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MANUAL FOR SPKTBIB: A PC-BASED CATALOGUE OF NEUTRON SPECTRA

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ABSTRACT

The spectral fluence response of practicable neutron dosemeters for routine use generally does not match the energy dependence of radiation protection quantities such as the ambient dose equivalent H*(10). As a consequence, significant errors may be encountered when monitoring in a neutron energy spectrum different from that in which the dosemeter has been calibrated. A collaborative CEC-supported project has been undertaken to develop new neutron calibration fields with energy spectra similar to those found in the working environment.

As a first step, a database of neutron spectra and instrument and dosimetric response functions has been prepared. A program package has been developed to assist the collection and manipulation of these data. The features of the programs are described and examples for dosimetric applications are given. This report constitutes an instruction manual for the package.

CONTENTS

1. INTRODUCTION

Routine monitoring for radiation protection purposes is performed using personal dosemeters or area survey instruments. For neutron radiation, the quantity for assessment is dose equivalent: personal dose equivalent, $H_p(10)$, for personnel measurements, and ambient dose equivalent, $H^*(10)$, for area monitoring[1].

The problems of designing adequate radiation protection devices for neutron radiation arise from several causes. For individual dosemeters, allowing for any anisotropic angular distribution of the radiation is in general difficult, and sensitivity can also be a problem. The greatest difficulty arises, however, from the combined effect of the very wide range of energies over which a neutron dosemeter should work, i.e. from thermal energies to perhaps 20 MeV, and the fact that the dose equivalent per unit fluence varies dramatically with neutron energy.

Although the spectral fluence response of practicable neutron dosemeters is also energy-variable, unfortunately none has a response which matches the appropriate dose equivalent quantity (see Figure 1). Thus, if a dosemeter is used to monitor in a field which has an energy spectrum different from that of the calibration field, the recorded dose equivalent may be significantly different from that received by the wearer.

The two calibration fields most commonly employed (^{241}Am-Be and ^{252}Cf) are un-moderated radionuclide sources and therefore consist wholly of a high energy distribution, with mean energies of approximately 4 MeV and 2 MeV. However, the fields encountered in the workplace tend to include lower energy scattered neutrons and moderated neutrons that have passed through shielding. Therefore, errors will be incurred in measuring these fields.

The situation is particularly grave in the case of fast neutron personal dosimetry, where the two most common types of dosemeter, NTA film and PADC plastic, exhibit little or no response to neutrons below a few hundred keV. Thus these devices may significantly under-read neutron dose in the workplace - see Figure 2. A thermal response has, however, been introduced into some devices, e.g. by the addition of a nylon 'radiator' to the CR-39 dosemeter, which helps to minimise, and in some cases reverses, this underread.

If all workplace spectra were similar, a few measurements would suffice to determine correction factors for dosemeter readings. But the problem is exacerbated by the wide variety of different spectra encountered in working environments.

It is seemingly impossible to derive calibration factors applicable to all spectra simultaneously as long as one is restricted to any one single dosemeter. One approach to minimising the discrepancy in the dosemeter reading is to calibrate in standard calibration fields and apply a calibration factor derived from knowledge of the dosemeter response and the energy spectrum of the field in which it is to be used. In the majority of situations, however, the neutron spectra are not known. Another method is to calibrate dosemeters in fields similar to those encountered in working environments, where the measurements need to be made.

Accordingly, a collaborative project, supported by the Commission of the European Communities, is being undertaken by the National Physical Laboratory in the UK, PTB (Physikalisch-Technische Bundesanstalt) and GSF (Forschungszentrum fur Umwelt und Gesundheit) in Germany, the Commissariat a l'Energie Atomique in France, and two Czech laboratories, the Czech Metrological Institute and the Nuclear Research Institute, to investigate neutron spectra in the workplace, with the objective of producing a few well-characterised neutron calibration fields that replicate typical spectral neutron fluence distributions encountered in radiation protection practice. An important part of this work is

the determination of a number of 'classes' of environments. A large number of papers aiming at the characterisation of operational neutron fields have already been published (see list in reference 2).

An important step in searching for optimal calibration procedures is to collect neutron spectra in relevant working environments. Therefore, the first part of the project involved measuring neutron energy spectra in a diverse range of situations, and compiling a catalogue of these spectra and others available in the open literature or through private communication.

In this paper a computer package will be presented which assists the collection, interpretation and analysis of the spectra[3]. The package, named SPKTBIB (an abbreviation for the German SPeKTren BIBliothek - library of spectra), consists of a computerised database of spectra, instrument and dosimetric response functions, and additional programs for the processing and analysis of the data.

In particular, the programs have been designed to provide the following features: quick access, display, and intercomparison of spectra aided by suitable indexing; computation of dosimetric quantities and dosemeter responses in these fields; testing the suitability of present calibration procedures; deriving combinations of dosemeters to give an optimised dose equivalent response; and superimposing calibration fields to simulate realistic spectra.

Examples are given to demonstrate the capabilities of this program package. Studies including a comparison of the new operational and limiting dose quantities for neutrons[4], an investigation of the effect of choice of calibration field on dosemeter response in the workplace[5], and categorisation of spectra according to various parameters[6] have also been performed using the system.

2. INSTALLATION

The following hardware and software requirements are needed for implementation and use of the program package:

- An IBM-compatible personal computer with 387 coprocessor or later;

  A hard-disk drive with at least 7 megabytes (MB) of free space;

  590 kB minimum of memory (the executable files require only 505 kB, but internal DOS calls by the programs necessitate the higher requirement);

- A floppy-disk drive;

- VGA graphics capability;

- MS-DOS® version 3.0 or later;

- 1 MB of random-access memory (RAM)*;

* optional but recommended as the programs require repeated access to many files.

A printer is optional.

The programs have been compiled using Microsoft® FORTRAN Version 5.1; two of the character fonts are needed to accompany the graphics.

Note: for the graphics functions to work correctly the ANSI.SYS device driver should be included in the PC's CONFIG.SYS file, and if RAM memory is to be used a RAMDRIVE device driver also needs to be included.

The files are contained on three floppy disks. To install the database, insert Disk 1 into the appropriate disk drive and copy the file INSTALL.BAT onto the hard disk. Then use the command

INSTALL *N*:

to start the installation procedure, where *N*: is the floppy disk drive (e.g. A:). The batch-file will create a sub-directory, SPKTBIB, under the current directory on the hard disk, and copy over the files from the three disks.

The files will be stored in four directories. The main directory, SPKTBIB, contains the executable versions of the programs, and various ancillary files associated with the programs. There are three sub-directories below this parent directory:

BIB000 contains files of 'unformatted' spectra, which are listed on one of seven files, READ*aut*.INP, for input to the programs READ000 and READGPM. "*aut*" represents the source of the data, and will be one of the following: GPM, I&M, CEA, GSF, NPL, PTB, or NEW. The GPM and I&M data are taken from two IAEA compendia[7,8]. CEA, GSF, NPL, and PTB are contractors in the project, and NEW is for data obtained from any other source. Additional spectra for the database should be added to the list in READNEW.INP. At present the database contains approximately 500 spectra.

BIB$$$ will initially contain the menu and help-files for SPKTBIB (SPKTBIB.MNU and SPKTBIB.H*n*) and a 'title-page' for each program, *filename*.TTL. However, after running READ000 and READGPM, the formatted spectra and the libraries SPKTBIB.*aut* will be output to this directory, as will stored groups of spectra created by the program SPKTBIB.

BIB&&& will contain both 'unformatted' and 'formatted' files of response function data, the data listings for the formatting programs (READ000&.INP and READGPM&.INP), libraries RSPBIB&.000 and RSPBIB&.GPM, menu and help-files for the program RSPBIB& (RSPBIB&.MNU and RSPBIB&.H0*n*), 'title-pages' for the programs associated with response function data (*filename*.TTL), and input and output files for the program DOSE_Q (DOSE_Q.INP and SPKTBIB.8DQ). Response function blocks created by RSPBIB& will also be written to this sub-directory.

A complete listing for each of the directories above is given in Appendix 1 for reference.

3. INSTRUCTIONS ON USE

This section outlines the function of each program and describes the various options offered within them. A flow chart of the system is given in Appendix 2. The diagram includes the output files and shows how they link the programs.

SPKTBIB operates on data held in files with a particular format. After installation of the programs and the original spectrum and response function files the data must be re-written into files with the required uniform format. Two programs are used to achieve this: READ000 and READ000& respectively. There are two additional programs, READGPM and READGPM&, designed specifically to format data extracted from the IAEA compendium of Griffith, Palfalvi and Madhvanath[7].

READ000:

Unformatted neutron spectra are stored in the sub-directory BIB000, and listed on the files READ*aut*.INP (see above). Enter the extension (i.e. *aut*) of the data to be formatted. Initially all six sets will require formatting. Subsequently, new spectra may be added to the list READNEW.INP and only this set will need to be processed.

The spectra may be plotted as the program is run; press <ENTER> to exit the graphics. Whilst running, the program calculates and returns the values of three quantities for each spectrum: the integrals of the lethargy and group fluence spectra (PL and PG respectively), and the mean energy of the spectrum, Eg.

The formatted spectra are output to the subdirectory BIB$$$ and assigned a filename of the form $xxx_yyy.*aut*, where x and y are integers derived from the order of the file in the list READ*aut*.INP and the number of spectra in the file. A library SPKTBIB.*aut* is also produced containing a list of headings for the spectra and their filenames.

Adding new spectra to the catalogue:

New spectra must be prepared according to the format in Appendix 3. Up to eight spectra can be included in any one file.

The first entry in the file is the number of comment lines below it (maximum 20). The first comment line is a title for the file and is equivalent to Heading(1) in the Overview and Search facilities of SPKTBIB. The next few lines constitute headings for each spectrum (Heading(2) in SPKTBIB), the author(s) of the data, and the name of their organisation. The first twelve characters of Heading(2) are used by some programs in the package as a reference to the spectrum, and should therefore constitute a reasonable description of the field. The remainder of the comment lines are not used for any specific function, but can be used to incorporate additional information about the spectra for external reference.

The comment lines are followed by four numbers, which are: the number of energy bins, the number of spectra in the file, and two numbers indicating whether the data is represented as group fluence or fluence per unit lethargy (0 or 1), and whether the energy units are eV or MeV (0 or 6) - see Appendix 3. The spectra are listed below these data.

The first column is the neutron energy, starting with the lowest energy bin limit and ascending. The maximum number of bins is 192. The adjacent columns are the spectral fluences associated with each energy bin. The data do not need to be normalised since the program READ000 performs this function. The final entry is a single value representing the upper limit of the highest energy bin.

Any new datafile should be stored in the sub-directory BIB000 and the filename added to the list in READNEW.INP. The number at the top of this file is the number of datafiles in the list, and should be increased accordingly. READ000 can then be used to convert the data to the format appropriate for use with SPKTBIB.

