit intake of a radionuclide at each age (0 y, 1 y, 2 y, …)

XXZZZUVW.RBS, created by RISKCAL module, records gender-specific estimates of mortality and morbidity risk by cancer site for activity intakes during age intervals, including lifetime intake. The calculation assumes intake (by the user-specified intake mode) of 1 Bq of the parent radionuclide per day throughout an indicated age range.

SEE files have a name of the form [parent]DL.SEE or [parent]HT.SEE, where

[parent] is the abbreviation, without hyphens or underscores, of the parent radionuclide (e.g., C14, CA45, or RA226);

DL indicates that the radiation weighting factor has not been applied (i.e., the SEEs are for absorbed dose calculations);

HT indicates that radiation weighting factors have been applied (i.e., the SEEs are for dose equivalent calculations).

3.5 NAMING CONVENTION FOR SOURCE REGIONS AND BIOKINETIC COMPARTMENTS

For purposes of computing radiation dose it is necessary to relate the compartments of the biokinetic model to anatomical regions of the body referred to as source regions. To allow DCAL to identify source regions on the basis of the names of the biokinetic compartments, a standard naming convention for source regions and biokinetic compartments has been adopted. This naming convention also has the advantages of facilitating quality assurance and of allowing ACTACAL to assemble biokinetic information in a consistent manner from a variety of permanent and temporary files.

A list of standard names of source regions is provided in Table 3.1. Names shown in bold are "reserved names" since they are used explicitly within some of the computational modules. All other names are fixed in the STDNAMES.TXT file in the folder \DCAL\DAT\MIS.

The name of a compartment of a biokinetic model must be an extension of the standard name of the source region. For example, if the biokinetic model includes liver as a separate compartment, then the name of this compartment could be simply “Liver” or could be of the form “Liver_X”, where the symbol “_X” represents, in effect, a subscript. The underscore character must be present if a subscript is used. If the biokinetic model includes multiple liver compartments, then the name of each compartment must be of the form “Liver_X” except that one of the compartments could be named “Liver”, with no subscript. As an illustration, if three compartments are used to represent the biokinetics of the material in the liver, then some possible names for these compartments are: (1) Liver_1, Liver_2, Liver_3; (2) Liver, Liver_1, Liver_2; (3) Liver_a, Liver_b, Liver_c; (4) Liver_1, Liver_a, Liver_b.

The name of the compartment representing the circulation (called the transfer compartment in some ICRP publications) must be of the form “Blood” or “Blood_X”. At least one “Blood” compartment must be included in the data files describing the biokinetics of systemic material. Systemic material destined for urinary excretion should be transferred to a compartment named “UB_Cont” if a dose estimate for the urinary bladder (UB) is to be made. Similarly, systemic material destined for fecal excretion should be transferred to either the “SI_Cont” or “ULI_Cont” compartment of the gastrointestinal tract (transfer to “SI_Cont” allows some reabsorption to blood as determined by the f_1 value). If the biokinetic model indicates that material is simply lost from the systemic circulation without specifying an excretion route, as in many of the older ICRP models, or if the specified route of excretion is different from urine and feces (e.g, hair or sweat), then the transfer should be specified to a compartment labeled “Excreta”. The compartments named “Excreta”, “Urine”, and “Feces” are outside the body and excluded from the dosimetric calculations.

3.6 NAMING CONVENTION FOR SYSTEMIC BIOKINETIC FILES AND f_1 FILES

DCAL locates its input data by searching for standard file names. In the case of element specific files, DCAL extracts the symbol of the element from the name of the radionuclide and forms a file name using specific file extensions. The extensions for systemic biokinetic files and f_1 files are DEF and GF1, respectively. With some exceptions described in the following paragraphs, the name of the systemic biokinetic file for the parent radionuclide will have the form X.DEF or XX.DEF, where X or XX is the chemical symbol of the element. With exceptions described below, the name of the f_1 file will have the form X.GF1 or XX.GF1, where X or XX is the abbreviation of the element. For example: the systemic biokinetic file for radium generally will have the name RA.DEF; the systemic biokinetic file for iodine will have the name I.DEF; and the f_1 file for americium will have the name AM.GF1.

Table 3.1. Standard names of source regions used in DCAL[a]

Systemic	Lung	GI-Tract	Excretion
Adrenals	Lung_Cont	***St_Cont***	***UB_Cont***
UB_Wall	***ET1-sur***	***SI_Cont***	***Urine***
C_Bone-S	***ET2-sur***	***ULI_Cont***	***Feces***
C_Bone-V	***ET2_bnd***	LLI_Cont	***Excreta***
T_Bone-S	***ET2-seq***		
T_Bone-V	***LN-ET***		
Brain	***BBi-gel***		
Breasts	***BBi-sol***		
St_Wall	***BBi-bnd***		
SI_Wall	***BBi-seq***		
ULI_Wall	***bbe-gel***		
LLI_Wall	***bbe-sol***		
Kidneys	***bbe-bnd***		
Liver	***bbe-seq***		
Lng_Tiss	***AI***		
Muscle	***LN-Th***		
Ovaries	***NP_Cont***		
Pancreas	***TB_Cont***		
Skin	***P_Cont***		
Spleen	LN_Lung		
Testes			
Thymus			
Thyroid			
GB_Cont			
GB_Wall			
Ht_Cont			
Ht_Wall			
Uterus			
Body_Tis			
Blood			
BT-Soft			
Other			

[a]Names shown in bold italics have special meaning within the DCAL system in that they may appear in kinetic files that are linked. Abbreviations: Cont = contents, GB = gallbladder, LLI = lower large intestine, ULI = upper large intestine, SI = small intestine, St = stomach, Ht = heart, Lng = lung; R = red, C = cortical, T = trabecular, S = surface, V = volume, W = whole, WB = whole-body, UB = urinary bladder.

In some cases, different chemical forms of a radionuclide are assigned different biokinetic models and hence are defined in different DEF files. In such cases, special root names must be given to the various DEF files for the radionuclide. These special names are listed in a file called $BIODEF.DAT in the appropriate biokinetic folder. For example, in ICRP Publication 67 (1993), different biokinetic models are used for organic and inorganic sulfur. The biokinetic folder \DCAL\DAT\BIO\FGR13 contains the file S_ORG.DEF representing organic sulfur and the file S_INORG.DEF for inorganic sulfur, and these files are defined in the file $BIODEF.DAT. In the interactive mode, DCAL checks the file $BIODEF.DAT to determine whether special file names are listed for the radionuclide under consideration. If special file names are present, then a prompt is issued to the user to select the appropriate file. For batch runs, the special files must be assigned in the batch input file (see Chapter 6.0).

There are also cases in which different isotopes of an element are assigned different biokinetic models and hence different DEF files. In the ICRP's series of publications on doses members of the public (ICRP 1989, 1993, 1995a, 1995b, 1996), the simplifying assumption is made that the decays in bone of some short-lived isotopes of bone seeking elements (usually but not always isotopes with half-life no greater than 15 d) occur on bone surfaces and decays of the long-lived isotopes occur in bone volume. Thus, separate biokinetic files are needed for short- and long-lived isotopes of these elements, because different sources regions within bone are considered in the two cases. A name of the form X_SUR.DEF or XX_SUR.DEF is assigned to the file for short-lived isotopes (where X or XX is the chemical symbol of the element) and a name of the form X_VOL.DEF or XX_VOL.DEF is assigned to the file for long-lived isotopes. Directions for assigning a given biokinetic file to a given isotope (i.e., ordered pairs of radionuclides and file names) may be given in the file $BIODEF.DAT found in the biokinetic folder. If no directions are given in $BIODEF.DAT, then DCAL assumes that the demarcation time between short-lived and long-lived is 15 d and, on the basis of the file names, decides which biokinetic file to assign to a given radionuclide. If no files with root names ending in "_SUR" and "_VOL" are found in the biokinetic folder, then the default biokinetic file [radioelement].DEF is assigned.

In some cases, the f_1 value for material moving from the respiratory tract to the GI tract is assumed to depend on the form of the radionuclide inhaled. The respiratory tract model of ICRP Publication 66 (1994a) expresses this in terms of an absorption type (Type F, M, or S). If the f_1 value assigned to a specific form Q of an inhaled radioelement X or XX is different from the f_1 value for the ingestion case, the form-specific f_1 value must be defined in a file named X$Q.GF1 or XX$Q.GF1. That is, the root name consists of the abbreviation of the radioelement, a dollar sign, and the form Q of the inhaled radionuclide, where Q is one of the letters F, M, or S.

If separate systemic biokinetic files are used for different chain members (i.e., if the option of independent kinetics, i.e., of separate, pre-defined biokinetic files for separate chain members is selected), the systemic biokinetic file for a decay chain member other than the parent must be of the form Y-X, Y-XX, YYX, or YYXX, where Y or YY is the abbreviation of the decay chain member and X or XX is the abbreviation of the parent. For example, a systemic biokinetic file for ^{222}Rn to be used in a calculation for intake of ^{226}Ra must have the name RNRA.DEF. If the abbreviation of the decay chain member consists of only one letter, a hyphen must be used in the second position because DCAL expects the first two positions to represent a decay chain member other than the parent and the following position(s) to represent the parent.

3.7 DCAL'S INI FILE SYSTEM

DCAL's computational modules use INI files to specify the location of the permanent data files needed during their execution. The default INI files are contained in the \DCAL\INI folder and should not require any editing if the software was installed using the installation procedure. The INI file structure can be used to maintain the integrity of the DCAL system while exploring alternative models and parameter values. Before attempting to edit an installed data file, the user should consider using DCAL's INI file feature rather than compromising a permanent data file. Before detailing this feature, it is necessary to understand the structure of the INI files.

The INI file structure was developed to provide the computational modules with access to a common set of permanent data files and to ensure that the access was not limited by the coding. For illustrative purpose, Fig. 3.3 list SEECAL's INI file.

```
'RegMass.a00' ,   '..\..\dat\saf\RegMass.a00' ,   0
'RegMass.a01' ,   '..\..\dat\saf\RegMass.a01' ,   0
'RegMass.a05' ,   '..\..\dat\saf\RegMass.a05' ,   0
'RegMass.a10' ,   '..\..\dat\saf\RegMass.a10' ,   0
'RegMass.a15' ,   '..\..\dat\saf\RegMass.a15' ,   0
'RegMass.am'  ,   '..\..\dat\saf\RegMass.am ' ,   0
'RegMass.af'  ,   '..\..\dat\saf\RegMass.af ' ,   0
'PSAFTX66.a00',   '..\..\dat\saf\PSAFTX66.a00', 126
'PSAFTX66.a01',   '..\..\dat\saf\PSAFTX66.a01', 126
'PSAFTX66.a05',   '..\..\dat\saf\PSAFTX66.a05', 126
'PSAFTX66.a10',   '..\..\dat\saf\PSAFTX66.a10', 126
'PSAFTX66.a15',   '..\..\dat\saf\PSAFTX66.a15', 126
'PSAFTX66.am' ,   '..\..\dat\saf\PSAFTX66.am ', 126
'PSAFTX66.af' ,   '..\..\dat\saf\PSAFTX66.af ', 126
'ElAlphAF.a00',   '..\..\dat\saf\ElAlphAF.a00',   0
'ElAlphAF.a01',   '..\..\dat\saf\ElAlphAF.a01',   0
'ElAlphAF.a05',   '..\..\dat\saf\ElAlphAF.a05',   0
'ElAlphAF.a10',   '..\..\dat\saf\ElAlphAF.a10',   0
'ElAlphAF.a15',   '..\..\dat\saf\ElAlphAF.a15',   0
'ElAlphAF.am' ,   '..\..\dat\saf\ELALphAF.am' ,   0
'ElAlphAF.af' ,   '..\..\dat\saf\ElAlphAF.af' ,   0
'StdNames.txt',   '..\..\dat\mis\StdNames.txt',   0
'AF_Alpha.lng',   '..\..\dat\saf\AF_Alpha.lng',   0
'AF_Elec.lng' ,   '..\..\dat\saf\AF_Elec.lng' ,   0
'index.dat'   ,   '..\..\dat\nuc\icrp3x.ndx'  , 160
'radition.dat',   '..\..\dat\nuc\icrp3x.rad'  ,  25
'beta.dat'    ,   '..\..\dat\nuc\icrp3x.bet'  ,   9
'gamdos'      ,   'linear'                    ,   0
```

Fig. 3.3 Listing of SEECAL.INI file.

Each line of an INI file has three comma-delimited fields. The first field is the name for the file as used in the module's coding; thus, this field must not be changed. The second field is the relative path and name of the file as existing in the indicated folder. The third field, if nonzero, is the record length of the file if it is a direct access file. For example, this entry is the value of the variable RECL in FORTRAN open statements for a direct access file. The numerical value depends on the compiler; hence, it was useful in the development of the software to assign these values via the INI file rather than hard code it in the module. DCAL users should edit only the second field. If necessary, the second field could be edited to include the drive designation. The following example associates the decay data files in the folder NUC of drive F with the corresponding file name in the module.

```
'index.dat'   ,   'f:\nuc\icrp38.ndx' , 160
'radition.dat',   'f:\nuc\icrp38.rad' , 25
'beta.dat'    ,   'f:\nuc\icrp38.bet' , 9
```

All of DCAL's computational modules check whether a copy of their INI file exists in the current work folder. If the file is present, the module will use that file rather than the default INI file in the INI folder. This feature makes it possible to evaluate changes to many standard parameters in the calculations without corrupting the permanent data file. For example, to calculate SEE values using a special set of alpha absorbed fractions for the respiratory tissues, the following steps should be followed:

1. Create a work folder for the investigation using <F4> from DCAL's Main Menu.
2. Copy the default SEECAL.INI from \DCAL\INI folder to the work folder.
3. Copy AF_Alpha.lng file from \DCAL\DAT\MIS to the work folder and rename it AF_Test.lng.
4. Edit the AF_Text.lng file as necessary.
5. Edit the SEECAL.INI file in the work folder to include the line

```
'AF_Alpha.lng' , 'AF_Test.lng' , 0
```

It is not necessary to give the full path for AF_Test.LNG because it is in the work folder. This procedure can be quite helpful in maintaining the integrity of system while using the system to carry out special investigations. It is not necessary to use this approach when examining special biokinetic models, as such files can be placed in a user-defined biokinetic folder.

4.0 DCAL'S MAIN MENU

This section describes DCAL's main menu, which serves as the starting point for all calculations within the system. The menu also provides access to a number of utilities and to parameter values that may aid the user's efforts to validate a calculation.

4.1 INTERACTIVE MODE

DCAL's Main Menu can be invoked by either clicking on the DCAL shortcut on the desktop or from Windows Explorer by clicking on DCAL2005.EXE in the DCAL folder. Fig 4.1 shows the DCAL Main menu as it appears as a console application.

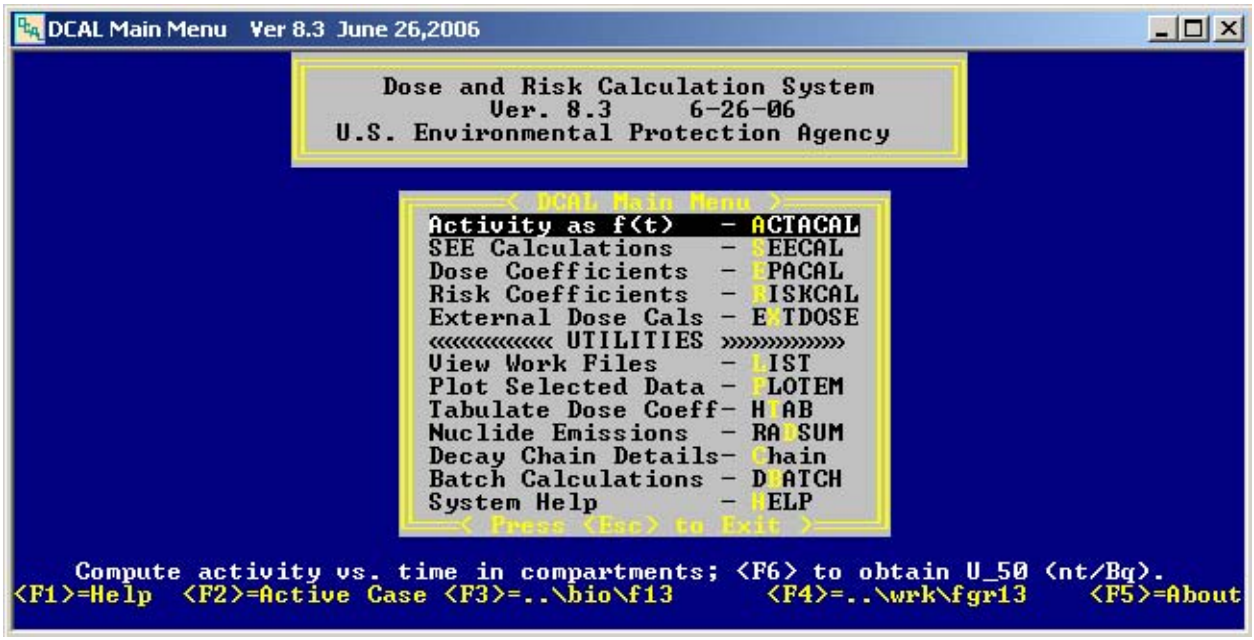


Fig. 4.1. DCAL's main menu.

The DCAL2005 module obtains information on the user's past usage of the DCAL System from the file DCALMENU.INI in the INI folder. The content of the INI file, as installed, is:

```
Default Directory
\bio\i68
\wrk\work
```

The second and third lines of the file identify the last used biokinetic and work folders, respectively, and are used to initialize the next session. Only the path beyond \DCAL\DAT is included with the folder name. As seen in Fig. 4.1, these assignments appear at the bottom of the menu screen and are labeled by the function keys <F3> and <F4>, respectively. It is assumed that folders below \bio\ and \wrk\ are alternative biokinetic and work folders, respectively. DCAL2005 constructs a list of such folders to appear in a menu that is invoked by pressing either <F3> or <F4>. From the menu an alternative folder can be selected or a new folder created. The name of the new folder is limited to no more than eight characters. If the user creates a new folder, it will become the active folder.

DCAL is limited to 15 biokinetic and 15 work folders and includes no provisions for deletion or removal of folders from the system. However, a folder can be rendered inactive, that is not recognized by DCAL2005.EXE, by padding the folder name such that its length is greater than 8 characters. If a folder is the default (active) folder do not attempt to delete it or alter its name.

DCAL's main menu is organized in two parts. The upper entries of the menu invoke the computational modules for calculation of dose and risk coefficients. The lower entries invoke various utilities and the batch computational facility. The calculations must be carried out in a particular order. As the calculations precede the DCAL menu will appear with the selection bar generally positioned at the next step in the calculations. For example, calculations of the dose coefficient for the inhalation of ^{60}Co in the workplace would proceed by first invoking ACTACAL, then SEECAL, then EPACAL. The results of the calculation could be summarized by invoking the HTAB utility and all files for this cased can be viewed by selecting LIST.

Note that as the menu select bar is moved by the up/down arrow keys, a one-line description of the menu item appears on the screen. More detailed information for each menu item is available by pressing <F1>. Table 4.1 lists each menu item with a brief discussion of its purpose. DCAL uses the up/down arrow key to move within menus. In the current version of DCALMENU the mouse is not used for such purposes and is not only operable within DCAL's utilities PLOTEM, LIST(PBVIEW), RADSUM, and CHAIN. See Chapter 12 for further information on DCAL's utility modules.

The line at the bottom of the main menu notes the assignment of the function keys, <F1> through <F11>. The default display covers <F1> through <F5> and the assignments for <F6> through <F11> can be seen by pressing the space bar. Table 4.2 explains the purpose of each of the function keys.

Table 4.1. Purposes of modules and utilities available in DCAL main menu.

Module or Utility	Purpose
1. ACTACAL	This is the starting point for all calculations involving the intake of a radionuclide. The module calculates activity as a function of time in body compartments following unit intake at an indicated age.
2. SEECAL	This computes the dose rates in the target tissues per unit activity residing in the source organs (SEE values) for the radionuclides identified by ACTACAL, for the commitment period. Calculations are for reference individuals of ages 0, 1-, 5-, 10-, 15-y, and adult, or ages selected by the user from this set.
3. EPACAL	This calculates the dose rates in the target organs based on the time-dependent activity in source organs generated by ACTACAL and the SEE values for the source-target pairs generated by SEECAL. The committed dose is computed as the time integral of the dose rate.
4. RISKCAL	This computes the health risk based on the absorbed dose rate files for the reference individuals, assuming an age-dependent intake function. External exposures are age-invariant.
5. EXTDOSE	This computes the external dose conversion coefficient for a user-provided radionuclide and environmental medium.
6. LIST	This utility is used to view output files in the indicated work folder.
7. PLOTEM	This provides a graphical display of the activity or dose rate data. The activity of each member of a decay chain is displayed.
8. HTAB	This generates a table of committed doses for the target organs for each reference individual considered in the calculation.
9. RADSUM	This utility summarizes the radiation emissions, specific activity, and gamma constant of a user-selected radionuclide. Radioactive progeny are identified with applicable branching fractions.
10 CHAIN	This utility displays the decay chain with the members' branching fractions and energies of emissions. Cumulative energies of alpha, electron, and photon emissions over a 100-year period are shown as a guide to truncation of the chain in dosimetric calculations if desired.
11. DBATCH	This is DCAL's batch computation facility.
12. HELP	This menu item provides the user with access to various data files and help files regarding the DCAL system.

Table 4.2. Purposes of the function keys of the DCAL main menu.

Key	Function
<F1>	This key provides a brief explanation of the highlighted menu item.
<F2>	This key shows the current (active) interactive case. Familiarity with the file-naming convention enables identification of the radionuclide, intake mode, dose type, and age. If ACTACAL is run with the desired dose type (absorbed or equivalent) not properly identified, the key combination Shift+F1 will toggle between the two dose types.
<F3>	This key enables the selection (or creation) of a biokinetic the folder containing the systemic biokinetic models.
<F4>	This key enables the selection (or creation) of a work folder for the output files generated by DCAL.
<F5>	This key provides the usual software "about" listing the individuals involved in the development of DCAL and its sponsor.
<F6>	This key invokes the ACTINT32.EXE utility to calculate the number of nuclear transformations of each member of the decay chain in the source organs during the 50-year period following a unit intake of the parent radionuclide.
<F7>	This key invokes the DRTINT32.EXE utility to integrate of the dose rate in each target organ over the time periods defined in the global DRTINT.INI file in the INI folder or the local DRTINT.INI in the work folder.
<F8>	This key invokes the BIOTAB32.EXE utility to tabulate the 24 hr urinary and fecal excretion and the retained activity in the body as a function of time.
<F9>	This key invokes the EXPORTM utility for the export of a DCAL output file (activity or dose) in a format suitable for import into a spread sheet program, e.g., Excel.
<F10>	This key invokes the DCALSYS utility to generate a table of DCAL's permanent data files currently on the computer.
<F11>	This key displays the pdf of this document. This function works only if files with the extension *pdf* are registered to be opened in Windows by a suitable reader.

5.0 INTERACTIVE IMPLEMENTATION OF DCAL

This section describes how to run DCAL using an existing library of biokinetic files, in the interactive mode. Later sections describe how to run DCAL in the batch mode and how to expand the library of systemic biokinetic models and f_1 values for elements by adding user-supplied files.

5.1 STEPS IN AN INTERACTIVE RUN OF DCAL

To initiate an interactive session, follow the three steps described below. After the third step has been completed, DCAL will invoke the ACTACAL module, which issues a series of prompts. At each prompt, a selection is made by pressing <Enter> for the default selection or typing in the selection (an identifying letter or number) and pressing <Enter>. The prompts will carry you through the end of the activity calculations, after which remaining steps in the dosimetric calculations are invoked from the DCAL main menu.

Step 1: To begin the session, click on the DCAL shortcut on the desktop.
The DCAL main menu will appear (Fig. 4.1). Menu item are selected by using the arrow keys to position the menu bar on the item and then pressing <Enter> or, when available, press the "hot key" indicated by a highlighted letter in the menu item.

Step 2: Determine that the folder containing the desired systemic biokinetic model and f_1 value is active. Methods for defining an alternate biokinetic model or f_1 value are described later.
In the bottom line of the DCAL main menu, the name of the active biokinetic folder appears after "<F3>=". There are two main biokinetic folders:

```
..\BIO\I68,
..\BIO\F13.
```

The folder I68 contains systemic biokinetic model files and f_1 files based on models and assumptions given in ICRP Publication 68 (1994b) on occupational exposure. The folder F13 contains systemic biokinetic model files and f_1 files used to generate the risk coefficients in *Federal Guidance Report 13* (EPA 1999). In addition, there is an initially empty biokinetic folder, \DCAL\DAT\BIO\USR, intended to contain user-constructed systemic biokinetic and f_1 files. To change the currently active biokinetic folder (i.e., to select the desired systemic biokinetic model and f_1 value), press <F3> and select the proper folder from the overlying menu that appears. Once the item is highlighted it is selected by pressing the <Enter> key.

The bottom line of the DCAL main menu also indicates the work folder that will receive DCAL output, after "<F4>=". To change the work folder, press <F4> and select from the choices given in the overlying menu that appears. Three work folders are initially created as an aid in organizing output if several cases are to be considered:

```
..\WRK\WORK
..\WRK\WORK2
..\WRK\FGR13.
```

After selection of the desired folder in the manner discussed above, the DCAL Main Menu becomes active.

Step 3: Select "Activity as f(t)" (activity as a function of time) on the DCAL main menu and press <Enter>.
This selection initiates an interactive session by invoking the module ACTACAL, which calculates the activity as a function of time in the compartments specified in the biokinetic data files, including the compartments of the gastrointestinal tract and, for inhalation intakes, the compartments of the respiratory tract. ACTACAL

performs the following functions: (1) it prompts you to describe the route of intake, the parent radionuclide, exposure mode, and, for the inhalation case, size and absorption type or solubility classification of inhaled particles; (2) it uses the biokinetic files to define the compartment model, establish the transfer rates between compartments, and define the source organs to be used in dose calculations; and (3) it calculates the activity of the parent and its radioactive progeny in each source organ as a function of time.

Where feasible, the prompts issued by ACTACAL provide various options given in parentheses and a default response given in square brackets. The default can be accepted by pressing <Enter>. A response other than the default must be typed and followed by <Enter>.

The first piece of information to be supplied is the parent radionuclide taken into the body. The request for a radionuclide follows a set of screen messages as shown below.

```
ACTACAL: Activity calculation
         Ver. 6.1 (Dec 22, 2003)
Authors: K.F. Eckerman & R.W. Leggett
         Oak Ridge National Laboratory
         Oak Ridge, TN 37831-6383

    Output Folder: ..\wrk\work2
Biokinetic Folder: ..\bio\i68

Input parent nuclide (e.g., Sr-90) ->
```

As described earlier, you may enter any of the 825 radionuclides considered in the preparation of ICRP Publication 30, plus 13 other radionuclides considered more recently considered by MIRD. You may also enter the symbol for a stable element (e.g., K or Ca) with no atomic weight. In this case, ACTACAL solves the biokinetic model for the element assuming no radioactive decay. ACTACAL will check that the entry is a valid radionuclide, i.e., that the nuclear decay data for the nuclide are contained in the files of the folder \DAT\NUC.

You are then asked if you want to perform calculations for a set of reference individuals specified in the file INTAKEXP.AGE.

```
Use the default age file; INTAKEXP.AGE:  ([y]/n)? y
```

The default ages at intake are defined in the data file INTAKEXP.AGE contained in the folder \DCAL\DAT\MIS. The file contains the six ages at intake considered in ICRP's series of documents on doses to the public from intake of radionuclides, i.e., infant (100 d), 1 y, 5 y, 10 y, 15 y, and adult. The adult is 20 y (7300 d) in most cases, but this depends on the biokinetic model. In biokinetic models in folder \DCAL\DAT\BIO\F13 that involve transfer rates based on bone turnover rates (models for Ca, Sr, Ba, Pb, Ra, Ac, Th, Pa, U, Np, Pu, Am, and Cm), mature adulthood is assumed to begin at age 25 y (9125d) because of substantial changes with age in bone turnover rates between ages 20 and 25 y.

If you select the default answer, [y] (yes), then separate calculations are performed for intake at each of the acute ages defined in the INTAKEXP.AGE file. If the answer to the above prompt is no, you are then prompted to specify the number of ages to be considered in the DCAL run. DCAL's modules can address 10 ages.

As indicated by the subsequent prompts for selected ages, the ages should be entered in days rather than years. You will be prompted for the next age until the indicated number of ages has been entered.

Input number of ages, < 11 ->

Enter age at exposure (integer format)

1 - age (d) ->

To avoid duplicate calculations, you should be familiar with the extent of age dependence, if any, considered in the biokinetic models and in SEE values used in the calculation. For example, suppose the calculation is for ingestion of ^{238}U and two ages are selected, 7300 d and 9125 d (20 y and 25 y, respectively). If the systemic biokinetic model selected is from the folder \BIO\I68, then the output will be identical for the two ages because the model for U in that folder includes parameter values only for the adult. If the systemic biokinetic model selected is from the folder \BIO\F13, then the output will be different for ages 20 y and 25 y because in this case the biokinetic parameter values are assumed to vary linearly with age until the adult age (in this case, 25 y) is reached. That is, the values for the 20 y old will be based on an interpolation of the biokinetic parameters assigned to the 15-y old (5475 d) and the 25-y old (9125 d).

Note that the age at intake is not restricted to the ages at which the biokinetic model is defined or to ages for which absorbed fraction data have been tabulated. DCAL derives data for ages other than those specified in the model by interpolation. Thus users can edit the INTAKEXP.AGE file in DCAL\DAT\MIS as needed.

The next inquiry concerns the dose quantity of interest.

Compute (a)bsorbed or (e)quivalent dose (a/[e])?

Equivalent doses are based on the radiation weighting factors currently recommended by the ICRP (1 for gamma, beta, or electron radiation, 20 for alpha radiation, and 5 for spontaneous fission neutrons). If risk coefficients are to be calculated, then absorbed dose quantity must be selected.

ACTACAL normally tabulates the activity as a function of time in source regions of the body. Depending on the biokinetic model, a source region may include multiple compartments. The next inquiry provides an option to generate a file detailing the activity in the various compartments in the biokinetic models.

Compute compartment & source region activity: ([n]/y)?

If the answer to this prompt is yes, ACTACAL will generate an additional file with extension CPT that lists the inventories of individual compartments in the biokinetic model, rather than simply the inventories of source regions used in subsequent dosimetric or risk calculations. This option is included to allow a detailed evaluation of ACTACAL's solution of the biokinetic model. For example, this option might be used to determine the cumulative urinary or fecal excretion predicted by the biokinetic model or to investigate the source of unexpected predictions of the biokinetic model.

The mode of intake is addressed in the next prompt.

Intake via: in(j)ection, in(h)alation, or in(g)estion: (j/h/[g])?

Injection refers to instantaneous entry of 1 Bq of the radionuclide into blood. Inhalation refers to instantaneous inhalation of 1 Bq of the radionuclide; only a portion of the inhaled activity will be deposited in the respiratory tract, with the shortfall being exhaled. Ingestion refers to instantaneous deposition of 1 Bq of the radionuclide in the stomach. If the selected intake mode is either injection or ingestion, no further information on the intake scenario is required, although prompts regarding other information will follow.

For inhalation intakes you are requested to select an absorption type for the aerosol as defined in the respiratory tract model (ICRP Publication 66, 1994a).

Lung absorption type: (f)ast, (m)oderate, or (s)low ([f]/m/s)?

After selecting an absorption type, you will also be asked to specify whether this is an environmental or occupational exposure. DCAL's default aerosol size is an activity median aerodynamic diameter (AMAD) of 1 µm for environmental exposures and an AMAD of 5 µm for consideration of occupational exposures in the absence of specific information about the physical characteristics of the aerosol.

Input AMAD; default is 1 µm ->

After the intake mode has been selected and, if applicable, any of the above follow-up questions concerning inhalation intakes have been answered, you are given the opportunity to enter additional documentation of the cases which will appear in the log file. After you enter the first line of text by pressing <Enter>, you are prompted for line 2 of text, and so forth, until you have entered the maximum number of lines or have pressed <Enter> after a blank line.

Input text information. Max. 9 lines, blank to terminate read.
1.

As discussed in Chapter 3, DCAL output files have standard names, all beginning with the name of the radionuclide. The LOG file generated for the ingestion of ^{90}Sr by the adult would be SR-90AG_.LOG, where A denoted adult, G denotes ingestion, and the underscore completes the eight-character root name for the file. If the standard output file names coincide with existing files in the active output folder, you will be warned and will be given the chance to change a character in the file names. For example,

File Sr90Ag_ exists!
[o]verwrite or [r]ename file ([o]/r)? o

If your response is to rename the output files, you are asked for a new last character.

New last character (e.g., z) ->

Next, you are shown two tables of information, based on data contained in the nuclear decay data index file in the folder \DCAL\DAT\NUC, concerning the radionuclide and any radioactive progeny. If both tables cannot be shown on a single screen, the first table is displayed and the system pauses until you press any key. The first table includes the radiological half-lives and branching fractions for the members of the chain. The second table includes the number of transformations over a 100-year period and the cumulative energies, separated by type

of radiation, over the same period. For example, the two tables for ^{90}Sr are as follows:

```
     Sr-90 Decay Chain: Half-lives and Branching Fractions
  Nuclide  Halflife    f1     Nuclide   f2    Nuclide   f3   Nuclide
  1 Sr-90   29.12y  1.0+00->  2 Y-90
  2 Y-90    64.0h

Sr-90: Activity, Transformations, & Cumulative Energies (MeV) at 100y
  Nuclide     T1/2     A(t)/Ao   intA/Ao(d)   Ealpha   Ebeta    Egamma
  1 Sr-90    29.12y  9.25216D-02 1.39249D+04 0.00E+00 2.73E+03 0.00E+00
  2 Y-90      64.0h  9.25448D-02 1.39246D+04 0.00E+00 1.57E+04 0.00E+00
```

The numerical values tabulated in the last three columns of the second table represent the cumulative energies emitted by alpha, beta (including discrete electrons), and photons (gamma and x-rays) for nuclear transformations occurring over 100 years in a sample consisting initially of 1 Bq of the parent. The columns in the second table labeled "A(t)/Ao" and "intA/Ao(d)" represent, respectively, the fractional activity present at 100 y and the fractional integrated activity (d) at 100 y.

These tables serve two main purposes. First, they remind you of the chain members whose biokinetics must be addressed in some manner, either explicitly through separate biokinetic files or implicitly through some blanket assumption (e.g., no translocation of decay products, or decay products inherit biokinetics of parent). Second, by showing cumulative energies associated with different segments of the chain, they help you determine whether the decay chain may be truncated without substantially affecting dose estimates. Although ACTACAL makes such a decision based on a virtual lack of increase in cumulative energy beyond some chain member, you may select a higher or lower cutoff point in the chain if you decide that is appropriate for the problem being addressed.

If radioactive progeny exist, you will be given different options concerning the biokinetics of chain members.