READGPM:

READGPM formats spectra from the IAEA compendium of Griffith, Palfalvi and Madhvanath[7], and has input and output files analogous to those of READ000. The program will only ever need to be run once, to create the library SPKTBIB.GPM. The data can be plotted as the program is run.

READ000&:

Analogous to READ000 but for response function data. Both the unformatted datafiles and the formatted output are stored in sub-directory BIB&&&&. READ000&.INP is the input file listing the data. The output files are assigned a name of the form &xxx_yyy.000, and the library RSPBIB&.000 will be created.

Adding new response functions to the database:

To add a new instrument or dosimetric response function to the catalogue, prepare a datafile with the format shown in Appendix 4. The first entry is the number of comment lines (maximum 19), whose order should be: a heading for the file (Heading(1) in the Overview and Search facilities of RSPBIB&), a title for each response function (Heading(2)), the author of the data, the establishment of its origin, and finally any additional relevant information.

After the comment lines enter two numbers: the number of energy points (maximum 192) and the number of response functions (maximum 8) in the file. Finally enter the response function data: the energies, in units of eV and ascending, form the first column, with the response function data associated with each energy located in those adjacent.

The datafile should be stored in the sub-directory BIB&&&&, and the filename entered in READ000&.INP. The number at the top of this file (i.e. the number of datafiles in the list) must be increased correspondingly. Run READ000& to convert the data to the format required by the program RSPBIB&.

READGPM&:

READGPM& formats response function data originating from the IAEA compendium of Griffith, Palfalvi and Madhvanath[7]. The program is analogous to READGPM, with the input list in READGPM&.INP and output RSPBIB&.GPM and &xxx_yyy.GPM. All data are stored in the sub-directory BIB&&&&.

The files RSPBIB&.000 and RSPBIB&.GPM must be merged to form the combined library RSPBIB&.DAT prior to running RSPBIB&. A program, **COMBINE&**, exists for this purpose.

RSPBIB&:

The function of this program is to handle the response function data and to produce blocks of up to eight response functions, which is the maximum number the program SPKTBIB can handle at one time.

Option 1 - Overview:
Lists the response function data in the library RSPBIB&.DAT by virtue of one of four attributes: the title of the datafile (Heading(1)), the heading for the response function (Heading(2)), the author of the data, or the establishment or organisation from where the data originated: enter 1, 2, 3, or 4.

Option 2 - Remove Entry:
Allows response functions to be removed from the main library RSPBIB&.DAT, creating a library tailored to the user's requirements. Requires knowledge of the entry numbers of the data in RSPBIB&.DAT; these numbers may be obtained using Option 1, or by inspection of the file RSPBIB&.DAT.

Option 3 - Show Entry:
Response functions selected using Option 4 can be plotted in Option 3. A title should be entered for each curve, which can either be typed in manually or extracted from the description printed on-screen using "<" to include the letter above the cursor or ">" to skip a letter.

The default plot has a linear vertical scale and a logarithmic horizontal (energy) axis. Pressing <ENTER> takes the user to the graphics menu from where the plot can be edited, saved, or exited. Instructions for the graphics menu are given in Appendix 5a.

Option 4 - Search for and Select Entries:
Response functions can be selected using appropriate keywords, descriptive either of the response function itself, the author of the data or the establishment of origin: enter 1, 2, 3, or 4 as in Option 1. Enter the keyword or expression. The matching data will be listed, and the list can be edited, rejected, or extended by additional searches. The final selection can be output to RSPBIB&.PRT.

Up to eight response functions can be selected and output to a response function block for use in SPKTBIB: Enter a title for the data, a filename, and a heading for each response function (maximum 12 characters). This heading will be used when plotting the data. It can either be entered manually or extracted from the comment line printed above the cursor using the "<" and ">" keys. The filename will be given the extension "RB&" to identify it as a response function block, and will be output to the sub-directory BIB&&&.

Option 5 - View Response Functions:
Used to plot response function blocks. Enter a filename from the list printed on-screen. Instructions for using the graphics menu are given in Appendix 5a.

Option 6 - Quit:
Exits the program.

An on-line help facility describing each of the above functions can be accessed by pressing <ENTER> at the menu prompt, followed by the relevant option number. Help is also available for the graphics via the "HELP" command-field in the graphics menu.

DOSE_Q:

In two of the programs, SPKTBIB and SPKTANL, spectra can be folded with a 'standard' group of dosimetric quantities. This group is determined by the contents of the file SPKTBIB.8DQ (located in sub-directory BIB&&&), which is created using the program DOSE_Q. The 'standard' set included with the package consists of the following data: the integrated neutron fluence, the mean neutron energy <E>, standard deviation on <E>, effective dose equivalent (A-P) (ICRP 51[9]), maximum dose equivalent (ICRP 21[10]), H*(10) calculated by Wagner et al[11], H*(10) after the recommendations of ICRP 60[12], and D*(10) Wagner et al[11].

To change the set, run DOSE_Q and select up to eight quantities from those listed. The data as a function of energy are given pointwise in the file DOSE_Q.INP at a finite number of energy values, and the required function is derived within SPKTBIB by Lagrangian interpolation.

Some of the quantities can be expressed either as absorbed dose or be multiplied by a radiation weighting factor to derive a dose equivalent quantity. Two options are offered for

the radiation weighting factor: the original data proposed in ICRP 60[12] and new data calculated by Siebert et al[13] ("SAHLS") which takes into account the latest stopping power calculations[14].

SPKTBIB:

SPKTBIB is the main data-handling program of the package, and is used to select and plot neutron spectra and to fold them with detector response functions and dosimetric quantities.

The program can be run on a RAM disk, which is the recommended option since the program accesses data from a large number of files. In this case the datafiles must be copied to the random-access memory, using the batch-file USE_RAM.BAT: type USE_RAM followed by the letter representing the RAM-drive (e.g. USE_RAM D if the RAM-drive is D:). The files must be copied over before starting SPKTBIB.

The program accesses spectra using the list in the 'library' file SPKTBIB.DAT. This file as included with the package contains the data from all seven sub-libraries. However, a new library may be created at this stage of a run using an alternative selection of sub-libraries. Note: SPKTBIB.DAT lists the available files, but for SPKTBIB to access them they must have been created using READ000 or READGPM. After reading in the data from SPKTBIB.DAT, the spectra are folded with the data in SPKTBIB.8DQ.

The initialisation is now complete, and a menu will appear outlining the main functions of the program:

Option 1 - Overview:
Lists all the spectra in SPKTBIB.DAT, using the title of the original datafile (Heading(1)), the heading for the individual spectra (Heading(2)), the author of the data, or the establishment of its origin: enter 1, 2, 3, or 4.

Option 2 - Remove Entry:
Spectra can be deleted from SPKTBIB.DAT to assemble a smaller library tailored to the needs of the user. Knowledge of the entry numbers of spectra in SPKTBIB.DAT is required. These can be obtained either within the program by use of the Overview facility above, or externally by inspection of SPKTBIB.DAT with a text editor.

Option 3 - Show Entry:
The spectra in the catalogue can be plotted: enter 0 to display spectra selected using Option 4, or the entry number of the data in SPKTBIB.DAT. (N.B. if spectra have not been selected and "0" is entered, Option 4 can be accessed from within Option 3 and spectra selected thus). A title for each spectrum must be entered. This can be typed in or extracted from Heading(2) using the "<" key to include a letter above the cursor or ">" to skip a letter.

Up to eight spectra can be displayed on any one plot. The default plot has a linear vertical scale and a logarithmic horizontal (energy) axis. Pressing <ENTER> takes the user to the graphics menu, where the plot can be edited, saved, or exited. Instructions for the graphics menu are given in Appendix 5a.

Option 4 - Search for and Select Entries:
Spectra can be selected using appropriate keywords descriptive of the measurement location (see Option 1), the author, or the establishment of the data's origin, or by a number representative of some parameter such as source type, unfolding procedure, etc. Enter 1, 2, 3, 4, or 5 accordingly. (N.B. 5 is not yet available).

The spectra matching the specification will be listed, and the list may be edited, cancelled, or extended through an additional search. Once the selection has been finalised, the spectra can be saved to a file named by the user, which will be assigned the extension "SB$", and given a title describing the data. The file will be output to the sub-directory BIB$$$. Alternatively, a group of spectra previously stored can be recalled by entering a filename from the list printed on-screen. (N.B. The contents and the order of the data in the library SPKTBIB.DAT must be the same as at the time the spectra were stored as they are accessed by virtue of their entry number in SPKTBIB.DAT). The selection can be output to the file SPKTBIB.PRT.

Option 5 - Fold spectra with Dosimetric Quantities:
A variety of dosimetric quantities, listed below, can be calculated for the spectra selected within Option 4. (N.B. Option 4 must be called prior to Option 5). The data for the dosimetric quantities are stored in tabular form in the file SPKTBIB.8DQ. Spectra are folded with these quantities using a 4-point Lagrangian interpolation and multiplying the group fluence with the value of the function at the logarithmic mean energy of the bin.

The results are output to the file SPKTBIB.DQF. Each spectrum occupies a row in the table, identified in the first column by the entry number of the spectrum in the current SPKTBIB.DAT. The adjacent columns contain: the integrated fluence (1.0 for a normalised spectrum), mean energy of the spectrum, standard deviation from the mean energy, effective dose equivalent for A-P irradiation (ICRP 51[9]), maximum dose equivalent (MADE, ICRP 21[10]), ambient dose equivalent and absorbed dose calculated using conversion factors from Wagner et al[11], and ambient dose equivalent calculated using conversion factors based on the ICRP 60 recommendations[12]. A fuller description of these parameters is given in Appendix 6. The data set used is determined by the contents of the file SPKTBIB.8DQ, which can be changed using the program DOSE_Q.

Option 6 - Fold spectra with Response Functions:
Spectra can be folded with a block of response functions from RSPBIB& - either detector response functions or dosimetric quantities. Options 4 and 9 must first be called to select the spectra and the response function block. The program requests a dosimetric quantity to be entered from a list (described above under Option 5) for "ranking" the spectra. This quantity will be calculated for each of the selected spectra, and may be used as a means of ordering the spectra at a later stage. The data are derived by fitting a spline to the response function data, and multiplying the group fluence with the value of the function at the logarithmic mean energy of the bin.

The results are output to the file SPKTBIB.RQF. The format of the output is similar to that of SPKTBIB.DQF: the columns represent, in order, the entry number in the current SPKTBIB.DAT of each spectrum, the spectrum-averaged value of the dosimetric quantity chosen for ranking, and the spectrum-folded responses. The order of the response functions is listed at the top of the output file. Appendix 7 contains a sample output.