Biokinetics of Decay Chain Members

Options to address biokinetics of decay chain members:
1. Independent kinetics; user-predefined files.
2. Shared kinetics; ICRP-30 approach.

Item 1 is a valid option only if the necessary biokinetic files for all members of the decay chain exist within the active biokinetic folder selected at the beginning of the interactive session. ACTACAL searches the biokinetic folder for pre-defined files for all chain members before giving the above prompt. If such files are not available for all chain members, Option 1 is replaced with “Independent kinetics N/A; predefined files not found”, and only Items 2 and 3 are shown in the prompt.

The treatment of radioactive progeny in biokinetic and dosimetric calculations is addressed in detail in Section 9. Briefly, a standard approach has been to use the assumption of shared kinetics, i.e., to assume that the biokinetics of a decay chain member is the same as that of the radionuclide taken into the body (called the parent radionuclide). This approach was used in ICRP Publication 30, with the exceptions that noble gases produced *in vivo* and iodine produced *in vivo* from decay of tellurium isotopes were assigned kinetics independent of the parent. For most radionuclides, this assumption has been carried over to later ICRP publications and to *Federal Guidance Report 13* (EPA 1999). For isotopes of a few elements, including lead, radium, uranium, and thorium, it is assumed in recent ICRP publications and in *Federal Guidance Report 13* that decay chain members produced *in vivo* have “independent kinetics”. This means that a radionuclide born in soft tissues or on bone surfaces redistributes in a manner consistent with its own characteristic biokinetic model,

and, in effect, the rate of translocation of a radionuclide born in bone volume is determined by the rate of restructuring of bone.

If you select item 3 from the options concerning decay chain members, you will be further prompted, as indicated below.

```
Member-by-member default options:
        a. No biological translocation.
        b. Prompt removal from the body.
        c. Assign kinetics of first member.
Respond to member-by-member query.

[Name of chain member]: - Options: a, b, c - (a/b/[c])?
```

Item *a* assumes the chain member remains at the site of production. Item *b* is implemented by assuming a transfer rate of 1000 d^{-1} from the site of production to "Excreta". Item *c* differs from the assumptions of ICRP Publication 30 only in that noble gases and isotopes of iodine are not treated as exceptional cases.

After selections have been made concerning the systemic biokinetics of chain members, ACTACAL checks the biokinetic files for consistency regarding paths of movement of systemic activity. Two types of checks are made. First, if potential absorption or reabsorption of any chain member from the GI tract to blood is implied by the selected intake mode or the systemic biokinetic model, then ACTACAL checks whether the appropriate f_1 file exists in the active systemic biokinetic folder. Second, if the option of pre-defined kinetic models for different chain members has been selected, then ACTACAL checks for consistency in the systemic biokinetic files for different chain members. In particular, ACTACAL checks whether the file for each chain member describes outflow of activity from all compartments that receive any higher chain member.

If a required f_1 file is missing from the active systemic biokinetic folder, you will receive a prompt, as illustrated here for ^{239}Pu.

```
The f1 file for Pu-239 does not exist!
Do you want to create the file now (y/[n])?
```

If you choose the default, that is, not to create the f_1 file, ACTACAL will abort. If you choose to create an f_1 file, then ACTACAL provides a series of prompts, as illustrated here for ^{239}Pu.

```
Creating f1 file for Pu-239
Input number of ages ->
```

If a single f_1 value is to be applied to all ages, enter "1". If age-specific f_1 values are to be considered, values linearly interpolated by age will be applied by ACTACAL to intermediate ages. After you have entered the number of ages, you are asked to provide a descriptive title line for the f_1 file being created.

```
Input title line; < 73 characters  ->
```

Next, ACTACAL requests the age and f_1 value for each age group.

Enter age (integer) & f1 (real) separated by a space.
1 ->

After the age and f_1 value for that age have been entered, values for the next age are requested.

If there is a missing compartment in the systemic biokinetic file for some chain member, a prompt will appear (radionuclide and compartment name are illustrative).

No removal of Po-210 from compartment kidneys_2 is provided.
Options included:
a. No biological removal.
b. Prompt transfer to blood.
c. Abort and correct files.

Use: a. No removal, b. Prompt removal, c. Abort (a/[b]/c)?

After a selection is made, ACTACAL will continue to give similar prompts, one by one, until all missing transfers have been assigned values. The supplied transfers are not entered into the permanent DEF files but are used only in the present application. Therefore, it is usually best to abort and insert the missing transfers in the DEF files for future use rather than attempting to patch the problem interactively. However, it is useful to let ACTACAL identify all missing transfers before aborting. This is accomplished by making arbitrary selections at each prompt so that the next prompt will appear. If you are applying the library of models of ICRP Publication 68 (1994b) (folder \DCAL\DAT\BIO\I68) or *Federal Guidance Report 13* (folder \DCAL\DAT\BIO\F13) and are following the assumptions concerning chains of radionuclides described in those documents, then the problem of missing transfers should not arise.

If no inconsistencies of the types described above are found in the biokinetic files, then ACTACAL begins calculations of activity as a function of time after intake. As calculations start, ACTACAL writes brief credits to the screen, such as the version number of the code and the names of the authors. The screen will show that computations of time-dependent activity have begun and will continually show the progress made by giving the last time (i.e., days after intake) for which activities were output to the activities file (extension ACT). For example, when day 1000 has been reached in calculations for ingestion of ^{90}Sr by the adult (age 9125 d), the screen will show the following:

MAJOR PROGRAM LOOP: computations for age # 1 (9125 d)
Computations started; time post intake = 1000.00 d.

When calculations of activity are complete, a message similar to the following will appear on the screen (numbers and file name are illustrative):

Computations started; time post intake = 28000.00 d.
Attained age > 100 y; computations halted.
System of 34 simultaneous differential equations solved in 2.5 s.
Activities written to file Sr-90Ag_.ACT.

SEECAL request file written: Sr-90Ag_.req
Program ACTACAL ended normally.

The message concerning the "SEECAL request file" indicates that ACTACAL has created a file, to be read by the SEECAL module, listing the source and target regions that should be considered in the SEE calculations.

The message that the program has ended normally is followed by a DCAL prompt:

Press any key to continue . . .

When a key is pressed, the DCAL main menu will appear and the second menu item (SEECAL) will be highlighted:

SEE Calculations - SEECAL

If dose calculations are not desired, press <Esc>. You will be returned to the DOS prompt in the work folder. The generated activity file, whose name begins with the radionuclide and which has the extension ACT, can be found in that folder. If dose calculations are desired, press <Enter> to start SEE calculations by the module SEECAL. From this point forward you are not required to provide any additional information regarding dose or risk calculations, but you will be returned to the DCAL main menu at some stages in the calculations and given options concerning the type of further calculations to be performed.

As SEE calculations start, SEECAL writes brief credits to the screen, such as the version of the code and the names of the authors. Next, information on the radiation types associated with the parent radionuclide and decay chain members appears on the screen. The information is updated as the calculations progress. The case of ingestion of ^{90}Sr by the adult is used here to illustrate the messages written to the screen by SEECAL.

```
MAJOR PROGRAM LOOP: working on age # 1 (adult male) ...

   Reading photon SAFs for age = adult male ...
   Reading electron & alpha AFs for age = adult male ...
   Calculating SEEs for nuclide = Sr-90   ...
     for beta +/- particles (n=   1)
   Calculating SEEs for nuclide = Y-90    ...
     for photons < 10 keV   (n=  12)
     for photons >= 10 keV  (n=   8)
     for beta +/- particles (n=   2)
     for monoen. electrons  (n=  25)

 The following SEE files have been written:
 Sr90ht.SEE     Y90ht.SEE
```

If the decay mode of one of these radionuclides includes spontaneous fission, you will be warned if the version of SEECAL does not handle radiations from spontaneous fissions and that such radiations will be ignored. Information concerning the frequency and energy of different spontaneous fission radiation types is also written to the screen.

The message that the program has ended normally is followed by a DCAL prompt:

```
Press any key to continue . . .
```

When a key is pressed, the DCAL main menu will appear with the third item on the menu (EPACAL) highlighted:

```
        Compute Dose      - EPACAL
```

Press <Enter> to begin dose calculations. The principal task of the EPACAL module is to combine the time- and age-specific activities calculated by ACTACAL with the age-specific SEE values calculated by SEECAL to calculate dose rates to target organs. EPACAL output is in the form of absorbed dose rate or equivalent dose rate calculations, depending on whether you selected "absorbed dose" or "equivalent dose", respectively, early in the interactive session. If "equivalent dose" was selected, the SEEs computed in a preceding step will include radiation weighting factors for different radiation types. EPACAL output can be found in the active output folder. The name of the output file will begin with the parent radionuclide and will have extension DRT if absorbed dose was selected and HRT if equivalent dose was selected.

As EPACAL calculations start, EPACAL writes brief credits to the screen, such as the name and version of the code and the authors. Next, information on the radiation types associated with the parent radionuclide and decay chain members appears on the screen and is updated as progress is made by EPACAL. Also, some warnings may be given to alert the reader to certain conventions or assumptions used in the calculation. In the following, the case of ingestion of ^{90}Sr by the adult is used to illustrate the messages written to the screen by

```
Headers in all SEE files matched OK.
 Source organ names in activity & SEE files matched OK
 Youngest age for SEE values to be read is: 7300 days (adult male)
 MAJOR PROGRAM LOOP: working on activity file #  1 (Sr-90Ag_.act) ...

    Reading SEE file for iNuc = 1 (Sr-90) ...
    Reading activity file for iNuc = 1 ...
    Calculating dose rates for iNuc = 1 ...
```

EPACAL. It is assumed here that you have elected to compute equivalent dose rather than absorbed dose.

The above three lines are repeated for ^{90}Y, iNuc=2, and concluded with

```
   Writing dose rates to dose rate file # 1 (SR-90AG_.HRT) ...

The following dose rate files have been written:
SR-90AG_.HRT

Program EPACAL ended normally.
```

The message that the program has ended normally is followed by a DCAL prompt:

```
Press any key to continue . . .
```

When a key is pressed, the DCAL main menu will appear. The fourth item on the menu will be highlighted:

```
      Compute Risk      - RISKCAL
```

If the absorbed dose option was selected earlier, a table of risk estimates may be calculated (by the RISKCAL module) by pressing <Enter>. The screen will show brief credits for RISKCAL, followed by the message:

```
      Input data files were successfully read.
```

As RISKCAL goes through organ-by-organ calculations of cancer risk from the specified intake, the screen will show the current stage of the calculation. For example:

```
      Computing risks for cancer: esophagus
```

After all risk calculations are complete, you will see a message similar to the following:

```
      File: SR-90AG_.RBS written successfully.
      RISKCAL terminated normally.
```

In addition to the indicated file with extension RBS, a file with the same stem and extension RSK has been written to the active work folder. The file with extension RBS contains age- and gender-specific and total estimates of radiogenic mortality and morbidity by cancer site. The file with extension RSK records the risk of cancer.

The messages indicating completion of risk calculations are followed by a DCAL Prompt:

```
      Press key to continue...
```

When a key is pressed, the DCAL menu will appear. The first item under “UTILITIES” will be highlighted: The utility LIST is included as a convenient way of examining DCAL output files written into the work folder.

```
      DCAL Work Files   - LIST
```

If you press <Enter>, a list of files in the active work folder will be shown. The mouse or arrow key can be used to move to the file of interest. Pressing <Enter> will reveal the file contents. Arrow keys can then be used to scroll or to move to the right to view any portion of the file. Pressing <Esc> twice will return you to the DCAL folder in the DOS path environment. See Section 12.1 for further options regarding the LIST utility.

If you selected the equivalent dose option earlier and want to calculate dose coefficients, move the menu bar to the third entry in the utility section of the menu:

Tabulate Dose Coeff- HTAB

Then press <Enter> to generate a concise table of "dose coefficients", similar in form to the tables provided in the ICRP's series of documents on doses to the public from intake of radionuclides (ICRP 1989, 1993, 1995a, 1995b, 1996). The table can be found in the active output folder and will have a name beginning with the parent radionuclide and with extension HEF. For each intake age considered, the table provides a list of committed doses, or committed equivalent doses, to each organ given in the standard list of target organs. The committed dose values are based on an integration period of 50 y for intake by adults and integration from time of intake to age 70 y for intake by children. The table will also include an effective dose for each age group. The effective dose takes into account that the relationship between equivalent dose and the probability of radiogenic effects depends on the organ or tissue irradiated. The effective dose is a weighted sum of equivalent doses to radiosensitive tissues, with the tissue weighting factor representing the relative contribution of that tissue to the total detriment for the case of uniform irradiation of the whole body. Tissue weighting factors used in DCAL are those recommended in ICRP Publication 60 (1991). If the "absorbed dose" option is selected and the parent radionuclide or some chain member emits high-LET radiations, the calculated effective dose will not be meaningful because the radiation weighting factors for high-LET radiations were not considered in the calculation of SEE values.

If you select the HTAB utility, a message similar to the following appears on the screen. The case of ingestion of ^{90}Sr by the adult is used here for illustrative purposes (see listing in Fig 5.1).

Tabulate Age-Dependent Dose Coefficients

Working on file SR-90Ag_.HRT...
Working on file SR-90 Bg_.HRT...
Working on file SR-90 Cg_.HRT...
Working on file SR-90 Dg_.HRT...
Working on file SR-90 Eg_.HRT...
Working on file SR-90 Fg_.HRT...

The file SR-90Ag_.HEF has been written.

Press any key to return to DCAL menu.

When a key is pressed, the DCAL main menu will appear. Again, the first item in the utility section of the menu will be highlighted:

DCAL Work Files - LIST

5.2 ACTACAL AND SEECAL INI FILES

In addition to their normal role, the INI files for ACTACAL and SEECAL each direct an aspect of their module's computations. The last entry of ACTACAL.INI is

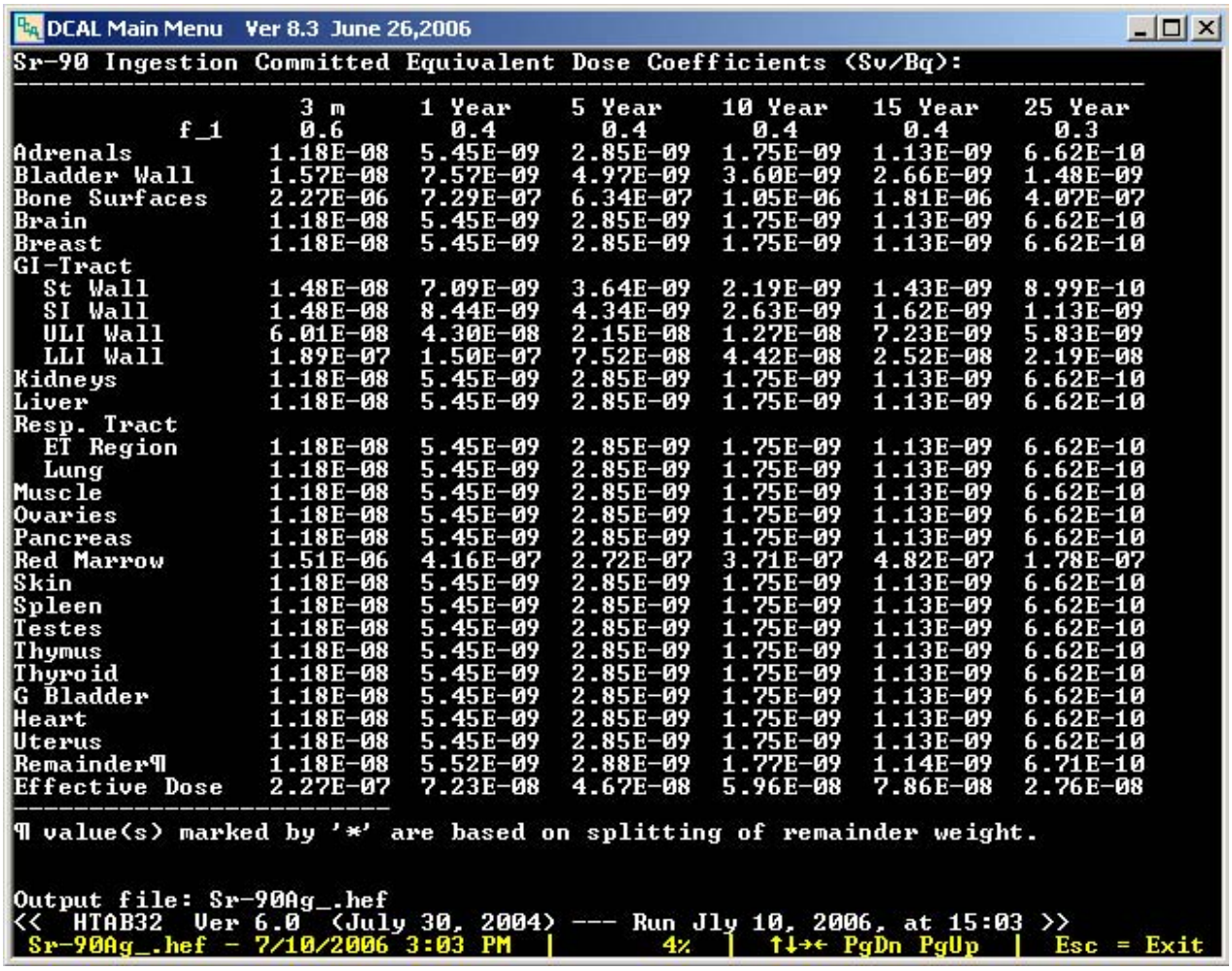
```
'ThalfDays'   , '1.0'                          , 0   Short Halflife
```

This line controls how ACTACAL handles short-lived radionuclides. For these radionuclides, no changes with age occur in the biokinetic or in organ sizes, so that the time-dependent details of the dose calculation are of little interest. ACTACAL acts on the above entry by scanning the decay chain to determine if the half-life of any member exceeds 1.0 d. If no such members are found, then ACTACAL will calculate the number of nuclear transformations (integral of the activity) in the source regions rather than activity as a function of time. EPACAL, when seeing only one datum per source organ, assumes the entries are the number of nuclear transformations. Similarly, RISKCAL assumes that the dose is delivered instantaneously as if it were external irradiation.

The last entry in the SEECAL.INI file is

```
'gamdos',       'linear',                      0 Interpolation scheme
```

This line defines the nature of the scheme by which the photons SAFs, as a function of energy, are interpolated in the calculations. The SAF library includes photon SAFs for each source-target pair for 12 monoenergetic photon sources. The above entry invokes linear interpolation in computing the contribution of the photon emissions of the radionuclide to the SEE value for the source-target pair. Linear interpolation in energy has historically been applied to the photon SAF data and continues to be used. SEECAL provides a log-log interpolation scheme using spline routines. To use this scheme, the entry for the second file is "pchip loglog". SEECAL will issue an error message if a proper interpolation scheme is not indicated in its INI file.



DCAL Main Menu Ver 8.3 June 26,2006

Sr-90 Ingestion Committed Equivalent Dose Coefficients (Sv/Bq):

	3 m	1 Year	5 Year	10 Year	15 Year	25 Year
f_1	0.6	0.4	0.4	0.4	0.4	0.3
Adrenals	1.18E-08	5.45E-09	2.85E-09	1.75E-09	1.13E-09	6.62E-10
Bladder Wall	1.57E-08	7.57E-09	4.97E-09	3.60E-09	2.66E-09	1.48E-09
Bone Surfaces	2.27E-06	7.29E-07	6.34E-07	1.05E-06	1.81E-06	4.07E-07
Brain	1.18E-08	5.45E-09	2.85E-09	1.75E-09	1.13E-09	6.62E-10
Breast	1.18E-08	5.45E-09	2.85E-09	1.75E-09	1.13E-09	6.62E-10
GI-Tract						
St Wall	1.48E-08	7.09E-09	3.64E-09	2.19E-09	1.43E-09	8.99E-10
SI Wall	1.48E-08	8.44E-09	4.34E-09	2.63E-09	1.62E-09	1.13E-09
ULI Wall	6.01E-08	4.30E-08	2.15E-08	1.27E-08	7.23E-09	5.83E-09
LLI Wall	1.89E-07	1.50E-07	7.52E-08	4.42E-08	2.52E-08	2.19E-08
Kidneys	1.18E-08	5.45E-09	2.85E-09	1.75E-09	1.13E-09	6.62E-10
Liver	1.18E-08	5.45E-09	2.85E-09	1.75E-09	1.13E-09	6.62E-10
Resp. Tract						
ET Region	1.18E-08	5.45E-09	2.85E-09	1.75E-09	1.13E-09	6.62E-10
Lung	1.18E-08	5.45E-09	2.85E-09	1.75E-09	1.13E-09	6.62E-10
Muscle	1.18E-08	5.45E-09	2.85E-09	1.75E-09	1.13E-09	6.62E-10
Ovaries	1.18E-08	5.45E-09	2.85E-09	1.75E-09	1.13E-09	6.62E-10
Pancreas	1.18E-08	5.45E-09	2.85E-09	1.75E-09	1.13E-09	6.62E-10
Red Marrow	1.51E-06	4.16E-07	2.72E-07	3.71E-07	4.82E-07	1.78E-07
Skin	1.18E-08	5.45E-09	2.85E-09	1.75E-09	1.13E-09	6.62E-10
Spleen	1.18E-08	5.45E-09	2.85E-09	1.75E-09	1.13E-09	6.62E-10
Testes	1.18E-08	5.45E-09	2.85E-09	1.75E-09	1.13E-09	6.62E-10
Thymus	1.18E-08	5.45E-09	2.85E-09	1.75E-09	1.13E-09	6.62E-10
Thyroid	1.18E-08	5.45E-09	2.85E-09	1.75E-09	1.13E-09	6.62E-10
U Bladder	1.18E-08	5.45E-09	2.85E-09	1.75E-09	1.13E-09	6.62E-10
Heart	1.18E-08	5.45E-09	2.85E-09	1.75E-09	1.13E-09	6.62E-10
Uterus	1.18E-08	5.45E-09	2.85E-09	1.75E-09	1.13E-09	6.62E-10
Remainder¶	1.18E-08	5.52E-09	2.88E-09	1.77E-09	1.14E-09	6.71E-10
Effective Dose	2.27E-07	7.23E-08	4.67E-08	5.96E-08	7.86E-08	2.76E-08

¶ value(s) marked by '*' are based on splitting of remainder weight.

Output file: Sr-90Ag_.hef

<< HTAB32 Ver 6.0 (July 30, 2004) --- Run Jly 10, 2006, at 15:03 >>

Sr-90Ag_.hef - 7/10/2006 3:03 PM | 4% | ↑↓→← PgDn PgUp | Esc = Exit

Fig. 5.1. Listing of HEF file of age-specific equivalent dose coefficients for ingestion of Sr-90.

5.3 INTERACTIVE HOUSEKEEPING PROCEDURE

During the course of an interactive session DCAL's ACTACAL module creates several files specific to the current case. This include a log file (*.LOG) containing information from all the computational modules, the REQ file by which ACTACAL communicates with SEECAL, and SEECAL's SEE files for the case. These files should be reviewed by the user; particularly when implementing new biokinetic data or when a computational problem is indicated. All files specific to the current interactive case are available for viewing using the LIST menu item. However upon the next issuance of ACTACAL the LOG, REQ, and SEE files of the previous case are deleted. This procedure provides a bit of housekeeping to limit the accumulation of files.

An annotated set of files created in the interactive calculation of the ^{106}Ru inhalation dose coefficient for workers can be found in Appendix A.

6.0 DCAL's BATCH MODE FACILITY

This section discusses the batch mode of operation of DCAL. This mode of operation can be used to process a user-defined set of nuclides for calculation of dose and risk.

Recall that in the interactive mode, the DCAL modules are driven by selections of operations from the DCAL main menu. All input comprising a DCAL run is assembled by the module ACTACAL and then passed to subsequent modules, either within specific input files accessed by the module or through a file named $StemNam.Dir. Several intermediate files written during the course of DCAL's calculations are saved for the purpose of quality assurance of DCAL output.

The batch mode of operation is provided for "production-type" calculations. In the batch mode, the sequence in which the computational modules are invoked and their input data are defined in a user-supplied input file. The input file also identifies the intermediate data files written during the course of DCAL's calculations that are to be deleted after cycling through the sequence of computational modules. This "house-keeping" option is provided because the total required storage space for these relatively large intermediate data files may not be available if a large number of cases are considered in a batch run. The user should run an input file with a small number of cases to ensure that the "house-keeping" is proper.

The following steps are required for a batch run of DCAL:

1. Using an editor (e.g., Windows NOTEPAD) create a batch input file with extension INP in the work folder of choice. This file can be constructed by editing the file EXAMPLE.INP provided in the work folder work2.

2. Click on the DCAL icon on the desktop to obtain the DCAL main menu. Determine whether the work folder indicated on the bottom line of the screen is the desired folder. If not, press <F4> and select the appropriate folder.

3. Select "DBATCH" from the menu or press <B>. A list of batch input files (extension INP) in the active work folder will appear. Select the appropriate batch input file using the arrow keys. Press <enter>. The calculations will then begin. When the calculations are complete the following message will appear:

```
Batch calculations are complete.
Press any key to return to menu.
```

The output of the batch run will be found in the work folder in which the batch input file resides (see Step 2). The output files use the root name of the batch input file (e.g., EXAMPLE) and include the log file (extension OUT). Output dose files will have extension GDB, HDB, or JDB, where the first letter G, H, or J represents ingestion, inhalation, or injection, respectively. If you choose to calculate risk coefficients, then risk files with extensions RBS and TAB will be generated. The file with extension RBS contains age- and gender-specific and total estimates of radiogenic mortality and morbidity by cancer site. The file with extension TAB contains summary risk estimates for the population in the form of a mortality risk coefficient and a morbidity risk coefficient for all radiogenic cancers combined. Files with these extensions should not be deleted during the course of the calculations. An example batch input file is shown in Fig. 6.1.

```
DCAL example batch input file for inhalation.
******* nn S ffffffff ffffffff aaaa  t 1.0E-02  ffffffff <-- Comments >
BATCH CODES                           <- List of codes to run in batch
ACTACAL.EXE
SEECAL.EXE
EPACAL.EXE
RISKCAL.EXE
END CODES                             <- End of listing of codes
DELETE CASE FILES                     <- List of case files to deleted
*.SEE
*.REQ
*.LOG
*.ACT
*.HRT
*.DRT
END DELETE                            <- End of case files to deleted.
GLOBAL INPUT                          <- Start of global input for cases
Dose_Type             Absorbed_Dose
Intake_Route          Inhalation
Exposure_Type         Environmental
Default_Amad          1.0
#_Ages_at_intake      6
100 365 1825 3650 5475 7300
END GLOBAL INPUT                      <- End of global case input
CASE INPUT DATA                       <- Start of case data
H-3          H_H2O                  V          H2OVapor
H-3          H_H2O                  G          HGas
Be-7                                F 1.0
Be-10                               F 1.0
C-14         C_Org                  F 1.0
C-14         C_CO2                  G          CO2GAS
Na-22                               F
Mg-28                               M
P-32                                F
S-35         S_Inorg                F
S-35         S_Inorg                V          SO2Gas
S-35         S_Org                  V          CS2Gas
END CASE DATA                         <- End of case data
Format information:
******* nn S ffffffff ffffffff aaaa  t 1.0E-02  ffffffff <-- Comments >
   |    |  |   |        |       |    |   |        |__ lung file
   |    |  |   |        |       |    |   |___ AMAD (micron)
   |    |  |   |        |       |    |___ absorption type
   |    |  |   |        |       |__ adult age <> global value
   |    |  |   |        |___ special f1 file
   |    |  |   |___ special biokinetic file
   |    |  |___ (S)hared or (I)ndependent kinetics, default S
   |    |__ index of last chain member, default by ACTACAL's procedure
   |    nuclide
```

Fig. 6.1. Illustration of a DCAL batch input file. The user may create a batch file by editing this file (found in the work2 folder). This is an example DCAL batch input file for inhalation cases.

In the sample input file shown in Fig. 6.1, the first line is a general description of the file:

```
DCAL example batch input file for inhalation.
```

The next line shows the structure of the nuclide-specific data given later in the file under "CASE INPUT DATA":

```
******* nn S ffffffff ffffffff aaaa  t 1.0E-02  ffffffff <-- Comments >
```

The structure (data format) is defined at the end of the sample input file.

Between the delimiters BATCH CODES and END CODES, the user lists the computational modules (codes) to be run in the batch mode. Available modules are summarized in Section 3. If only activity calculations are needed, list only the file ACTACAL.EXE. If absorbed dose or equivalent dose estimates are needed, list ACTACAL.EXE, SEECAL.EXE, and EPACAL.EXE; the choice of absorbed dose or equivalent dose is specified later in the input stream. To calculate risk coefficients, list those three files and also RISKCAL.EXE (as shown below), and later in the input stream choose the absorbed dose option. For each case input defined under CASE INPUT DATA, the specified sequence of computational modules will be executed.

```
BATCH CODES                              <- List of codes to run in batch
ACTACAL.EXE
SEECAL.EXE
EPACAL.EXE
RISKCAL.EXE
END CODES                                <- End of listing of codes
```

Next, between the delimiters DELETE CASE FILES and END DELETE, list the extensions of the files generated by the sequence of computational modules (codes) that you do not want to retain. The output files that will be generated depend on the codes selected in the previous step. DCAL output files are described in Section 3. The inclusion of an extension for a file that was not generated does not result in an error.

```
DELETE CASE FILES                       <- List of case files to deleted
*.SEE
*.REQ
*.LOG
*.ACT
*.HRT
*.DRT
END DELETE                              <- End of case files to deleted.
```

The remaining portion of the input file consists of two data blocks, the "global" data block and the case-specific data block. The global data block is bounded by the delimiters GLOBAL INPUT and END GLOBAL INPUT. The statements must appear in the order shown. The global block indicates:

- the type of dose to be computed (Equivalent_Dose or Absorbed_Dose);
- the intake route;
- for inhalation, the type of exposure (environmental or occupational);
- for inhalation, the default particle size (AMAD);
- the number of ages at intake to be considered;
- a list of the ages to be considered.

The case-specific input data are bounded by the delimiters CASE INPUT DATA and END CASE DATA. The format of the case input records is given at the top of the file and again near the bottom of the file, and is explained at the bottom of the file. Case-specific input consists of the following:

- the name of the radionuclide;
- the length of the decay chain to be considered (if not provided, ACTACAL will decide);
- the assumption concerning the biokinetics of decay chain members (S for shared kinetics and I for independent kinetics; if not provided, shared kinetics is assumed);
- the name of the radionuclide's biokinetic file (required only if a file different from the file X.DEF or XX.DEF is to be used, where X or XX is the symbol for the element);
- the name of the radionuclide's f_1 file (required only if a file different from the file X.GF1 or XX.GF1 is to be used, where X or XX is the symbol for the element);
- the intake age of the adult if different from the global value;
- if intake is by inhalation, the behavior of the aerosol (absorption type);
- if intake is by inhalation, the type of exposure (occupational or environmental) and AMAD must be indicated if different from the global value;
- if intake is by inhalation and special assumptions are to be made regarding the respiratory kinetics of a radionuclide, the name of the lung file describing the special kinetics.

If DCAL encounters a problem in the batch input data file, the calculations for that case are terminated and the next case is considered. The batch log file (extension OUT) should be consulted regarding possible aborted cases. Limited information is available in the batch mode to diagnose the cause of an aborted case. Attempting to process the aborted case in the interactive mode may reveal the problem.

The use of the INI files of the computational modules, located in the INI folder, in the batch mode is the same as in the interactive mode. That is, if the INI file is present in the folder with the batch file (the *.INP file) being processed, that local INI file is used rather than the global file in the INI folder.

An annotated set of files created during batch the calculation of age-specific dose and risk coefficients can be found in Appendix B

7.0 CREATING ADDITIONAL BIOKINETIC FILES

You can form your own biokinetic library by copying or creating systemic biokinetic files (file extension name DEF) and f_1 files (file extension name GF1) and adding them to a biokinetic folder that you have created or to the folder \DCAL\DAT\BIO\USR created during installation of DCAL. The purpose of this Section is to describe the form and content of the DEF and GF1 files.

7.1 FORM OF A DEF FILE DESCRIBING A SYSTEMIC BIOKINETIC MODEL

DCAL requires that the kinetics of materials in the body be described in terms of compartment models with first-order transfers between compartments. Transfer coefficients of a model are allowed to vary with age. Transfer coefficients are specified in the DEF file for up to 10 selected ages, and DCAL interpolates linearly with age to derive age-specific coefficients for intermediate ages. Coefficients for the lowest selected age are assigned to lower ages, and coefficients for the highest selected age are assigned to higher ages.

A DEF file describes a systemic biokinetic model for an element, representing either a parent radionuclide or a subsequent decay chain member. As an illustration, the DEF file corresponding to the ICRP's systemic biokinetic model for iodine in the worker (ICRP Publication 68, 1994b) is given below. As in all of DCAL's DEF files, the transfer coefficients are in units of d^{-1}.

```
File I.DEF, iodine biokinetics, ICRP Pub. 68
  1 : Number of age groups
*****************************************
File checked or updated by KFE, 5/2/2006.
Iodine kinetics
 7300 Adult
Blood     ->Thyroid    8.3178E-01
Blood     ->UB_Cont    1.9408E+00
Thyroid   ->Other      8.6643E-03
Other     ->Blood      4.6210E-02
Other     ->ULI_Cont   1.1552E-02
EOF Data
Notes:
UB_Cont is urinary bladder contents
ULI_Cont is upper large intestine contents
```

This biokinetic file for iodine consists of the following:

Line 1: Title or description of file.

Line 2, format (I4): Number of age groups, i.e., ages at which transfer coefficients are specified.

Lines 3-5: Additional text, intended to allow more extensive description or documentation of the file.

Next N lines, N < 11, format (I5,1x,A8): The N selected ages (in days) in increasing order, and (optional) descriptive names for these age groups at which the biokinetics will be specified. For example, if ages 100 and 7300 d are selected and the descriptive names are "3-mo-old" and "Adult", respectively, the next two lines would read:

```
  100 3-mo-old
 7300 Adult
```

Remaining data lines, format (A10,2x,A10,10(1PE11.4)): Complete set of systemic transfer coefficients between compartments of model consisting of name of donor compartment X, name of receptor compartment Y, and N transfer coefficients (units of d^{-1}) from X to Y for N selected age groups in order of increasing age.

Last required line, format (A10): Consists of "EOF Data", to denote that the data have been completely specified. Notes may be added after this line, as indicated in the example.