Option 7 - Run User Options:
Option 7 was designed to be a facility within which additional functions required by the user could be added. At present it contains four routines:

Routine 0 performs a similar function to Option 5, but folds all the spectra in the library SPKTBIB.DAT with the dosimetric quantities in SPKTBIB.8DQ. The output, SPKTBIB.US0, has the same format as SPKTBIB.DQF. Routine 1 is analogous to Option 6, but folds the selected response function block with all spectra. The output, SPKTBIB.US1, is similar to SPKTBIB.RQF. The final two routines (2 and 3) output the selected spectra and the response function data to SPKTBIB.US2 and SPKTBIB.US3 respectively. These can be renamed using

USE_ANL.BAT and input to the program SPKTANL. Since SPKTANL works with a maximum of 8 spectra, the list of selected spectra may have to be reduced if necessary prior to output.

Option 8 - Plot Calculated Quantities:
Assuming that the necessary Options (4 and 9) have been run, dosimetric quantities or response functions folded with spectra can be plotted. The graphs can be edited, saved, or exited from within the graphics menu (see Appendix 5a).

Dosimetric quantities (DQ): Choose a quantity from the list in order to rank the spectra. This quantity will form the horizontal axis of the plot and also act as a means of identifying and ordering the spectra. The data may be normalised ("scaled"), dividing each quantity by the maximum value of the quantity for any spectrum, so that all the data can be plot on the same graph; this is advisable since some of the quantities differ in value by several orders of magnitude.

Responses (RQ): Responses can either be plotted as a function of a dosimetric quantity (see Option 5) or by using one of the responses itself as the horizontal axis. The data can be "scaled" before plotting, as described above.

The data plotted are the values of each spectrum folded with each dosimetric quantity or response function. The data for a particular spectrum appear in a vertical line anchored to a particular x-coordinate, which is the spectrum-averaged value of the quantity chosen for ranking the data. The y-axis will range from 0 to 1 if the data have been "scaled". Otherwise the y-axis will represent each of the quantities plotted.

Option 9 - Select Response Functions:
Enter the filename of a response function block (prepared using RSPBIB&) from the list printed on-screen, and the heading of the file is printed for confirmation. The response functions can be plotted (see Appendix 5a) and the data output to the file SPKTBIB.US3. Before returning to the menu, the data are folded with the spectra in SPKTBIB.DAT for use in subsequent routines.

Option 10 - Quit:
Exits SPKTBIB, and outputs the current version of the library to SPKTBIB.DAT. The original library is copied to SPKTBIB.OLD. Since the output files are overwritten each time SPKTBIB is run, the files should be renamed immediately if the data are to be kept.

An on-line help facility for each option is available by pressing <ENTER> at the menu prompt followed by the required option number. Help is also available for the graphics via the "HELP" command-field in the graphics menu.

SPKTORD:

SPKTORD orders the data in SPKTBIB.DQF, SPKTBIB.RQF, SPKTBIB.US0, and SPKTBIB.US1 according to the value of a quantity selected for ranking the spectra, and outputs the ordered data to SPKTORD.OUT. This file can be used as input to another program, SPKTCOR. The data may be plotted, using the selected 'ranking' quantity as the abscissa. The program can also plot the ratio of any two quantities. The graphs can be edited, saved, and exited from within the graphics menu (see Appendix 5a).

SPKTANL:

Run SPKTANL using the batch-file USE_ANL.BAT. This renames the two required output files from SPKTBIB (SPKTBIB.US2 is renamed SPKTANL.SPI, SPKTBIB.US3 becomes SPKTANL.RSI) and starts the program.

Option 1 - Investigate effect of changing bin structures:
Choose the spectrum number from the list. SPKTANL re-bins the spectrum in a variety of different representations and folds the data with in-built dosimetric quantities (i.e. those in SPKTBIB.8DQ) and the response functions in SPKTANL.RSI. For some of the quantities, the percentage deviation from the original format is also calculated. The results are output to SPKTANL.M01. The bin structures are: the original format, ten bins per decade, five per decade, double the original binning ("twice"), a conversion from "twice" to ten per decade, and from five per decade to ten per decade. The spectrum is plotted with each of these six bin structures - see Appendix 5a for graphics commands.

This program can therefore be used to study the effect of energy bin representation on the shape of a spectrum, and on the values of dosimetric quantities and instrument responses folded over the spectrum. This can highlight the possible pitfalls when trying to create a fine-resolution spectrum from a low-resolution measurement.

Option 2 - Analyse and output spectra:
Select up to eight spectra. The analysis may be performed using the spectra in their original energy bin structures, or the spectra can be standardised to five or ten bins per energy decade. Ten per decade is the recommended format, but if the spectra are to be output for use in SPKTCOR then the format five bins per decade should be used.

Following standardisation, energy bands may be defined between which partial integrals over the spectra of dosimetric quantities and the response functions in SPKTANL.RSI can be calculated. Define the energy bands by constructing lines at the boundaries of the energy interval on the plot of the spectra (see Appendix 5a for instructions). Exit the plot. The program first calculates the quantities folded over the whole energy spectrum, after which the energy intervals for partial integration can be selected. Each energy 'line' has been assigned a number. To define an interval and perform the calculation, enter the two line numbers defining the boundaries of the region, the lower energy first (e.g. enter "1" then enter "3" to integrate from line 1 to 3). To integrate from the minimum energy of the spectrum to the energy at line number n, enter 0 followed by n. To exit the routine enter any first number larger than the second. The results can be output to the file SPKTANL.M02.

If the spectra have been standardised to five energy bins per decade they can be output to the file SPKTANL.CRS for later use in the program SPKTCOR. The final column of data represents the neutron energy in eV.

Option 3 - Plot and output response functions:
The response functions in SPKTANL.RSI can be plotted (see Appendix 5a for instructions on use of graphics menu), and individual response functions on the graph may be multiplied by a scaling factor. N.B. this factor is used solely when plotting the data and does not affect the output to SPKTANL.CRR. The response functions can also be plotted as a function of a dosimetric quantity, selected from the list in SPKTBIB.8DQ. This graph will incorporate any scaling factors applied to the plot of the fluence responses, and in addition the data in this new plot may also be scaled.

The response functions may be output to the file SPKTANL.CRR, which is used as input to the program SPKTCOR. SPKTCOR derives a weighted least squares fit of a combination of

response functions to the dosimetric quantity chosen by the user for fitting at this stage in SPKTANL, and which appears as the first column of data in SPKTANL.CRR. The data are formatted to 10 energy points per logarithmic decade, and the neutron energy in eV is included as the final column of data in the output file.

Option 4 - Derive calibration factors for dosemeter responses:
The responses in SPKTANL.RSI can be weighted as if they had been calibrated to read a quantity (usually dose equivalent) in a particular calibration spectrum. Select a spectrum from the list in SPKTANL.SPI for the 'calibration spectrum'; then select the dosimetric quantity which the detectors are to be calibrated to read (standard set in SPKTBIB.8DQ).

The program calculates a 'calibration factor' for each detector response, which can optionally be used to weight the data for use in any further functions including output to SPKTANL.CRR. To illustrate, if Option 4 is repeated a second time with a new 'realistic' field chosen as the calibration spectrum, the calculated factors will indicate how much each detector would under- or over-read in this field if calibrated in the calibration spectrum of the original run.

SPKTCOR:

SPKTCOR is a program designed to derive combinations of detector responses to simulate a dosimetric quantity. It can also be used to expand spectra encountered in the workplace in terms of a number of calibration spectra. The files SPKTORD.OUT, SPKTANL.CRR, and SPKTANL.CRS act as input to the program.

The code allows solution of an over-determined system of linear equations by the method of least squares for any combination of up to eight parameters. For the example of fitting dosemeter responses to ambient dose equivalent, the equations will be of the form:

$$H^*_i/\Phi = (a_1R_{i1} + a_2R_{i2} + \quad + a_jR_{ij})/\Phi$$

where j is the number of detectors used for the combination and a_j are the weighting factors. H^*_i/Φ is the fluence to ambient dose equivalent conversion factor for the ith energy point (or ith spectrum if SPKTORD.OUT is the input). R_{ij}/Φ is the fluence response for the jth detector folded with energy (or spectrum) i. (In the case of fitting spectra, H^*_i would be replaced by the spectrum to be simulated, and R_{ij} would represent the calibration spectra).

SPKTORD.OUT:
The data in SPKTORD.OUT are response functions folded with neutron spectra. SPKTCOR can be used to investigate combinations of these responses to fit the spectrum-averaged values of the dosimetric quantity selected for 'ranking'. The ratio of any two responses can also be calculated and added to the list of response functions (N.B. this new data will overwrite an existing response function if there are already eight in the list).

Select a quantity to be fitted. This will usually be the dosimetric quantity chosen in SPKTORD for 'ranking' the data, although any of the other response functions are also possible. Up to eight responses can then be selected for the combination.

The energy range over which the fit is determined can be sub-divided into discrete energy intervals, and different weights assigned to each interval. Thus if, for example, a dosemeter has no intermediate energy response, this region can be neglected, or if an energy range is of particular importance it can be assigned a high weight compared to the remainder of the spectrum.

Energy intervals are defined on a plot of the data using the lines option (see Appendix 5a). Each line represents either the start or the end of an interval, but not both (e.g. to divide the range 0 to 200 into two, one could define lines at 0, 100, 100.1 and 200). Any data in between the end of one energy interval and the start of the next will be ignored.

Once the intervals have been defined on the plot, weights can be assigned to each region. The default weight is 1.0. If you do not wish to change the weight enter a negative number. The data are replotted with the quantity to be fitted scaled by the weight assigned to each region.

The weighting factors for each response function are printed on-screen, together with the covariance matrix representing the uncertainties in the fit. In deciding which responses to include for the optimum combination the relative sizes of these weighting factors may prove useful. Also printed is a Figure of Merit (FOM), which is

$$f_{FOM} = \sqrt{\sum \left(\frac{x_{t,i} - x_{f,i}}{x_{f,i}}\right)^2}$$

where $x_{t,i}$ and $x_{f,i}$ are the true and fitted values of the dosimetric quantity for the ith spectrum, and is roughly equivalent to χ^2. The accuracy of the fit is indicated by its proximity to zero.

The fitted and the true values of the dosimetric quantity are plotted, together with up to six of the responses. The responses can be plot, and output, including or excluding the weights calculated for the fit. Data can be plotted as a function of the quantity fitted, an alternative dosimetric quantity, or the rank number of the spectrum in the input file. Three methods of plotting the data are possible: the "absolute" data, i.e. the fitted, true and weighted or unweighted responses; all data plotted as a ratio to the quantity fitted; or a plot of the percentage difference between the fitted and true data.

Alternative energy intervals, or "fit-ranges", and weights can be investigated for the same combination of responses, and the process may also be repeated using a new combination of response functions.

The results are output to the file SPKTCOR.D0*n* (*n* is incremented for each different combination). The format of the output is the same for all three input files: the detectors/spectra used for the fit are listed at the top of the file, followed by the weighting factors for each quantity and the covariance matrix. The data printed underneath the matrix are the true values of the fitted quantity, the corresponding values calculated using the least squares fit, the response function or spectral data (optionally scaled by their weighting factor), and the error on the fit:

$$e = \left(\frac{x_{f,i} - x_{t,i}}{x_{t,i}}\right) . 100\%$$

SPKTANL.CRR:
SPKTANL.CRR contains response functions output from SPKTANL. The procedure is much the same as with SPKTORD.OUT. However, here the energy-response function data are used for the fit rather than spectrum-folded responses. This technique can therefore be used to optimise the dosimetric response of a group of detectors. The results are plotted against neutron energy, although the ordinal number of the equations in the least squares fit is also a possible abscissa. The data are output as above.