Another sample DEF file, this one with age-dependent transfer coefficients, is shown below. This file shows the age-specific biokinetic model for iodine used in the ICRP's series of documents on doses to members of the public from intake of radionuclides (ICRP 1989, 1993, 1995b, 1996). With regard to the adult, this DEF file is identical to the previous file representing the systemic biokinetics of iodine in the worker.

```
File I.DEF, age-specific biokinetics of iodine, ICRP Pubs 56, 67, 71, 72
  6 : Number of age groups
*************************************
File checked or updated by KFE, 8/13/95.
Iodine kinetics
  100 3 mo-old
  365 1 y-old
 1825 5 y-old
 3650 10 y-old
 5475 15 y-old
 7300 Adult
Blood     ->Thyroid  8.3178E-01 8.3178E-01 8.3178E-01 8.3178E-01 8.3178E-01 8.3178E-01
Blood     ->UB_Cont  1.9408E+00 1.9408E+00 1.9408E+00 1.9408E+00 1.9408E+00 1.9408E+00
Thyroid   ->Other    6.1888E-02 4.6210E-02 3.0137E-02 1.1951E-02 1.0345E-02 8.6643E-03
Other     ->Blood    4.9511E-01 3.6968E-01 2.4109E-01 9.5606E-02 8.2764E-02 4.6210E-02
Other     ->LI_Cont  1.2378E-01 9.2420E-02 6.0274E-02 2.3902E-02 2.0691E-02 1.1552E-02
EOF Data
Notes:
UB_Cont is urinary bladder contents
ULI_Cont is upper large intestine contents
```

In the DEF files, the names of donor and receptor compartments must correspond to DCAL-standardized names of anatomical regions of the body representing source regions in dosimetric calculations. The naming convention used in DCAL for source regions and compartments of biokinetic models is described in Section 3, and standard names of source regions are listed in Table 3.1 of that chapter. Briefly, in order for DCAL to relate the biokinetic compartments to standard source regions used in radiation dosimetry, the name of a compartment of a biokinetic model must be an extension of the standard name of a source region. For example, if the liver is an explicitly defined source region in a systemic biokinetic model, then DCAL assigns the activity in compartments beginning with the name "Liver" to the source region Liver. The name of a compartment within the liver could be "Liver" or could be of the form "Liver_X", where the symbol "_X" represents a subscript and X can be any number or letter. The underscore character is required to identify a subscript. See Section 3.5 for additional discussion. Up to 15 compartments are allowed for a given source region.

7.2 SPECIAL CONSIDERATIONS FOR NAMING COMPARTMENTS USED TO DESCRIBE CIRCULATION OR EXCRETION OF MATERIAL

A compartment within blood must be of the form "Blood" or "Blood_X". At least one "Blood" compartment must be included in the data files describing the kinetics of the systemic materials.

Material that leaves the systemic circulation via urinary excretion should be transferred to the compartment named "UB_Cont" if a dose estimate for the urinary bladder (UB) is to be developed. Similarly, systemic

material lost through fecal excretion should be transferred to either the "SI_Cont" or "ULI_Cont" compartment of the gastrointestinal tract. Part of any material routed through "SI_Cont" will be lost through fecal excretion at a rate indicated by the gastrointestinal tract model of ICRP Publication 30 (1979), but a fraction (f_1) will be absorbed back into the systemic circulation. Reabsorption of material to blood can be avoided by routing the fraction of outflow from blood intended for fecal excretion directly into the "ULI_Cont" compartment.

If the biokinetic model indicates that material is lost from the systemic circulation by an unspecified excretion route, or if the specified route of excretion is not used in dosimetric calculations (e.g., hair or sweat), then the transfer should be specified to a compartment labeled "Excreta". The compartments "Excreta", "Urine", and "Feces" exist outside the body and do not enter into dosimetric calculations. The "Urine" and "Feces" compartments are reached by material that has first been transferred to compartments representing the urinary bladder contents or contents of the intestines.

7.3 FORM OF A GF1 FILE DESCRIBING FRACTIONAL UPTAKE FROM THE GASTROINTESTINAL TRACT

Absorption of material from the gastrointestinal tract to blood is represented as occurring in the small intestine. Fractional absorption from the small intestine to blood is described by an f_1 value. A file with extension GF1 is a list of age-specific f_1 values and the corresponding ages, in days. As is the case for transfer coefficients, f_1 values for intermediate ages are determined in DCAL by linear interpolation.

A GF1 file for an element consists of the following:

Line 1: Title or description of file.

Line 2, format (I4): Number of age groups, i.e., ages at which transfer coefficients are specified.

Lines 3-5: Additional text, intended to allow more extensive description or documentation of the file.

Each of next N lines, N < 11, format - free form: N age-specific f_1 values and corresponding age groups. Each line contains an f_1 value and the corresponding age group (in days), separated by space or comma.

Three sample GF1 files are shown below. The first sample file gives the ICRP's f_1 value for iodine in adults. The second sample file specifies the same f_1 value but at age 100 d, indicating that this value is applied to all age groups starting at 100 d. The third sample file gives the age-specific f_1 values for Sr specified in ICRP Publication 67 (1993), i.e., 0.6 in the infant (100 d), 0.4 at age 365 d (1 y), 0.4 at age 5475 d (15 y), and 0.3 for age 9125 d (definition of adulthood for strontium biokinetics) and higher.

```
File I.gf1, GI uptake of iodine by a worker (ICRP Pub. 68)
   1 : Number of age groups
****************************************
File checked and/or updated by KFE, 5/2/2006.
Age-specific f1 values for ingested or inhaled (Type F) iodine.
1.0     7300
```

```
File I.gf1, age-specific GI uptake of iodine (ICRP Pubs. 56, 67)
1 : Number of age groups
****************************************
File checked and/or updated by KFE, 5/2/2006.
Age-specific f1 values for ingested or inhaled (Type F) iodine.
1.0     100
```

```
File Sr.gf1, age-specific GI uptake of strontium (ICRP Pub. 67)
   4 : Number of age groups
****************************************
File checked and/or updated by KFE, 5/2/2006.
Age-specific f1 values for ingested or inhaled (Type F) strontium.
0.6    100
```

The f_1 values are implemented in DCAL in terms of a transfer coefficient from the small intestine (SI) contents to blood. This coefficient is set to give the proper fractional transfer from SI contents to blood, considering that this transfer is in competition with transfer at a rate of 6 d^{-1} from SI contents to upper large intestine contents. The transfer coefficient from SI contents to blood is interpolated linearly with age to account for changes with age in f_1 values. With regard to f_1 values given in the sample file for Sr, the transfer coefficient from SI contents to blood would remain constant between ages 365 d and 5475 d because the f_1 value is 0.4 at each end of this age interval; however, this transfer coefficient would decrease with age between ages 5475 d and 9125 d because the f_1 value decreases from 0.4 at age 5475 d to 0.3 at age 9125 d. The f_1 value 0.3 for Sr assigned to age 9125 d applies to all higher ages, so that the transfer coefficient describing the rate of movement of Sr from SI contents to blood would not change after age 9125 d.

7.4 CREATING DEF or GF1 FILES BY COPYING AND EDITING AN EXISTING FILE

The folders \DCAL\DAT\BIO\F13 and \DCAL\DAT\BIO\I68 contain files representing systemic biokinetic models (extension DEF) or f_1 values (extension GF1). The easiest method of creating a new DEF or GF1 file usually is to locate, copy, and edit a similar file found in one of these two folders. The copied and edited file should be saved in a biokinetic folder other than \DCAL\DAT\BIO\F13 or \DCAL\DAT\BIO\I68, i.e., either in the folder \DCAL\DAT\BIO\USR created when DCAL is installed, or in a biokinetic folder that you have created.

As an illustration, suppose you want to estimate thyroid dose from ingestion of ^{131}I by an adult based on a biological half-time in the thyroid that is half as large as that assumed by the ICRP. An easy way to do this is to copy the file I.DEF in \DCAL\DAT\BIO\I68 (the first sample file shown in this section) to a selected biokinetic folder and modify the transfer coefficient in the following line:

```
                    Thyroid   ->Other      8.6643E-03
```

The transfer coefficient 8.6643E-03 (d^{-1}) used in ICRP Publication 68 corresponds to a biological half-time of 80 d, i.e., ln(2)/(80 d) = 8.6643 d^{-1}. Replace 8.6643E-03 with the value 1.7328E-02 d^{-1} (= ln(2)/40 d), save the edited file as I.DEF in the selected folder, and run DCAL with that folder selected as the active biokinetic folder to get dose estimates for ingested ^{131}I in the adult based on a 40-d biological half-time in thyroid.

8.0 THE METHOD USED BY ACTACAL TO SOLVE BIOKINETIC MODELS

8.1 BACKGROUND

Many of the biokinetic models for radionuclides currently used by the ICRP depict continual redistribution of activity among a large number of compartments at rates that vary with age. Some applications of these models give rise to large and complicated systems of differential equations representing the time-dependent activity in different organs of the body. This is particularly true when these models are used in conjunction with the assumption of independent kinetics of radioactive progeny. As one example, application of the ICRP's current models and assumptions (ICRP, 1994a, 1995a) to the case of inhalation of ^{232}Th by a child requires solution of a first-order model involving about 400 compartments, feedback of activity between compartments, and transfer coefficients that vary with age and hence time. The large number of compartments stems from the fact that each compartment of the ICRP's respiratory tract model (with numerous compartments), gastrointestinal (GI) tract model, and systemic biokinetic model for thorium (also having several compartments) must be viewed as 11 "layers" of compartments, with different layers corresponding to different members of the ^{232}Th chain.

Most techniques for solving compartmental models cannot be applied to such large and complicated systems due to some combination of the following difficulties: prohibitive time requirements; limitations on the number of compartments; instability or poor accuracy; and inability to solve models with time-varying coefficients. Some workers have been able to solve such models using sophisticated solvers, but large amounts of system resources and computing time are required.

The solver used in ACTACAL is an elementary approximation technique developed and refined by ORNL's dosimetry team. The technique is particularly well suited to the type of physiologically-detailed biokinetic models now coming into use in radiation protection, nuclear medicine, and chemical risk analysis. The technique applies to models with time-dependent transfer coefficients and recycling of material between compartments and has no restrictions of practical importance on the number of compartments, the network of flows between compartments, the number of radioactive daughter products, and the paths of movement of daughter products. For a specified level of accuracy, computing time and storage requirements increase roughly in proportion to the number of compartments in the model. For most other techniques, these quantities increase with the square, and sometimes the cube, of the number of compartments or equations involved (Leggett et al., 1993).

8.2 DESCRIPTION OF THE METHOD

In the following, the term "transfer coefficient" will be used to indicate fractional transfer per unit time from one compartment to another.

The objective is to estimate the time-dependent inventory of compartments of a first-order model. The computational method relies on replacement of a relatively complex, exact mathematical formulation of a first-order compartmental model with a relatively simple, approximate mathematical formulation. A first-order compartmental model usually is viewed mathematically as a system of first-order differential equations. With the present approach, the model is viewed as a series of isolated compartments and the time period of interest is viewed as a series of time steps, and the content of each compartment at the end of each time step is estimated by applying a simple linear differential equation.

If one assumes first-order kinetics in an isolated compartment that has a constant inflow rate P, a constant transfer rate coefficient R describing outflow, and an initial activity Y_0 at time 0, the activity Y at time T is given

by the solution of the differential equation $\frac{dY}{dT} = -RY + P$, namely:

$$Y = \left(Y_0 - \frac{P}{R} \right) e^{-RT} + \frac{P}{R} \tag{8.1}$$

The integrated activity *YINT* from time 0 to time *T* is then

$$YINT = \frac{1 - e^{-RT}}{R} \left(Y_0 - \frac{P}{R} \right) + \frac{PT}{R} \ . \tag{8.2}$$

Although these equations do not apply directly to first-order compartmental models involving recycling or variable transfer coefficients, they may be applied iteratively to approximate the solutions of such models to any desired degree of accuracy.

The calculation proceeds in a series of time steps measured in days, with the kth step defined by a starting time T_k and an ending time $T_{k+1} > T_k$. Compartments are numbered 1 through *NC*. The activity *Y(i)* in compartment *i* at time T_{k+1} is calculated from Eq. 8.1 by initializing time 0 to T_k, defining the initial activity in the compartment to be the activity calculated at the ending time in the preceding time step, and replacing *T* with $T_{k+1} - T_k$. The integrated activity *YINT(i)* in the compartment during the same time interval is calculated similarly using Eq. 8.2. During each time step the inflow rate *P* is taken to be the constant value that would yield the total activity that flows out of all feeding compartments with lower numbers during the same time step, plus that flowing out of all feeding compartments with higher numbers during the previous time step. That is, the inflow rate P_i into compartment *i* during the *k*th time step is

$$P_i = \sum_{j=1}^{NC} \frac{R(j, i)\ YINT(j)}{(T_{k+1} - T_k)} \ , \tag{8.3}$$

where *R(j, i)* is the transfer coefficient (fractional transfer per day) from compartment *j* to compartment *i* (or zero if there is no flow from *j* to *i*) at the midpoint of the time step and *YINT(j)* is the last-computed integrated activity in compartment *j*. Thus, *YINT(j)* represents the integral from T_{k-1} to T_k if $i < j$ or from T_k to T_{k+1} if $i > j$. The procedure is repeated until all times of interest have been reached.

In the case of age-specific biokinetic models, it is common practice to specify transfer coefficients for a small set of "basic" ages, $AGE_1 < AGE_2 < ... < AGE_{LAST}$, and to assign coefficients at intermediate ages by interpolating linearly with age (ICRP, 1989). Suppose, for example, that calculations for acute intake at age *AGEINJ* have been made up to time t_1 and that t_2 is the right endpoint of the next time step. Parameter values for the time step are based on the age of the exposed person at the end of the time step, $AGEINJ + t_2$. If this age is less than or equal to AGE_1, transfer coefficients for AGE_1 are used during the time step, and if this age is AGE_{LAST} or greater, transfer coefficients for AGE_{LAST} are used. Otherwise, one selects the smallest k such that $AGE_k \leq AGEINJ + t_2 < AGE_{k+1}$, assigns transfer coefficients for $AGEINJ + t_2$ by linearly interpolating input data for ages AGE_k and AGE_{k+1}, and applies the interpolated data to this entire time step.

The following FORTRAN code fragment illustrates how calculations could be performed over a single time step of length *T* for compartment *i* of an age-specific biokinetic model with *NC* compartments and with recycling among compartments:

```
Y0 = Y(I)
P = 0.0
R1 = 0.0
DO J=1,NC
    P = P + R(J,I) * YINT(J) / T
    R1 = R1 + R(I,J)
END DO
Y(I) = (Y0 - (P/R1))EXP(-R1*T) + P/R1
YINT(I) = ((1.0 - EXP(-R1*T)) / R1)(Y0 - (P/R1)) + P*T / R1
```

In the above code fragment, *Y0, P, Y,* and *YINT* are as defined earlier, and *R(J,I)* is the interpolated age-specific transfer coefficient from compartment *J* to compartment *I*. If there is radiological decay of material, then a radiological decay rate must be added to the total biological removal rate from compartment *I*.

This code fragment represents the central idea of the solver used in ACTACAL. Of course, this code segment had to be expanded considerably in ACTACAL in order to maximize computing efficiency and deal with such problems as significance, division by zero, interpolation of transfer coefficients, time steps of variable length, and growth and potential migration of radioactive progeny.

The computation loops through the indicated calculation once for each compartment in each time step. Due to the simplicity of the calculation, it is possible to loop through thousands of time steps per second using current PCs.

8.3 SOURCES AND SIZES OF ERRORS

At the end of each time step, the calculated sum *SC* of the contents of all compartments of a recycling model,

$$SC = \sum_{i=1}^{NC} Y(i) \tag{8.4}$$

usually is a slight underestimate of the activity in the system because there is a delay of one time step in flow from compartments with higher numbers to compartments with lower numbers. Thus, in a step of length *T*, there is an "upward recycling error", *URE*, in the total system given by

$$URE = \sum_{j>i} R(j,i) \bullet YINT(j) \tag{8.5}$$

where *YINT(j)* is the integrated activity in compartment *j* during the same step. It is easy to show that the upward recycling error at the end of a time step of length *T* is no larger than *T*•*RMAX*, where *RMAX* is the largest sum of transfer coefficients *R(j, i)* out of any one compartment *j* (assuming a unit amount in the system):

$$RMAX = \max_{j} \sum_{i=1}^{NC} R(j,i) \tag{8.6}$$

In recycling models representing systemic biokinetics of radionuclides, the upward recycling error may be orders of magnitude smaller than *T*•*RMAX*. The error depends on the number of compartments in the system, the way in which the substance is distributed among compartments, and the way in which the compartments are numbered. In any case, the upward recycling error can be reduced to a negligible amount by selection of sufficiently small time steps.

Errors are also associated with approximation of non-constant inflow rates and variable transfer coefficients by constants over each time step. These averaging errors can also be reduced to negligible amounts by using sufficiently small steps. It is difficult to find tight bounds on the propagation of this error over several time steps, but the averaging error in any single time step is bounded above by $(T \bullet RMAX)^2$. The averaging error usually produces slight overestimates of the activity in compartments.

For biokinetic models of various levels of complexity, we have checked estimates derived by our method against exact solutions obtained by methods described later, isolated the averaging errors and the upward recycling errors, and compared the total shortfall and the upward recycling error. We have found that the upward recycling error usually is the dominant error in recycling models and that the total shortfall error generally differs little from the upward recycling error. After several time steps, the upward recycling error becomes distributed among compartments roughly in proportion to the true compartment contents, so that the total shortfall error is a useful indicator of the relative error in each compartment. For example, if it is required that estimates be accurate within 0.5% for all compartments at all times, then time steps are chosen so that the total shortfall is always substantially less than 0.5% of the amount in the system.

8.4 SCHEMES FOR SELECTING TIME STEPS

There are two main criteria for selection of time steps. First, the steps should be sufficiently short that errors remain within a prescribed limit. Second, times for which estimates are desired should be included in the time grid defining the steps, since computations are made only at the endpoints of time steps. Alternatively, estimates for times of interest could be linearly interpolated or otherwise extrapolated from calculations made for the right endpoints of time steps, but this introduces additional error.

The simplest approach, though usually not the most efficient one, is to maintain a fixed step length throughout the calculation. In practical applications of ACTACAL, it usually suffices to estimate time-dependent compartmental activities within a few tenths of a percent. This level of accuracy is usually obtained if one uses steps of length 10^{-N} *d*, where *N* is the smallest positive integer *N* such that $10^{-N+1} < ln(2)/RMAX$. If only crude estimates are desired, one might use steps of length 10^{-N+1} *d* or 10^{-N+2} *d*, for example. When a given time step is maintained, the upward recycling error gradually disappears in the frequently encountered case in which a large portion of the material in the system builds up in compartments with low turnover or goes to excretion. In this case, if one is interested only in compartment contents at times remote from exposure (say 20 y or 50 y), then very large time steps (say, 10 d) could be applied.

Except perhaps for batch runs involving hundreds or thousands of cases, computing time generally is not an important consideration when solving current biokinetic models by this method due to the high speed of current desktop computers. If computing time does become an important consideration, it can be reduced considerably by varying the lengths of the steps to reflect changes with time in the rate of relocation of material in the system. For example, for consideration of an acute intake at time 0, accurate estimates may require relatively short steps for the time soon after intake, when contents of some compartments may be changing rapidly, but it may suffice to use longer steps at times remote from intake, when compartmental contents typically are changing more slowly. The following generic scheme suffices for most purposes:

(a) The smallest positive integer *N* is found such that $10^{-N+1} < ln(2)/RMAX$, where *RMAX* is the highest sum of fractional outflow rates from any compartment in the system.

(b) The following time steps are used: 1000 steps of length 10^{-N} *d* (taking the calculations from 0 to 10^{-N+3} *d*), 900 steps of length 10^{-N+1} *d* (taking the calculations from 10^{-N+3} to 10^{-N+4} *d*), 900 steps of length 10^{-N+2} *d*, and so forth, until 100 d is reached; then steps of 1 d until 4000 d is reached; and steps of 10 d thereafter.

This scheme produces desirable endpoints of time steps, typically yields accuracy well within 0.5% even when step lengths reach 10 d, and requires relatively little computing time.

The default time-stepping scheme used in ACTACAL is the generic scheme described above with *N* = 3, i.e., 1000 steps of length 0.001 d, 900 steps of length 0.01 d, 900 steps of length 0.1 d, 3900 steps of length 1 d, and 2155 steps of length 10 d, giving a total of 8855 steps to reach 70 y (25,550 d) from time of intake. Directions for changing the time-stepping scheme in DCAL are given in a later section.

The default scheme used in ACTACAL was based on consideration of the largest transfer coefficient occurring in most of the models of ICRP Publication 68 (1994b) and the ICRP's series of documents on age-dependent doses to members of the public from intake of radionuclides (ICRP 1989, 1993, 1995a, 1995b, 1996). Although transfer coefficients in those models occasionally do not satisfy item (a) above, we have found that the default scheme produces suitable approximations for the applications in radiation protection to which DCAL is expected to be applied. A much coarser time grid would work for most applications of DCAL, particularly applications to biokinetic models that do not involve recycling of material. Because the present scheme is already reasonably time-efficient, however, the time saved by changing to an optimal scheme for a new application of DCAL would usually be more than offset by the time required to edit the file.

8.5 COMPARISONS WITH OTHER SOLVERS

Numerous checks of the accuracy of this method have been made through comparison of solutions of this and other solvers for a variety of biokinetic models. For some relatively simple models, it is possible to solve the models in closed form and thus produce exact solutions that may be checked against ACTACAL's solutions. For example, the ICRP's current model for movement of material through the segments of the GI tract (ICRP Publication 30, 1979) can be solved in closed form. Comparisons of ACTACAL estimates with exact calculations of contents of segments of the GI tract were made for different times following acute ingestion of 1 Bq of a long-lived radionuclide, assuming no absorption to blood (Table 8.1). ACTACAL estimates generally agree with the exact solutions through five significant digits except at very early times (0.01 d in this table), for which disagreement in the third or fourth significant digit is seen for upper and lower large intestines. As a rule, the largest relative errors produced by ACTACAL occur in the first few time steps (10 steps were needed here to reach 0.01 d) or immediately after an increase in the step size.

Many comparisons have been made with published tables of nuclear transformations over 50 y in source organs, based on the models of ICRP Publication 30 (1979). These tables are found in the supplements to that document and were produced by the code TIMED, which was formerly used at ORNL and which incorporates a widely used adaptive predictor-corrector solver. While these comparisons have shown excellent agreement between TIMED and ACTACAL, this is not a strong test of ACTACAL because the models of ICRP Publication 30 generally are not complex and the tables in the supplements to Publication 30 provide only two significant digits.

Checks on the accuracy of ACTACAL's solutions of the recycling models appearing in the ICRP's series of documents on doses to the public from intake of radionuclides (ICRP 1989, 1993, 1995a, 1995b, 1996) have been made through comparisons with two virtually exact solvers with regard to the relatively "non-stiff" models of this series: a computer code called DIFSOL, which obtains analytical solutions of linear ordinary differential equations with constant coefficients (Killough and Eckerman 1984); and a computer code developed by Birchall and James (1989) for solving first-order compartmental models with recycling but with constant transfer coefficients. DIFSOL is built around routines from EISPACK (Smith et al. 1974), a sophisticated software collection for eigensystem analysis.

To check ACTACAL solutions of age-dependent biokinetic models, we developed a computer code based on the algorithm developed by Birchall and James (1989) but allowing time-dependent transfer coefficients. Essentially, the Birchall-James algorithm is "stepped" in the same way as in our method. Errors are controlled by controlling the step size. This method has the advantage that it involves only one of the relatively minor sources of error associated with our method, namely, that of approximating variable transfer coefficients by constants over short time steps. Virtually exact solutions can be obtained by making successive computer runs and shrinking the step sizes until convergence is reached. The method has the distinct disadvantage, however, that computing time increases with the cube of the number of compartments. This prohibits application to

biokinetic models for parent radionuclides that give rise to long chains of radionuclides.

Comparisons of the DCAL solver with the various methods summarized above are illustrated in Tables 8.2-8.4.

The comparisons in Table 8.2 are for the iodine model used in ICRP Publication 56 (1989) (the DEF file is shown in Section 7.1), assuming acute intake to blood of an adult and no radiological decay of iodine. Four different time-stepping schemes were used in ACTACAL to illustrate the increased accuracy with decreasing step sizes. In three cases, fixed time steps (1 d, 0.1 d, or 0.01 d) were used. In the fourth case, DCAL's default time-stepping scheme was used. The exact solution was produced by DIFSOL and checked using the Birchall-James code.

The comparisons in Table 8.3 are for the same iodine model, but in this case it is assumed that acute intake to blood occurs at age 1 y. Thus, in this case the transfer coefficients are age dependent. The exact solution to four significant digits was produced by our modified Birchall-James method. That is, time-steps were decreased until convergence through four digits was achieved. Three different time-stepping schemes were used to produce the three sets of ACTACAL estimates: fixed time steps of 0.1 d, fixed time steps of 0.01 d, and the default time-stepping scheme.

The comparisons in Table 8.4 are for the age-specific biokinetic model for americium used in ICRP Publication 67 (1993). Compartments and paths of movement in the model are shown in Fig.8.1, and the DEF file representing the model is given in Table 8.5. For ages intermediate to those indicated in Table 8.5, transfer coefficients are defined by linear interpolation, as described earlier. The estimates in Table 8.4 are for the case of injection of "stable" Am at age 1 y. Comparison is made with the modified Birchall-James method based on time steps of 1 d. It appeared that convergence of the modified Birchall-James method through at least three digits had been attained when time steps were no greater than 1 d. For models involving 20 or more compartments, application of the Birchall-James method would require considerable computing time on a relatively fast desktop computer to reach a time of several thousand days by using time steps substantially shorter than 1 d.

Table 8.1. Comparison of ACTACAL estimates with exact calculations (closed form solution) of contents of segments of the gastrointestinal tract at times following acute ingestion of 1 Bq of a very long-lived radionuclide, based on the ICRP's gastrointestinal tract model.

Method	Time (d)	Stomach	Small intestine	Upper large intestine	Lower large intestine
ACTACAL	0.01	7.8663E-01	2.0685E-01	6.4807E-03	3.9992E-05
Exact solution		7.8663E-01	2.0685E-01	6.4833E-03	3.9833E-05
ACTACAL	0.1	9.0718E-02	6.1080E-01	2.7732E-01	2.0567E-02
Exact solution		9.0718E-02	6.1079E-01	2.7733E-01	2.0567E-02
ACTACAL	0.2	8.2297E-03	3.9062E-01	5.0675E-01	8.8629E-02
Exact solution		8.2297E-03	3.9062E-01	5.0675E-01	8.8628E-02
ACTACAL	0.5	6.1442E-06	6.6375E-02	5.3308E-01	3.3018E-01
Exact solution		6.1442E-06	6.6375E-02	5.3308E-01	3.3018E-01
ACTACAL	1.0	3.7751E-11	3.3050E-03	2.5057E-01	4.6376E-01
Exact solution		3.7751E-11	3.3050E-03	2.5057E-01	4.6376E-01
ACTACAL	2.0	0.0	8.1924E-06	4.2187E-02	2.8635E-01
Exact solution		0.0	8.1923E-06	4.2187E-02	2.8635E-01
ACTACAL	5.0	0.0	1.2477E-13	1.9060E-04	1.8555E-02
Exact solution		0.0		1.9059E-04	1.8555E-02
ACTACAL	10.0	0.0	0.0	2.3521E-08	1.2786E-04
Exact solution		0.0	0.0	2.3521E-08	1.2786E-04

Table 8.2. Comparison of estimates based on our method with exact solutions, applied to a biokinetic model for iodine (ICRP 1989), assuming intake to blood of an adult and no radiological decay

Stepping scheme	Contents (fraction of intake to blood)				
	Blood	Thyroid	Other	Cumulative Urine	Cumulative Feces
At 1 d:					
Fixed (1 d)	0.6250E-01	0.2800E+00	0.1180E-02	0.6563E+00	0.6884E-05
Fixed (0.1 d)	0.6251E-01	0.2795E+00	0.1671E-02	0.6563E+00	0.7681E-05
Fixed (0.01 d)	0.6252E-01	0.2795E+00	0.1676E-02	0.6563E+00	0.7703E-05
Default	0.6252E-01	0.2795E+00	0.1676E-02	0.6563E+00	0.7703E-05
Exact solution[a]	0.6252E-01	0.2795E+00	0.1676E-02	0.6563E+00	0.7703E-05
At 10 d:					
Fixed (1 d)	0.2638E-03	0.2774E+00	0.1809E-01	0.7023E+00	0.1095E-02
Fixed (0.1 d)	0.2957E-03	0.2772E+00	0.1838E-01	0.7029E+00	0.1137E-02
Fixed (0.01 d)	0.2979E-03	0.2772E+00	0.1839E-01	0.7030E+00	0.1137E-02
Default	0.2979E-03	0.2772E+00	0.1839E-01	0.7030E+00	0.1137E-02
Exact solution	0.2982E-03	0.2772E+00	0.1839E-01	0.7030E+00	0.1137E-02
At 100 d:					
Fixed (1 d)	0.4307E-03	0.1528E+00	0.2560E-01	0.7881E+00	0.3189E-01
Fixed (0.1 d)	0.4278E-03	0.1527E+00	0.2559E-01	0.7892E+00	0.3198E-01
Fixed (0.01 d)	0.4276E-03	0.1527E+00	0.2560E-01	0.7893E+00	0.3199E-01
Default	0.4278E-03	0.1527E+00	0.2559E-01	0.7892E+00	0.3198E-01
Exact solution	0.4276E-03	0.1527E+00	0.2560E-01	0.7893E+00	0.3199E-01
At 1000 d:					
Fixed (1 d)	0.1479E-05	0.5219E-03	0.8790E-04	0.9206E+00	0.7879E-01
Fixed (0.1 d)	0.1452E-05	0.5158E-03	0.8689E-04	0.9206E+00	0.7879E-01
Fixed (0.01 d)	0.1450E-05	0.5153E-03	0.8679E-04	0.9206E+00	0.7879E-01
Default	0.1476E-05	0.5207E-03	0.8769E-04	0.9206E+00	0.7879E-01
Exact solution	0.1450E-05	0.5152E-03	0.8679E-04	0.9206E+00	0.7879E-01

[a]Exact solution produced by DIFSOL and BIRCHALL methods.

Table 8.3. Comparison with exact solutions of estimates based on our method, applied to an age-specific biokinetic model for iodine (ICRP 1989), assuming intake to blood at age 1 y and no radiological decay

Stepping scheme	Contents (fraction of injected I)				
	Blood	Thyroid	Other	Urine	Feces
At 1 d:					
Default	0.6310E-01	0.2724E+00	0.7551E-02	0.6566E+00	0.2919E-03
Fixed T (0.1 d)	0.6300E-01	0.2724E+00	0.7526E-02	0.6565E+00	0.2910E-03
Fixed T (0.01 d)	0.6310E-01	0.2724E+00	0.7551E-02	0.6566E+00	0.2919E-03
Exact solution[a]	0.6311E-01	0.2724E+00	0.7551E-02	0.6566E+00	0.2919E-03
At 10 d:					
Default	0.2991E-02	0.2093E+00	0.2226E-01	0.7476E+00	0.1776E-01
Fixed T (0.1 d)	0.2996E-02	0.2092E+00	0.2225E-01	0.7470E+00	0.1775E-01
Fixed T (0.01 d)	0.2991E-02	0.2093E+00	0.2226E-01	0.7476E+00	0.1776E-01
Exact solution	0.2990E-02	0.2093E+00	0.2227E-01	0.7476E+00	0.1776E-01
At 100 d:					
Default	0.1449E-03	0.1016E-01	0.1096E-02	0.9126E+00	0.7597E-01
Fixed T (0.1 d)	0.1450E-03	0.1016E-01	0.1097E-02	0.9126E+00	0.7597E-01
Fixed T (0.01 d)	0.1442E-03	0.1014E-01	0.1094E-02	0.9126E+00	0.7598E-01
Exact solution	0.1441E-03	0.1013E-01	0.1094E-02	0.9126E+00	0.7598E-01
At 1000 d:					
Default	0.3943E-15	0.3455E-13	0.3731E-14	0.9210E+00	0.7895E-01
Fixed T (0.1 d)	0.3024E-15	0.2724E-13	0.2941E-14	0.9210E+00	0.7895E-01
Fixed T (0.01 d)	0.2936E-15	0.2651E-13	0.2862E-14	0.9211E+00	0.7895E-01
Exact solution	0.2927E-15	0.2643E-13	0.2854E-14	0.9211E+00	0.7895E-01

[a]Exact solution produced by modified BIRCHALL method.

Table 8.4. Estimated organ contents (Bq) at different times after injection of americium at age 1 y, based on the americium model of ICRP Publication 67 (1993) and two different computational methods[a]

Method	Time(d)	Skeleton	Liver	Kidneys	Other	Testes
Birchall[b]	1	0.6150	0.08778	0.02049	0.1972	0.000026
ACTACAL[c]		0.6149	0.08776	0.02048	0.1972	0.000026
Birchall	10	0.7072	0.09942	0.01284	0.0841	0.000030
ACTACAL		0.7071	0.09942	0.01284	0.0841	0.000030
Birchall	100	0.7356	0.09588	0.00525	0.0463	0.000033
ACTACAL		0.7354	0.09585	0.00525	0.0463	0.000033
Birchall	1000	0.5346	0.13829	0.00551	0.0570	0.000068
ACTACAL		0.5332	0.13793	0.00549	0.0568	0.000068
Birchall	10000	0.1974	0.02684	0.00041	0.1064	0.000249
ACTACAL		0.1969	0.02700	0.00041	0.1061	0.000248

[a]To decrease running time for the Birchall method, no gastrointestinal tract compartments were added. Thus, for purposes of this comparison, the Am model of ICRP Publication 67 was modified to eliminate reabsorption of a small amount of Am from the gastrointestinal tract to blood.
[b]As modified by our group to address age-dependent transfer coefficients.
[c]Using the default time-step scheme. Increased accuracy can be obtained using a finer grid.

8.6 TREATMENT OF DECAY CHAINS OF RADIONUCLIDES

Consider a decay chain of *M* radionuclides that flow among *N* compartments. The different members of the chain may have element-specific transfer coefficients between compartments, or they may be assigned the transfer coefficients of the parent, as in ICRP Publication 30 (1979). Selection of step sizes is based on the considerations described earlier in this section, keeping in mind that the highest biological transfer coefficient *(RMAX*) in the system could be associated with a member of the chain other than the parent.

Number the chain members so that there is no decay from higher numbered to lower numbered members. Denote by *A(k,i)(t)* the activity of chain member *i* in compartment *k* at time *t*. For a given time step, *A(k,1)* at the right endpoint of the step is calculated as described earlier, using inflow from all compartments that feed chain member 1 into compartment *k*. Outflow of chain member 1 from compartment *k* consists of biological removal plus radiological decay of chain member 1. For the same time step, *A(k,2)* is calculated by the method described earlier, but using an average inflow rate based on inflow from all compartments that feed chain member 2 into compartment *k*, plus inflow from compartment *k* due to radiological decay of chain member 1 during that time step. The calculation is continued through all *M* members of the chain and then goes to the next time step. In effect, we are treating the problem as if there is only a single radionuclide flowing among *N x M* compartments and are handling radiological decay as if it were biological flow from a compartment defined by a pair (*k, i*) to a compartment defined by a pair (*k*, j), where $j > i$.