SPKTANL.CRS:
This is the input file for combining spectra. Any spectrum in the file can be simulated by a combination of the others using a weighted least squares fit - see the procedure under SPKTORD.OUT. The results can be plotted with neutron energy as the abscissa or, alternatively, the ordinal number of the equations used in the least squares fit. In addition to the "absolute" plot (the fitted spectrum, the simulation, and the spectra used for the fit with or without the weightings calculated), there are five other possible representations of the data:

1) as a ratio to the simulated spectrum;
2) the percentage difference between the true and fitted spectrum;
3) the true and fitted spectra weighted with H*(10) and D*(10);
4) the integrals of the true and fitted spectra weighted with H*(10) and D*(10);
5) the ratio of the integrals in (4).

SHOW:

The program SHOW allows graphs saved to a file during a run of any of the above programs to be re-plotted externally. Use the command:

SHOW *filename*

to reproduce the plot, with the parameters (axis ranges, curve symbols, etc.) specified when the file was saved as default. See Appendix 5a for graphics options.

4. EXAMPLES

4.1. Folding spectra with response functions.

Example: To investigate the response of fast neutron personal dosemeters in realistic spectra after calibration with Am-Be, ^{252}Cf, and D_2O-moderated ^{252}Cf neutron sources.

Neutron spectra can be folded with dosemeter response functions within the program SPKTBIB. A response function block was prepared using RSPBIB&, containing personal dose equivalent in the ICRU slab phantom, $H_p(10)$ A-P[15], and the following personal dosemeter responses: neptunium-237[16], two PADC responses[17,18], and NTA film[7]. The data have been plotted in Figure 3. Using SPKTBIB, a group of spectra were selected comprising the three calibration spectra[19] (plotted as Figure 4), and a variety of 'workplace' spectra ranging from the hardest, with neutrons up to nearly 20 MeV, to the very soft with essentially no neutrons above 1 MeV. The list comprised spectra measured in the environments of a neutron source preparation facility[20], a reprocessing plant[21], fuel transport containers[22,23], and pressurized water[7], boiling water[24] and gas-cooled reactors[21,25]. The response function block was read in using Option 9, and the data were folded with the spectra using Option 6. The mean energy of each spectrum was also calculated - this was the quantity chosen for 'ranking' the spectra in SPKTORD.

The results (SPKTBIB.RQF) are shown in Appendix 7. The columns are: the entry number of each spectrum in SPKTBIB.DAT, the mean energy, the spectrum-averaged personal dose equivalent, and the response of each dosemeter (listed in order at the top of the file) in that field.

This data can be used to investigate the suitability of the three calibration fields for different measurement environments. The ratio of the measured dose equivalent value, assuming the dosemeter has been calibrated in a particular field, to the correct value is given by:

$$(\frac{R_r}{R_c}) \quad (\frac{H_c}{H_r})$$

where R_r is the response in the 'realistic' field;
R_c is the response in the calibration field;
H_r is the spectrum-averaged personal dose equivalent in the 'realistic' field;
and H_c is the spectrum-averaged personal dose equivalent in the calibration field.

The results for the data above are presented in Table 1. For each dosemeter there are three columns in the table representing 'calibration' with the three different sources: ^{241}Am-Be, bare ^{252}Cf, and D_2O-moderated ^{252}Cf. The calculations were in addition performed substituting each of the three calibration spectra for the 'realistic' field, and these data have been added to the top of the results table. Included with the description of each spectrum is its entry number in the 'standard' version of SPKTBIB.DAT included with the package for identification purposes.

Because these types of dosemeter respond primarily in the high energy region, if they are calibrated in an un-moderated high energy field and then used in a typical working situation (where the spectrum includes low-energy scattered neutrons and neutrons moderated through shielding), the dosemeter will significantly under-read the neutron dose equivalent.

The NTA film dosemeter, with its relatively high energy threshold of 0.5 MeV, was the worst offender for the reasons explained above. This type of dosemeter would experience problems in all but the highest energy field, with the response decreasing from 50% to less than 2% in the spectrum with the lowest mean energy. (N.B. the NTA dosemeter[7] used for these calculations had no response to thermal neutrons).

The best all-round performer would seem to be the first of the PADC dosemeters, which has a thermal as well as a fast neutron response due to the incorporation of a nylon radiator in front of the plastic element in the badge. The dosemeter had an accurate response to fields with mean energies above 100 keV, and the response never fell below 50% in any field. The neptunium dosemeter also performed well in the highest and lowest energy fields, but was less accurate for those in between, with mean energies from 50-400 keV, where its response sometimes fell below 40%.

The second PADC dosemeter, which has no radiator and hence little low energy response, worked well in fields with a mean energy of over 100 keV, but its response worsened as the energy of the field fell, to below 10% for the softest spectrum. The heavy-water moderated ^{252}Cf source would seem to be the most appropriate calibration source for all of the fields investigated above, although it too is far from ideal when considering dosemeter response in the lower energy fields. The ^{241}Am-Be source was more appropriate than bare ^{252}Cf for the PADC dosemeters, whereas ^{252}Cf would be more suitable than ^{241}Am-Be for the NTA and neptunium devices. This trend is borne out in the top three rows of data in the table where the PADC dosemeters under-respond in an ^{241}Am-Be field if calibrated using ^{252}Cf, whereas the neptunium and NTA film dosemeters would overestimate the dose equivalent in this situation. This is due to the relative overlap between the energy response of the dosemeters and the energy spectra of the various calibration fields. The PADC dosemeters have a larger response in the region of the ^{252}Cf spectrum whereas the neptunium and NTA film responses peak at a higher energy and thus overlap more with the higher energy ^{241}Am-Be spectrum.

Table 1. Responses of four types of personal dosemeters in a variety of different neutron spectra after calibration in three fields. The quantity tabulated is the measured / true personal dose equivalent as defined in a slab phantom.

Spectrum	E_{mean}	^{237}Np			PADC 1			PADC 2			NTA film		
Calibration field: 1: ^{241}Am-Be 2: ^{252}Cf 3: D_2O-moderated ^{252}Cf		1	2	3	1	2	3	1	2	3	1	2	3
^{241}Am-Be [342]	4.2 MeV	1.00	1.14	1.19	1.00	0.85	1.01	1.00	0.83	1.01	1.00	1.43	1.71
^{252}Cf [340]	2.1 MeV	0.88	1.00	1.04	1.18	1.00	1.20	1.21	1.00	1.22	0.70	1.00	1.19
D_2O-moderated ^{252}Cf [341]	540 keV	0.84	0.96	1.00	0.99	0.84	1.00	0.99	0.82	1.00	0.59	0.84	1.00
^{241}Am-Be source fabrication [298]	760 keV	0.91	1.03	1.08	1.05	0.89	1.06	1.02	0.84	1.03	0.71	1.01	1.21
Fuel reprocessing [304]	420 keV	0.66	0.75	0.79	1.15	0.97	1.16	1.09	0.90	1.10	0.41	0.58	0.70
Fuel reprocessing [305]	73 keV	0.71	0.81	0.85	0.99	0.84	1.01	0.75	0.62	0.76	0.26	0.37	0.44
Fuel transport cask [350]	110 keV	0.34	0.38	0.40	0.78	0.66	0.79	0.71	0.58	0.71	0.12	0.17	0.20
Fuel transport cask [273]	110 keV	0.62	0.71	0.74	0.98	0.83	1.00	0.85	0.70	0.86	0.21	0.31	0.37
PWR [69]	240 keV	0.61	0.69	0.72	1.10	0.93	1.11	1.00	0.83	1.01	0.35	0.50	0.59
PWR [62]	57 keV	0.33	0.37	0.39	0.59	0.50	0.60	0.45	0.37	0.45	0.06	0.09	0.11
BWR [276]	63 keV	0.78	0.89	0.93	0.77	0.65	0.78	0.62	0.51	0.62	0.16	0.23	0.27
GCR [302]	17 keV	0.80	0.91	0.95	0.73	0.62	0.74	0.37	0.31	0.38	0.06	0.09	0.10
GCR [300]	2.8 keV	0.91	1.04	1.08	0.80	0.68	0.81	0.10	0.08	0.10	0.01	0.02	0.02

4.2. Ordering spectra in terms of a dosimetric quantity.

Example: Ordering workplace spectra in terms of ambient dose equivalent, and investigating the hardness of these spectra using the 9" to 3" Bonner sphere ratio.The "hardness" of a neutron spectrum is a measure of the proportion of fast neutrons in the field. An example of a very hard spectrum is that of a bare radionuclide source, such as ^{241}Am-Be, which consists wholly of fast neutrons. The more shielding between the source and measurement point, the softer the spectrum is likely to be since the fast neutron component will be reduced, replaced by moderated thermal and intermediate energy neutrons. The 9" to 3" Bonner sphere response ratio is a good measure of spectrum hardness because the 9" sphere response falls primarily in the fast neutron energy region, above a few hundred keV, whereas the 3" sphere has a good response to neutrons below this energy. The response functions are plotted in Figure 5.

A response function block containing the 3" and 9" Bonner sphere responses[26] was prepared. The 'workplace' fission spectra were selected (Option 4 of SPKTBIB) and folded with the response function block using Option 6, choosing "H*(10)-Wagner" as the quantity for ranking the spectra. SPKTORD was run, with SPKTBIB.RQF as the input. The spectra were ranked according to their value of H*(10), and the data output to SPKTORD.OUT.

The spectra with the highest spectrum-averaged dose equivalent (identified from the first column of data, which is the entry number of the spectrum in SPKTBIB.DAT) were those measured at a neutron source fabrication plant and at nuclear fuel processing facilities. These were the hardest spectra since little shielding material was present between the source and the measurement location, and hence there was little moderation of the initial fission spectrum. The spectrum-averaged dose equivalent for these spectra ranged upwards from 100 pSv cm^2. The softest spectra encountered were those measured around gas-cooled reactors, and generally fell below 30 pSv cm^2. The remainder of the spectra had fluence-to-dose equivalent conversion factors falling between 10 and 150 pSv cm^2, and were measured in the vicinity of PWRs and BWRs (found throughout the dose equivalent range), and fuel transport containers (located at the upper end of the range). The variation in the data indicates just how dependent the spectrum is on the exact measurement location, changing according to the amount of shielding and scattering material present in the vicinity, and the reactor or fuel type, and emphasises the difficulties likely to be faced in trying to categorise neutron fields for calibration purposes.

The 9" to 3" Bonner sphere response ratio for the data was calculated using SPKTCOR on the output file from SPKTORD, (there is an option to plot, but not output, this ratio within SPKTORD). The data have been plotted in Figure 6, and show a fairly monotonic increase with ambient dose equivalent. The increase is fairly linear up to about 200 pSv cm^2. Above this value there seems to be a proportionality between the logarithm of the ratio and H*(10). There are, however, limitations to this proposed relationship. Although it appears to be true for these moderated fission spectra, it may not work for very high energy spectra, such as leakage spectra from high energy accelerators, and is not a feasible replacement for practical spectrometry. The 9" to 3" ratio may still have potential as a crude method of categorising spectra and could prove a useful aid in deciding on the type of dosemeter to be employed in a particular field. (See also reference 6).

4.3. Integrating responses over specified energy intervals.

One of the first steps in analysing spectra is to study the proportions of fluence and dose equivalent deriving from certain energy regions. SPKTANL (Option 2) can be used to subdivide the spectrum into discrete energy intervals over which dosimetric and detector

response functions can be folded. In the example below, eight spectra have been partitioned into a thermal, an intermediate, and a fast neutron energy range and folded with various dosimetric quantities and personal dosemeter response functions.

The spectra and response functions selected were those of Example 1, and the data were output using routines 2 and 3 of Option 7 in SPKTBIB. SPKTANL was run, using USE_ANL.BAT to rename the output files and start the program. Eight of the spectra were selected, ranging from a fast-neutron ^{241}Am-Be radionuclide source spectrum to a soft spectrum measured in the vicinity of a gas-cooled reactor, and were standardised to a bin structure of ten per logarithmic decade. Lines were defined on the plot of the spectra at 5 eV, 50 keV, and 50 MeV, to divide the spectra into thermal, intermediate and fast energy regions. Integrations of the dosimetric quantities and dosemeter responses were performed over each of these intervals and the results, extracted from the file SPKTANL.M02, are presented below in Table 2. The spectra have been plotted in Figure 7, which also includes the lines defining the energy intervals for analysis.

The Am-Be spectrum is a very hard, fast neutron spectrum, with 99% of its fluence above 50 keV. The remainder are fission spectra with shielding, and thus consist roughly of a high energy fission peak, an intermediate energy 1/E component, and a thermal component. The relative size of the high energy and thermal peaks and the energies of the peaks are variable. The mean energies of the spectra ranged from 4 MeV for the Am-Be source down to 3 keV for the GCR spectrum.

For all but the radionuclide source spectrum, the majority of the fluence fell in the thermal and intermediate energy regions. The ambient dose equivalent averaged over the spectrum was roughly equivalent in the two lower energy intervals, however, the majority of the dose equivalent (over 70% in all but the 'softest' case) was contributed by the fast energy component because of the shape of the fluence-to-dose equivalent curve. The dose equivalent conversion factor for spectrum 4 was slightly higher than that of number 2, despite spectrum 2 having a mean energy nearly twice that of 4 and a higher peak energy, because the size of its fast neutron component, i.e. the integrated fluence, was greater - see Figure 7 . This trend was mirrored in the calculations for the dosemeters, where the response of the two PADC dosemeters was slightly higher for spectrum 4 than for spectrum 2.

The neptunium dosemeter tended to under-read dose equivalent at thermal energies and over-read in the intermediate energy region, whereas PADC dosemeter number 1 (incorporating the thermal radiator) responded well in the thermal region but under-read dramatically at intermediate energies where it has very little response. This dosemeter provided the best measure of the fast neutron component. Neither the second PADC dosemeter (without a thermal response) nor the NTA film showed any response outside the fast energy region due to their energy thresholds, of 100 keV and 400 keV respectively.

By comparing the dosemeter response in each energy interval to the spectrum-averaged dose equivalent in that range, these results help us to comprehend the findings of Example 1 and highlight the problems deriving from the relatively high neutron energy thresholds of the NTA film badge and the PADC dosemeter without radiator.

Using SPKTCOR to derive combinations of response functions to fit a dosimetric quantity, and to represent a neutron spectrum as a combination of other spectra:

The function of SPKTCOR is to derive a weighted combination of quantities to approximate another quantity using a least squares fitting procedure. Dosemeter response functions can be fitted to a dosimetric quantity (although fitting to another detector response is also a possibility), and neutron spectra can be expanded in terms of a number of calibration spectra.

Table 2. Calculation of dosimetric quantities and dosemeter responses in the thermal, intermediate, and fast energy regions of eight spectra.

DOSIMETRIC QUANTITIES FOR SPECTRA:

1: Am-Be (ISO spectrum) [342]
2: Am-Be source in glove box in line of glove boxes [298]
3: LK100 transportation container [273]
4: Reprocessing, plutonium finishing plant, little shielding [304]
5: Reprocessing, plutonium finishing plant, well shielded [305]
6: PWR, within containment [69]
7: BWR, inside containment [276]
8: GCR, Calder Hall [300]

Total integral
Energies: 7.000E-04 to 1.397E+08 in eV
ABSOLUTE values for Dosimetric Quantities and Responses

spectrum no:	1	2	3	4	5	6	7	8
sumPHI	1.000+0	1.000+0	1.000+0	1.000+0	1.000+0	1.000+0	1.000+0	1.000+0
<E>≡(mean)	4.170+6	7.680+5	1.104+5	4.263+5	7.423+4	2.395+5	6.440+4	2.850+3
stdd(E)	2.569+6	1.826+6	3.612+5	9.598+5	3.950+5	7.166+5	2.912+5	2.943+4
HE_51 (AP)	2.734+2	6.198+1	1.932+1	5.076+1	1.252+1	3.218+1	1.256+1	4.628+0
H-MADE	3.738+2	1.011+2	4.525+1	1.032+2	2.843+1	6.913+1	3.035+1	1.233+1
H*-Wagner	3.814+2	1.022+2	4.961+1	1.107+2	2.839+1	7.397+1	3.172+1	1.028+1
H*(10)-new	3.916+2	1.123+2	6.194+1	1.329+2	3.462+1	9.031+1	3.918+1	1.313+1
D*-Wagner	4.798+1	1.261+1	5.682+0	1.119+1	4.169+0	8.043+0	4.398+0	2.752+0
Hp(10) A-P	4.883+2	1.405+2	7.981+1	1.699+2	4.450+1	1.155+2	5.045+1	1.606+1
Np-237	1.637+3	4.229+2	1.653+2	3.763+2	1.024+2	2.464+2	1.163+2	5.393+1
PADC (1)	3.441-5	1.036-5	5.504-6	1.374-5	3.076-6	8.878-6	2.748-6	8.893-7
PADC (2)	3.681-5	1.076-5	5.111-6	1.390-5	2.493-6	8.692-6	2.357-6	1.185-7
NTA	6.228-4	1.277-4	2.213-5	9.101-5	1.508-5	5.155-5	1.069-5	2.777-7

Summary
Line 1 at 5.000E+00 eV
Line 2 at 5.000E+04 eV
Line 3 at 5.000E+07 eV

spectrum no:	1	2	3	4	5	6	7	8
sumPHI	.003	491	.331	.379	.649	.453	.307	.773
sumPHI	.011	212	.440	.209	.250	.255	.529	.215
sumPHI	.987	297	.229	.412	.102	.293	.165	.012
-								
<E>≡(mean)	1.840+0	2.385-1	7.325-1	3.462-1	2.628-1	1.093+0	6.031-1	3.443-1
<E>≡(mean)	5.427+3	6.374+3	5.262+3	5.621+3	5.314+3	7.050+3	7.188+3	2.193+3
<E>≡(mean)	4.226+6	2.580+6	4.715+5	1.032+6	7.162+5	8.123+5	3.682+5	2.051+5
-								
HE_51 (AP)	4.976-5	3.310-2	7.607-2	2.91	2.004-	6.604-2	1.066-1	7.046-1
HE_51 (AP)	1.764-4	1.585-2	1.033-1	1.88	9.074-	3.802-2	1.971-1	2.014-1
HE_51 (AP)	9.998-1	9.511-1	8.206-1	9.51	7.089-	8.959-1	5.962-1	9.404-2
-								

```
H-MADE       9.591-5 5.401-2 8.578-2 3.914-2 2.411-1 8.076-2 1.169-1  .055-1
H-MADE       3.476-4 2.616-2 1.188-1 2.505-2 1.077-1 4.792-2 2.189-1  .050-1
H-MADE       9.996-1 9.198-1 7.954-1 9.358-1 6.512-1 8.713-1 6.642-1  .950-2
-
H*-Wagner    7.759-5 4.299-2 6.400-2 2.905-2 1.918-1 6.262-2 9.109-2 6.870-1
H*-Wagner    2.603-4 2.010-2 8.254-2 1.793-2 8.236-2 3.584-2 1.645-1 1.789-1
H*-Wagner    9.997-1 9.369-1 8.535-1 9.530-1 7.259-1 9.015-1 7.444-1 1.341-1
-
H*(10)-new   3.323-2 1.027-1 2.000-1 8.076-2 3.066-1 1.459-1 3.097-1 9.012-1
H*(10)-new   2.868-2 1.029-1 1.802-1 8.544-2 3.243-1 1.369-1 2.994-1 7.906-1
H*(10)-new   1.013+0 3.123+0 3.727+0 2.309+0 7.075+0 3.072+0 4.537+0 1.147+1
-
D*-Wagner    1.826-4 1.012-1 1.629-1      -2 3.871-1 1.686-1 1.916-1 7.487-1
D*-Wagner    6.024-4 4.635-2 2.108-1      -2 1.634-1 9.064-2 3.331-1 2.087-1
D*-Wagner    9.992-1 8.524-1 6.263-1      -1 4.494-1 7.407-1 4.753-1 4.257-2
-
-
-
Hp(10) A-P   9.687-5 4.679-2 6.073-2 3.075-2 1.991-1 6.355-2 8.786-2 6.781-1
Hp(10) A-P   3.152-4 2.259-2 7.956-2 1.810-2 8.146-2 3.546-2 1.595-1 1.792-1
Hp(10) A-P   9.996-1 9.306-1 8.597-1 9.511-1 7.195-1 9.010-1 7.527-1 1.428-1
-
Np-237       4.041-5 2.298-2 4.416-2 1.352-2 8.209-2 4.214-2 5.117-2 2.784-1
Np-237       8.912-4 6.424-2 3.677-1 7.584-2 3.389-1 1.233-1 5.299-1 6.898-1
Np-237       9.991-1 9.128-1 5.881-1 9.106-1 5.790-1 8.346-1 4.189-1 3.182-2
-
PADC (1)     4.569-5 4.512-2 4.990-2 2.533-2 1.981-1 3.580-2 9.605-2 8.104-1
PADC (1)     5.533-5 3.666-3 1.433-2 2.771-3 1.472-2 5.973-3 3.343-2 4.740-2
PADC (1)     9.999-1 9.512-1 9.358-1 9.719-1 7.872-1 9.582-1 8.705-1 1.422-1
-
PADC (2)     0.000+0 0.000+0 0.000+0 0.000+0 0.000+0 0.000+0 0.000+0 0.000+0
PADC (2)     0.000+0 0.000+0 0.000+0 0.000+0 0.000+0 0.000+0 0.000+0 0.000+0
PADC (2)     1.000+0 1.000+0 1.000+0 1.000+0 1.000+0 1.000+0 1.000+0 1.000+0
-
NTA          0.000+0 0.000+0 0.000+0 0.000+0 0.000+0 0.000+0 0.000+0 0.000+0
NTA          0.000+0 0.000+0 0.000+0 0.000+0 0.000+0 0.000+0 0.000+0 0.000+0
NTA          1.000+0 1.000+0 1.000+0 1.000+0 1.000+0 1.000+0 1.000+0 1.000+0
```

In the case of fitting responses there are two possibilities. The response functions themselves can be fitted to the desired quantity (this method is similar to the procedure for combining spectra), or the response functions can first be folded with spectra and combined to fit the values of the spectrum-averaged dosimetric quantity.