Since there is no "upward recycling" of daughter products with this method, the only error associated with estimation of daughter growth in this way is the relatively small "averaging" error described earlier, that is, replacement of the time-varying growth of a daughter product with a constant inflow rate on each time step.

Of course, with a recycling model there will be upward recycling errors associated with moving the ingrowing daughters among compartments according to their given transfer coefficients. Those errors will be controlled as described earlier by the choice of time steps since the biological transfer coefficients of all members of the chain

are considered when setting the time steps.

Errors involved in estimating growth of daughter products in this way may be checked by comparison of estimates with results obtained using the Bateman equation. We have found that the error is typically no larger than 0.2% when the time step is 10 d or less, even for chains with several members whose radiological half-times differ by many orders of magnitude (e.g., the ^{226}Ra or ^{228}Ra chains).

8.7 HOW TO CHANGE THE TIME STEPS IN DCAL

You can change the time-stepping scheme used to solve biokinetic models by editing the first two lines of the file timin.dat found in folder \DCAL\DAT\MIS. For the default time-stepping scheme used in DCAL, these two lines are as follows:

```
0.0, 0.001, 0.01, 0.1, 1., 10.
8857, 1000, 1900, 2800, 6700
```

Note that the values are separated by a comma and space.

The first line represents the variables *delt0, delt1, delt2, delt3, delt4,* and *delt5*. The variable *delt0* is set to zero if increasing time steps are desired. A nonzero *delt0* overrides subsequent values on this line and assigns constant step length *delt0* (days) throughout the calculation. The values *delt1, delt2, delt3, delt4,* and *delt5* are the first through fifth different step lengths (days) for the case of variable time steps. One need not use all five step lengths. Whether or not a step length is reached during the calculation depends on the values in the second line.

The second line represents the variables *ncycle, icyc1, icyc2, icyc3,* and *icyc4*. The value *ncycle* is the total number of steps to be used in the calculation. The values *icyc1* through *icyc4* represent the step number at which the next step length is started when variable step lengths are used. For example, if *delt0* = 0.0, step length *delt1* is used for time steps 1 through *icyc1 - 1,* step length *delt2* is used for time steps *icyc1* through *icyc2 -1,* and so forth.

Table 8.5. The DEF file representing the systemic biokinetic model for americium used in ICRP Publication 67 (1993).

```
File am.def
  6 : Number of age groups
File checked and/or updated by RWL, 8/10/95
Biokinetics of Am,ICRP 67.
****************************************
  100 Infant
  365 1-yr_old
 1825 5-yr_old
 3650 10-yr_old
 5475 15-yr_old
 9125 Adult
Blood     ->Liver_1    2.3300E+00 2.3300E+00 6.9800E+00 6.9800E+00 6.9800E+00 1.1600E+01
Blood     ->Other_0    1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01 1.0000E+01
Blood     ->Other_1    1.6700E+00 1.6700E+00 1.6700E+00 1.6700E+00 1.6700E+00 1.6700E+00
Blood     ->Other_2    4.6600E-01 4.6600E-01 4.6600E-01 4.6600E-01 4.6600E-01 4.6600E-01
Blood     ->C_Bone-S   8.1500E+00 8.1500E+00 5.8200E+00 5.8200E+00 5.8200E+00 3.4900E+00
Blood     ->T_Bone-S   8.1500E+00 8.1500E+00 5.8200E+00 5.8200E+00 5.8200E+00 3.4900E+00
Blood     ->Kidneys_1  4.6600E-01 4.6600E-01 4.6600E-01 4.6600E-01 4.6600E-01 4.6600E-01
Blood     ->ULI_Cont   3.0300E-01 3.0300E-01 3.0300E-01 3.0300E-01 3.0300E-01 3.0300E-01
Blood     ->Kidneys_2  1.1600E-01 1.1600E-01 1.1600E-01 1.1600E-01 1.1600E-01 1.1600E-01
Blood     ->Testes     4.7000E-04 7.0000E-04 7.9000E-04 9.3000E-04 7.5000E-03 8.2000E-03
Blood     ->Ovaries    2.8000E-04 3.7000E-04 9.3000E-04 1.6000E-03 2.8000E-03 2.6000E-03
Blood     ->UB_Cont    1.6300E+00 1.6300E+00 1.6300E+00 1.6300E+00 1.6300E+00 1.6300E+00
Liver_1   ->Blood      1.8500E-03 1.8500E-03 1.8500E-03 1.8500E-03 1.8500E-03 1.8500E-03
Liver_1   ->SI_Cont    4.9000E-05 4.9000E-05 4.9000E-05 4.9000E-05 4.9000E-05 4.9000E-05
Other_0   ->Blood      1.3860E+00 1.3860E+00 1.3860E+00 1.3860E+00 1.3860E+00 1.3860E+00
Other_1   ->Blood      1.3900E-02 1.3900E-02 1.3900E-02 1.3900E-02 1.3900E-02 1.3900E-02
Other_2   ->Blood      1.9000E-05 1.9000E-05 1.9000E-05 1.9000E-05 1.9000E-05 1.9000E-05
C_Bone-S_1->Blood      7.6000E-03 7.6000E-03 7.6000E-03 7.6000E-03 7.6000E-03 7.6000E-03
C_Bone-S  ->C_Bone-S_1 8.2200E-03 2.8800E-03 1.5300E-03 9.0400E-04 5.2100E-04 8.2100E-05
C_Bone-S  ->C_Bone-V   8.2200E-03 2.8800E-03 1.5300E-03 9.0400E-04 5.2100E-04 4.1100E-05
C_Bone-V  ->C_Bone-S_1 8.2200E-03 2.8800E-03 1.5300E-03 9.0400E-04 5.2100E-04 8.2100E-05
R_Marrow  ->Blood      7.6000E-03 7.6000E-03 7.6000E-03 7.6000E-03 7.6000E-03 7.6000E-03
T_Bone-S  ->R_Marrow   8.2200E-03 2.8800E-03 1.8100E-03 1.3200E-03 9.5900E-04 4.9300E-04
T_Bone-S  ->T_Bone-V   8.2200E-03 2.8800E-03 1.8100E-03 1.3200E-03 9.5900E-04 2.4700E-04
T_Bone-V  ->R_Marrow   8.2200E-03 2.8800E-03 1.8100E-03 1.3200E-03 9.5900E-04 4.9300E-04
Kidneys_1 ->UB_Cont    9.9000E-02 9.9000E-02 9.9000E-02 9.9000E-02 9.9000E-02 9.9000E-02
Kidneys_2 ->Blood      1.3900E-03 1.3900E-03 1.3900E-03 1.3900E-03 1.3900E-03 1.3900E-03
Testes    ->Blood      1.9000E-04 1.9000E-04 1.9000E-04 1.9000E-04 1.9000E-04 1.9000E-04
Ovaries   ->Blood      1.9000E-04 1.9000E-04 1.9000E-04 1.9000E-04 1.9000E-04 1.9000E-04
EOF Data
```

9.0 HOW DCAL IMPLEMENTS DIFFERENT OPTIONS CONCERNING DECAY CHAIN MEMBERS

In Chapter 5 we described different options available in the DCAL system for treating the biokinetics of decay chain members produced *in vivo*. The present chapter provides some background information that may be useful in deciding on an appropriate option for a given case and describes how the different options are implemented in DCAL.

9.1 ASSUMPTIONS USED IN ICRP DOCUMENTS

Estimates of accumulated dose to organs following intake of a radionuclide may depend strongly on assumptions concerning the retention of radioactive chain members produced inside the body (Leggett, Dunning and Eckerman 1984). However, a paucity of experimental data on many important chains of radionuclides and the desire to simplify biokinetic models and dosimetric calculations have led to the use of broad, simplistic assumptions concerning ingrowing chain members.

In ICRP Publication 2 (1959), a radionuclide born in an organ was assigned its own characteristic biokinetic model, meaning the biokinetic model derived for that element assuming its direct deposition into the organ from blood. A radical departure from that approach was made in ICRP Publication 30 (1979), where decay chain members produced in the body were assigned the biokinetic model of the parent (i.e., the radionuclide taken into the body), with exceptions made for radioiodine produced by decay of radiotellurium and for noble gases appearing in certain decay chains. Iodine as a daughter of tellurium was assumed to be translocated instantaneously to the transfer compartment in inorganic form and then to follow the same kinetics as iodine introduced into blood as a parent radionuclide. The assumption for noble gases varied with radiological half-time and site of production in the body. For example, it was assumed that: ^{222}Rn ($T_{1/2}$ = 3.8 d) produced from ^{226}Ra in soft tissues escapes from the body before decay; 70% of ^{222}Rn produced in bone escapes from the body and the remaining 30% decays at the site of production; ^{220}Rn ($T_{1/2}$ = 56 s) produced from ^{224}Ra decays at the site of production, either in soft tissues or bone; 20% of ^{83m}Kr ($T_{1/2}$ = 1.83 h) produced from ^{83}Rb decays at the site of production and the remaining 80% escapes from the body; and ^{79}Kr ($T_{1/2}$ = 35 h) produced from ^{79}Rb escapes from the body.

Current evidence suggests that the biokinetics of decay chain members may often be better described by some combination of the assumptions made in ICRP Publications 2 and 30 (Leggett, Dunning, and Eckerman 1984; ICRP 1993, 1995a, 1995b). That is, experimental data on laboratory animals together with limited postmortem data on human subjects suggest that radionuclides born in soft tissues and on bone surfaces tend to relocate as if injected directly into blood, while radionuclides born in bone volume are more limited in their ability to migrate from the parent radionuclide (Leggett, Dunning, and Eckerman 1984). With regard to inhaled material deposited in the lung, a reasonable default assumption may be that a radionuclide born in the respiratory tract remains with the parent if originating in an undissolved particle but otherwise translocates according to its own characteristic parameter values (i.e., values derived for that element assuming its direct deposition into the respiratory tract). There is little information on the behavior of decay chain members produced in the gastrointestinal tract, but the rate of translocation through different segments of the tract should be relatively independent of the radionuclide. Also, in view of the tightly controlled and highly selective nature of absorption of material through the gastrointestinal tract wall, it seems reasonable to assume that the absorption fraction for decay chain members produced in the gastrointestinal tract contents is independent of absorption properties of the parent radionuclide.

Some progress toward a more realistic treatment of decay chain members was achieved in ICRP Publication 67 (1993) and Publication 69 (1995a). In those documents, systemic biokinetic models for radioactive progeny of

isotopes of Pb, Ra, Th, or U were based on the following general principles of "independent kinetics" (i.e., kinetics different from that of the parent): (1) a radionuclide born in soft tissues or on bone surfaces tends to redistribute in a manner consistent with its own characteristic biokinetic model; (2) a radionuclide born in bone volume is more limited in its ability to relocate. Implementation of these assumptions was facilitated by the application of biologically realistic model structures. In particular, the model structures include return of material from organs to blood, which allows explicit depiction of migration of ingrowing activity from organs to blood and subsequent redistribution among organs in a pattern specified by chain-member-specific models. By contrast, all of the systemic biokinetic models of ICRP Publication 30 (1979) except the iodine model and many of the models in the ICRP's series of publications on doses to members of the public (ICRP 1989, 1993, 1995a, 1995b, 1996) depict a physically unrealistic one-directional flow of material from organs to excreta. Such a modeling approach precludes any physically meaningful or simple method for redistributing ingrowing activity among systemic organs.

In the ICRP's series of documents on doses to members of the public (ICRP 1989, 1993, 1995a, 1995b, 1996), fractional absorption from the gastrointestinal tract was assumed to be element-specific for Pb, Ra, Th, or U chains (ICRP 1993, 1995a); that is, a chain member produced *in vivo* was assigned its element-specific f_1 value. For inhaled material deposited in the respiratory tract, absorption parameters of the parent generally were applied to all members of the decay chain (ICRP 1995b). Exceptions were made for noble gases; for example, ^{222}Rn formed in the respiratory tract was assumed to escape from the body at a rate of 100 d^{-1}, and radioisotopes of xenon formed in the respiratory tract from the decay of iodine were assumed to escape from the body without decay.

9.2 TECHNICAL OR CONCEPTUAL PROBLEMS THAT MAY ARISE FROM THE ASSUMPTION OF INDEPENDENT KINETICS OF DECAY CHAIN MEMBERS

In general, application of the principle of independent kinetics of chain members is not simply a matter of concatenating the different biokinetic models for different chain members. Technical or conceptual problems often arise from structural inconsistencies among models for different chain members or from a lack of biological realism in the models. These problems may be divided into two main categories:

Category 1 problems: Structural differences in biokinetic models for different chain members that lead to an incomplete set of conditions describing the biokinetics of some members. If the biokinetic models for different chain members address different regions of the body or comprise different compartments, the situation may arise that a decay chain member B is produced in a compartment included in the biokinetic model of a preceding chain member but not included in the biokinetic model for B. When this happens, the rate of removal of B from that compartment and the destination of the removed activity must be defined before the model can be solved.

Category 2 problems: Differences in the meaning of the "Other" region for different decay chain members. Even if the biokinetic files contain sufficient information to provide a unique solution of the concatenated models for all chain members, ambiguities may remain concerning the anatomical location of nuclear transformations occurring in the regions of the different models referred to as "Other" or "Rest of Body (ROB)". These ambiguities may arise when the ROB compartments have different meanings for different chain members, i.e., when the models for different decay chain members include different explicitly identified systemic source organs. Either or both of the following situations may occur:

(a) Chain member A decays to chain member B and the biokinetic model for B contains an explicitly identified source region S that is included implicitly in A's ROB. A portion of the decays of A in A's ROB theoretically occur in S, but solution of the biokinetic models using the pre-defined kinetic files (DEF files) will not reflect this.

(b) Chain member A decays to chain member B and the biokinetic model for A contains an explicitly identified source region S that is included implicitly in B's ROB. Although the pre-defined kinetic files

account for ingrowth of B in S (after correction of Category 1 problems, if required), they do not account for a portion of activity of B in B's ROB that theoretically belongs to S.

Although the two types of Category 2 problems are described in terms of adjacent chain members A and B, analogous problems for radionuclide pairs (A, B) may occur in the more general situation in which A eventually gives rise to B through a series of decays.

Ideally, both Category I and Category II problems may be avoided by applying a common model structure to the entire chain and providing a complete set of transfer rates for all decay chain members with respect to all compartments in a common model. In practice, the user may not be in a position to make the modifications of the characteristic models of different chain members required to produce such a uniform and detailed set of transfer rates. For this reason, DCAL was designed to identify such problems, prompt the user to decide how to resolve Category 1 problems, and provide a computer-generated resolution to Category II problems. DCAL scans the DEF files for the different chain members for missing transfers and prompts the user to supply a minimal amount of missing information (transfer rates) necessary to allow ACTACAL to produce a unique set of solutions concerning the distribution of each decay chain member with respect to compartments of that chain member's biokinetic model. Then, for dosimetric purposes only, DCAL reapportions the calculated ROB activity of individual chain members according to a consistent scheme that provides a practical resolution to problems 2a and 2b. The specific procedures followed in DCAL are described in the following section in connection with DCAL's implementation of the option of using pre-defined kinetic files for each chain member.

9.3 HOW DIFFERENT OPTIONS CONCERNING DECAY CHAIN MEMBERS ARE IMPLEMENTED IN DCAL

Recall that ACTACAL provides the following options for treating decay chain members:

1. Independent kinetics; user-predefined files.
2. Shared kinetics; ICRP-30 approach.
3. Member-by-member default options:
    a. No biological translocation.
    b. Prompt removal from the body.
    c. Assign kinetics of first member.

9.3.1 Implementation of Option 1: Independent Kinetics; User-Predefined Files

The option of pre-defined kinetic files for each chain member can be applied to any type of assumption concerning the behavior of decay chain members, provided the assumption is compatible with the structures of the models being applied. However, this option is intended primarily for application of the principle of independent kinetics of decay chain members, while Options 2 and 3 are provided for ease of application of simplistic assumptions concerning the biokinetics of decay chain members. Use of Option 1 to implement the simplistic assumptions covered by Options 2 and 3 requires repetitive assignment of transfer rates, a task that can be performed by the computer.

As indicated in the preceding section with regard to the principle of independent kinetics of decay chain members, application of Option 1 is not simply a matter of using separate DEF files for different chain members. Before beginning an application that will involve Option 1, you should examine the DEF files for the types of problems described above and, as far as practical, modify the files for consistency as well as for purposes of achieving the intended behavior of ingrowing decay chain members. If you apply the pre-defined kinetic files describing the models of *Federal Guidance Report 13* (EPA 1999) (in folder \DAT\BIO\FGR13) or the models of ICRP Publication 68 (1994b) (in folder \DAT\BIO\I68) and follow the assumptions concerning decay chain members in the corresponding documents, then no modifications of DEF files are needed.

When Option 1 is selected, the following steps are followed in ACTACAL:

Step 1. The biokinetic models (DEF files) of all chain members are scanned to establish a common set of source regions for the entire chain. This set of source regions consists of explicitly identified source regions appearing in a model of any decay chain member, plus a common source region "Other" consisting of tissues remaining after subtraction of all the explicitly identified source regions. Recall that a region is considered a source region for a given radionuclide provided it receives that radionuclide from one or more sources other than by ingrowth through radioactive decay. An explicitly identified source region is a region with an explicitly identified anatomical name.

In the following, we use "ROB" when referring to the "Other" region in the biokinetic model for a specific chain member and reserve the term "Other" for the source organ common to the entire chain.

Step 2. The mass of ROB for each chain member is computed.

Step 3. The DEF files for different chain members are scanned to determine whether Category 1 problems exist (see the preceding section). If such problems are found, the user is prompted to supply missing transfers (see Section 5). When a minimal set of transfers is available to describe the kinetics of all ingrowing activity in all regions, the time-dependent activities in the compartments of the biokinetic model for each chain member are computed using the biokinetics described by the pre-defined kinetic files (DEF files).

Step 4. The activities in the compartments are assigned to source regions based on the naming convention of the DEF files (see Section 3). The activity associated with a source region is the sum of the activities in the compartments of the region.

Step 5. The following additional adjustments are made, if applicable:

(a) For a source region S of a member's (B's) biokinetic model that is not explicitly identified in the model of any preceding chain member, a fraction of B's ROB activity is added to its computed activity in S. Also, for each member C following B in the chain, a fraction of C's ROB activity is added to C's computed activity in S. The fraction added in each case is the mass fraction of S relative to the mass of ROB in the parent's biokinetic model. The member's ROB activity is decreased by the activity assigned to S.

(b) For a source region S of the chain that is not an explicit source region in a chain member's (M's) biokinetics, a fraction of M's ROB activity is added to S. The fraction is the mass fraction of S relative to the mass of M's ROB. The activity of M's ROB is decreased by the activity assigned to S. If Step 5a also applies to M because S is an explicitly identified source organ of a preceding chain member B but is not an explicitly identified source organ of the first member of the chain, then Step 5a is carried out and Step 5b is omitted. Note that the adjustment of the activity of M in S that would result from Step 5a usually is not precisely the same as the adjustment that would result from Step 5b, because the two adjustments depend on the masses of two different ROBs. In most cases, however, these two masses differ by at most a few percent, and making both adjustments would usually result in relocation of roughly two times too much activity of M from ROB to S.

Step 6. If item 5a or 5b is applicable to some chain member, that member's activity in the common source organ "Other" is set equal to the adjusted activity in ROB.

It is emphasized that the above reapportionments of activity are made for dosimetric purposes only and are made external to ACTACAL solutions of the time-dependent distribution of activity in compartments. Adjustments made for a given time do not affect ACTACAL's calculations for a later time. As indicated in Step 3, the activities in the compartments of the biokinetics for each chain member are computed solely on the basis of the pre-defined kinetic files.

9.3.2 Implementation of Option 2: The "ICRP-30" Approach

This refers to the general principle as well as the exceptional cases first applied in ICRP Publication 30 (1979) and, with some exceptions, carried over to ICRP Publication 68 (1994b). That is, decay chain members produced in the body generally are assigned the biokinetic model of the parent, except that (a) radioiodine produced by decay of radiotellurium is assigned the characteristic biokinetic model for iodine, and (b) noble gases in certain decay chains are assigned special models (assumptions) that vary with the radiological half-time of the noble gas and the site of production in the body.

When this option is selected, DCAL assigns to each non-exceptional decay chain member the same compartments and transfer rates that appear in the DEF file for the parent. The models and/or assumptions for the exceptional decay chain members are "hard-wired" into the ACTACAL subroutine, i.e., are described within the computer code rather than by input data.

Option 2 may be applied whether or not the biokinetic models of ICRP Publication 30 are used, but the models for the exceptional decay chain members cannot be changed. Application of the general principles of ICRP Publication 30 but with different assumptions for these exceptional cases, or with additional exceptions to the general principle, would require selection of the first option (pre-defined kinetic models for all chain members) after the appropriate biokinetic (DEF) files have been created and inserted into the DCAL library.

9.3.3 Implementation of Option 3: Member-by-Member Default Options

These options are applied individually to decay chain members. For example, one could assign Assumption 3a to the second decay chain member, Assumption 3c to the third, Assumption 3a to the fourth, Assumption 3b to the fifth, and so forth.

Assumption 3a (no biological translocation) is implemented in DCAL as follows: The same paths of movement described in the biokinetic (DEF) file for the parent are assigned to the decay chain member (B). Then the transfer rate of B along each path is set at 10^{-10} d^{-1}.

Assumption 3b (prompt removal from the body) is implemented as follows: First, the same paths of movement and transfer rates described in the biokinetic (DEF) file for the parent are assigned to the decay chain member (B). Second, for each path of movement X to Y depicted in the model, an additional path of movement from X to excreta is added. Third, the transfer rate of B along each additional path is set at 1000 d^{-1}, corresponding to a biological half-time of about 1 min.

Assumption 3c (assign kinetics of first member) is implemented in the obvious way, i.e., the paths of movement and transfer rates in the biokinetic file for the parent are assigned without change to the decay chain member.

10. HOW DCAL ESTIMATES THE RISK OF RADIOGENIC CANCERS

10.1 GENERAL CONSIDERATIONS

The risk calculations performed by DCAL are for attributable risk. Attributable risk is the likelihood, according to a given risk model, of death from cancer or development of cancer due to a radiation exposure.

Calculations of attributable risk are based on risk projection models for specific cancer sites. The age- and gender-specific radiation risk models used in DCAL are taken from an EPA report (EPA 1994) that provides a methodology for calculation of radiogenic cancer risks based on a critical review of data on the Japanese atomic bomb survivors and other study groups. Some parameter values in those models have been modified for use in DCAL to reflect updated vital statistics for the U.S. and to achieve greater consistency in the assumptions made for different age groups and genders. The following age-at-exposure groups are considered in the models: 0-9, 10-19, 20-29, 30-39, and 40+ y.

In estimating the likelihood of a radiogenic cancer, it is considered that an exposed person may die from a competing cause before a radiogenic cancer could develop. For some of the cancer sites considered in DCAL, the risk model is based on the assumption that the likelihood of a radiogenic cancer depends on the baseline cancer mortality rate in the population. The gender-specific survival data and mortality data for specific cancers used by DCAL are based on vital statistics for the United States.

Age-specific risk coefficients generally are average values for fairly broad age intervals and are discontinuous at the endpoints of these intervals. Also, vital statistics for the U.S. are discrete data, typically tabulated at one or five year intervals. For use in DCAL, risk coefficients and vital statistics have been transformed into continuous functions by fitting a cubic spline to the discrete data. DCAL calculates interpolated values, derivatives, and integrals directly from the spline coefficients (de Boor 1978, Fritsch and Carlson 1980; Fritsch and Butland 1982).

10.2 EXPOSURE SCENARIOS

Estimates of attributable risk calculated by DCAL for internally deposited activity are based on a lifetime intake of the parent radionuclide of 1 Bq. The intake rate is assumed to be proportional to the usage of the environmental medium containing the radionuclide. Intakes may be by any one of the three intake modes for which DCAL can generate absorbed dose rate files, i.e., inhalation, ingestion, or injection.

A dose rate file generated by DCAL for internally deposited activity is based on acute intake of a radionuclide at a specified age. Age-specific dose rates to organs during chronic intakes can be estimated from the files generated for acute intakes by considering a chronic intake as a large number of small, acute intakes spaced over the intake interval.

The default ages at acute intake considered by DCAL are infant (100 d), 1 y, 5 y, 10 y, 15 y, and adult (20 or 25 y, depending on the biokinetic model). Dose rates following intake at some age other than a default age are estimated by linearly interpolating data for the default ages. Dose rates for acute intake as a young adult are applied to intake at any adult age.

For each of the internal exposure modes, the risk coefficient for a radionuclide includes the contribution to dose from production of decay chain members in the body after intake of the parent radionuclide, regardless of the half-lives of the decay chain members. For both internal and external exposure, a risk coefficient for a given radionuclide is based on the assumption that *this is the only radionuclide present in the environmental medium*.

That is, doses due to decay chain members produced in the environment *prior* to intake of, or external exposure to, the radionuclide are *not* considered. However, a separate risk coefficient is provided for each decay chain member of potential dosimetric significance. This allows the user to assess the risks from radionuclides produced in the environment by radioactive decay of parent radionuclides.

10.3 RISK MODELS USED IN DCAL

One of two basic types of radiogenic cancer risk projection model is used for a given cancer site: an absolute risk model or a relative risk model. An absolute risk model is based on the assumption that the age-specific excess force of mortality or morbidity (that is, the mortality or morbidity rate for a given cancer type) due to a radiation dose is independent of cancer mortality or morbidity rates in the population. A relative risk model is based on the assumption that the age-specific excess force of mortality or morbidity due to a radiation dose is the product of an exposure-age-specific relative risk coefficient and baseline cancer mortality or morbidity rate. The risk models used in DCAL for bone, skin, and thyroid cancer are based on an absolute risk hypothesis, and risk models for other sites are based on a relative risk hypothesis.

In an absolute risk model, the absolute risk at age x due to a unit absorbed dose received at an earlier age y is calculated as the product $A(y)\ B(t)$ where A is an age- and gender-specific "risk model coefficient", B is a time-since exposure step function that defines the plateau period (the time period during which the risk is expressed), and $t = x - y$. The value of $B(t)$ is 1 for times t within the plateau period and otherwise is 0. In a relative risk model, the risk is calculated as the product $C(x,y)\ D(y)\ E(t,y)$, where $C(x,y)$ represents the baseline force of cancer mortality at age x due to a unit absorbed dose received at age $y < x$, $D(y)$ is an age- and gender-specific risk model coefficient, and $E(t,y)$ is the relative magnitude of the response at different times $t = x - y$ after exposure at age y.

The mortality risk model coefficients used in DCAL are shown in Table 10.1 for cancers other than leukemia and in Table 10.2 for leukemia. These values are based on methods and assumptions described in an EPA report (EPA 1994). The coefficients tabulated in that report were modified in some cases to reflect the use of updated vital statistics for the U.S. and to achieve greater consistency in the assumptions made for different age groups and genders. The term "risk coefficient" was used in the EPA report but has been replaced here and in *Federal Guidance Report 13* (EPA 1999) with the term "risk model coefficient" to avoid confusion with the radionuclide risk coefficients tabulated by DCAL. Those risk coefficients refer to risk per unit intake or external exposure to a specific radionuclide in a specific environmental medium.

The method used in DCAL to calculate risk of cancer morbidity is to divide the mortality risk coefficient by a corresponding lethality factor, k. Only mortality is considered for calculating skin cancer morbidity, i.e., k is considered to be 1. The lethality fractions used in DCAL are given in Table 10.4.

Calculations of radiogenic risk by DCAL account for the possibility that an exposed person who may have eventually died from, or developed, a radiogenic cancer will die at an earlier age from a competing cause of death. It is assumed that the survival function is not significantly affected by the exposures being assessed, that is, that the number of radiogenic cancer deaths at any age is small compared with the number of deaths at that age from competing causes. Therefore, a risk coefficient should not be applied to exposure levels that are sufficiently high to cause a substantial increase in the mortality rate at any age. The DCAL user is referred to *Federal Guidance Report 13* (EPA 1999) for details concerning the formulas and steps used by DCAL in the calculation of cancer risk morbidity or mortality.

Table 10.1. Mortality risk model coefficients for cancers other than leukemia, based on the EPA radiation risk methodology (EPA 1994)

Cancer type	Risk model type[a]	Age group				
		0-9 y	10-19 y	20-29 y	30-39 y	40+ y
Male:						
Esophagus	R	0.2877	0.2877	0.2877	0.2877	0.2877
Stomach	R	1.223	1.972	2.044	0.3024	0.2745
Colon	R	2.290	2.290	0.2787	0.4395	0.08881
Liver	R	0.9877	0.9877	0.9877	0.9877	0.9877
Lung	R	0.4480	0.4480	0.0435	0.1315	0.1680
Bone	A	0.09387	0.09387	0.09387	0.09387	0.09387
Skin	A	0.06597	0.06597	0.06597	0.06597	0.06597
Breast	R	0.0	0.0	0.0	0.0	0.0
Ovary	R	0.0	0.0	0.0	0.0	0.0
Bladder	R	1.037	1.037	1.037	1.037	1.037
Kidney	R	0.2938	0.2938	0.2938	0.2938	0.2938
Thyroid	A	0.1667	0.1667	0.08333	0.08333	0.08333
Residual	R	0.5349	0.5349	0.6093	0.2114	0.04071
Female:						
Esophagus	R	1.805	1.805	1.805	1.805	1.805
Stomach	R	3.581	4.585	4.552	0.6309	0.5424
Colon	R	3.265	3.265	0.6183	0.8921	0.1921
Liver	R	0.9877	0.9877	0.9877	0.9877	0.9877
Lung	R	1.359	1.359	0.1620	0.4396	0.6047
Bone	A	0.09387	0.09387	0.09387	0.09387	0.09387
Skin	A	0.06597	0.06597	0.06597	0.06597	0.06597
Breast	R	0.7000	0.7000	0.3000	0.3000	0.1000
Ovary	R	0.7185	0.7185	0.7185	0.7185	0.7185
Bladder	R	1.049	1.049	1.049	1.049	1.049
Kidney	R	0.2938	0.2938	0.2938	0.2938	0.2938
Thyroid	A	0.3333	0.3333	0.1667	0.1667	0.1667
Residual	R	1.122	1.122	0.8854	0.3592	0.1175

[a] A indicates that an absolute risk model is used (coefficient units, 10^{-4} Gy^{-1} y^{-1}), and R indicates that a relative risk model is used (Gy^{-1}).

Table 10.2. Mortality risk model coefficients (Gy^{-1}) for leukemia, based on the EPA radiation risk methodology (EPA 1994)[a]

Gender	Age group				
	0-9 y	10-19 y	20-29 y	30-39 y	40+ y
Male	982.3	311.3	416.6	264.4	143.6
Female:	1176	284.9	370.0	178.8	157.1

[a]A relative risk model is used (coefficient units, Gy^{-1}). Risk model coefficients for leukemia are not directly comparable to those for other types of cancer (Table 10.1) due to differences in the scales of the time-since-exposure response functions for leukemia and other cancers.

Table 10.3. Lethality data for cancers by site in adults

Cancer site	Lethality fraction *k*
Esophagus	0.95
Stomach	0.90
Colon	0.55
Liver	0.95
Lung	0.95
Bone	0.70
Skin[b]	0.002
Breast	0.50
Ovary	0.70
Bladder	0.50
Kidney	0.65
Thyroid	0.10
Leukemia (acute)	0.99
Residual	0.71

10.4 Continuity Considerations

While the integration of a smoothly varying function using a spline is straightforward, the radiogenic cancer models are inherently discontinuous. For example, the time since exposure function for most solid cancers typically has a value of zero for times since exposure that are less than the 10 y minimal latency and a value of one for times equal to or greater than the minimal latency. Suppose that the function to be integrated (the integrand) is evaluated at one year increments. For the models used in DCAL, the function will change abruptly from a value of zero for times since exposure less than 10 y to a generally smoothly varying function of time for times equal to or greater than 10 years. However, fitting a spline to the integrand provides a continuous transition from the value at 9 y to the value at 10 y. If the integral is evaluated on the basis of these spline coefficients, it will include an unintended contribution from this interval.

One way to solve the problem is to integrate functions in piecewise continuous intervals. This method is exact and would work well for the simple example considered above. In general, however, the value of the integrand at each discontinuity depends on the interval of integration; the method becomes unwieldy for situations with many discontinuities. An alternative method for situations where the function is reasonably smooth on either side of a discontinuity is to replace the value of the function at the discontinuity with the average of the values immediately above and below it. For the case above, the value of the time since exposure response function at 10 y is changed from 1 to (0 + 1) / 2 = 0.5. The reduced excess in the integral between 9 and 10 y is then

compensated for by a comparable reduction in the 10 to 11 year interval. This method was used to smooth the risks and lifetime losses represented in the risk models used in DCAL.

10.5 Cancer Type and Dose Location Associations

The dose locations associated with each cancer type are shown in Table 10.4. When more than one dose location is shown in the table, risks are calculated for a weighted mean of the doses at these locations using the weights shown in the table. The residual cancer category represents a composite of primary and secondary cancers that are not otherwise considered in the model. The dose location associated with these cancers, the pancreas, was chosen to be generally representative of soft tissues; the pancreas is not considered the origin of all these neoplasms.

Table 10.4. Dose regions associated with cancer types

Cancer type	Dose region	Weighting factor
Esophagus	Esophagus[a]	1.0
Stomach	Stomach Wall	1.0
Colon	Upper Large Intestine Wall	0.568
	Lower Large Intestine Wall	0.432
Liver	Liver	1.0
Lung	Bronchial Region – Basal Cells	0.1667
	Bronchial Region – Secretory Cells	0.1667
	Bronchiolar Region – Secretory Cells	0.3333
	Alveolar-Interstitial Region	0.3333
Bone	Bone Surface	1.0
Skin	Skin	1.0
Breast	Breasts	1.0
Ovary	Ovaries	1.0
Bladder	Urinary Bladder Wall	1.0
Kidney	Kidney	1.0
Thyroid	Thyroid	1.0
Leukemia	Red Marrow	1.0
Residual	Muscle	0.3334
	Pancreas	0.3333
	Adrenals	0.3333

[a]For intakes of radionuclides, the estimated dose to the thymus is applied to the esophagus, which is not represented explicitly in the mathematical phantoms used for internal dosimetric calculations. The esophagus is represented explicitly in the phantom used for external dose calculations (EPA 1993).

11. EXTERNAL DOSE COMPUTATIONAL MODULE

In this section we describe the external computational module EXTDOSE included within DCAL. The DCAL system was developed largely to address the doses and risks resulting from the intake of radionuclides. However, the EXTDOSE module, initially developed during the preparation of *Federal Guidance Report 12* (EPA 1993), has been integrated into DCAL.

11.1 FGR-12 CALCULATIONAL METHODS

Photons and electrons are the most important radiations emitted by radionuclides distributed in the environment that can penetrate the body from outside to deposit ionizing energy within its radiosensitive tissues. This section briefly discusses the methods used to calculate the dose coefficients for external exposure to photons and electrons for submersion in contaminated air, immersion in contaminated water, and exposure to contaminated ground surfaces and volumes.

Some radionuclides produce bremsstrahlung that can contribute to the external dose. In *Federal Guidance Report 12*, the contribution from bremsstrahlung was included in the dose calculations. The version of EXTDOSE incorporated into DCAL address bremsstrahlung however it differs from the earlier version in that the bremsstrahlung contribution is computed directly rather than read from a pre-calculated data file. This result in minor numerical differences in external coefficients derived using DCAL and those tabulated in FGR 12 for pure beta emitters; e.g., Sr-90. In addition, the radiations associated with spontaneous fission are taken into account in the DCAL version which results in external dose coefficients derived using DCAL for such emitters (e.g., Cf-252) that differ from those tabulated in *Federal Guidance Report 12*.

11.2 ORGAN DOSES FROM MONOENERGETIC ENVIRONMENTAL PHOTON SOURCES

The calculation of organ doses from irradiation of the body by photon emitters distributed in the environment requires the solution of a complex radiation transport problem. It is impractical to solve this problem for the precise spectrum of photons emitted by each radionuclide. Therefore, in *Federal Guidance Report 12*, organ doses were computed for monoenergetic photon sources at twelve energies between 0.01 and 5.0 MeV. These results were then used in *Federal Guidance Report 12* and here by EXTDOSE to derive radionuclide-specific dose coefficients. EXTDOSE considers exposure to radionuclides distributed:

- in the air surrounding an individual (submersion)
- in the water which the individual is immersed (immersion)
- on the surface of the ground
- in the top 1-, 5-, or 15 cm layer of soil
- uniformly within the soil depth

Federal Guidance Report 12 describes in detail the computations of the organ dose for a monoenergetic photon emitter distributed as above. The organ doses for such an emitter are contained in Tables II.4 - II.6, and Tables II.12 - II.15 of *Federal Guidance Report 12* and these data are included in the folder \DCAL\DAT\EXT.

11.3 SKIN DOSES FROM MONOENERGETIC ENVIRONMENTAL ELECTRON SOURCES

The contribution of electrons to dose to organs and tissues of the body other than skin need not be considered, due to the short range in tissue of electrons emitted by radionuclides. The DOSFACTER code developed by Kocher (DOE 1988) was used to calculate skin dose coefficients for a series of monoenergetic electron emissions, which were convoluted to the spectra of the various radionuclides, using the energy and intensity of beta and electron emissions of radionuclides tabulated in ICRP Publication 38 (ICRP 1983; Eckerman et al. 1993). In *Federal Guidance Report 12*, skin doses for the monoenergetic emissions were presented in a series

of graphs (Figs II.24-II.26) and these data are contained in data files in \DCAL\DAT\EXT. For a discussion of the computational details see Kocher (DOE 1988) or *Federal Guidance Report 12*.

11.4 DOSE COEFFICIENT FORMULATION FOR RADIONUCLIDES

The energies and intensities of the radiations emitted in spontaneous nuclear transformations of radionuclides are contained in the nuclear decay data files in the folder \DCAL\DAT\NUC. These files have been described by Eckerman et al. (1993), provide a complete tabulation of the energies (average or unique) and intensities of the emitted radiations including the beta spectra.

Only photons and electrons (including bremsstrahlung) emitted by the radionuclides are sufficiently penetrating to contribute to the dose to tissues and organs of the body. The energy spectra of emitted radiations are either (1) discrete, as in the case of gamma emissions, or (2) continuous, as in the case of bremsstrahlung and beta particles. The beta spectral file is used here to evaluate the contribution of the beta particles to the skin dose.

The dose coefficient h_T^S for tissue T and exposure mode S can be expressed as

$$h_T^S = \sum_{j=\,e,\,\gamma} \left[\sum_i y_j(E_i)\ \hat{h}_{T,\,j}^S(E_i) + \int_0^\infty y_j(E)\,\hat{h}_{T,\,j}^S(E)\,dE \right] , \qquad (11.1)$$

where $y_j(E_i)$ is the yield of discrete radiations of type j and energy E_i, and $y_j(E)$ denotes the yield of continuous radiations per nuclear transformation with energy between E and $E + dE$. The other summation is over all electron and photon radiations while the two terms within the bracket address the contributions of the discrete and the continuous emissions. The contribution of the radiations to the dose in tissue or organ T is defined by the quantity $\hat{h}_T^S(E)$ which is tabulated as a function of energy for each exposure mode. In the case of the discrete emissions, a value appropriate to the energy of the discrete radiation being evaluated is obtained by interpolation. For photons, these data are tabulated for 25 target tissues of the body at each of 12 monoenergetic photon energies and for electrons the values are tabulated only for the skin.

11.5 EXTDOSE CALCULATIONS

To initiate calculations of the external dose coefficients, select EXTDOSE from the DCAL main menu. Note that the results of the calculations will be contained in the work folder indicated at the bottom of the main menu, i.e., labeled by <F4>. Following the credit display, the following prompt appears

Use (f)ile or (i)nput nuclides ([f]/i)?

If we elect to input the radionuclides of interest (response *i*), this results in the following prompts

Input nuclides of interest, e.g., Ba-137m
'End' or blank response exits input routine.
Nuclide ->?

As the nuclides are entered, they are written to a scratch file to be processed after the input is complete.

If the user had created a file, using an ASCII editor (or Windows notepad), in the work folder, then electing that option would result in a request to identify the file name

Input file name ->

The work folder \wrk\work2 contains the example file EXTLIST.INP for illustrative purposes. Entering EXTLIST will result in the following prompt (this prompt also appears after entering the nuclides of interest).
to indicate the environmental media within which the radionuclides are distributed. If “soil” is identified, then

```
Source media: (a)ir, (w)ater, or (s)oil ([a]/w/s)?
```

additional information on the distribution is requested

```
Distribution: (s)urface or (v)olume ([s]/v)?
```

Selecting a volume distribution results in an additional prompt concerning the depth to which the radionuclides are distributed

```
(1) cm, (5) cm, (15) cm, or (i)nfinite thickness? ->
```

The calculations then proceed based on the above information. The output file name is controlled by the EXTDOSE.INI file. The entries in that file of interest are

```
'dfful.sub'   , 'tabsubm.dat' , 0  table: submersion
'dfful.imm'   , 'tabwater.dat', 0  table: water immersion
'dffulsur.grd', 'tabsurf.dat' , 0  table: ground surface source
'dfful1.grd'  , 'tab1cm.dat'  , 0  table: 1 cm slab soil source
'dfful5.grd'  , 'tab5cm.dat'  , 0  table: 5 cm slab soil source
'dfful15.grd' , 'tab15cm.dat' , 0  table: 15 cm slab soil source
'dffulinf.grd', 'tabinfin.dat', 0  table: infinite slab soil source
```

Recall that the second field is the name assigned to the actual files and the text at the extreme right serves as a reminder of the file content. Thus, if we elect to evaluate the radionuclides distributed in air, the results of the calculations will be contained in the file TABSUM.DAT in the work folder. In addition, EXTDOSE, like the other computational modules, will check for the INI file in the work folder, thus enabling the user to make use of a INI specific to the particular work folder.

The screen output when the example input file is run is shown below.

```
      EXTDOSE: External Dose Calculation
         Ver. 5.0 (May 20, 2001)
Authors: K.F. Eckerman & J.C. Ryman
         Oak Ridge National Laboratory
         Oak Ridge, TN 37831-6480

 Use (f)ile or (i)nput nuclides ([f]/i)? f
 Input file name (ext INP assumed)-> extexamp
 Source media: (a)ir, (w)ater, or (s)oil ([a]/w/s)? a
Nuclide    T1/2    Dec Mode Photon Elect Beta
H-3        12.35y  B-          0    0    1
Co-60      5.271y  B-          6   40    3
I-131       8.04d  B-         25  129    6
Cs-137      30.0y  B-          0    0    2
Ba-137m    2.552m  IT          3   27    0
Th-232  1.405E10y A           23   32    0
 Elapsed time (100 s) =       5
Press any key to continue . . .
```

12. DCAL'S UTILITY ROUTINES

DCAL includes a number of utility routines which provide additional capabilities and access to the computational results. The utilities can be invoked either via the menu bar on DCAL's main men u or from the function keys while DCAL's main menu is displayed. In this chapter we briefly discuss these utilities.

12. 1. UTILITIES INVOKED FROM DCAL MAIN MENU

12.1. 1 View Work Files – List

This menu item enables the user to view the output files in the work folder, indicated by the <F4> key on DCAL's main menu display, for the current or active case (the case can be determined by press <F2>). Selecting this menu item invokes PBVIEW32.EXE residing in the BIN folder. From PBVIEW32's menu the file of interest can be selected for viewing on the screen. The arrow key (up and down, left and right) can be used to examine the file. See Fig. 5.1 for an example of PBVIEW32's display.

The popular shareware DOS utility LIST[3] can be used as an alternative to PBVIEW32. This DOS utility will be used by DCAL2005.EXE if LIST.COM is present in DCAL's BIN folder.

12.1.2 Plot Selected Data – PLOTEM

This menu item invokes the plotting facility, PLOTEM, which provides a visual inspection of the activity (ACT and CPT files) and dose rate files (DRT and HRT files) of the current interactive case. A series of menus are provided to select the specific data for plotting. This utility is not intended to produce publication quality plots but rather to provide for a prompt visual inspection of the data. The export utility EXPORTM (invoked by the <F9> key) can be used to export the data for input into a plotting program or spreadsheet program. Fig. 12.1 illustrates a plot of the ^{90}Sr and ^{90}Y activity in cortical bone following an ingestion intake by a worker.

PLOTEM is a 32 bit console application (executable is PLOT32.EXE) and functions in a manner typical of Windows applications; e.g., the mouse can be used to respond to its menus. The graphics are generated using DPlot Jr[4]. DPlot Jr provides a quick means to generate and display graphical output from a developer's code. Input to DPlot Jr is accomplished through Dynamic Data Exchange (DDE), with PLOTEM as the driving module. DPlot Jr lacks many of the editing and data input features of full-blown plotting package; e.g., as in DPlot[1], however its capability more than satisfies DCAL's needs.

When PLOTEM is invoked its initial menu lists the files; e.g., ACT, DRT, and HRT, associated with the current cases from which data might be selected for plotting as the "Files of type" option defaults to "Current DCAL Case." A menu of all the files in the work folder can be obtained by pulling down the "Files to type" window to show "All files". The file of interest is then selected and from subsequent menus the data set of interest selected for plotting; e.g., from an *.ACT file the activity in the source region "Blood" as a function of time. Multiple data sets can be plotted by selecting the data sets from the menu and then viewing the plots setting Windows' focus on the DPlot Jr screen (click on the screen).

PLOTEM's graphic of the Sr-90/Y-90 activity in the volume of cortical bone following an ingestion intake of Sr-90 is shown in Fig. 12.1. Note DPlot Jr's menu bar in the figure. Under the "Options" item the "Linear/Log Scaling" and the "Extent/Tick marks/Size…"entries can be used to change the type of *x*- and *y*-axis and their

[3] The LIST utility can be downloaded from /www.buerg.com/.

[4] DPlot Jr is available from HydeSoft Computing, Inc., 110 Roseland Drive, Vicksburg, MS 39180 and can be downloaded from the website www.dplot.com/index.htm.

numerical range. If multiple plots were requested from PLOTEM's menu they can be displayed via the "Window" item. Additional information regarding DPlot Jr's functions can be obtained from "Help" on the menu bar. Plots can be saved and printed from the "File" item.

To exit PLOTEM, use the Alt-Tab key combination to display PLOTEM's menu and click on "Cancel". You are then asked to close the DPlot Jr window, and then click on "Cancel" to return to the main menu display. The DCAL and DPlot Jr icons will be visible as you toggle the Alt-Tab key combination and then you can close DPlot Jr by clicking on the X button in the upper right corner of the display.

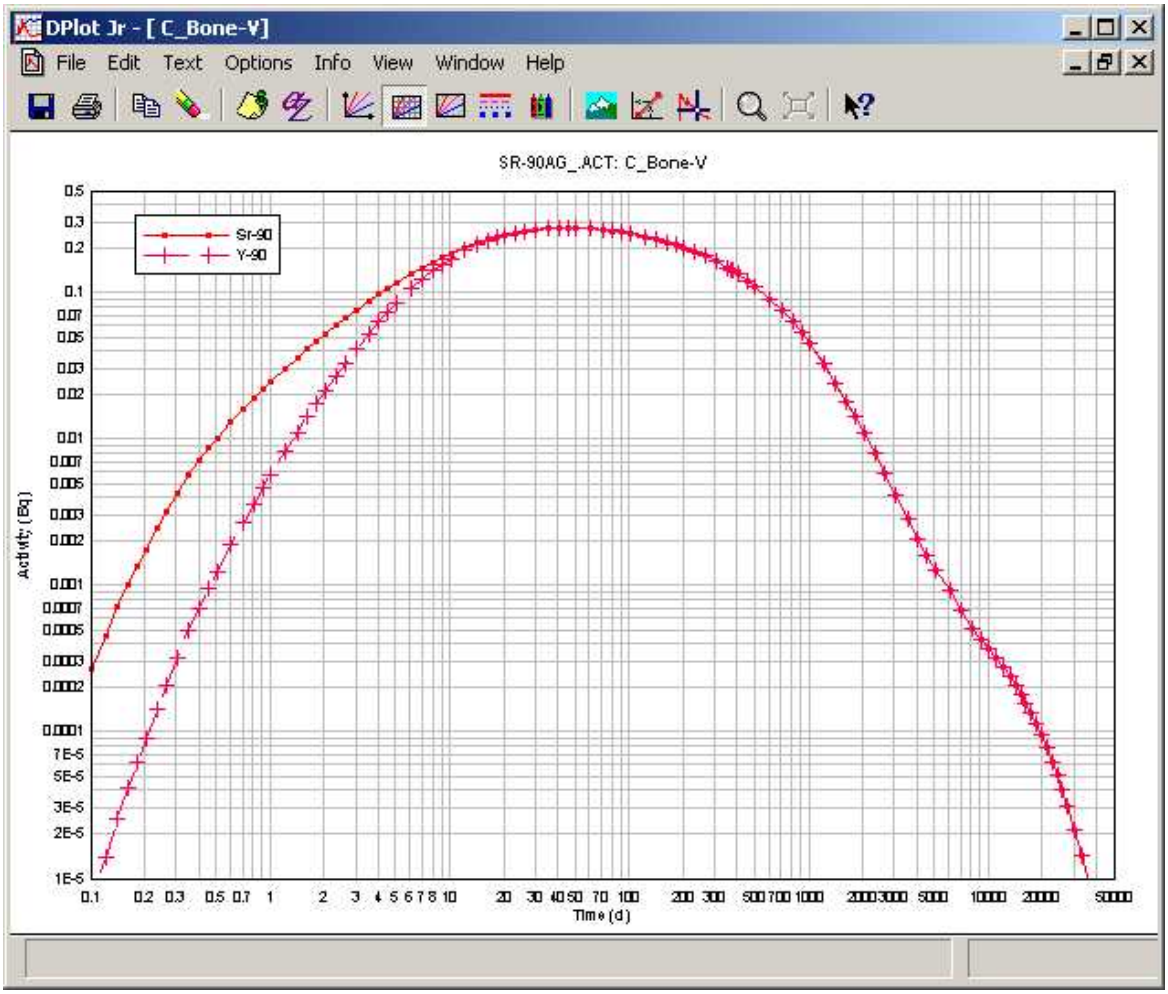


Fig. 12.1. DCAL's PLOTEM display. DPlot Jr graphic display of the Sr-90/Y-90 activity in the volume of cortical bone following an ingestion intake of 1 Bq by an adult.

12.1.3 Tabulate Dose Coefficients – HTAB

The utility HTAB can be used to tabulate the committed absorbed dose (EPACAL's output file *.DRT) or equivalent dose (EPACAL's output file *.HRT) dose coefficients. This utility can only be used in the interactive mode as the $STEMNAM.DIR file, written by ACTACAL, is used to identify the current case. The current or active case, the contents of $STEMNAM.DIR, can be displayed by pressing <F2>. If the user elected to compute absorbed dose then the summary table will list the low and high LET components of the absorbed dose. For inhalation cases, the user will be query as to whether the dose coefficients for the regions of the lung (ET1, ET2… AI) should be tabulated. The tabulation created by HTAB are saved as *.HEF when * is the root name of the active case. See Fig. 5.1 for an example of such a file.

12.1.4 Nuclide Emissions – RADSUM

This utility summarizes the emitted radiations of the user specified radionuclide. The utility displays a periodic chart and using the mouse the radioelement of interest is selected (see Fig. 12.2). If data for radioisotopes of the element are included in the nuclear decay data library a menu of available radionuclides is displayed. Clicking on the radionuclide of interest results in a summary display of its emission (see Fig. 12.3). The half-life, specific activity, and decay mode of the selected radionuclide are shown in the display. The emitted radiations are summarized is six categories; alpha, gamma rays, x-rays, beta -, beta +, internal conversion electrons, and Auger electrons. The number, frequency, total and average energy of the emissions in each category as well as the total over the categories are displayed. If the radionuclide decays by beta decay the average energy of the beta spectra is computed and displayed. For photon emitters the gamma constant in conventional units and SI units is also displayed. RADSUM does not provide any information regarding the emissions accompanying spontaneous fission. Finally, we note that users may create a shortcut to the RADSUM32.EXE to be able to invoke this module directly from the desktop without invoking DCAL.

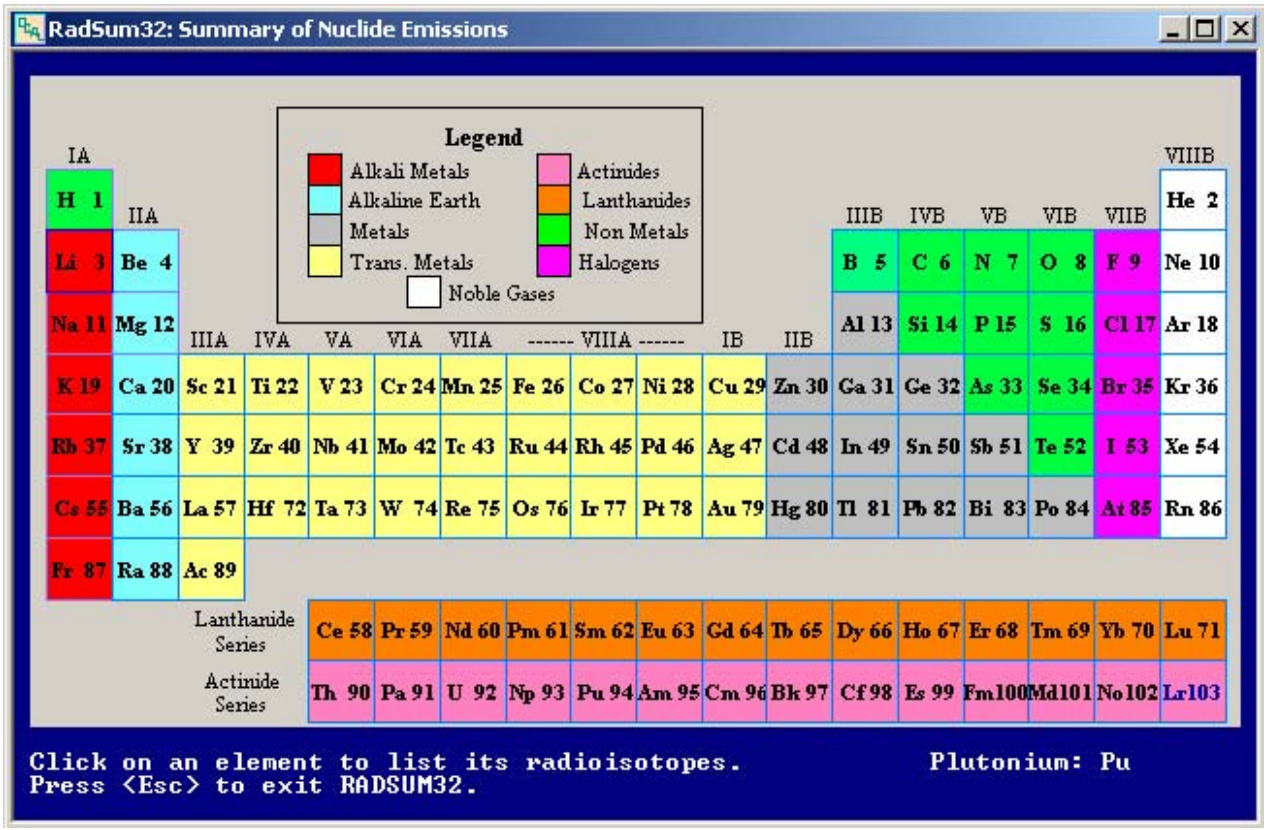


Fig. 12.2. RADSUM display from which the radioisotope of interest is selected. The position of the mouse is not evident in the figure. The information in the lower right corner is updated as the mouse is moved over the elements. A list of the radioisotopes of the element is displayed by clicking of an element

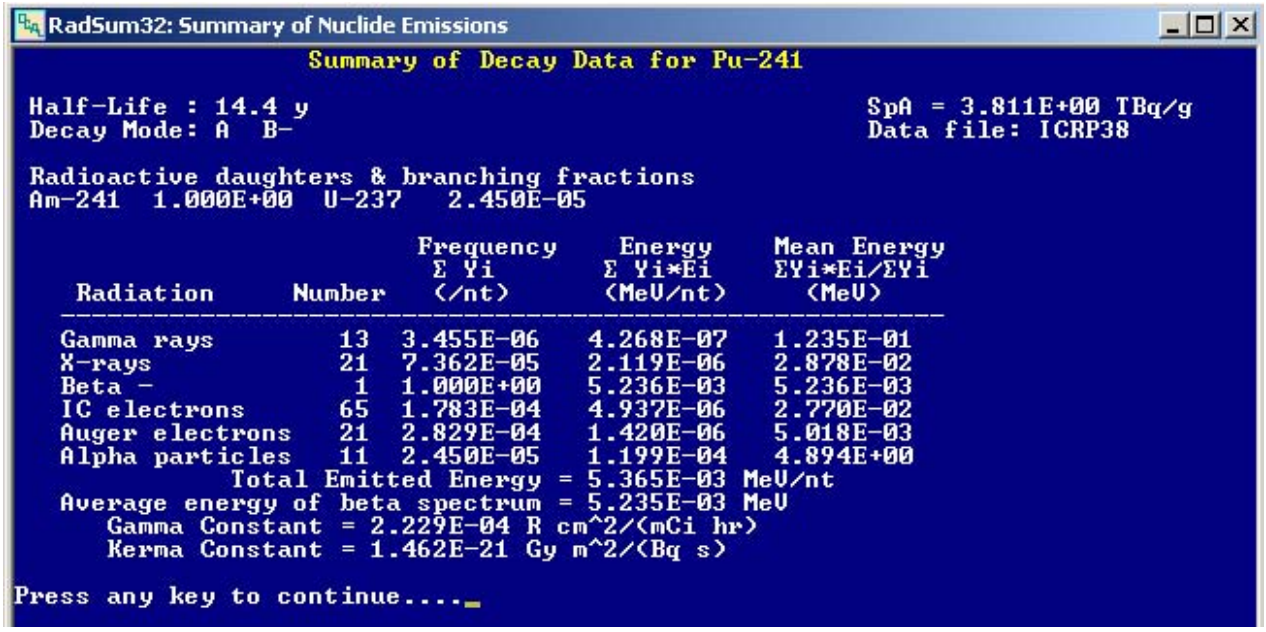


Fig. 12.3. RADSUM's summary table of the emissions of Pu-241. If the selected radionuclide decays to radioactive daughters the daughters and their branching fractions are listed in the display.

12.1.5 Decay Chain Details – CHAIN

This utility tabulates the decay chain for the specified radionuclide and tabulates the number of nuclear transformations over a 100-y period for each chain member as well as the cumulative energies, by type of radiation, over that period. The radionuclide of interest is selected in the manner of RADSUM (see Fig. 12.2).As an example, below is the tabulation for $^{90}Sr/^{90}Y$ chain.

```
Sr-90 Decay Chain: Half-lives and Branching Fractions
Nuclide  Halflife    f1     Nuclide   f2    Nuclide   f3   Nuclide
1 Sr-90   29.12y  1.0+00->  2 Y-90
2 Y-90    64.0h

Sr-90: Activity, Transformations, & Cumulative Energies (MeV) at 100y
Nuclide     T1/2     A(t)/Ao   intA/Ao(d)   Ealpha   Ebeta    Egamma
1 Sr-90    29.12y  9.25216D-02 1.39249D+04 0.00E+00 2.73E+03 0.00E+00
2 Y-90      64.0h  9.25448D-02 1.39246D+04 0.00E+00 1.57E+04 0.00E+00
```

The numerical values tabulated in the last three columns in CHAIN's second table above represent the cumulative energies emitted by alpha, beta (including discrete electrons), and photons (gamma and x-rays) for nuclear transformations occurring over 100 years in a sample consisting initially of 1 Bq of the parent. The third and fourth columns in the second table represent the fractional activity at 100 y and the fractional integrated activity (d) at 100 y, respectively for each chain member. The cumulative energies indicate for each chain member is a aid in determining whether the decay chain may be truncated without substantially affecting dose estimates. ACTACAL makes such a decision based on a virtual lack of increase in cumulative energy beyond some chain member; however it can be is useful to use the CHAIN utility to preview the situation.

The CHAIN utility uses information in the NDX files (for example, ICRP38.NDX) to construct the chain and compute the cumulative energies.

The serial transformation by radioactive decay of each member of a radioactive series is described by the

Bateman equations (EPA 1993). Assume that at time zero the activity of the parent nuclide is A_1^0 and that of all daughters is zero. The activity at time t of a chain member *i*, i = *1*, 2, ..., can be expressed as

$$\frac{A_i(t)}{A_1^0} = \prod_{j=1}^{i-1} f_{j,j+1}\,\lambda_j \sum_{j=1}^{i} \frac{e^{-\lambda_j t}}{\prod_{\substack{k=1 \\ k\neq j}}^{i} (\lambda_k - \lambda_j)} \qquad (12.1)$$

$$\prod_i^n a_i = \begin{cases} a_1\, a_2\, a_3 \ldots a_n\,, \text{ if } n \geq 1 \\ 1\,, \text{ if } n = 0 \end{cases}.$$

Where $f_{j,j+1}$ denotes denotes the fraction of the nuclear transformations of chain member *j* forming member *j+1*, and λ_i is the decay constant for nuclide *i* ($\lambda = 0.6931\ldots / T_{1/2}$). The number of nuclear transformations of a chain member *i*, $U_i(t)$, is given by

$$\frac{U_i(t)}{A_1^0} = \prod_{j=1}^{i-1} f_{j,\,j+1}\,\lambda_j \sum_{j=1}^{i} \frac{1 - e^{-\lambda_j t}}{\prod_{\substack{k=1 \\ k\neq j}}^{i} (\lambda_k - \lambda_j)}\,. \qquad (12.2)$$

The user should note that computations based on these formulations can suffer from loss in numerical significance when evaluating members of long chains and times near zero. However, this difficulty is not of great dosimetric significance. Finally, we note that users may create a shortcut to the CHAIN32.EXE to be able to invoke this module directly from the desktop without invoking DCAL.

12.1.6 Batch Calculations – DBATCH

Because of the importance of the batch utility within DCAL the utility was discussed in detail a separate chapter. See Chapter 6.

12.1.7 System Help – HELP

This utility provides some online helpful information regarding DCAL and its various output files.

12.2 UTILITIES INVOKED BY FUNCTION KEYS

A number of DCAL utilities are invoked by the function keys <F1> - F<11>. The keys <F1> - F<5> have been discussed above and, completeness, are included briefly here. These keys are displayed at the bottom of DCAL's main menu. Keys <F6> - <F11> can be displayed by pressing the space bar when the main menu is active.

12.2.1 Help: <F1> Key

The key displays a brief message regarding the function of the DCAL main menu item upon which the select bar is positioned.

12.2.2 Active Case: <F2> Key

This key displays the content of the $STEMNAM.DIR file which identifies the current or active case being processed in an interactive manner. This key can be helpful if an interactive session has been interrupted.

12.2.3 <F3> =: <F3> key

The biokinetic folder to be used in the calculations is displayed with the "<F3> =" label at the bottom of the main menu display. This key can be used to select the biokinetic folder of interest or create a new folder. Note the current folder will be used in both the interactive and batch sessions.

12.2.4 <F4>=: <F4> key

The work folder which will contain output files created during the session is displayed with the "<F4>=" label at the bottom of the main menu display. This key can be used to select a work folder or create a new folder. Note the work folder will be used in both the interactive and batch sessions. The batch utility is selected from DCAL's main menu looks for suitable input files (*.INP) in the work folder (see Chapter 6).

12.2.5 About: <F5> key

This key displays a list the authors of DCAL and the sponsor; the U.S. Environmental Protection Agency.

12.2.6 ACTINT Utility: <F6> Key

This utility computes the number of nuclear transformations (Bq s) per Bq-intake over a 50-year period following an intake of the parent radionuclide. The utility can be run following ACTACAL calculations. If the user had requests that ACTACAL tabulate the activity as a function of time in the compartments (CPT file) as well as in source regions (ACT file), then the utility will process both files and report the results in a single output file. The name of the output file is composed of the root of the ACT file name with an extension U50.

If ACTACAL was run for a stable element (e.g., Ca), the utility tabulates the integral of the fraction of the intake residing in the compartments in seconds. For example the integral might be considered as g-s per g intake in the compartment or source region.

12.2.7 DRTINT Utility: <F7> Key

This utility integrates the calculated dose rates following the intake over user defined time periods. Values for the dose rate and committed dose are calculated by EPACAL, and the utility HTAB (available on the main menu) provides a tabulation of the committed values (either absorbed or equivalent dose). DRTINT provides additional capability by letting the user define the lower and upper time limits on the dose rate integral. The integration times are specified in the DRTINT.INI file in the INI folder or by a DRTINT.INI file located in the work folder. The former is referred to as the global INI file and the latter is the local INI file. The installed INI file is listed below. The name given the output file has the root of the DRT or HRT file being processed with the extension INT assigned.

```
DRTINT.INI file defines the limits of integration of the dose
rate files.  DRTINT is limited to 500 times in days.
START Input  <- Starting delimiter
0.0 1.0
1.0 2.0
2.0 3.0
0.0 3.0
0.0 30.0
0.0 365.0
0.0 18250.0
END Input  <- Ending delimiter
```

12.2.8 BIOTAB Utility: <F8> Key

This utility tabulates the fraction of the intake expected to be excreted in 24-hr urine and fecal samples at various times following an acute intake. In addition, the fraction of the activity retained in the body is also tabulated. Data are presented for all members of the decay chain, all expressed in terms of a unit intake of the parent member. If in response to ACTACAL's request for the name of the radionuclide only the chemical symbol is given (DCAL's calculations are for the stable element) then BIOTAB's tabulation represents the expected 24 h excretion and retention of the stable element. BIOTAB is applicable to both workers (adults) and member of the public, including children. The urine (and fecal) excretion rates are derived by integrating over

24 hr the product of the time-dependent contents of the urinary bladder (and lower large intestine) and its removal rate constant. The fractional removal rate from the urinary bladder depends on age (or time) and BIOTAB.INI provides the utility with the location of the ICRP67.BLD file containing these data. The name of the output file is derived from the root of the ACT file with the extension EUD.

12.2.9 EXPORTM Utility: <F9> Key

This utility will export the time dependent activity in CPT and ACT files and the time dependent dose rates in DRT and HRT into an Excel spreadsheet. This utility remains under development at this time.

12.2.10 DcalSys Utility: <F10> Key

This function key invokes the utility DCALSYS.EXE which generates a listing of DCAL's executable files and data libraries. The utility creates a file, DCALFILE.TXT, in DCAL's root folder. This file can be compared to the file, DCALSYS.TXT, in the root folder which lists the files installed by the installation procedure. This utility is provided as a mean to verify that DCAL's files have not been corrupted.

12.2.11 Manual: <F11> Key

This key displays the pdf of this documentation. It is necessary the extension *pdf* has been registered by Windows to be opened by a suitable viewer; e.g., Adobe Acrobat Reader. Acrobat Reader can be obtained from www.adobe.com.

13. SUMMARY AND CONCLUSIONS

This version of the DCAL software has been used to prepare a number of federal guidance reports and publications of the ICRP. Specifically, this release of the software is that used to produce *Federal Guidance Report 13* (EPA 1999). DCAL has demonstrated that a single PC-based software package would serve both interactive and production calculations. Further development of DCAL is underway. Specifically this will encompass:

- Development of a Windows version of the software.
- Inclusion of a more detailed treatment of gender,
- Inclusion of spontaneous fission within SEECAL,
- Consideration of chronic intakes,
- Inclusion of a module for calculation of deposition in respiratory tract,
- Inclusion of a module for evaluation of genetic risk,
- Addition of the risk modules into the menu.

In addition, updating of many of the data libraries is in progress:

- Updating the nuclear decay data files,
- Integrating information on bremsstrahlung into the nuclear decay files,
- Incorporating the year 2000 decennial cancer mortality data and life tables,
- Incorporating newer biokinetic data,
- Including newer SAF data for the various radiations.

Extension of DCAL to consider *in utero* exposures remains to be addressed. DCAL is expected to remain the basis for the calculation of dose and risk by the Dosimetry Research Group and thus the software will remain under active development.

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REFERENCES

Birchall, A. and A. C. James. 1989. "A Microcomputer Algorithm for Solving First-Order Compartmental Models Involving Recycling." *Health Phys*. **56**, 857-868.

Cristy, M. and K. F. Eckerman. 1987. *Specific Absorbed Fractions of Energy at Various Ages from Internal Photon Sources*. ORNL/TM-8381/V1-7, Oak Ridge National Laboratory, Oak Ridge, TN.

Cristy, M. and K. F. Eckerman. 1993. *SEECAL: Program to Calculate Age-Dependent Specific Effective Energies.* ORNL/TM-12351, Oak Ridge National Laboratory, Oak Ridge, TN.

Eckerman, K. F., et al. 1993. *Nuclear Decay Data Files of the Dosimetry Research Group*. ORNL/TM-12350, Oak Ridge National Laboratory, Oak Ridge, TN.

de Boor, C. A. 1978. *Practical Guide to Splines. Applied Mathematical Sciences, Vol. 27.* Springer-Verlag, New York.

U. S. Environmental Protection Agency (EPA). 1993. *External Exposure to Radionuclides in Air, Water, and Soil, Federal Guidance Report 12*. EPA-402-R-93-081, Oak Ridge National Laboratory, Oak Ridge, Tenn.; U. S. Environmental Protection Agency, Washington, DC.

U. S. Environmental Protection Agency (EPA). 1994. *Estimating Radiogenic Cancer Risks.* EPA 402-R-93-076, U. S. Environmental Protection Agency, Washington, DC.

U. S. Environmental Protection Agency (EPA). 1999. *Cancer Risk Coefficients for Environmental Exposure to Radionuclides, Federal Guidance Report 13*. EPA-402/R-99-001, Oak Ridge National Laboratory, Oak Ridge, Tenn.; U. S. Environmental Protection Agency, Washington, DC.