4.4. Combining Bonner sphere responses folded with fission spectra, to fit ambient dose equivalent.

A response function block was prepared in RSPBIB& containing 3", 4", 5", 6", 8", 10", 12" and 15" Bonner sphere responses[27]. These have been plotted in Figure 8. SPKTBIB Option 9 was used to retrieve these response functions, and they were folded with the fission spectra from Example 2 using Option 6. Ambient dose equivalent, calculated by Wagner et al, was chosen for ranking the spectra, which is also the quantity to be fitted in SPKTCOR. SPKTORD was

run on the output file SPKTBIB.RQF, ranking the data according to H*(10).

Using the program SPKTCOR, with SPKTORD.OUT as input, various combinations of Bonner spheres were investigated for fitting to H*-Wagner. The fitting was performed over the whole dose equivalent range, without weighting any particular region of the dose equivalent curve. The program calculates the optimum weighting for each detector in the group selected, and outputs the true dose equivalent, the value calculated according to the fit, the weighted responses, and the error on the fit for each spectrum, to the file SPKTCOR.D0*n*. From a number of "trial and error" combinations, the best groupings were identified by the size of the FOM, and by examining the deviation of the fitted data from the true dose equivalent using the 'error' column in the output. Four examples are illustrated below, using combinations of six, four, three and two differently-sized spheres. The weighting factor assigned to each detector, the mean of the absolute value of the errors on the fit, and the standard deviation of the error are presented in Table 3. The data are shown in Figure 9.

Table 3. Weighting factors applied to Bonner sphere responses folded with fission spectra to simulate the spectrum-averaged ambient dose equivalent, for four combinations of spheres.

Sphere	Weight
5"	1.29×10^2
6"	-4.36×10^2
8"	6.39×10^2
12"	-6.34×10^2
15"	6.02×10^2
Mean of errors	2.7%
SD of error	4.4%

Sphere	Weight
3"	2.16×10^1
5"	-7.97×10^1
8"	1.77×10^2
12"	4.20×10^1
Mean of errors	3.7%
SD of error	7.6%

Sphere	Weight
3'	
5"	-9.88×10^1
8'	2.12×10^2
Mean of errors	3.8%
SD of error	6.5%

Sphere	Weight
10"	2.02×10^2
Mean of errors	10.0%
SD of error	17.4%

The best fits were achieved using the largest number of spheres, as one would expect. After various combinations were tested, good approximations to the dose equivalent were also achieved using smaller groups. In the calculations using three or more spheres, the majority of the fitted data fell within ±10% of the true dose equivalent. For the two-sphere group this

value was higher at ±20%. The largest deviations from the fitted data were encountered in spectra with low spectrum-averaged dose equivalents. The larger spheres, which exhibit a more 'dose equivalent response', tended to be assigned the heaviest weightings.

4.5. Combining Bonner sphere response functions to simulate ambient dose equivalent.

The combinations derived in the previous example were re-evaluated by fitting the Bonner sphere response functions themselves to the dose equivalent curve.

The response function block containing the Bonner sphere responses was output from SPKTBIB using Option 7 and the output file, SPKTBIB.US3, was re-named to SPKTANL.RSI. Option 3 of SPKTANL was used to re-format the data for use with SPKTCOR, and to select the dosimetric quantity to be fitted which was "H*-Wagner".

The input data for combining response functions in SPKTCOR is found in the output from SPKTANL, SPKTANL.CRR. The four sphere combinations derived in Example 4 were selected, and the weighting factors assigned to each sphere and the errors on the fit are presented in the table below, as before:

Table 4. Weighting factors applied to Bonner sphere responses to simulate ambient dose equivalent, for four combinations of spheres.

Sphere	Weight
3"	
5"	
6"	-7.93×10^{2}
8"	1.04×10^{3}
12"	-1.25×10^{3}
15"	1.13×10^{3}
Mean of errors	69.9%
SD of error	94.7%

Sphere	Weight
3"	-3.09×10^{-1}
5"	-1.40×10^{1}
8"	2.86×10^{1}
12"	2.47×10^{2}
Mean of errors	86.3%
SD of error	116.6%

Sphere	Weight
5"	-1.38×10^{2}
8"	2.66×10^{2}
Mean of errors	125.8%
SD of error	165.6%

Sphere	Weight
10"	2.37×10^{2}
Mean of errors	103.6%
SD of error	112.9%

The fitted data are plotted in Figure 10. The weighting factors calculated for each combination of spheres are similar, but by no means identical, to those calculated in the previous example. The difference is due, in part, to the effective 'weighting' given to different energy regions according to the relative spectral fluence for the spectrum-folded responses. The more spectra used in Example 4, the closer the two sets of results should become.

Some general trends in the fitted data were apparent whichever combination of spheres was used: the fit greatly under-estimated H*(10) at low energies and sometimes had a negative value. The match was best as the dose equivalent curve starts to increase sharply, from about 50 to 300 pSv cm^{-2}. The fit then overestimates H* until it starts to drop because of the decrease in Bonner sphere response at very high energies, and therefore underestimates H* as it rises again at the upper end of the energy spectrum.

The calculations for the three sphere combination (3", 5" and 8") were repeated, making use of the feature to assign importances (weights) to different energy regions. Six calculations were performed, fitting the data over the whole energy spectrum (as before), the fast neutron energy region (above 100 keV), below 10 keV, and with the spectrum divided into three intervals: 0.01-0.5 eV, 0.5 eV-50 keV, and 50 keV-3 MeV. These intervals were chosen as representative of the three main features of a typical fission 'workplace' spectrum, i.e. a thermal peak, a small intermediate energy fluence, and a fast neutron peak. Calculations were performed with the intervals assigned weights of 3:1:10, 1:0:5, and 1:0:1.

The results are presented in Table 5, and the fitted data have been plotted in Figure 11. For the calculations over a discrete part of the energy spectrum (Figure 11(a)) the fit is reasonable over the region covered and very inaccurate over the remainder of the spectrum. The weights assigned to each Bonner sphere are therefore very different. The results for the sub-divided spectrum (Figure 11(b)) are fairly similar to each other, changing only slightly according to the importances assigned to specific regions of the spectrum. The weights calculated for the three Bonner spheres are similar to those for the spectrum-folded responses in Example 4.

4.6. Combining calibration fields to simulate a 'realistic' spectrum.

The aim of the project, of which this database is a part, was to produce some new calibration fields similar to those encountered in the working environment. It would be very convenient if these fields could be achieved by a combination of the calibration fields used at present.

In this example four calibration spectra were used selected to cover between them the entire energy range from thermal energies to several MeV: a thermal Maxwellian spectrum (representative of the NPL thermal pile[28]), a D_2O-moderated ^{252}Cf fission source, and bare ^{252}Cf and ^{241}Am-Be sources[19]. The 'realistic' field chosen was a spectrum measured in a neutron source fabrication plant[20], and consisted of a fast neutron peak at about 4 MeV, an intermediate energy 1/E component, and a thermal peak due to low-energy scattered neutrons from structural material in the vicinity of the measurement location. The spectra have been plotted in Figure 12.

The spectra were selected using Option 4 of SPKTBIB. The data were output from within Option 7 (#2 Output Spectra) and the output file, SPKTBIB.US2, was re-named to SPKTANL.SPI. SPKTANL was run to format the spectra for use with SPKTCOR: using Option 2 and all five spectra, the data were standardised to five bins per energy decade and output to the file SPKTANL.CRS. SPKTCOR was run using this file as the input, selecting the workplace spectrum as the quantity to be fitted. Calculations were performed using various combinations of calibration spectra to find the best overall fit.

The best simulation of the 'realistic' field was achieved using all four calibration spectra, although the fit was only slightly less accurate when one or other of the bare radionuclide sources were omitted from the calculation. In the absence of the D_2O-moderated ^{252}Cf spectrum, the contribution in the intermediate energy region was removed. The weighting factors (per unit fluence) assigned to each spectrum, and the errors on the fit are shown below in Table 6, and have been extracted from the output files SPKTCOR.D0*n*. The results are illustrated in Figure 13.

Table 5. Weighting factors applied to three Bonner sphere responses to simulate ambient dose equivalent, applying different weights to different parts of the spectrum.

Full spectrum Sphere	Weight
3"	
5'	-1.38×10^2
8'	2.66×10^2
Mean of errors	125.8%
SD of error	165.6%

> 100 keV Sphere	Weight
3"	
5"	-5.50×10^2
8"	-4.42×10^2
Mean of errors	8600%
SD of error	6500%

< 10 keV Sphere	Weight
3"	
5"	-2.00×10^1
8"	4.36×10^1
Mean of errors	34.1%
SD of error	35.8%

Weights 3:1:10 Sphere	Weight
3"	
5"	-9.29×10^1
8'	2.06×10^2
Mean of errors	57.1%
SD of error	78.3%

Weights 1:0:5 Sphere	Weight
3"	
5"	
8"	
Mean of errors	83.0%
SD of error	97.2%

Weights 1:0:1 Sphere	Weight
3"	
5"	
8"	2.06×10^2
Mean of errors	73.1%
SD of error	91.5%

Table 6. Weighting factors applied to calibration spectra to simulate a 'realistic' neutron field.

Spectrum	Weight
Thermal	
D_2O-moderated ^{252}Cf	3.58×10^{-1}
^{252}Cf	1.00×10^{-1}
^{241}Am-Be	7.65×10^{-2}
Mean of errors	21.7%
SD of error	51.0%

Spectrum	Weight
Thermal	
D_2O-moderated ^{252}Cf	3.67×10^{-1}
^{252}Cf	1.58×10^{-1}
Mean of errors	25.0%
SD of error	33.2%

Spectrum	Weight
D_2O-moderated ^{252}Cf	
^{241}Am-Be	1.28×10^{-1}
Mean of errors	27.7%
SD of error	35.5%

Spectrum	Weight
Thermal	
^{252}Cf	2.42×10^{-1}
Mean of errors	67.4%
SD of error	49.9%

The fit is good in the thermal region, but there are problems at energies just above as the Maxwellian thermal distribution falls to zero and where the low-energy part of the D_2O-moderated ^{252}Cf spectrum is small. The intermediate energy part of the spectrum follows the shape of the moderated source. The fast neutron peak of the 'realistic' spectrum falls in between the peaks of the bare ^{252}Cf and ^{241}Am-Be sources, so the fit is best when both of these spectra are included.

The 'realistic' spectrum simulated here (an ^{241}Am-Be source in a glove box) peaked at a fairly high neutron energy. Many other spectra peak in the keV region, and there would be problems simulating such spectra in this way as there are no radionuclide sources available whose spectra peak at these lower energies.

5. CONCLUDING REMARKS

The reader is kindly asked here to assist with the achievement of the objectives set out in this paper. If he has measured or calculated neutron spectra or instrument response functions he is asked to communicate them to the authors. Questionnaires detailing the information required will be sent upon request. Any comments or suggestions for further applications are also welcome.

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REFERENCES

1. International Commission on Radiation Units and Measurements. *Quantities and Units for Measurement and Calculation in Radiation Protection.* Report 51 (Bethesda MD: ICRU Publications) (1993).

2. A.Aroua, M.Grecescu, S.Pretre and J.-F.Valley. *On the Use of some Spectrum Hardness Quantifiers for Operational Neutron Fields.* Radiat. Prot. Dosim. **54**(2) 99-108 (1994).

3. B.R.L.Siebert, H.Schraube and D.J.Thomas. *A Computer Library of Neutron Spectra for Radiation Protection Environments.* Radiat. Prot. Dosim. **44**(1/4) 135-137 (1992).

4. M.Marshall, D.J.Thomas, C.A.Perks and O.F.Naismith. *Radiation Quantities: Significance of the Angular and Energy Distribution of the Radiation Field.* Radiat. Prot. Dosim. **54**(3/4) 239-248 (1994).

5. D.J.Thomas and O.F.Naismith. *Developments in Neutron Spectrometry for Radiation Protection.* Proceedings of 4th International Conference on Applications of Nuclear Techniques: "Neutrons and their Applications". Crete, Greece. 12-18 June 1994.

6. O.F.Naismith and B.R.L.Siebert. *A Database of Neutron Spectra, Instrument Response Functions, and Dosimetric Conversion Factors for Radiation Protection Applications.* Radiat. Prot. Dosim. (to be published).

7. R.V.Griffith, J.Palfalvi and U.Madhvanath. *Compendium of Neutron Spectra and Detector Responses for Radiation Protection Purposes.* IAEA Technical Reports Series No.318. (Vienna: IAEA) (1990).

8. H.Ing and S.Makra. *Compendium of Neutron Spectra in Criticality Accident Dosimetry.* IAEA Technical Reports Series No.180. (Vienna: IAEA) (1978).

9. International Commission on Radiological Protection. *Data for Use in Protection Against External Radiation.* Publication 51 (Oxford: Pergamon) (1987).

10. International Commission on Radiological Protection. *Data for Protection against Ionizing Radiation from External Sources: Supplement to ICRP Publication 15.* Publication 21 (Oxford: Pergamon) (1973).

11. S.R.Wagner et al. *Unified Conversion Functions for the New ICRU Operational Radiation Protection Quantities.* Radiat. Prot. Dosim. **12**(2) 231-235 (1985).

12. International Commission on Radiological Protection. *1990 Recommendations of the International Commission on Radiological Protection.* Publication 60 (Oxford: Pergamon) (1991).

13. B.R.L.Siebert. *Radiation Quantities: Their Inter-Relationship.* Radiat. Prot. Dosim. **54** 193-202 (1994).

14. International Commission on Radiation Units and Measurements. *Stopping Powers and Ranges for Protons and Alpha Particles.* Report 49 (Bethesda MD: ICRU Publications) (1993).

15. R.A.Hollnagel. *Conversion Functions of the Dose Equivalent $H_{sl}(10)$ in the ICRU Slab used for the Calibration of Personal Neutron Dosemeters.* Radiat. Prot. Dosim. **54**(3/4) 227-230 (1994).

16. K.G.Harrison, A.J.Taylor and J.A.B.Gibson. *The Neutron Response of a Neptunium Dosemeter worn on the Body*. Radiat. Prot. Dosim. **2**(2) 95-104 (1982).

17. D.T.Bartlett, NRPB Chilton, private communication.

18. C.Perks, AEA Harwell, private communication.

19. International Organization for Standardization (ISO). *Neutron Reference Radiations for Calibrating Neutron Measuring Devices used for Radiation Protection Purposes and for Determining their Response as a Function of Neutron Energy*. ISO 8529 (Geneva: Switzerland: ISO) (1989).

20. D.J.Thomas et al. *An Intercomparison of Neutron Field Dosimetry Systems*. Radiat. Prot. Dosim. **44**(1/4) 219-222 (1992).

21. D.T.Bartlett et al. *Neutron Spectra, Radiological Quantities and Instrument Responses at a Magnox Reactor and a Fuel Reprocessing Installation*. Radiat. Prot. Dosim. **44**(1/4) 233-238 (1992).

22. F.Posny, J.L.Chartier and M.Buxerolle. *Neutron Spectrometry System for Radiation Protection: Measurements at Work Places and in Calibration Fields*. Radiat. Prot. Dosim. **44**(1/4) 239-242 (1992).

23. F.Nitsche, A.Rimpler. *Untersuchungen zur Neutronenstrahlung an einem Transportbehalter fur Abgebrannten Kernbrennstoff*. Kernenergie 28(1) 27-31 (1985).

24. H.Schraube, GSF Munich, private communication.

25. D.J.Thomas, NPL Teddington, private communication.

26. V.Mares, G.Schraube and H.Schraube. *Calculated Neutron Response of a Bonner Sphere Spectrometer with ^{3}He Counter*. Nucl. Instrum. Methods **A307** 398-412 (1991).

27. B.Wiegel, A.V.Alevra and B.R.L.Siebert. *Calculations of the Response Functions of Bonner Spheres with a Spherical ^{3}He Proportional Counter using a Realistic Detector Model*. Report PTB-N-21, Braunschweig (1994).

28. T.B.Ryves and E.B.Paul. *The Construction and Calibration of a Standard Thermal Neutron Flux Facility at the National Physical Laboratory*. J. Nucl. Energy **22** 759-775 (1968).

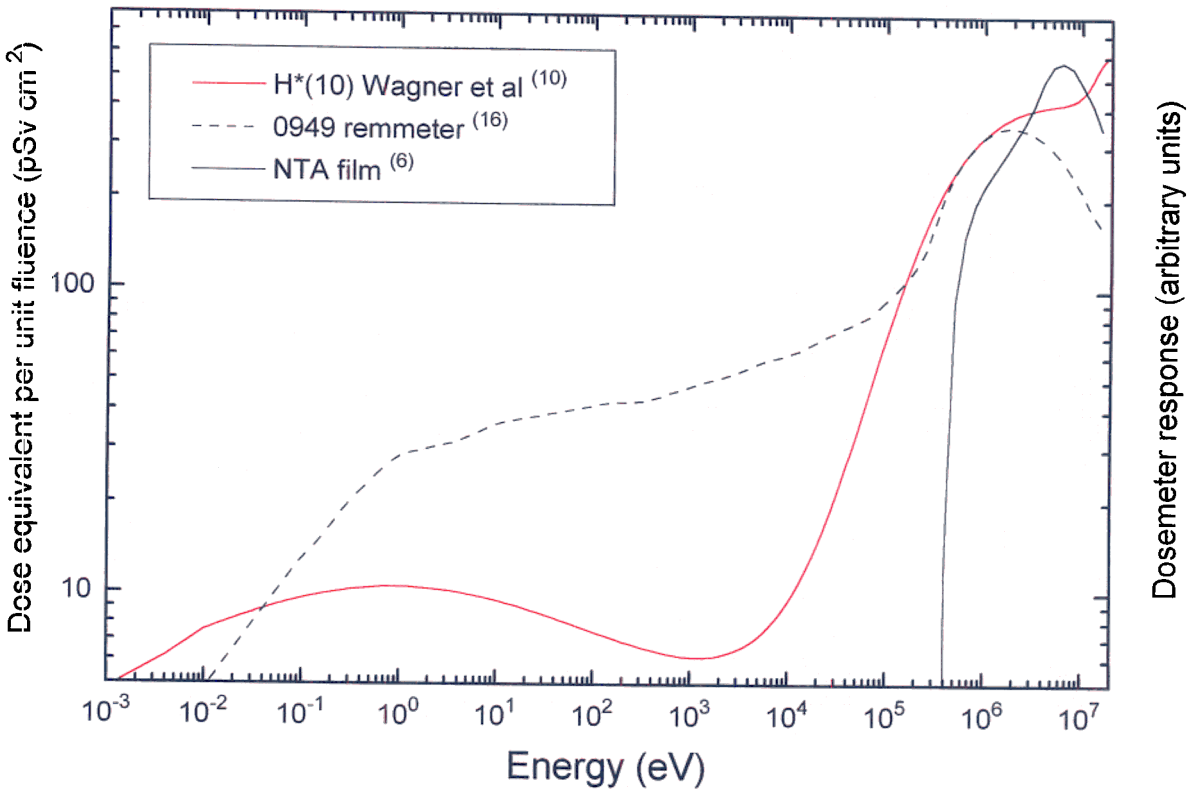


Figure 1. Response functions of a typical area survey meter and personal dosemeter compared with ambient dose equivalent. (The quantity for personal monitoring, $H_p(10)$, has a similar shape).