Fritsch, F. N. and J. A. Butland. 1982. *A Method for Constructing Local Monotone Piecewise Cubic Interpolants*. UCRL-87559.

Fritsch, F. N. and R. E. Carlson. 1980. "Monotone Piecewise Cubic Interpolation," *SIAM J. Numer. Anal.* **17**, 238-246.

I*nternational Commission on Radiological Protection (ICRP). 1959. Report of Committee II on Permissible Dose of Internal Radiation. ICRP Publication 2, Pergamon Press, Oxford.*

International Commission on Radiological Protection (ICRP). 1975. Report of the Task Group on Reference Man. ICRP Publication 23, Pergamon Press, Oxford.

International Commission on Radiological Protection (ICRP). 1979. Limits for Intakes by Workers. ICRP Publication 30, Part 1, Pergamon Press, Oxford.

International Commission on Radiological Protection (ICRP). 1980. Limits for Intakes by Workers. ICRP Publication 30, Part 2, Pergamon Press, Oxford.

International Commission on Radiological Protection (ICRP). 1981. *Limits for Intakes by Workers*. ICRP Publication 30, Part 3, Pergamon Press, Oxford.

International Commission on Radiological Protection (ICRP). 1983. *Radionuclide Transformations Energy and Intensity of Emission.* ICRP Publication 38, Pergamon Press, Oxford.

International Commission on Radiological Protection (ICRP). 1988. *Limits for Intakes by Workers: An Addendum.* ICRP Publication 30, Part 4, Pergamon Press, Oxford.

International Commission on Radiological Protection (ICRP). 1989. *Age-Dependent Doses to Members of the Public from Intake of Radionuclides, Part 1*. ICRP Publication 56, Pergamon Press, Oxford.

International Commission on Radiological Protection (ICRP). 1991. *1990 Recommendations of the International Commission on Radiological Protection*. ICRP Publication 60, Pergamon Press, Oxford.

International Commission on Radiological Protection (ICRP). 1992. *The Biological Basis for Dose Limitation in the Skin.* ICRP Publication 59, Pergamon Press, Oxford.

International Commission on Radiological Protection (ICRP). 1993. *Age-Dependent Doses to Members of the Public from Intake of Radionuclides, Part 2.* ICRP Publication 67, Pergamon Press, Oxford.

International Commission on Radiological Protection (ICRP). 1994a. *Human Respiratory Tract Model for Radiological Protection.* ICRP Publication 66, Pergamon Press, Oxford.

International Commission on Radiological Protection (ICRP). 1994b. *Dose Coefficients for Intakes of Radionuclides by Workers.* ICRP Publication 68, Pergamon Press, Oxford.

International Commission on Radiological Protection (ICRP). 1995a. *Age-Dependent Doses to Members of the Public from Intake of Radionuclides, Part 3*. ICRP Publication 69, Pergamon Press, Oxford.

International Commission on Radiological Protection (ICRP). 1995b. *Age-Dependent Doses to Members of the Public from Intake of Radionuclides, Part 4.* ICRP Publication 71, Pergamon Press, Oxford.

International Commission on Radiological Protection (ICRP). 1996. *Age-Dependent Doses to Members of the Public from Intake of Radionuclides, Part 5. Compilation of Ingestion and Inhalation Dose Coefficients*. ICRP Publication 72, Pergamon Press, Oxford.

Killough, G. G. and K. F. Eckerman. 1984. "A Conversational Eigenanalysis Program for Solving Differential Equations," In: *Computer Applications in Health Physics*, 4.49-4.58. Proceedings of the 17th Midyear Topical Symposium of the Health Physics Society. Eds. R. L. Kathren, D. P. Higby, and M. A. McKinney.

Kocher, D. C. and K.F. Eckerman. 1988. External Dose Rate Conversion Factors for Calculations of Dose to the Public. DOE/EH-0070.

Leggett, R. W., D. E. Dunning, Jr., and K. F. Eckerman. 1984. "Modelling the Behaviour of Chains of Radionuclides Inside the Body. *Radiat. Prot. Dosim.* ***9***, 77-91.

Leggett, R. W., K. F. Eckerman, and L. R. Williams. 1993. "An Elementary Method for Implementing Complex Biokinetic Models. *Health Phys.* ***64***, 260-278.

National Center for Health Statistics (NCHS). 1992. *Vital Statistics Mortality Data, Detail, 1989.* NTIS order number for data file tapes: PB92-504554, Hyattsville, MD.

National Center for Health Statistics (NCHS). 1993a. *Vital Statistics Mortality Data, Detail, 1990*. NTIS order number for data file tapes: PB93-504777, Hyattsville, MD.

National Center for Health Statistics (NCHS). 1993b. *Vital Statistics Mortality Data, Detail, 1991*. NTIS order number for data file tapes: PB93-506889, Hyattsville, MD.

National Center for Health Statistics (NCHS). 1997. *U. S. Decennial Life Tables for 1989-91*, Vol. 1, No. 1. DHHS, PHS-98-1150-1, Washington, DC.

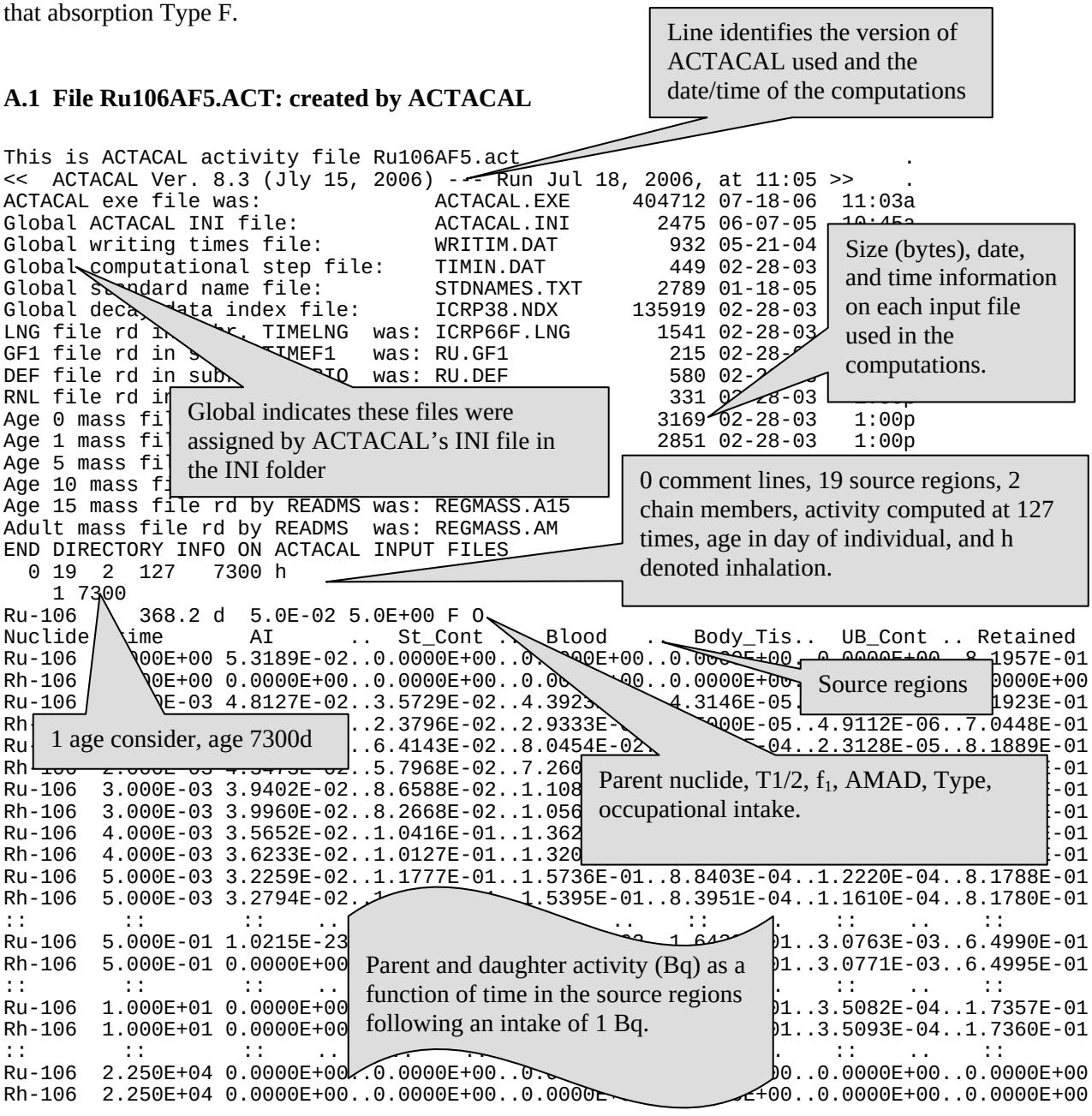
Smith, B. T., et al. 1974. *Matrix Eigensystem Routines-EISPACK Guide*. Springer-Verlag, New York.

Weber, D. A., et al. 1989. *MIRD: Radionuclide Data and Decay Schemes.* Society of Nuclear Medicine, New York.

APPENDIX A
ANNOTATED LISTINGS OF DCAL OUTPUT FILES

This appendix contains an annotated set of DCAL's output files to highlight items that are critical to not only in the user reviewing his calculations but also to quality assurance. The complete set of output files created by DCAL's computational and utility modules are presented for the inhalation of ^{106}Ru by a worker; the aerosol is assumed to be characterized by and activity median aerodynamic diameter of 5 μm and the chemical form is that absorption Type F.

A.1 File Ru106AF5.ACT: created by ACTACAL




```
This is ACTACAL activity file Ru106AF5.act                              .
<<  ACTACAL Ver. 8.3 (Jly 15, 2006) --- Run Jul 18, 2006, at 11:05 >>    .
ACTACAL exe file was:              ACTACAL.EXE     404712 07-18-06  11:03a
Global ACTACAL INI file:           ACTACAL.INI       2475 06-07-05  10:45a
Global writing times file:         WRITIM.DAT         932 05-21-04
Global computational step file:    TIMIN.DAT          449 02-28-03
Global standard name file:         STDNAMES.TXT      2789 01-18-05
Global decay data index file:      ICRP38.NDX      135919 02-28-03
LNG file rd in subr. TIMELNG  was: ICRP66F.LNG       1541 02-28-03
GF1 file rd in subr. TIMEF1   was: RU.GF1             215 02-28-03
DEF file rd in subr. DEFIO    was: RU.DEF             580 02-28-03
RNL file rd in                                        331 02-28-03
Age 0 mass fi                                        3169 02-28-03   1:00p
Age 1 mass fi                                        2851 02-28-03   1:00p
Age 5 mass fi
Age 10 mass fi
Age 15 mass file rd by READMS was: REGMASS.A15
Adult mass file rd by READMS  was: REGMASS.AM
END DIRECTORY INFO ON ACTACAL INPUT FILES
  0 19  2  127   7300 h
    1 7300
Ru-106     368.2 d  5.0E-02 5.0E+00 F O
Nuclide  Time       AI      ..  St_Cont ..  Blood   ..  Body_Tis..  UB_Cont .. Retained
Ru-106    0.000E+00 5.3189E-02..0.0000E+00..0.000E+00..0.000E+00..0.0000E+00..8.1957E-01
Rh-106    0.000E+00 0.0000E+00..0.0000E+00..0.000E+00..0.0000E+00..0.0000E+00..0.0000E+00
Ru-106    1.000E-03 4.8127E-02..3.5729E-02..4.3923E-03..4.3146E-05..1.9923E-01
Rh-106    1.000E-03 4.8127E-02..2.3796E-02..2.9333E-03..2.9000E-05..4.9112E-06..7.0448E-01
Ru-106    2.000E-03 4.8127E-02..6.4143E-02..8.0454E-02..7.8104E-04..2.3128E-05..8.1889E-01
Rh-106    2.000E-03 4.8127E-02..5.7968E-02..7.260                                  ..7.0448E-01
Ru-106    3.000E-03 3.9402E-02..8.6588E-02..1.108                                  ..8.1889E-01
Rh-106    3.000E-03 3.9960E-02..8.2668E-02..1.056                                  ..7.0448E-01
Ru-106    4.000E-03 3.5652E-02..1.0416E-01..1.362                                  ..8.1889E-01
Rh-106    4.000E-03 3.6233E-02..1.0127E-01..1.320                                  ..7.0448E-01
Ru-106    5.000E-03 3.2259E-02..1.1777E-01..1.5736E-01..8.8403E-04..1.2220E-04..8.1788E-01
Rh-106    5.000E-03 3.2794E-02..1.1                     1.5395E-01..8.3951E-04..1.1610E-04..8.1780E-01
::          ::        ::    ..                          ..    ::    ..    ::    ..    ::
Ru-106    5.000E-01 1.0215E-23                                  1.643                01..3.0763E-03..6.4990E-01
Rh-106    5.000E-01 0.0000E+00                                                       01..3.0771E-03..6.4995E-01
::          ::        ::    ..                                                  ..    ::    ..    ::
Ru-106    1.000E+01 0.0000E+00                                                       01..3.5082E-04..1.7357E-01
Rh-106    1.000E+01 0.0000E+00                                                       01..3.5093E-04..1.7360E-01
::          ::        ::    ..    ..    ..                                    ..    ::    ..    ::
Ru-106    2.250E+04 0.0000E+00..0.0000E+00..0.0                                    00..0.0000E+00..0.0000E+00
Rh-106    2.250E+04 0.0000E+00..0.0000E+00..0.0000E                                +00..0.0000E+00..0.0000E+00
```

A.2 File Ru106AF5.REQ: created by ACTACAL

This file provides the SEECAL module with the information needed to compute the relevant SEE values.

```
This is user request file Ru106AF5.REQ
..\..\dat\nuc\icrp38.ndx
TITLE                    | Delimiter TITL
<<  ACTACAL Ver. 8.3 (Jly 15, 2006) --- Run Jul 18, 2006, at 11:05 >>
END TITLE                | Delimiter END TITLE
NUCLIDES                 | Delimiter NUCLIDES
Ru-106                   |
Rh-106                   |
END NUCLIDES             | Delimiter END NUCLIDES
EQUIVALENT DOSE          |
TOTAL ONLY               | Table type
AGE GROUPS               | Delimeter AGE GROUPS
Adult Male               |
END AGE GROUPS           | Delimeter END AGE GROUPS
SOURCE REGIONS           | Delimeter SOURCE REGIONS
AI                       |
bbe-gel                  |
bbe-sol                  |
bbe-seq                  |
BBi-gel                  |
BBi-sol                  |
BBi-seq                  |
ET2-sur                  |
ET1-sur                  |
ET2-seq                  |
LN-Th                    |
LN-ET                    |
St_Cont                  |
SI_Cont                  |
Blood                    |
ULI_Cont                 |
LLI_Cont                 |
Body_Tis                 |
UB_Cont                  |
END SOURCE REGIONS       | Delimeter END SOUR
TARGET REGIONS           | Delimeter TARGET REGIONS
Adrenals                 |
UB_Wall                  |
Bone_Sur                 |
Brain                    |
Breasts                  |
  //                  //
  ||                  ||
  //                  //
Ht_Wall                  |
Uterus                   |
END TARGET REGIONS       | Delimeter END TARG
```

Identifies the nuclear decay data set used by ACTACAL which SEECAL is to use.

Source regions for which ACTACAL has compute the time dependent activity and thus SEECAL must provide the SEE values for these regions.

Set of target organs/tissues for which SEEs are needed. This set is not dependent on the case being computed.

A.3 File Ru106HT.SEE: created by SEECAL

Note a similar file (Rh106HT.SEE) is also created for the 106Rh daughter.

```
This is SEECAL file Ru106ht.SEE
<< SEECAL   Ver. 8.4 (Jly 15, 2006) --- Run Jul 18, 2006, at 11:05 >>
SEECAL exe file was:               SEECAL.EXE      288080 07-15-06  10:01a
Global SEECAL INI file:            SEECAL.INI        1415 09-04-05   1:23p
User request file was:             RU106AF5.REQ      5158 07-18-06  11:05a
File with standard names was:      STDNAMES.TXT      2789 01-18-05   3:47p
1 = number of age groups
Photon SAF file was:               PSAFTX66.AM
Electron-alpha AF file was:
Region mass file was:              REGMASS.AM
1 = number of title lines, copied from file RU
<<  ACTACAL Ver. 8.3 (Jly 15, 2006) --- Run Jul 18, 2006, at 11:05 >>
Following 3 lines identify the nuclide decay files
Index file was:                    ICRP38.NDX      135919 02-28-03   1:00p
Radiation data file was:           ICRP38.RAD     5971698 02-28-03   1:00p
Beta spectrum data file was:       ICRP38.BET      684882 02-28-03   1:00p
'equivalent dose' = dose type (equivalent dose or absorbed dose)
'total only' = table type (full table, total only, or low-hi let)
'Ru-106 ','   368.2 d ','B-      ' = nuclide, half-life, decay mode
'n' 'n' 'y' 'n' 'n' 'n' = flags for Ph<10, Ph>=10, Beta, Elec, Alpha, SpFiss
Age Group Name
'Adult Male          '
19, 7, 3 = # of source regions, # of source regions/page, # of pages/age
S. Region  Masses (kg) for each age group, in order as above
'AI      ' 0.00E+00
'bbe-gel ' 0.00E+00
 //              //
 ||              ||
 //              //
'Body_Tis' 6.88E+01
'UB_Cont ' 1.20E-01
31 = number of target regions
T. Region  Masses (kg) for each age group, in order as above
'Adrenals' 1.40E-02
'UB_Wall ' 4.50E-02
 //              //
 ||              ||
 //              //
'Ht_Wall ' 3.30E-01
'Uterus  ' 8.00E-02
equivalent dose (Sv/nt) for Ru-106  & Age=Adult Male          , p. 1 of 3      .
TARGETS RAD_____________________________SOURCE REGIONS_____________________________.
------- ---AI        bbe-gel   bbe-sol   bbe-seq   BBi-gel   BBi-sol   BBi-seq  .
Adrenals t 0.0       0.0       0.0       0.0       0.0       0.0       0.0      0
UB_Wall  t 0.0       0.0       0.0       0.0       0.0       0.0       0.0      0
Bone_Sur t 0.0       0.0       0.0       0.0       0.0       0.0       0.0      0
Brain    t 0.0       0.0       0.0       0.0       0.0       0.0       0.0      0
Breasts  t 0.0       0.0                                                 0.0      0
St_Wall  t 0.0       0.0                                                 0.0      0
SI_Wall  t 0.0       0.0                                                 0.0      0
ULI_Wall t 0.0       0.0                                                 0.0      0
LLI_Wall t 0.0       0.0                                                 0.0      0
Kidneys  t 0.0       0.0       0.0       0.0       0.0       0.0       0.0      0
Liver    t 0.0       0.0       0.0       0.0       0.0       0.0       0.0      0
ET1-bas  t 0.0       0.0       0.0       0.0       0.0       0.0       0.0      0
ET2-bas  t 0.0       0.0       0.0       0.0       0.0       0.0       0.0      0
LN-ET    t 0.0       0.0       0.0       0.0       0.0       0.0       0.0      0
BBi-bas  t 0.0       0.0       0.0       0.0       0.0       0.0       1.988E-15
BBi-sec  t 0.0       0.0       0.0       0.0       4.196E-17 1.589E-15 7.447E-19
bbe-sec  t 6.025E-22 4.898E-15 1.737E-14 2.153E-15 0.0       0.0       0.0      0
AI       t 1.461E-15 0.0       0.0       0.0       0.0       0.0       0.0      0
LN-Th    t 0.0       0.0       0.0       0.0       0.0       0.0       0.0      0
Muscle   t 0.0       0.0       0.0       0.0       0.0       0.0       0.0      0
```

List of the files and their attributes being used by SEECAL.

The 19 source regions established by ACTACAL for which SEE values are provided.

The 31 target organs for which SEE values are tabulated.

Equivalent dose (Sv) in target per nt in source or equivalent dose rate (Sv/s) in target per Bq in source region.

Ovaries	t	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
Pancreas	t	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
R_Marrow	t	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
Skin	t	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
Spleen	t	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
Testes	t	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
Thymus	t	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
Thyroid	t	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
GB_Wall	t	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
Ht_Wall	t	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
Uterus	t	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0

equivalent dose (Sv/nt) for Ru-106 & Age=Adult Male , p. 3 of 3 .

TARGETS RAD		SOURCE REGIONS				
-------	---	Blood	ULI_Cont	LLI_Cont	Body_Tis	UB_Cont
Adrenals	t	2.335E-17	0.0	0.0	2.335E-17	0.0
UB_Wall	t	2.335E-17	0.0	0.0	2.335E-17	6.696E-15
Bone_Sur	t	2.335E-17	0.0	0.0	2.335E-17	0.0
Brain	t	2.335E-17	0.0	0.0	2.335E-17	0.0
Breasts	t	2.335E-17	0.0	0.0	2.335E-17	0.0
St_Wall	t	2.335E-17	0.0	0.0	2.335E-17	0.0
SI_Wall	t	2.335E-17	0.0	0.0	2.335E-17	0.0
ULI_Wall	t	2.335E-17	3.652E-15	0.0	2.335E-17	0.0
LLI_Wall	t	2.335E-17	0.0	5.952E-15	2.335E-17	0.0
Kidneys	t	2.335E-17	0.0	0.0	2.335E-17	0.0
Liver	t	2.335E-17	0.0	0.0	2.335E-17	0.0
ET1-bas	t	2.335E-17	0.0	0.0	2.335E-17	0.0
ET2-bas	t	2.335E-17	0.0	0.0	2.335E-17	0.0
LN-ET	t	2.335E-17	0.0	0.0	2.335E-17	0.0
BBi-bas	t	2.335E-17	0.0	0.0	2.335E-17	0.0
BBi-sec	t	2.335E-17	0.0	0.0	2.335E-17	0.0
bbe-sec	t	2.335E-17	0.0	0.0	2.335E-17	0.0
AI	t	2.335E-17	0.0	0.0	2.335E-17	0.0
LN-Th	t	2.335E-17	0.0	0.0	2.335E-17	0.0
Muscle	t	2.335E-17	0.0	0.0	2.335E-17	0.0
Ovaries	t	2.335E-17	0.0	0.0	2.335E-17	0.0
Pancreas	t	2.335E-17	0.0	0.0	2.335E-17	0.0
R_Marrow	t	2.335E-17	0.0	0.0	2.335E-17	0.0
Skin	t	2.335E-17	0.0	0.0	2.335E-17	0.0
Spleen	t	2.335E-17	0.0	0.0	2.335E-17	0.0
Testes	t	2.335E-17	0.0	0.0	2.335E-17	0.0
Thymus	t	2.335E-17	0.0	0.0	2.335E-17	0.0
Thyroid	t	2.335E-17	0.0	0.0	2.335E-17	0.0
GB_Wall	t	2.335E-17	0.0	0.0	2.335E-17	0.0
Ht_Wall	t	2.335E-17	0.0	0.0	2.335E-17	0.0
Uterus	t	2.335E-17	0.0	0.0	2.335E-17	0.0

A.4 File Ru106HT.SEE: created by EPACAL

```
This is EPACAL dose rate file Ru106AF5.hrt
<<   EPACAL Ver. 8.4 (Jly 15, 2006) --- Run Jul 18, 2006, at 11:05 >>
EPACAL exe file was:              EPACAL.EXE      261656 07-15-06   9:58a
Global EPACAL ini file:           EPACAL.INI          48 12-23-03   5:41p
Global lung apportionment file:   LUNGAS.DAT         357 09-04-05   5:03p
Activity file was:                RU106AF5.ACT      66203 07-18-06  11:05a
... Following info is from file RU106AF5.ACT:
<<  ACTACAL Ver. 8.3 (Jly 15, 2006) --- Run Jul 18, 2006, at 11:05 >>
ACTACAL exe file was:             ACTACAL.EXE     404712 07-18-06  11:03a
Global ACTACAL INI file:          ACTACAL.INI       2475 06-07-05  10:45a
Global writing times file:        WRITIM.DAT         932 05-21-04   3:34p
Global computational step file:   TIMIN.DAT          449 02-28-03   1:00p
Global standard name file:        STDNAMES.TXT      2789 01-18-05   3:47p
Global decay data index file:     ICRP38.NDX      135919 02-28-03   1:00p
LNG file rd in subr. T
GF1 file rd in subr. T
DEF file rd in subr. T
RNL file rd in subr. TIMEBLD  was: ICRP67.BLD         331 02-28-03   1:00p
Age 0 mass file rd by READMS  was: REGMASS.A00       3169 02-28-03   1:00p
Age 1 mass file rd by READMS  was: REGMASS.A01       2851 02-28-03   1:00p
Age 5 mass file rd by READMS  was: REGMASS.A05       2849 02-28-03   1:00p
Age 10 mass file rd by READMS was: REGMASS.A10       2850 02-28-03   1:00p
Age 15 mass file rd by READMS was: REGMASS.A15       2965 02-28-03   1:00p
Adult mass file rd by READMS  was: REGMASS.AM        2995 02-28-03   1:00p
END DIRECTORY INFO ON ACTACAL INPUT FILES
  0 19  2  127   7300 h  nTitle, nSOrg, nNuc, NumTim, ExpAge, InMode
    1 7300
Ru-106     368.2 d  5.0E-02 5.0E+00 F O
19 = number of source organs
... End of info from file RU106AF5.ACT
SEE input file was:               RU106HT.SEE      14596 07-18-06  11:05a
SEE input file was:
... Following info is f
<< SEECAL   Ver. 8.4 (J
SEECAL exe file was:
Global SEECAL INI file:           SEECAL.INI        1415 09-04-05   1:23p
User request file was:            RU106AF5.REQ      5158 07-18-06  11:05a
File with standard names was:     STDNAMES.TXT      2789 01-18-05   3:47p
1 = number of age groups
Photon SAF file was:              PSAFTX66.AM     271721 09-11-04   6:57p
Electron-alpha AF file was:       ELALPHAF.AM       2344 02-28-03   1:00p
Region mass file was:             REGMASS.AM        2995 02-28-03   1:00p
1 = number of title lines, copied from file RU106AF5.REQ, that follow:
<<  ACTACAL Ver. 8.3 (Jly 15, 2006) --- Run Jul 18, 2006, at 11:05 >>
Following 3 lines identify the nuclide decay files
Index file was:                   ICRP38.NDX      135919 02-28-03   1:00p
Radiation data file was:          ICRP38.RAD     5971698 02-28-03   1:00p
Beta spectrum data file was:      ICRP38.BET      684882 02-28-03   1:00p
... End of info from file RU106HT.SEE
... Following info is from file RH106HT.SEE :
<< SEECAL   Ver. 8.4 (Jly 15, 2006) --- Run Jul 18, 2006, at 11:05 >>
SEECAL exe file was:              SEECAL.EXE      288080 07-15-06  10:01a
Global SEECAL INI file:           SEECAL.INI        1415 09-04-05   1:23p
User request file was:            RU106AF5.REQ      5158 07-18-06  11:05a
File with standard names was:     STDNAMES.TXT      2789 01-18-05   3:47p
Following 3 lines identify the nuclide decay files
Index file was:                   ICRP38.NDX      135919 02-28-03   1:00p
Radiation data file was:          ICRP38.RAD     5971698 02-28-03   1:00p
Beta spectrum data file was:      ICRP38.BET      684882 02-28-03   1:00p
... End of info from file RH106HT.SEE
END HEADER RECORDS
 7300.0 d, or 20.00 y = exposure age (from activity file)
127 = # of times (from activity file)
Time array, in days (from activity file):
```

List of all files and their attributes used in the calculations.

Equivalent dose rate (Sv/d) in the adrenals per Bq of intake by the route specified in ACTACAL.

```
 0.000E+00 1.000E-03 2.000E-03 3.000E-03 4.000E-03 5.000E-03 6.000E-03 7.000E-03
 8.000E-03 9.000E-03 1.000E-02 1.200E-02 1.400E-02 1.600E-02 1.800E-02 2.000E-02
 2.300E-02 2.600E-02 3.000E-02 3.500E-02 4.000E-02 4.500E-02 5.000E-02 6.000E-02
 7.000E-02 8.000E-02 9.000E-02 1.000E-01 1.200E-01 1.400E-01 1.600E-01 1.800E-01
 2.000E-01 2.300E-01 2.600E-01 3.000E-01 3.500E-01 4.000E-01 4.500E-01 5.000E-01
 6.000E-01 7.000E-01 8.000E-01 9.000E-01 1.000E+00 1.200E+00 1.400E+00 1.600E+00
 1.800E+00 2.000E+00 2.300E+00 2.600E+00 3.000E+00 3.500E+00 4.000E+00 4.500E+00
 5.000E+00 6.000E+00 7.                                                  01 1.400E+01
 1.600E+01 1.800E+01 2.                                                  01 4.000E+01
 4.500E+01 5.000E+01 6.                                                  02 1.200E+02
 1.400E+02 1.600E+02 1.                                                  02 3.500E+02
 3.650E+02 3.670E+02 3.                                                  02 7.000E+02
 8.000E+02 9.000E+02 1.                                                  03 2.000E+03
 2.300E+03 2.600E+03 3.000E+03 3.500E+03 4.000E+03 4.500E+03 5.000E+03 6.000E+03
 7.000E+03 8.000E+03 9.000E+03 1.000E+04 1.100E+04 1.200E+04 1.300E+04 1.400E+04
 1.500E+04 1.600E+04 1.700E+04 1.825E+04 1.950E+04 2.100E+04 2.250E+04
19 = # of source organs (from activity file; for info only). Source organs were:
AI        bbe-gel   bbe-sol   bbe-seq   BBi-gel   BBi-sol   BBi-seq   ET2-sur
ET1-sur   ET2-seq   LN-Th     LN-ET     St_Cont   SI_Cont   Blood     ULI_Cont
LLI_Cont  Body_Tis  UB_Cont
31 = # of target organs (from SEE files)
EQUIVALENT DOSE
equivalent dose rates (Sv/d/Bq) at each time for each target organ follow:
Adrenals, t = equivalent dose rate (Sv/d/Bq) from Total radiations
 0.0       1.272E-11 2.724E-11 3.802E-11 4.660E-11 5.367E-11 5.955E-11 6.445E-11
 6.854E-11 7.196E-11 7.482E-11 7.922E-11 8.232E-11 8.450E-11 8.605E-11 8.713E-11
 8.819E-11 8.878E-11 8.917E-11 8.929E-11 8.921E-11 8.903E-11 8.882E-11 8.837E-11
 8.795E-11 8.758E-11 8.725E-11 8.697E-11 8.648E-11 8.608E-11 8.571E-11 8.537E-11
 8.505E-11 8.457E-11 8.411E-11 8.349E-11 8.274E-11 8.201E-11 8.131E-11 8.064E-11
 7.941E-11 7.832E-11 7.736E-11 7.651E-11 7.574E-11 7.447E-11 7.338E-11 7.243E-11
 7.159E-11 7.083E-11 6.978E-11 6.880E-11 6.758E-11 6.615E-11 6.480E-11 6.352E-11
 6.228E-11 5.995E-11 5.779E-11 5.578E-11 5.390E-11 5.215E-11 4.899E-11 4.621E-11
 4.377E-11 4.161E-11 3.969E-11 3.718E-11 3.505E-11 3.265E-11 3.019E-11 2.817E-11
 2.648E-11 2.502E-11 2.264E-11 2.074E-11 1.918E-11 1.787E-11 1.676E-11 1.503E-11
 1.367E-11 1.259E-11 1.170E-11 1.095E-11 9.992E-12 9.175E-12 8.230E-12 7.214E-12
 6.937E-12 6.901E-12 6.759E-12 6.335E-12 5.567E-12 4.893E-12 3.782E-12 2.923E-12
 2.259E-12 1.746E-12 1.350E-12 8.064E-13 4.817E-13 2.878E-13 1.719E-13 1.027E-13
 4.743E-14 2.190E-14 7.817E-15 2.156E-15 5.949E-16 1.641E-16 4.527E-17 3.445E-18
 2.622E-19 1.995E-20 1.519E-21 1.169E-22 8.897E-24 6.770E-25 5.152E-26 3.921E-27
 2.984E-28 2.271E-29 1.728E-30 6.908E-32 2.
Committed Dose (Sv/Bq) = 8.494E-09
   //        //          //          //
   ||        ||          ||          ||
   //        //          //          //
Effective Dose Rate (Sv/d/Bq).  Standard formula                    ainder, ICRP 61
 6.604E-13 4.180E-10 6.015E-10 7.049E-10 7.75                    .272E-10 8.637E-10 8.884E-10
 9.039E-10 9.120E-10 9.142E-10 9.061E-10 8.8                     10 8.617E-10 8.333E-10 8.038E-10
 7.600E-10 7.184E-10 6.680E-10 6.135E-10                     .78E-10 5.298E-10 4.982E-10 4.508E-10
 4.199E-10 4.012E-10 3.918E-10 3.891E-1                      3.978E-10 4.175E-10 4.422E-10 4.686E-10
 4.947E-10 5.310E-10 5.627E-10 5.974E-10 6.297E-10 6.517E-10 6.656E-10 6.732E-10
 6.744E-10 6.629E-10 6.436E-10 6.194E-10 5.923E-10 5.355E-10 4.773E-10 4.223E-10
 3.721E-10 3.273E-10 2.705E-10 2.250E-10 1.791E-10 1.399E-10 1.145E-10 9.805E-11
 8.733E-11 7.527E-11 6.906E-11 6.515E-11 6.221E-11 5.973E-11 5.547E-11 5.184E-11
 4.867E-11 4.590E-11 4.346E-11 4.031E-11 3.767E-11 3.475E-11 3.182E-11 2.947E-11
 2.754E-11 2.590E-11 2.328E-11 2.121E-11 1.954E-11 1.815E-11 1.698E-11 1.515E-11
 1.373E-11 1.262E-11 1.171E-11 1.09                      11 9.971E-12 9.148E-12 8.202E-12 7.187E-12
 6.911E-12 6.876E-12 6.734E-12                       1E-12 5.546E-12 4.875E-12 3.767E-12 2.912E-12
 2.25                                                    4.799E-13 2.867E-13 1.713E-13 1.023E-13
 4.72                                                    5.926E-16 1.635E-16 4.510E-17 3.432E-18
 2.61                                                    8.863E-24 6.745E-25 5.133E-26 3.906E-27
 2.97                                                    2.742E-33 5.756E-35 0.0
Commi
Remainder, equiv. dose rate.  Normal formulation;  Max weighted organ: Colon
 1.889E-16 4.535E-11 5.808E-11 6.472E-11 7.001E-11 7.477E-11 7.916E-11 8.323E-11
 8.704E-11 9.060E-11 9.393E-11 1.000E-10 1.054E-10 1.103E-10 1.147E-10 1.186E-10
 1.239E-10 1.285E-10 1.338E-10 1.392E-10 1.436E-10 1.471E-10 1.498E-10 1.535E-10
 1.554E-10 1.559E-10 1.554E-10 1.541E-10 1.502E-10 1.452E-10 1.399E-10 1.346E-10
```

Listing of the 127 times at which ACTACAL computed the activity in the source regions and the times at which the dose rate will be computed.

Committed equivalent dose in adrenals computed by integrating the equivalentdose rate.

Normal (not split) form of the remainder dose – the colon received the highest equivalent dose.

```
 1.295E-10 1.226E-10 1.165E-10 1.098E-10 1.031E-10 9.792E-11 9.395E-11 9.087E-11
 8.648E-11 8.357E-11 8.152E-11 7.996E-11 7.870E-11 7.675E-11 7.515E-11 7.380E-11
 7.261E-11 7.155E-11 7.013E-11 6.887E-11 6.739E-11 6.574E-11 6.425E-11 6.289E-11
 6.161E-11 5.926E-11 5.710E-11 5.511E-11 5.325E-11 5.152E-11 4.839E-11 4.565E-11
 4.323E-11 4.110E-11 3.920E-11 3.672E-11 3.461E-11 3.224E-11 2.981E-11 2.782E-11
 2.615E-11 2.471E-11 2.236E-11 2.048E-11 1.894E-11 1.765E-11 1.655E-11 1.484E-11
 1.350E-11 1.243E-11 1.155E-11 1.081E-11 9.867E-12 9.059E-12 8.127E-12 7.123E-12
 6.850E-12 6.814E-12 6.674E-12 6.255E-12 5.497E                              -12
 2.231E-12 1.724E-12 1.333E-12 7.962E-13 4.757E                              -13
 4.683E-14 2.163E-14 7.718E-15 2.129E-15 5.874E                              -18
 2.589E-19 1.970E-20 1.499E-21 1.154E-22 8.784E                              -27
 2.946E-28 2.242E-29 1.706E-30 6.821E-32 2.726E-33 5.724E-35 0.0
Committed Dose (Sv/Bq) = 8.413E-09
```

Committed equivalent dose to the remainder group of tissues.

A.5 File Ru106AF5.LOG: created by the DCAL Modules

The computational modules ACTACAL, SEECAL, and EPACAL all contribute to the log file for the calculations. This file identifies the time stamp of the executables and all input files used during the course of the calculations. Input files directed for use by the modules' INI file are referred to as "global" if they were assigned by the modules INI file located in the folder DCAL\INI or "local" if the INI file was present in the work folder.

```
--------------------------------------------------------------------------------
This is ACTACAL log file Ru106AF5.log
<<  ACTACAL Ver. 8.3 (Jly 15, 2006) --- Run Jul 18, 2006, at 11:05 >>
ACTACAL exe file was:              ACTACAL.EXE     404712 07-18-06  11:03a
Global ACTACAL INI file:           ACTACAL.INI       2475 06-07-05  10:45a
Global writing times file:         WRITIM.DAT         932 05-21-04   3:34p
Global computational step file:    TIMIN.DAT          449 02-28-03   1:00p
Global standard name file:         STDNAMES.TXT      2789 01-18-05   3:47p
Global decay data index file:      ICRP38.NDX      135919 02-28-03   1:00p
Activities written to file: Ru106AF5.act
Title lines (0) follow, if any:

Ru-106 Decay Chain: Half-lives and Branching Fractions
    Nuclide  Halflife    f1       Nuclide   f2       Nuclide   f3       Nuclide
  1 Ru-106     368.2d  1.0+00-> 2 Rh-106
  2 Rh-106      29.9s
Ru-106: Activity, Transformations, & Cumulative Energies (MeV) at 100y
     Nuclide  T1/2        A(t)/Ao   intA/Ao(d)   Ealpha    Ebeta    Egamma
   1 Ru-106     368.2d  1.37462D-30 5.31200D+02 0.00E+00 5.31E+00 0.00E+00
   2 Rh-106      29.9s  1.37463D-30 5.31200D+02 0.00E+00 7.56E+02 1.09E+02
LNG file rd in subr. TIMELNG  was: ICRP66F.LNG       1541 02-28-03   1:00p
GF1 file rd in subr. TIMEF1   was: RU.GF1             215 02-28-03   1:00p
DEF file rd in subr. TIMEBIO  was: RU.DEF             580 02-28-03   1:00p
RNL file rd in subr. TIMEBLD  was: ICRP67.BLD         331 02-28-03   1:00p
  Number of source organs = 19
 ------------------------------------------------------------------------
 Source      Biokinetic Compartments
 ai       <- ai_1       ai_2       ai_3
 bbe-gel  <- bbe-gel
 bbe-sol  <- bbe-sol
 bbe-seq  <- bbe-seq
 bbi-gel  <- bbi-gel
 bbi-sol  <- bbi-sol
 bbi-seq  <- bbi-seq
 et2-sur  <- et2-sur
 et1-sur  <- et1-sur
 et2-seq  <- et2-seq
 ln-th    <- ln-th
 ln-et    <- ln-et
 st_cont  <- st_cont
 si_cont  <- si_cont
 blood    <- blood
 uli_cont <- uli_cont
```

Mapping of biokinetic compartments and source regions.

```
 lli_cont <- lli_cont
 body_tis <- body_tis_a body_tis_b body_tis_c
 ub_cont  <- ub_cont
 ------------------------------------------------------------------------------
Age 0 mass file rd by READMS  was: REGMASS.A00       3169 02-28-03   1:00p
Age 1 mass file rd by READMS  was: REGMASS.A01       2851 02-28-03   1:00p
Age 5 mass file rd by READMS  was: REGMASS.A05       2849 02-28-03   1:00p
Age 10 mass file rd by READMS was: REGMASS.A10       2850 02-28-03   1:00p
Age 15 mass file rd by READMS was: REGMASS.A15       2965 02-28-03   1:00p
Adult mass file rd by READMS  was: REGMASS.AM        2995 02-28-03   1:00p
 Source              Masses (kg) for reference age
 Region    Newborn   1-y      5-y      10-y     15-y     Adult
 AI       0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
 bbe-gel  0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
 bbe-sol  0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
 bbe-seq  0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
 BBi-gel  0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
 BBi-sol  0.00                                         0.00E+00
 BBi-seq  0.00                                         0.00E+00
 ET2-sur  0.00                                         0.00E+00
 ET1-sur  0.00                                         0.00E+00
 ET2-seq  0.00                                         0.00E+00
 LN-Th    0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
 LN-ET    0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
 St_Cont  1.06E-02 3.62E-02 7.51E-02 1.33E-01 1.95E-01 2.50E-01
 SI_Cont  2.03E-02 5.31E-02 1.06E-01 1.79E-01 3.22E-01 4.00E-01
 Blood    0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
 ULI_Cont 1.12E-02 2.87E-02 5.79E-02 9.75E-02 1.76E-01 2.20E-01
 LLI_Cont 6.98E-03 1.83E-02 3.66E-02 6.17E-02 1.09E-01 1.35E-01
 Body_Tis 3.54E+00 9.54E+00 1.95E+01 3.26E+01 5.58E+01 6.88E+01
 UB_Cont  1.04E-02 2.60E-02 6.76E-02 7.80E-02 8.84E-02 1.20E-01
  1 Ru-106 : Number of systemic compartments; excluding blood =  1
```

Masses assigned to source regions. These data are used to define the "Other" biokinetic compartment if present in biokinetic model.

```
Nuclide: Ru-106  Age(d)-->           7300
 Number of compartments =  26
ai_1      ( 1)--> bbe-gel   ( 4)  2.000E-02
ai_1      ( 1)--> blood     (17)  1.000E+02
ai_2      ( 2)--> bbe-gel   ( 4)  1.000E-03
ai_2      ( 2)--> blood     (17)  1.000E+02
ai_3      ( 3)--> bbe-gel   ( 4)  1.000E-04
ai_3      ( 3)--> ln-th     (13)  2.000E-05
ai_3      ( 3)--> blood     (17)  1.000E+02
bbe-gel   ( 4)--> bbi-gel   ( 7)  2.000E+00
bbe-gel   ( 4)--> blood     (17)  1.000E+02
bbe-sol   ( 5)--> bbi-gel   ( 7)  3.000E-02
bbe-sol   ( 5)--> blood     (17)  1.000E+02
bbe-seq   ( 6)--> ln-th     (13)  1.000E-02
bbe-seq   ( 6)--> blood     (17)  1.000E+02
bbi-gel   ( 7)--> et2-sur   (10)  1.000E+01
bbi-gel   ( 7)--> blood     (17)  1.000E+02
bbi-sol   ( 8)--> et2-sur   (10)  3.000E-02
bbi-sol   ( 8)--> blood     (17)  1.000E+02
bbi-seq   ( 9)--> ln-th     (13)  1.000E-02
bbi-seq   ( 9)--> blood     (17)  1.000E+02
et2-sur   (10)--> st_cont   (15)  1.000E+02
et2-sur   (10)--> blood     (17)  1.000E+02
et1-sur   (11)--> excreta   (24)  1.000E+00
et2-seq   (12)--> ln-et     (14)  1.000E-03
et2-seq   (12)--> blood     (17)  1.000E+02
ln-th     (13)--> blood     (17)  1.000E+02
ln-et     (14)--> blood     (17)  1.000E+02
st_cont   (15)--> si_cont   (16)  2.400E+01
si_cont   (16)--> blood     (17)  3.158E-01
si_cont   (16)--> uli_cont  (18)  6.000E+00
blood     (17)--> uli_cont  (18)  6.932E-02
blood     (17)--> body_tis_a(20)  8.087E-01
blood     (17)--> body_tis_b(21)  6.931E-01
```

This listing, plus the initial conditions noted below, is a complete statement of the compartment model that ACTACAL has assembled. Note the transfer coefficients (/d) are for biological processes.

```
blood     (17)--> body_tis_c(22)  4.621E-01
blood     (17)--> ub_cont   (23)  2.773E-01
uli_cont  (18)--> lli_cont  (19)  1.800E+00
lli_cont  (19)--> feces     (25)  1.000E+00
body_tis_a(20)--> uli_cont  (18)  1.733E-02
body_tis_a(20)--> ub_cont   (23)  6.932E-02
body_tis_b(21)--> uli_cont  (18)  3.961E-03
body_tis_b(21)--> ub_cont   (23)  1.584E-02
body_tis_c(22)--> uli_cont  (18)  1.386E-04
body_tis_c(22)--> ub_cont   (23)  5.545E-04
ub_cont   (23)--> urine     (26)  1.200E+01

Nuclide: Rh-106  Age(d)-->           7300
 Number of compartments =  26
ai_1      ( 1)--> bbe-gel   ( 4)  2.000E-02
ai_1      ( 1)--> blood     (17)  1.000E+02
ai_2      ( 2)--> bbe-gel   ( 4)  1.000E-03
ai_2      ( 2)--> blood     (17)  1.000E+02
ai_3      ( 3)--> bbe-gel   ( 4)  1.000E-04
ai_3      ( 3)--> ln-th     (13)  2.000E-05
ai_3      ( 3)--> blood     (17)  1.000E+02
bbe-gel   ( 4)--> bbi-gel   ( 7)  2.000E+00
bbe-gel   ( 4)--> blood     (17)  1.000E+02
bbe-sol   ( 5)--> bbi-gel   ( 7)  3.000E-02
bbe-sol   ( 5)--> blood     (17)  1.000E+02
bbe-seq   ( 6)--> ln-th     (13)  1.000E-02
bbe-seq   ( 6)--> blood     (17)  1.000E+02
bbi-gel   ( 7)--> et2-sur   (10)  1.000E+01
bbi-gel   ( 7)--> blood     (17)  1.000E+02
bbi-sol   ( 8)--> et2-sur   (10)  3.000E-02
bbi-sol   ( 8)--> blood     (17)  1.000E+02
bbi-seq   ( 9)--> ln-th     (13)  1.000E-02
bbi-seq   ( 9)--> blood     (17)  1.000E+02
et2-sur   (10)--> st_cont   (15)  1.000E+02
et2-sur   (10)--> blood     (17)  1.000E+02
et1-sur   (11)--> excreta   (24)  1.000E+00
et2-seq   (12)--> ln-et     (14)  1.000E-03
et2-seq   (12)--> blood     (17)  1.000E+02
ln-th     (13)--> blood     (17)  1.000E+02
ln-et     (14)--> blood     (17)  1.000E+02
st_cont   (15)--> si_cont   (16)  2.400E+01
si_cont   (16)--> blood     (17)  3.158E-01
si_cont   (16)--> uli_cont  (18)  6.000E+00
blood     (17)--> uli_cont  (18)  6.932E-02
blood     (17)--> body_tis_a(20)  8.087E-01
blood     (17)--> body_tis_b(21)  6.931E-01
blood     (17)--> body_tis_c(22)  4.621E-01
blood     (17)--> ub_cont   (23)  2.773E-01
uli_cont  (18)--> lli_cont  (19)  1.800E+00
lli_cont  (19)--> feces     (25)  1.000E+00
body_tis_a(20)--> uli_cont  (18)  1.733E-02
body_tis_a(20)--> ub_cont   (23)  6.932E-02
body_tis_b(21)--> uli_cont  (18)  3.961E-03
body_tis_b(21)--> ub_cont   (23)  1.584E-02
body_tis_c(22)--> uli_cont  (18)  1.386E-04
body_tis_c(22)--> ub_cont   (23)  5.545E-04
ub_cont   (23)--> urine     (26)  1.200E+01
 Number of source regions =  19
 Nonzero initial conditions for inhalation: AMAD =  5.000 æm
 ai_1       = 1.596E-02
 ai_2       = 3.191E-02
 ai_3       = 5.319E-03
 bbe-gel    = 6.569E-03
 bbe-sol    = 4.384E-03
 bbe-seq    = 7.721E-05
 bbi-gel    = 1.171E-02
 bbi-sol    = 5.921E-03
```

Since shared kinetics is assumed in this case and thus this listing is the same as that for the parent.

Listing of compartments with nonzero initial conditions. In this case the deposition in the compartments of the lung model assumes an intake of 1 Bq – aerosol AMAD = 5 microns..

```
 bbi-seq    = 1.243E-04
 et2-sur    = 3.989E-01
 et1-sur    = 3.385E-01
 et2-seq    = 1.996E-04
      Total = 8.196E-01
Total number of transfers = 43
 Compartments are exhausted, quit.
Calculations completed over 17496 cycles.
Data reported for 127 time steps.
Computational time (100s) =   39.
Computations ended normally.
SEECAL request file written: Ru106AF5.req
--------------------------------------------------------------------------------
This is SEECAL   log file Ru106AF5.log
<< SEECAL   Ver. 8.4 (Jly 15, 2006) --- Run Jul 18, 2006, at 11:05 >>
 ... Title lines from user request file follow:
 <<  ACTACAL Ver. 8.3 (Jly 15, 2006) --- Run Jul 18, 2006, at 11:05 >>
 ... End of title lines; number of title lines = 1
 Quantity to be calculated = "equivalent dose"
 Table type for SEE files = "total only"
 Index iACalc; Age Group Name;          Index iAge
            1  "adult male         "   6
 End of age group list; number of age groups = 1
 Index iSCalc; SOURCE Name; Index iS
            1  "ai      "   33
            2  "bbe-gel "   29
            3  "bbe-sol "   30
            4  "bbe-seq "   32
            5  "bbi-gel "   25
            6  "bbi-sol "   26
            7  "bbi-seq "   28
            8  "et2-sur "   21
            9  "et1-sur "   20
           10  "et2-seq "   23
           11  "ln-th   "   34
           12  "ln-et   "   24
           13  "st_cont "   10
           14  "si_cont "   12
           15  "blood   "   58
           16  "uli_cont"   14
           17  "lli_cont"   16
           18  "body_tis"   57
           19  "ub_cont "    2
 End of source region list; number of sources = 19
 Index iTCalc; TARGET Name; Index iT
            1  "adrenals"    1
            2  "ub_wall "    2
            3  "bone_sur"    3
            4  "brain   "    4
            5  "breasts "    5
            6  "st_wall "    6
            7  "si_wall "    7
            8  "uli_wall"    8
            9  "lli_wall"    9
           10  "kidneys "   10
           11  "liver   "   11
           12  "et1-bas "   12
           13  "et2-bas "   13
           14  "ln-et   "   14
           15  "bbi-bas "   15
           16  "bbi-sec "   16
           17  "bbe-sec "   17
           18  "ai      "   18
           19  "ln-th   "   19
           20  "muscle  "   24
           21  "ovaries "   25
           22  "pancreas"   26
```

SEECAL's internal translation of the source regions character name; e.g. "bbe-gel" into the assigned integer index in SAFs files.

SEECAL's internal translation of the target organ/tissue character name; e.g. "st_wall" into the assigned integer index in SAFs files.

```
           23  "r_marrow"   27
           24  "skin    "   28
           25  "spleen  "   29
           26  "testes  "   30
           27  "thymus  "   31
           28  "thyroid "   32
           29  "gb_wall "   33
           30  "ht_wall "   34
           31  "uterus  "   35
 End of target region list; number of targets = 31
 SEE output file Ru106ht.SEE will be written.
 SEE output file Rh106ht.SEE will be written.

SEECAL exe file was:              SEECAL.EXE      288080 07-15-06  10:01a
Global SEECAL INI file:           SEECAL.INI        1415 09-04-05   1:23p
User request file was:            RU106AF5.REQ      5158 07-18-06  11:05a
File with standard names was:     STDNAMES.TXT      2789 01-18-05   3:47p
Photon SAF file was:              PSAFTX66.AM     271721 09-11-04   6:57p
Electron-alpha AF file was:       ELALPHAF.AM       2344 02-28-03   1:00p
Region mass file was:             REGMASS.AM        2995 02-28-03   1:00p
Index file was:                   ICRP38.NDX      135919 02-28-03   1:00p
Radiation data file was:          ICRP38.RAD     5971698 02-28-03   1:00p
Beta spectrum data file was:      ICRP38.BET      684882 02-28-03   1:00p

Photon SAF interpolation is linear

 MAJOR PROGRAM LOOP: working on age # 1 (adult male) ...

      Reading photon SAFs for age = adult male ...
      Reading electron & alpha AFs for age = adult male ...
      Calculating SEEs for nuclide = Ru-106  ...
         for beta +/- particles (n=   1)
      Calculating SEEs for nuclide = Rh-106  ...
         for photons < 10 keV   (n=  12)
         for photons >= 10 keV  (n= 168)
         for beta +/- particles (n=  37)
         for monoen. electrons  (n= 987)

 The following SEE files have been written:
 Ru106ht.SEE    Rh106ht.SEE

 Program SEECAL ended normally.
-------------------------------------------------------------------------------
This is EPACAL   log file Ru106AF5.log
<<   EPACAL Ver. 8.4 (Jly 15, 2006) --- Run Jul 18, 2006, at 11:05 >>

 Activity data read from file Ru106AF5.act
 All activity input files were opened successfully.
 Dose rate output file Ru106AF5.hrt will be written

EPACAL exe file was:              EPACAL.EXE      261656 07-15-06   9:58a
Global EPACAL ini file:           EPACAL.INI          48 12-23-03   5:41p
Global lung apportionment file:   LUNGAS.DAT         357 09-04-05   5:03p
Activity file was:                RU106AF5.ACT     66203 07-18-06  11:05a
 SEE data read from file Ru106ht.see
 SEE data read from file Rh106ht.see
 All SEE input files were opened successfully
SEE input file was:               RU106HT.SEE      14596 07-18-06  11:05a
SEE input file was:               RH106HT.SEE      14596 07-18-06  11:05a
 Reading headers of SEE files and check
Quant = equivalent dose
 Headers in all SEE files matched OK.
 Source organ names in activity &
 **** Minor warning !
      Target organ "GB_wall " in the SEE files is not an organ used
      in computing effective dose.  It will appear in the dose rate output
      files but will be ignored in computing effective dose. ****
```

EPA's messages regarding a check on the set of target organs/tissues.

```
**** Minor warning !
     Target organ "Ht_Wall " in the SEE files is not an organ used
     in computing effective dose.  It will appear in the dose rate output
     files but will be ignored in computing effective dose. ****
Exposure ages (days) in activity files are:
  7300.0
Youngest age for SEE values to be read is: 7300 days (adult male/female)
MAJOR PROGRAM LOOP: working on activity file #  1 (RU106AF5.ACT) ...
    Reading SEE file for iNuc = 1 (Ru-106) ...
    Reading activity file for iNuc = 1 ...
    Calculating dose rates for iNuc = 1 ...
    Reading SEE file for iNuc = 2 (Rh-106) ...
    Reading activity file for iNuc = 2 ...
    Calculating dose rates for iNuc = 2 ...
    Writing dose rates to dose rate file # 1 (Ru106AF5.hrt) ...
The following dose rate files have been written:
Ru106AF5.hrt
Program EPACAL ended normally.
```

Note regarding completion of EPACAL's calculations.

A.6 File Ru106AF5.U50: created by ACTINT32

```
<<  ACTINT32 Ver. 8.4 (July 15, 2006) --- Run Jly 18, 2006, at 11:05 >>
ACTINT32 exe file was:    ACTINT32.EXE           47KB 07-15-06 11:49
Activity file was:        RU106AF5.ACT           65KB 07-18-06 11:05
Number of times =  127
Number of nuclides =  2
Number of source regions =  20
          U50 (nt/Bq intake)
 Region   Ru-106    Rh-106
AI       4.596E+01 4.423E+01
bbe-gel  5.568E+00 5.355E+00
bbe-sol  3.787E+00 3.645E+00
bbe-seq  6.671E-02 6.420E-02
BBi-gel  9.301E+00 8.922E+00
BBi-sol  5.115E+00 4.922E+00
BBi-seq  1.074E-01 1.034E-01
ET2-sur  1.728E+02 1.604E+02
ET1-sur  2.919E+04 2.923E+04
ET2-seq  1.725E-01 1.660E-01
LN-Th    1.835E-05 1.830E-05
LN-ET    1.726E-06 1.722E-06
St_Cont  7.203E+02 7.193E+02
SI_Cont  2.735E+03 2.735E+03
Blood    1.088E+04 1.089E+04
ULI_Cont 1.140E+04 1.142E+04
LLI_Cont 2.048E+04 2.052E+04
Body_Tis 2.398E+06 2.401E+06
UB_Cont  1.375E+03 1.375E+03
Retained 2.475E+06 2.478E+06
```

Number of nuclear transformations (nt or Bq-s) of the parent and its daughter in the source regions addressed in the file RU106AF5.ACT>

A.7 File Ru106AF5.EUD: created by BIOTAB32

```
<<  BioTab32 Ver. 8.4  (Jly 18, 2006) --- Run Jly 18, 2006, at 11:05 >>
BIOTAB32 exe file was:    BIOTAB32.EXE           58KB 07-18-06 10:50
Activity file was:        RU106AF5.ACT           65KB 07-18-06 11:05
Ru106AF5.ACT: Inhalation: Age(d)=7300 Type=F f_1 = 5.0E-02 AMAD(æm)=5.0E+00
Ru-106
          ----- E_f(t) -----  ----- E_u(t) -----
  T(d)      24-h   Cumulative   24-h   Cumulative  R_WB    R_lung     R_ET
 0.0E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 8.196E-01 8.197E-02 7.376E-01
   4 h   6.067E-04 6.067E-04 6.190E-03 6.190E-03 7.606E-01 4.550E-09 2.864E-01
   8 h   4.899E-03 4.899E-03 1.499E-02 1.499E-02 7.033E-01 7.425E-16 2.424E-01
  12 h   1.378E-02 1.378E-02 2.207E-02 2.207E-02 6.499E-01 1.266E-23 2.051E-01
```

```
  16 h   2.613E-02 2.613E-02 2.744E-02 2.744E-02 6.005E-01 0.000E+00 1.736E-01
  20 h   4.052E-02 4.052E-02 3.155E-02 3.155E-02 5.552E-01 0.000E+00 1.469E-01
 1.0E+00 5.574E-02 5.574E-02 3.478E-02 3.478E-02 5.140E-01 0.000E+00 1.243E-01
  //         //          //           //           //           //          //
  ||         ||          ||           ||           ||           ||          ||
  //         //          //           //           //           //          //
 4.0E+00 1                                                     000E+00 6.153E-03
  //                                                           //          //
  ||                                                          ||          ||
  //                                                          //          //
 1.0E+01 1                                                     000E+00 1.508E-05
  //         //          //           //           //           //          //
  ||         ||          ||           ||           ||           ||          ||
  //         //          //           //           //           //          //
 5.0E+01 1.565E-04 2.283E-01 5.986E-04 1.570E-01 8.254E-02 0.000E+00 5.942E-23
  //         //          //           //           //           //          //
  ||         ||          ||           ||           ||           ||          ||
  //         //          //           //           //           //          //
 1.0E+03 6.175E-07 2.368E-01 2.463E-06 1.900E-01 4.433E-03 0.000E+00 0.000E+00
  //         //          //           //           //           //          //
  ||         ||          ||           ||           ||           ||          ||
  //         //          //           //           //           //          //
 2.0E+04 0.000E+00 0.000E+00 0.000E+00 0.000E+00 4.127E-24 0.000E+00 0.000E+00
Rh-106
          ----- E_f(t) -----  ----- E_u(t) -----
  T(d)      24-h   Cumulative   24-h   Cumulative  R_WB    R_lung     R_ET
 0.0E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
   4 h   6.048E-04 6.048E-04 6.181E-03 6.181E-03 7.606E-01 4.626E-09 2.865E-01
   8 h   4.893E-03 4.893E-03 1.498E-02 1.498E-02 7.033E-01 7.548E-16 2.424E-01
  12 h   1.377E-02 1.377E-02 2.206E-02 2.206E-02 6.500E-01 0.000E+00 2.051E-01
  16 h   2.612E-02 2.612E-02 2.743E-02 2.743E-02 6.005E-01 0.000E+00 1.736E-01
  20 h   4.050E-02 4.050E-02 3.155E-02 3.155E-02 5.552E-01 0.000E+00 1.469E-01
 1.0E+00 5.573E-02 5.573E-02 3.478E-02 3.478E-02 5.141E-01 0.000E+00 1.243E-01
  //         //          //           //           //           //          //
  ||         ||          ||           ||           ||           ||          ||
  //         //          //           //           //           //          //
 4.0E+00 1                                                     000E+00 6.181E-03
  //                                                           //          //
  ||                                                          ||          ||
  //                                                          //          //
 1.0E+01 1                                                     000E+00 1.515E-05
  //         //          //           //           //           //          //
  ||         ||          ||           ||           ||           ||          ||
  //         //          //           //           //           //          //
 5.0E+01 1.566E-04 2.287E-01 5.986E-04 1.571E-01 8.255E-02 0.000E+00 5.969E-23
  //         //          //           //           //           //          //
  ||         ||          ||           ||           ||           ||          ||
  //         //          //           //           //           //          //
 1.0E+03 6.182E-07 2.372E-01 2.464E-06 1.901E-01 4.439E-03 0.000E+00 0.000E+00
  //         //          //           //           //           //          //
  ||         ||          ||           ||           ||           ||          ||
  //         //          //           //           //           //          //
 2.0E+04 0.000E+00 0.000E+00 0.000E+00 0.000E+00 4.181E-24 0.000E+00 0.000E+00
```

The activity in fecal (E_f) and urinary (E_u) excretion at various times post intake as well as retention within the whole body (R_WB), lung (R_lung) and in the extrathoracic airway (R_ET) for the parent.

The activity in fecal (E_f) and urinary (E_u) excretion at various times post intake as well as activity within the whole body (R_WB), lung (R_lung) and in the extrathoracic airway (R_ET) of the daughter for a 1Bq intake of the parent..

A.8 File Ru106AF5.HEF: created by HTAB32 utility

```
Ru-106 Inhalation Committed Equivalent Dose Coefficients (Sv/Bq): Type: F, AMAD = 5.0 æm
------------------------
                  20 Year
           f_1    0.05
Adrenals         8.49E-09
Bladder Wall     9.78E-09
Bone Surfaces    8.47E-09
Brain            8.33E-09
Breast           8.29E-09
GI-Tract
```

```
  St Wall        8.76E-09
  SI Wall        9.30E-09
  ULI Wall       1.44E-08
  LLI Wall       2.59E-08
Kidneys          8.46E-09
Liver            8.46E-09
Resp. Tract
  ET Region      1.20E-08
  Lung           8.42E-09
Muscle           8.39E-09
Ovaries          8.56E-09
Pancreas         8.52E-09
Red Marrow       8.44E-09
Skin             8.26E-09
Spleen           8.45E-09
Testes           8.39E-09
Thymus           8.43E-09
Thyroid          8.43E-09
G Bladder        8.49E-09
Heart            8.48E-09
Uterus           8.54E-09
Remainder        8.41E-09
Effective Dose   9.87E-09
-------------------------
  value(s) marked by '*' are based on splitting of remainder weight.

Output file: Ru106AF5.hef
<<  HTAB32  Ver 8.4  (July 18, 2006) --- Run Jly 18, 2006, at 11:11 >>
HTAB32 exe file was:      HTAB32.EXE             52kb 07-18-06 10:45
Dose rate file was :     RU106AF5.HRT            55kb 07-18-06 11:05
```

Summary of the committed dose coefficients. The coefficients for the various regions in the lung can be listed is the user so indicates when HTAB32 is invoked.

A.9 File Ru106AF5.INT: created by the ACTINT32 utility

```
<<  DRTINT32 Ver 8.4 (July 15, 2006) --- Run Jly 18, 2006, at 11:05 >>
DRTINT32 exe file was:  DRTINT32.EXE             53kb 07-16-06 18:28
Dose rate file was:     RU106AF5.HRT             55kb 07-18-06 11:05
Global INI File was:    DRTINT.INI                1kb 07-18-06 10:54
Nuclide: Ru-106 T1/2 = 368.2 d
Intake mode: Inhalation
  Type = F O f1 = 5.0E-02
  AMAD = 5.0E+00 um
Age at intake = 7300.0 d
Number of times =  127
Number of target regions = 35
Max time in dose rate table =  .7250E+04 d
Equivalent Dose (Sv/Bq intake at time 0)
    T1      -     T2 (d)  Adrenals  UB_Wall   .. ET_Reg    Lung_66   Remaindr  Effective
 0.000E+00 -  1.000E+00 8.076E-11 3.243E-10 .. 2.436E-09 1.089E-10 1.011E-10 6.071E-10
 1.000E+00 -  2.000E+00 7.302E-11 1.561E-10 .. 8.243E-10 7.256E-11 7.467E-11 4.532E-10
 2.000E+00 -  4.000E+00 1.353E-10 2.374E-10 .. 5.120E-10 1.339E-10 1.351E-10 3.860E-10
 0.000E+00 -  4.000E+00 2.891E-10 7.178E-10 .. 3.772E-09 3.154E-10 3.109E-10 1.446E-09
 0.000E+00 -  3.650E+02 5.803E-09 7.069E-09 .. 9.299E-09 5.765E-09 5.756E-09 7.190E-09
 0.000E+00 -  1.825E+04 8.494E-09 9.777E-09 .. 1.197E-08 8.424E-09 8.413E-09 9.870E-09
```

The equivalent dose in the target organs over the period T1 to T2. The integration times are defined in the global DRTINT.INI file.

APPENDIX B
ANNOTATED LISTINGS OF DCAL BATCH OUTPUT FILES

This appendix contains an annotated set of DCAL's files created during a batch calculation of risk for an inhalation intake. DCAL's batch mode of operation was discussed in Section 6.0.

B.1 EXAMPINH.INP File

This is the example batch input file in the folder DCAL\WRK\WORK2. This file was run through DCAL using the biokinetic data in the folder DCAL\DAT\BIO\F13.

```
DCAL example batch input file for inhalation.
******* nn S ffffffff ffffffff aaaa  t 1.0E-02  ffffffff <-- Comments >
BATCH CODES                            <- Delimited starting list of codes to run in batch
ACTACAL.EXE
SEECAL.EXE
EPACAL.EXE
RISKCAL.EXE
END CODES                              <- End of listing of codes
DELETE CASE FILES                      <- Start list of case files to be deleted
*.SEE
*.REQ
*.LOG
*.ACT
*.DRT
END DELETE                             <- End of case files to be deleted.
GLOBAL INPUT                           <- Start of global input for cases
Dose_Type             Absorbed_Dose
Intake_Route          Inhalation
Exposure_Type         Environmental
Default_Amad          1.0
#_Ages_at_intake      6
100 365 1825 3650 5475 7300
END GLOBAL INPUT                       <- End of global case input
CASE INPUT DATA                        <- Start of case data
H-3          H_H2O                   F 1.0
H-3          H_H2O                   V          H2OVapor
H-3          H_H2O                   G          HGas
Be-7                                 F 1.0
C-14         C_Org                   F 1.0
C-14         C_CO                    G          COGAS
C-14         C_CO2                   G          CO2GAS
Na-24                                F
S-35         S_Inorg                 F
S-35         S_Inorg                 V          SO2Gas
S-35         S_Org                   V          CS2Gas
Sr-90                          9125  F
Tc-99                                F
I-131    1                           F
I-131    1                           V          IVapor
I-131    1                           V          IMethyl
Th-232     I                   9125  M
U-238      I                   9125  F
U-238      I                   9125  M
Pu-239                         9125  M
Pu-239                         9125  S
END CASE DATA                          <- End of case data
******* nn S ffffffff ffffffff aaaa  t 1.0E-02  ffffffff <-- Comments >
```

List of codes in the order they are to be run in the calculations.

List of files to be deleted as calculation cycle through the above sequence of codes.

Specification of the exposure situation.

Nuclide cases to be processed – see Sect 6.0 for details.

B.2. EXAMPINH.HDB File

The *.HDB file is created by EPACAL and lists the calculated committed dose coefficients. The type of coefficient (absorbed or equivalent) depends on the specification in the batch input file (*.INP). Since the input

file EXAMPINH.INP is computing risk coefficients, RISKCAL.EXE included among the batch code listing, the coefficients are committed absorbed dose and hence values are given for low and high LET – see the Th-232 data below. Coefficients are included in the full table for equivalent dose to the remainder and the effective dose (Sv/Bq) but these are only presents for possible QA purposes.

```
Inhalation Dose Coefficients: Committed Absorbed Dose per Unit Intake (Gy/Bq)                |
Nuclide  Age   AMAD   Type/f1        Adrenals .. Thyroid  .. Lung_66  .. Biokinetic ..Date   |
H-3      100 1.0E+00 F E 1.0E+00 1 L 2.457E-11.. 2.457E-11.. 2.482E-11.. H_H2O.DEF  ..07-20-06
H-3      365 1.0E+00 F E 1.0E+00 1 L 1.921E-11.. 1.921E-11.. 1.938E-11.. H_H2O.DEF  ..07-20-06
H-3     1825 1.0E+00 F E 1.0E+00 1 L 1.074E-11.. 1.074E-11.. 1.083E-11.. H_H2O.DEF  ..07-20-06
H-3     3650 1.0E+00 F E 1.0E+00 1 L 7.993E-12.. 7.993E-12.. 8.044E-12.. H_H2O.DEF  ..07-20-06
H-3     5475 1.0E+00 F E 1.0E+00 1 L 5.827E-12.. 5.827E-12.. 5.860E-12.. H_H2O.DEF  ..07-20-06
H-3     7300 1.0E+00 F E 1.0E+00 1 L 6.159E-12.. 6.159E-12.. 6.186E-12.. H_H2O.DEF  ..07-20-06
H-3      100 0.0E+00 V E 1.0E+00 1 L 6.347E-11.. 6.347E-11.. 6.347E-11.. H_H2O.DEF  ..07-20-06
  //       //        //        //        //        //        //        //        //        //
  ||       ||        ||        ||        ||        ||        ||        ||        ||        ||
  //       //        //        //        //        //        //        //        //        //
I-131    100 1.0E+00 F E 1.0E+00 1 L 1.959E-10.. 1.434E-06.. 3.887E-10.. I.DEF        07-20-06
I-131    365 1.0E+00 F E 1.0E+00 1 L 1.399E-10.. 1.426E-06.. 3.006E-10.. I.DEF        07-20-06
I-131   1825 1.0E+00 F E 1.0E+00 1 L 6.390E-11.. 7.294E-07.. 1.642E-10.. I.DEF        07-20-06
I-131   3650 1.0E+00 F E 1.0E+00 1 L 3.813E-11.. 3.705E-07.. 1.106E-10.. I.DEF        07-20-06
I-131   5475 1.0E+00 F E 1.0E+00 1 L 1.993E-11.. 2.232E-07.. 7.310E-11.. I.DEF        07-20-06
I-131   7300 1.0E+00 F E 1.0E+00 1 L 1.691E-11.. 1.469E-07.. 5.956E-11.. I.DEF        07-20-06
  //       //        //        //        //        //        //        //        //        //
  ||       ||        ||        ||        ||        ||        ||        ||        ||        ||
  //       //        //        //        //        //        //        //        //        //
I-131    100 0.0E+00 V E 1.0E+00 1 L 3.328E-10.. 2.597E-06.. 5.084E-10.. I.DEF        07-20-06
I-131    365 0.0E+00 V E 1.0E+00 1 L 2.324E-10.. 2.529E-06.. 3.853E-10.. I.DEF        07-20-06
I-131   1825 0.0E+00 V E 1.0E+00 1 L 1.208E-10.. 1.463E-06.. 2.300E-10.. I.DEF        07-20-06
I-131   3650 0.0E+00 V E 1.0E+00 1 L 7.170E-11.. 7.395E-07.. 1.484E-10.. I.DEF        07-20-06
I-131   5475 0.0E+00 V E 1.0E+00 1 L 4.113E-11.. 4.834E-07.. 8.859E-11.. I.DEF        07-20-06
I-131   7300 0.0E+00 V E 1.0E+00 1 L 3.372E-11.. 3.067E-07.. 7.243E-11.. I.DEF        07-20-06
  //       //        //        //        //        //        //        //        //        //
  ||       ||        ||        ||        ||        ||        ||        ||        ||        ||
  //       //        //        //        //        //        //        //        //        //
Th-232   100 1.0E+00 M E 5.0E-03 2 L 7.827E-08.. 5.847E-08.. 8.797E-08.. TH.DEF        07-20-06
                                   H 7.865E-07.. 7.865E-07.. 5.318E-06..                    $
Th-232   365 1.0E+00 M E 5.0E-04 2 L 8.319E-08.. 6.145E-08.. 8.648E-08.. TH.DEF        07-20-06
                                   H 7.765E-07.. 7.765E-07.. 4.261E-06..                    $
Th-232  1825 1.0E+00 M E 5.0E-04 2 L 8.009E-08.. 5.719E-08.. 7.217E-08.. TH.DEF        07-20-06
                                   H 5.775E-07.. 5.775E-07.. 2.753E-06..                    $
Th-232  3650 1.0E+00 M E 5.0E-04 2 L 7.436E-08.. 5.195E-08.. 6.080E-08.. TH.DEF        07-20-06
                                   H 4.216E-07.. 4.216E-07.. 1.860E-06..                    $
Th-232  5475 1.0E+00 M E 5.0E-04 2 L 7.090E-08.. 4.892E-08.. 5.568E-08.. TH.DEF        07-20-06
                                   H 3.608E-07.. 3.608E-07.. 1.557E-06..                    $
Th-232  9125 1.0E+00 M E 5.0E-04 2 L 5.137E-08.. 3.565E-08.. 4.253E-08.. TH.DEF        07-20-06
                                   H 3.330E-07.. 3.330E-07.. 1.356E-06..                    $
```

B.3. EXAMPINH.TAB File

The *.TAB file, written by RISKCAL.EXE, is a compact listing of the mortality and morbidity risk coefficients. This output file was used to create the tables in Federal Guidance Report 13.

```
Mortality and Morbidity Risk Coefficients (per Bq intake)
Nuclide     T1/2   AMAD    Type/f1  Mortality  Morbidity
H-3       12.35 y  1.000  F 1.0E+00  3.61E-13   5.28E-13
H-3       12.35 y  0.000  V 1.0E+00  1.04E-12   1.52E-12
H-3       12.35 y  0.000  G 1.0E+00  1.04E-16   1.52E-16
Be-7       53.3 d  1.000  F 5.0E-03  2.17E-12   3.12E-12
C-14       5730 y  1.000  F 1.0E+00  1.15E-11   1.68E-11
C-14       5730 y  0.000  G 1.0E+00  6.14E-14   9.09E-14
C-14       5730 y  0.000  G 1.0E+00  3.68E-13   5.39E-13
Na-24     15.00 h  1.000  F 1.0E+00  8.94E-12   1.28E-11
S-35      87.44 d  1.000  F 8.0E-01  3.93E-12   6.28E-12
S-35      87.44 d  0.000  V 8.0E-01  8.63E-12   1.34E-11
S-35      87.44 d  0.000  V 8.0E-01  5.30E-11   7.85E-11
```

```
Sr-90      29.12 y  1.000  F 3.0E-01  1.08E-09   1.17E-09
Tc-99     2.13E5 y  1.000  F 8.0E-01  1.86E-11   3.14E-11
I-131       8.04 d  1.000  F 1.0E+00  5.55E-11   5.27E-10
I-131       8.04 d  0.000  V 1.0E+00  1.48E-10   1.36E-09
I-131       8.04 d  0.000  V 1.0E+00  1.10E-10   1.06E-09
Th-232 1.405E10 y  1.000  M 5.0E-04  5.18E-07   6.45E-07
U-238   4.468E9 y  1.000  F 2.0E-02  1.09E-08   1.54E-08
U-238   4.468E9 y  1.000  M 2.0E-02  2.38E-07   2.52E-07
Pu-239     24065 y  1.000  M 5.0E-04  7.94E-07   9.00E-07
Pu-239     24065 y  1.000  S 1.0E-05  8.45E-07   8.96E-07
```

B.4. EXAMPINH.RBS File

The *.RBS file, written by RISKCAL.EXE, list the mortality and morbidity risk coefficients within age groupings (defined in the GROUPS.DAT file in the folder DCAL\DAT\RSK). Only the panel of the mortality risk coefficients is shown below. The tables in Federal Guidance Report 13 gave only the total mortality coefficients for the 0-110 age group. Note the value for H-3 Type F below (3.61E-13) corresponds to that list in the EXAMPINH.TAB table above. See the discussion following the annotated listing regarding the nature of the coefficients for the age groups.

```
Mortality and Morbidity Risk Coefficients: Risk per Unit Intake (/Bq)
                                   ---------------- Mortality -----------------
Nuclide  AMAD  Type/f1     Cancer     0-  5    5- 15   15- 25   25- 70    0-110
H-3     1.000 F E 1.0E+00 esophagus 2.06E-14 1.07E-14 8.24E-15 7.07E-15 7.28E-15
                          stomach   1.29E-13 7.38E-14 6.34E-14 1.42E-14 2.87E-14
                          colon     4.89E-13 2.48E-13 1.06E-13 1.96E-14 6.51E-14
                          liver     2.64E-14 1.40E-14 1.13E-14 9.69E-15 9.86E-15
                          lung      3.33E-13 1.74E-13 7.20E-14 3.82E-14 6.04E-14
                          bone      1.68E-15 8.75E-16 6.84E-16 5.82E-16 6.11E-16
                          skin      3.01E-15 1.39E-15 9.05E-16 4.48E-16 6.25E-16
                          breast    1.78E-13 9.10E-14 4.57E-14 1.41E-14 2.90E-14
                          ovary     2.68E-14 1.37E-14 9.86E-15 8.33E-15 8.72E-15
                          bladder   3.82E-14 2.03E-14 1.66E-14 1.60E-14 1.59E-14
                          kidney    9.21E-15 4.86E-15 3.93E-15 3.31E-15 3.38E-15
                          thyroid   1.24E-14 5.77E-15 2.78E-15 1.02E-15 1.94E-15
                          leukemia  1.19E-13 4.60E-14 2.79E-14 3.69E-14 3.65E-14
                          residual  4.69E-13 2.45E-13 1.86E-13 4.72E-14 9.26E-14
                          Total     1.86E-12 9.50E-13 5.55E-13 2.17E-13 3.61E-13
  //                      //                        //                        //
  ||                      ||                        ||                        ||
  //                      //                        //                        //
Be-7    1.000 F E 5.0E-03 esophagus 1.14E-13 4.86E-14 2.83E-14 2.31E-14 2.65E-14
                          stomach   4.80E-13 2.73E-13 1.89E-13 4.02E-14 9.22E-14
                          colon     4.54E-12 2.15E-12 7.21E-13 1.26E-13 5.16E-13
                          liver     1.42E-13 6.39E-14 4.04E-14 3.31E-14 3.68E-14
                          lung      2.11E[illegible] 2.11E-13 1.54E-13 2.88E-13
                          bone      2.74[illegible]-15 7.00E-15 7.84E-15
                          skin      1.45[illegible] 1.30E-15 [illegible]E-15
                          breast    7.05[illegible]E-14
                          ovary     2.42[illegible]E-14
                          bladder   2.05[illegible]E-14
                          kidney    6.74[illegible]E-14
                          thyroid   6.29[illegible]E-15
                          leukemia  1.62[illegible]E-13
                          residual  3.59[illegible]-12 1.63E-12 9.[illegible]E-13
                          Total     1.39E-11 6.30E-12 2.89E-[illegible]E-12
  //                      //                        //                        //
  ||                      ||                        ||                        ||
  //                      //                        //                        //
Pu-239  1.000 S E 1.0E-05 esophagus 7.86E-10 4.78E-10 3.53E-10 1.42E-10 2.06E-10
                          stomach   3.09E-09 1.57E-09 8.04E-10 1.58E-10 4.50E-10
                          colon     1.10E-08 4.00E-09 1.26E-09 3.00E-10 1.05E-09
                          liver     7.99E-08 6.17E-08 5.75E-08 2.55E-08 3.22E-08
```

Set of cancers considered

Risk coefficients by cancer type and age group. The coefficients represent the contribution to risk during these ages of for a cohort of newborns. See below.

```
lung      4.83E-06 2.39E-06 8.44E-07 4.99E-07 7.96E-07
bone      1.62E-08 1.55E-08 1.65E-08 7.78E-09 9.17E-09
skin      7.42E-11 3.66E-11 2.30E-11 6.96E-12 1.31E-11
breast    2.04E-09 8.59E-10 3.74E-10 9.60E-11 2.50E-10
ovary     5.24E-09 4.18E-09 3.27E-09 1.31E-09 1.82E-09
bladder   1.57E-09 1.01E-09 8.28E-10 3.74E-10 4.92E-10
kidney    8.79E-10 5.35E-10 4.45E-10 2.24E-10 2.78E-10
thyroid   2.60E-10 1.09E-10 5.44E-11 1.80E-11 3.64E-11
leukemia  3.97E-09 2.40E-09 2.64E-09 1.50E-09 1.67E-09
residual  1.16E-08 5.36E-09 2.76E-09 4.71E-10 1.52E-09
Total     4.96E-06 2.48E-06 9.31E-07 5.37E-07 8.45E-07
```

The risk coefficients represent the mortality experience of the age groups of a cohort of newborns. To derive a coefficient applicable to individuals enter the age group ($x1 - x2$); that is, survived to the age $x1$, the coefficient should be divided by $S(x1)$ where $S(x1)$ is the value of the survival function at age $x1$. For example, the lifetime lung cancer mortality risk for individuals of age 25-70 is 4.99E-07 / 0.97671 where 0.97671 is the survival to age 25 (see file SURV90E.DAT in folder DCAL\DAT\RSK) which yields 5.11E-07 Bq^{-1}.

B.4 RSKRSK.RSK File

The *.RSK file, written by RISKCAL.EXE, list the mortality and morbidity risk coefficients for each nuclide by cancer, age, and gender. This can be a rather large file.

```
     ---- Mortality (/Bq) ----   ---- Morbidity (/Bq) ----
 Age  Male     Female   Both      Male     Female   Both
H-3     1.000 F E 1.0E+00
Cancer site: esophagus
  0  2.19E-14 4.84E-14 3.49E-14  2.44E-14 5.38E-14 3.87E-14
  1  1.73E-14 3.82E-14 2.75E-14  1.93E-14 4.24E-14 3.06E-14
  2  1.44E-14 3.18E-14 2.29E-14  1.60E-14 3.53E-14 2.54E-14
  3  1.23E-14 2.70E-14 1.95E-14  1.36E-14 3.00E-14 2.16E-14
  4  9.71E-15 2.14E-14 1.54E-14  1.08E-14 2.37E-14 1.71E-14
  5  9.71E-15 2.14E-14 1.54E-14  1.08E-14 2.37E-14 1.71E-14
  6  8.99E-15 1.98E-14 1.43E-14  9.99E-15 2.20E-14 1.59E-14
  7  8.45E-15 1.86E-14 1.34E-14  9.39E-15 2.07E-14 1.49E-14
  8  8.02E-15 1.77E-14 1.27E-14  8.92E-15 1.96E-14 1.41E-14
  9  7.23E-15 1.59E-14 1.15E-14  8.04E-15 1.77E-14 1.28E-14
 10  7.23E-15 1.59E-14 1.15E-14  8.04E-15 1.77E-14 1.27E-14
 //                              //                      //
 ||                              ||                      ||
 //                              //                      //
 11  6.75E-15 1.49E-14 1.07E-14  7.50E-15 1.65E-14 1.19E-14
 12  6.25E-15 1.38E-14 9.92E-15  6.95E-15 1.53E-14 1.10E-14
 13  5.79E-15 1.27E-14 9.19E-15  6.44E-15 1.42E-14 1.02E-14
 14  5.28E-15 1.16E-14 8.37E-15  5.86E-15 1.29E-14 9.31E-15
 15  5.28E-15 1.16E-14 8.38E-15  5.87E-15 1.29E-14 9.31E-15
 16  5.25E-15 1.16E-14 8.33E-15  5.84E-15 1.28E-14 9.26E-15
 17  5.27E-15 1.16E-14 8.36E-15  5.86E-15 1.29E-14 9.29E-15
 18  5.34E-15 1.17E-14 8.47E-15  5.94E-15 1.30E-14 9.41E-15
 19  5.61E-15 1.23E-14 8.88E-15  6.23E-15 1.37E-14 9.87E-15
 20  5.61E-15 1.23E-14 8.89E-15  6.24E-15 1.37E-14 9.88E-15
 //                              //                      //
 ||                              ||                      ||
 //                              //                      //
100  1.48E-18 7.51E-18 6.32E-18  1.64E-18 8.35E-18 7.02E-18
101  9.43E-19 4.64E-18 3.94E-18  1.05E-18 5.16E-18 4.38E-18
102  5.81E-19 2.74E-18 2.35E-18  6.45E-19 3.04E-18 2.61E-18
103  3.42E-19 1.53E-18 1.33E-18  3.80E-19 1.70E-18 1.48E-18
104  1.92E-19 8.13E-19 7.11E-19  2.13E-19 9.03E-19 7.89E-19
105  1.01E-19 4.06E-19 3.58E-19  1.12E-19 4.51E-19 3.98E-19
106  4.96E-20 1.89E-19 1.68E-19  5.51E-20 2.10E-19 1.87E-19
107  2.23E-20 8.06E-20 7.22E-20  2.47E-20 8.96E-20 8.03E-20
108  8.92E-21 3.08E-20 2.78E-20  9.91E-21 3.42E-20 3.09E-20
109  3.02E-21 9.98E-21 9.06E-21  3.36E-21 1.11E-20 1.01E-20
```

```
110  2.78E-22 8.84E-22 8.06E-22  3.09E-22 9.82E-22 8.95E-22
Cancer site: stomach
  0  1.67E-13 3.34E-13 2.48E-13  1.86E-13 3.71E-13 2.76E-13
  1  1.19E-13 2.38E-13 1.77E-13  1.33E-13 2.65E-13 1.97E-13
  2  9.65E-14 1.92E-13 1.43E-13  1.07E-13 2.14E-13 1.59E-13
  3  8.03E-14 1.60E-13 1.19E-13  8.93E-14 1.78E-13 1.33E-13
  4  6.21E-14 1.24E-13 9.22E-14  6.90E-14 1.38E-13 1.02E-13
  5  6.21E-14 1.24E-13 9.22E-14  6.90E-14 1.38E-13 1.02E-13
  6  5.69E-14 1.13E-13 8.46E-14  6.33E-14 1.26E-13 9.40E-14
  7  5.30E-14 1.06E-13 7.88E-14  5.89E-14 1.17E-13 8.75E-14
  8  4.99E-14 9.95E-14 7.42E-14  5.55E-14 1.11E-13 8.24E-14
  9  4.44E-14 8.84E-14 6.59E-14  4.93E-14 9.83E-14 7.32E-14
 10  5.83E-14 1.01E-13 7.92E-14  6.48E-14 1.12E-13 8.80E-14
 //                              //                      //
 ||                              ||                      ||
 //                              //                      //
Cancer site: colon
  0  6.87E-13 1.02E-12 8.50E-13  1.25E-12 1.86E-12 1.55E-12
  1  5.33E-13 7.91E-13 6.59E-13  9.69E-13 1.44E-12 1.20E-12
  2  4.40E-13 6.53E-13 5.44E-13  8.00E-13 1.19E-12 9.89E-13
 //                              //                      //
 ||                              ||                      ||
 //                              //                      //
Cancer site: liver
  0  5.38E-14 3.52E-14 4.47E-14  5.66E-14 3.70E-14 4.71E-14
  1  4.25E-14 2.77E-14 3.53E-14  4.47E-14 2.92E-14 3.71E-14
 //                              //                      //
 ||                              ||                      ||
 //                              //                      //
Cancer site: lung
  0  4.37E-13 6.99E-13 5.65E-13  4.60E-13 7.36E-13 5.94E-13
  1  3.44E-13 5.50E-13 4.45E-13  3.63E-13 5.79E-13 4.68E-13
 //                              //                      //
 ||                              ||                      ||
 //                              //                      //
Cancer site: bone
  0  2.83E-15 2.85E-15 2.84E-15  4.04E-15 4.07E-15 4.06E-15
  1  2.23E-15 2.24E-15 2.24E-15  3.19E-15 3.20E-15 3.20E-15
 //                              //                      //
 ||                              ||                      ||
 //                              //                      //
Cancer site: skin
  0  5.02E-15 5.58E-15 5.29E-15  5.02E-15 5.58E-15 5.29E-15
  1  3.90E-15 4.34E-15 4.11E-15  3.90E-15 4.34E-15 4.11E-15
 //                              //                      //
 ||                              ||                      ||
 //                              //                      //
Cancer site: breast
  0  0.00E+00 6.16E-13 3.01E-13  0.00E+00 1.23E-12 6.01E-13
  1  0.00E+00 4.86E-13 2.37E-13  0.00E+00 9.71E-13 4.74E-13
 //                              //                      //
 ||                              ||                      ||
 //                              //                      //
Cancer site: ovary
  0  0.00E+00 9.30E-14 4.54E-14  0.00E+00 1.33E-13 6.48E-14
  1  0.00E+00 7.33E-14 3.58E-14  0.00E+00 1.05E-13 5.11E-14
  2  0.00E+00 6.10E-14 2.98E-14  0.00E+00 8.72E-14 4.26E-14
 //                              //                      //
 ||                              ||                      ||
 //                              //                      //
Cancer site: bladder
  0  8.63E-14 4.19E-14 6.46E-14  1.73E-13 8.38E-14 1.29E-13
  1  6.81E-14 3.30E-14 5.10E-14  1.36E-13 6.61E-14 1.02E-13
 //                              //                      //
 ||                              ||                      ||
 //                              //                      //
Cancer site: kidney
```

```
  0  1.89E-14 1.20E-14 1.56E-14  2.91E-14 1.85E-14 2.40E-14
  1  1.50E-14 9.49E-15 1.23E-14  2.30E-14 1.46E-14 1.89E-14
 //                              //                       //
 ||                              ||                       ||
 //                              //                       //
Cancer site: thyroid
  0  1.37E-14 3.02E-14 2.18E-14  1.37E-13 3.02E-13 2.18E-13
  1  1.07E-14 2.35E-14 1.69E-14  1.07E-13 2.35E-13 1.69E-13
 //                              //                       //
 ||                              ||                       ||
 //                              //                       //
Cancer site: leukemia
  0  2.04E-13 1.88E-13 1.96E-13  2.06E-13 1.90E-13 1.98E-13
  1  1.64E-13 1.48E-13 1.56E-13  1.65E-13 1.50E-13 1.58E-13
 //                              //                       //
 ||                              ||                       ||
 //                              //                       //
Cancer site: residual
  0  6.49E-13 9.46E-13 7.94E-13  9.15E-13 1.33E-12 1.12E-12
  1  5.13E-13 7.45E-13 6.26E-13  7.22E-13 1.05E-12 8.82E-13
 //                              //                       //
 ||                              ||                       ||
 //                              //                       //
Cancer site: Total
  0  2.35E-12 4.07E-12 3.19E-12  3.44E-12 6.36E-12 4.86E-12
  1  1.83E-12 3.17E-12 2.49E-12  2.69E-12 4.95E-12 3.79E-12
 //                              //                       //
 ||                              ||                       ||
 //                              //                       //
```

APPENDIX C
DCAL LIMITING DIMENSIONS

This appendix summarizes the limiting dimensions of the parameters in potential user prepared input files. In most instances DCAL's modules are dimensions are of sufficient size to readily accommodate any reasonable size problem the user might prepare. In Tables C.1 – C.4 detail the restrictions place on specific data elements. Tables C.5 – C.7 address restrictions within the major computational modules.

Table C.1 Restrictions on Compartment Model Definition

Description	Limit	Module
Biokinetic compartments	90	ACTACAL
Transfers from any compartment	60	ACTACAL
Total transfers in model	240	ACTACAL
Ages specified in systemic model	10	ACTACAL
Anatomical source regions	60	SEECAL

Table C.2 Restrictions on Decay Chain Definition

Description	Limit	Module
Chain members	30	ACTACAL SEECAL
Branching fractions for any member	3	ACTACAL SEECAL RADSUM32 CHAIN32

Table C.3 Restrictions on Emitted Radiations

Description	Limit	Module
Radiations	4000	SEECAL
Branching fractions for any member	3	ACTACAL

Table C.4 Restrictions within ACTACAL

Description	Limit
Biokinetic compartments	90
Transfers from any compartment	60
Total transfers in model	240
Ages specified in systemic model	10
Anatomical source regions	60
Anatomical target regions	37
Particle sizes in ICRP 66 lung model	15
Age-specific phantoms	6
Activity f(t)	150

Table C.5 Restriction within SEECAL

Description	Limit
Age-specific phantoms	8
Anatomical source regions	60
Anatomical source regions	37
Nuclides	30

Table C.6 Restriction within EPACAL

Description	Limit
Age-specific phantoms	6
Anatomical source regions	60
Anatomical target regions	37
Nuclides	20
LET	2

Table C.7 Restriction within RISKCAL

Description	Limit
Age-specific absorbed dose rates	10
Anatomical target regions	37
Cancer types	12
Years in life table	120
LET	2

APPENDIX D
NUCLEAR DECAY DATA FILES

The Dosimetry Research Group (DRG) of the Life Science Division at Oak Ridge National Laboratory (ORNL) has for several years maintained data bases of nuclear decay data for use in dosimetric calculations. Although other sources of such information are available, the ORNL database, in machine-readable form, has been explicitly designed to address the needs in medical, environmental, and occupational radiation protection. This release of DCAL contains the nuclear decay data collection initially documented in ORNL/TM-12350 (Eckerman et al. 1993). The collection denoted as "ICRP38" collection consists of data for 825 radionuclides that appeared in Publication 38 (ICRP 1983), plus an additional 13 radionuclides evaluated during the preparation of a monograph for the Medical Internal Radiation Dose (MIRD) Committee of the Society of Nuclear Medicine (Weber *et al.* 1989). The collection is located in the folder \DCAL\DAT\NUC\.

The ICRP38 nuclear data collection consists of three data files. The triplet of files has the root name "ICRP38" with extensions NDX, RAD, and BET. The ICRP38.NDX file is an index file that serves as the entry into the other two larger files. The file ICRP38.RAD contains data on the unique or average energy and the intensity of each emitted radiation while the file ICRP38.BET contains, for beta emitters, the beta spectra. The NDX file contains one record for each nuclide. The nuclide record has fields giving the location of the nuclide records (and the number of such records) in the RAD and BET files. In addition to the pointers, other fields of the NDX record give the half-life, the mode of decay, the identity of any radioactive decay products (daughters), the fraction of the transformation forming the daughters (the branching fractions), and the total energy emitted by alpha, electron, and photon radiations (excluding electrons and photons accompanying spontaneous fission). The NDX records are sorted by the nuclide field so DCAL's modules can use a binary search to locate the record for the nuclide of interest. While the purpose of the NDX file was to provide entrance into the two other larger files, its records are of considerable utility in their own right. For example, the modules ACTACAL and CHAIN construct the decay chain for a radionuclide and determine possible truncation of the chain based on information in the NDX file.

In some instances, a radionuclide is not uniquely identified by its atomic number (or chemical symbol) and mass number. Nuclei of the same atomic and mass numbers, but with distinguishable nuclear properties, are referred to as isomers. Identification of an isomer requires reference to it physical half-life. In DCAL, these nuclei are identified by the nonstandard notation listed in Table D.1.

Some changes were introduced into the NDX and RAD files since the publication of ORNL/TM-12350 to enable DCAL's SEECAL module to access directly the nuclear decay data. Specifically, the RAD file records for each nuclide have been sorted by radiation type and by increasing energy within each radiation type with additional pointers added to the NDX file to enable accessing the data. Table D.2 lists the current content of the nuclide records in NDX. As noted above, the NDX file was sorted by the nuclide field such that a binary search is used by DCAL's modules to locate the data for a given nuclide. The fields *n1* through *n5* were added to enable the location of specific radiation types. The *n1* field gives the number of photons of energy less than 10 keV (SEECAL treats these photons as non penetrating radiations). If the radionuclide of interest is an alpha emitter, *n5* is greater than zero; the RAD record for the lowest energy alpha particle emitted by the nuclide is $irad + n1 + n2 + n3 + n4 + 1$ where *irad* is record number of the nuclide in the RAD file, *n1* the number of photons of energy less than 10 keV, *n2* is the number of photons of energy equal to or greater than 10 keV, *n3* is the number of beta lines (their average energy is contained in the RAD file), and *n4* is the number of discrete electrons. Since *irad* is the header record of the nuclide in the RAD file, not its first data record, it is necessary to add 1 as noted. The following code fragment illustrates the reading of the *n5* alpha records in the RAD file. The format of the records in the RAD file is given in Table D.3

```
irec = irad + n1 + n2 + n3 + n4
do i = 1, n5
   Read(20, '(i1,2E12.0)',rec = irec + i) icode, f(i), e(i)
end do
```

The RAD records for photons (x- and gamma rays), discrete electrons (Auger and internal conversion electrons), beta particles, and alpha particles have been sorted by increasing energy. This sorting facilitated the procedure used to interpolate the specific absorbed fraction data.

The direct-access files ICRP38.BET and MIRD.BET contain the beta spectra data for the beta emitters in these collections. The spectral data were computed on a fixed energy grid, to facilitate tabulation of the composite spectra; i.e., summed over all beta transitions. Fig. D.1 illustrates the composite spectra for ^{87}Kr. The structure of the records is given in Table B.4. For each nuclide, the header record gives the name of the nuclide. The header is followed by a record containing the end-point energy of the spectrum, in MeV. The subsequent data records contain the frequency *N(E)* (number of betas per MeV per decay) at the standard energy grid points that are less than the end-point energy. The very last record is the frequency at the nuclide-unique end-point energy. The number of beta particles per decay *Y* is

$$Y = \int_{o}^{\infty} N(E)\, dE \tag{D1}$$

and the average energy of the spectrum is

$$\overline{E} = \frac{1}{Y} \int_{0}^{\infty} E\, N(E)\, dE \tag{D.2}$$

DCAL's CHAIN and RADSUM utilities can also be used to examine the data for a specific radionuclide.

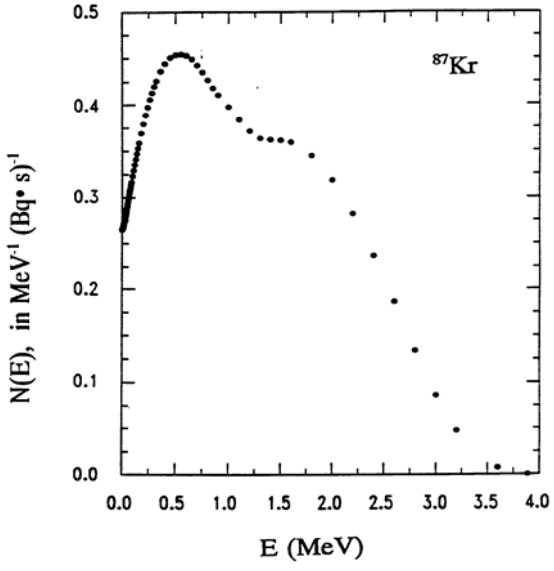


Fig. D-1. Spectrum of beta particles emitted by Kr-87.

REFERENCES

Eckerman, K. F., et al. 1993. *Nuclear Decay Data Files of the Dosimetry Research Group*. ORNL/TM-12350, Oak Ridge National Laboratory, Oak Ridge, TN.

International Commission on Radiological Protection (ICRP). 1983. *Radionuclide Transformations Energy and Intensity of Emission.* ICRP Publication 38, Pergamon Press, Oxford.

D. A. Weber, et al. 1989. *MIRD: Radionuclide Data and Decay Schemes.* Society of Nuclear Medicine, New York.

Table D.1. Isomers with nonstandard naming convention[a]

Nuclide	$T_{1/2}$	Decay Mode	Radioactive Daughters and Branching Fractions			
Eu-150a	12.62h	B- EC B+				
Eu-150b	34.2y	EC				
In-110a	69.1m	EC B+				
Ir-186a	15.8h	EC B+				
Ir-186b	1.75h	EC B+				
Ir-190m	1.2h	IT				
Ir-190n	3.1h	IT EC				
Nb-89a	66m	EC B+	Zr-89	1.00		
Nb-89b	122m	EC B+	Zr-89	1.00		
Np-236a	115E3y	EC B-	Pu-236	0.089	U-236	0.911
Np-236b	22.5h	B- EC	Pu-236	0.48	U-236	0.52
Re-182a	12.7h	EC B+				
Re-182b	64.0h	EC				
Sb-120a	15.89m	EC B+				
Sb-120b	5.76d	EC				
Sb-124m	93s	IT B-	Sb-124	0.80		
Sb-124n	20.2m	IT	Sb-124m	1.00		
Sb-128a	10.4m	B-				
Sb-128b	9.01h	B-				
Ta-178a	9.31m	EC				
Ta-178b	2.2h	EC				
Tb-156m	24.4h	IT	Tb-156	1.00		
Tb-156n	5.0h	IT	Tb-156	1.00		

[a]The MIRD collection contains only the Ir-190 isomers. The collection does contain the 9.31m Ta-178 isomer but not the Ta-178b isomer.

Table D.2. Structure of data records in NDX file

Variable	Format	**Description** (records 2 and beyond)[a]
Head record		
i1, i2	(2i4)	number of first (2) and last data records
Data Records (2, ..., last)[a]		
Nuclide	A7	Name of nuclide; e.g., Am-241, Tc-99m
Half-life	A8	Half-life of nuclide
Units	A2	Half-life units: us-microseconds, ms-milliseconds, s-seconds m-minutes, d-day, and y-year.
Decay Mode	A8	A, B-, B+, EC, IT, & SF denote alpha, beta minus, beta plus, electron capture, internal transition, and spontaneous fission.
Irad	I7	Record number of nuclide in RAD file
Nrad	I5	Number of records for nuclide in RAD file
Ibet	I6	Record number of nuclide in BET file
Nbet	I4	Number of records for nuclide in BET file
j1	I4	Record number of first daughter in NDX file
F1	E11.0	Branching fraction forming first daughter
j2	I4	Record number of second daughter in NDX file
F2	E11.0	Branching fraction forming second daughter
j3	I4	Record number of third daughter in NDX file
F3	E11.0	Branching fraction forming third daughter
Ea	F7.0	Total energy of alpha emissions (MeV/nt)
Ee	F8.0	Total energy of electron emission (spectra and discrete) (MeV/nt)
Ep	F8.0	Total energy of photon emissions (MeV/nt)
n1	I4	Number of photons of energy less than 10keV per nt
n2	I4	Number of photons of energy equal or greater than 10 keV per nt
n3	I4	Number of beta lines with reported average energies per nt
n4	I5	Number of discrete electron emitted per nt
n5	I4	Number of alpha particles emitted per nt
Spf	I3	Spontaneous fission flag
Mass	I11	Atomic mass
Date	A10	Date of ENSDF evaluation

[a]FORMAT(a7,a8,a2,a8,i7,i5,i6,i4,3(i4,E11.0),e7.0,2f8.0,3i4,i5,i4,i3,i11,a10) record length = 160

Table D.3. Structure of records in RAD files

Variable	Format	Description
Nuclide head records[a]		
Nuclide	a7	Name of nuclide; e.g., Am-241, Tc-99m
Half-life	a13	Half-life of nuclide
Nrad	i5	Number of records for this nuclide
Data records (nrad records for nuclide)[a]		
Icode	i1	Code for radiation type (see below)
Y (%)	e12.0	Yield in % per nt
E (MeV)	e12.0	Unique or average energy of radiation

Icode	Mnemonic[b]	Description
1	G	Gamma rays
2	X	x-rays
3	Aq	Annihilation photons
4	b+	Beta + particles
5	b-	Beta - particles
6	ic	Internal conversion electrons
7	ae	Auger electrons
8	a	Alpha particles
9		Spontaneous fission

[a]Record length = 25.
[b]DEXRAX uses the following mnemonics for radiations associated with spontaneous fission: ff – fission fragments, n – neutrons, pg – prompt gamma rays, dg – delayed gamma rays, sb – beta emissions.

Table D.4. Structure of records in BET files

Variable	Format	Description
Head record (record ibet)[a]		
Nuclide	A7	Name of nuclide; e.g., Am-241
Data records		
E_{max}	f9.0	End-point energy of spectrum
Y(E)	e9.0	Value of differential energy spectrum (1, ..., nbet values)

[a]Record length = 9.