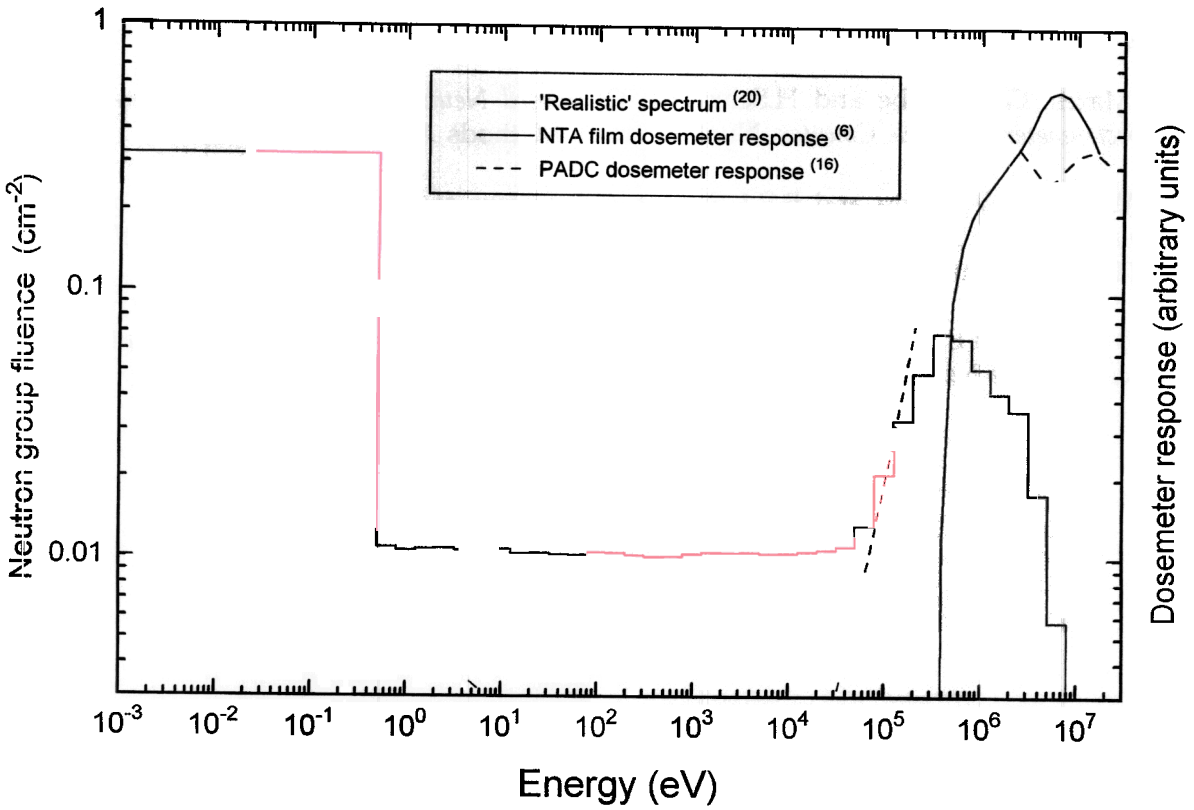


Figure 2. Response functions of NTA film and PADC personal dosemeters and their overlap with a typical workplace spectrum.

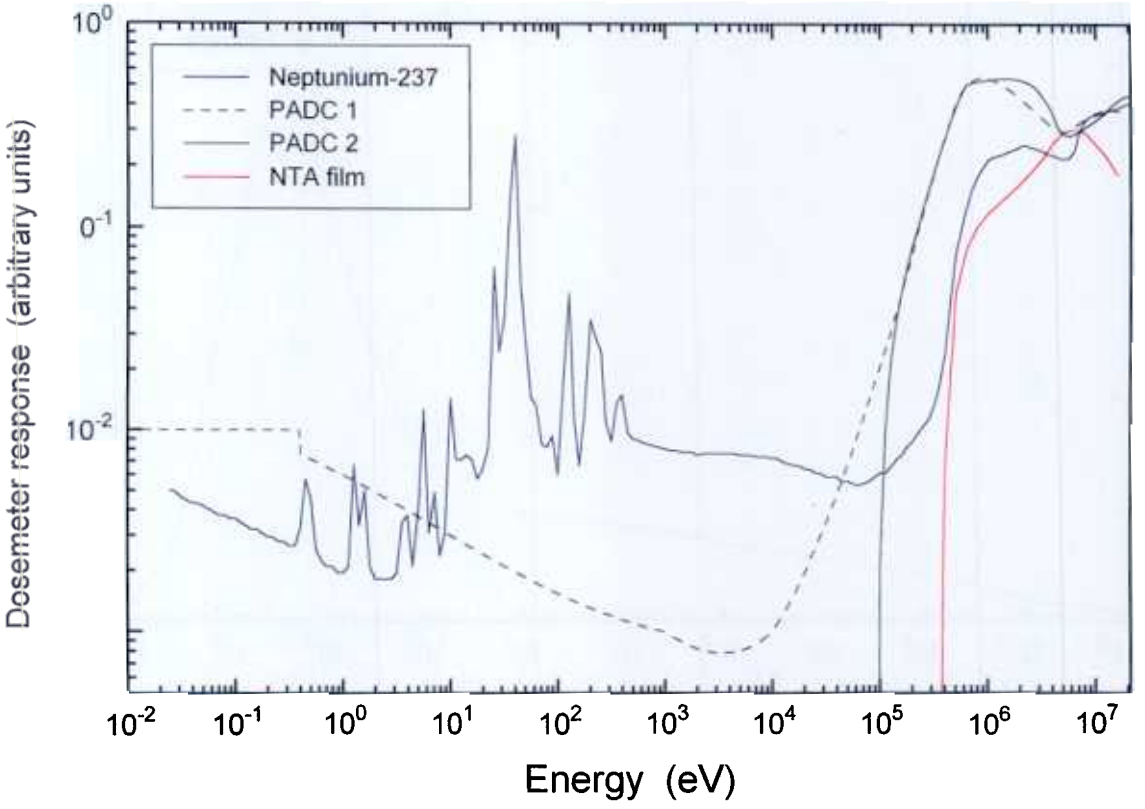


Figure 3. Response functions of four personal dosemeters, used in Example 1.

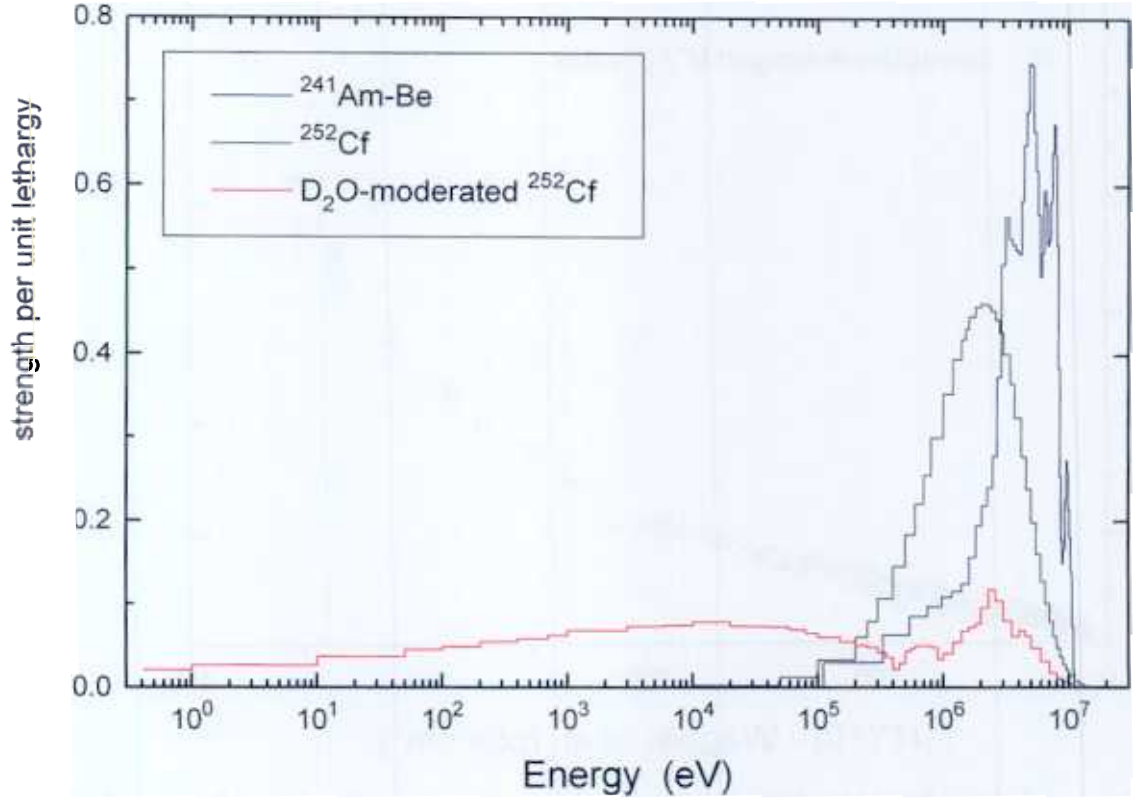


Figure 4. Bare and moderated radionuclide source calibration spectra for Example 1.

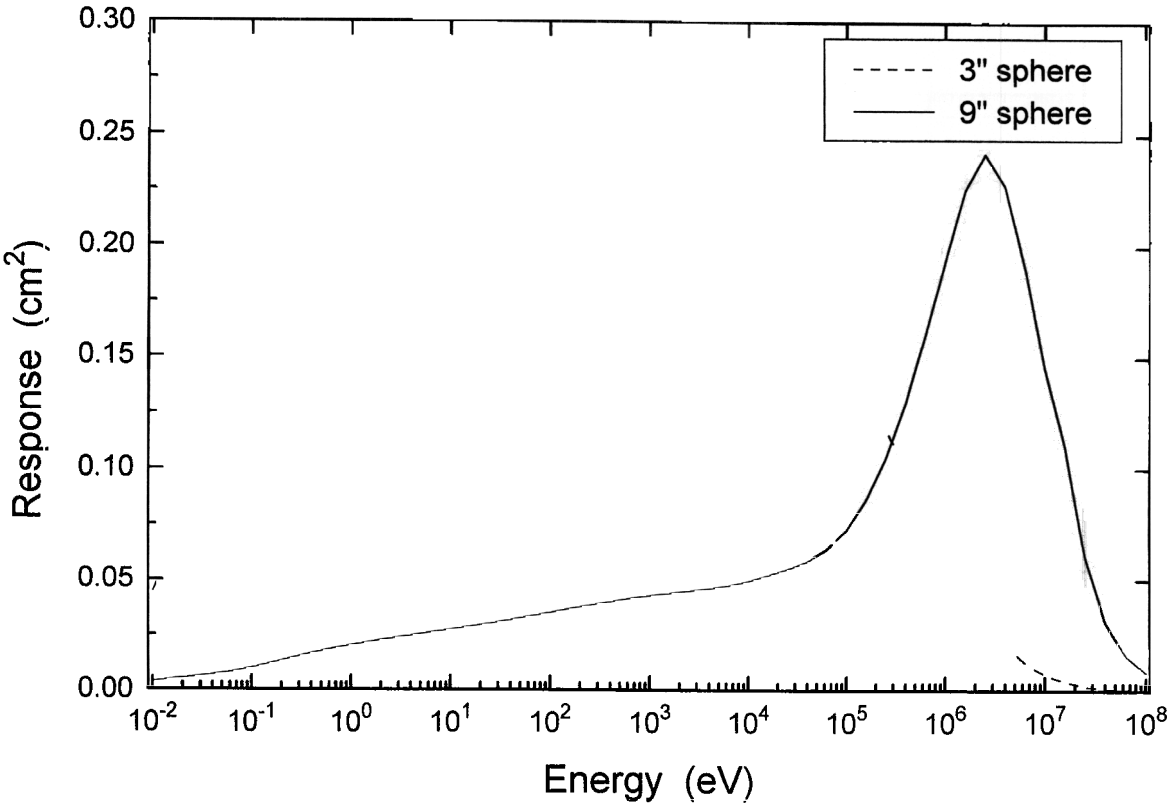


Figure 5. 9" and 3" Bonner sphere response functions.

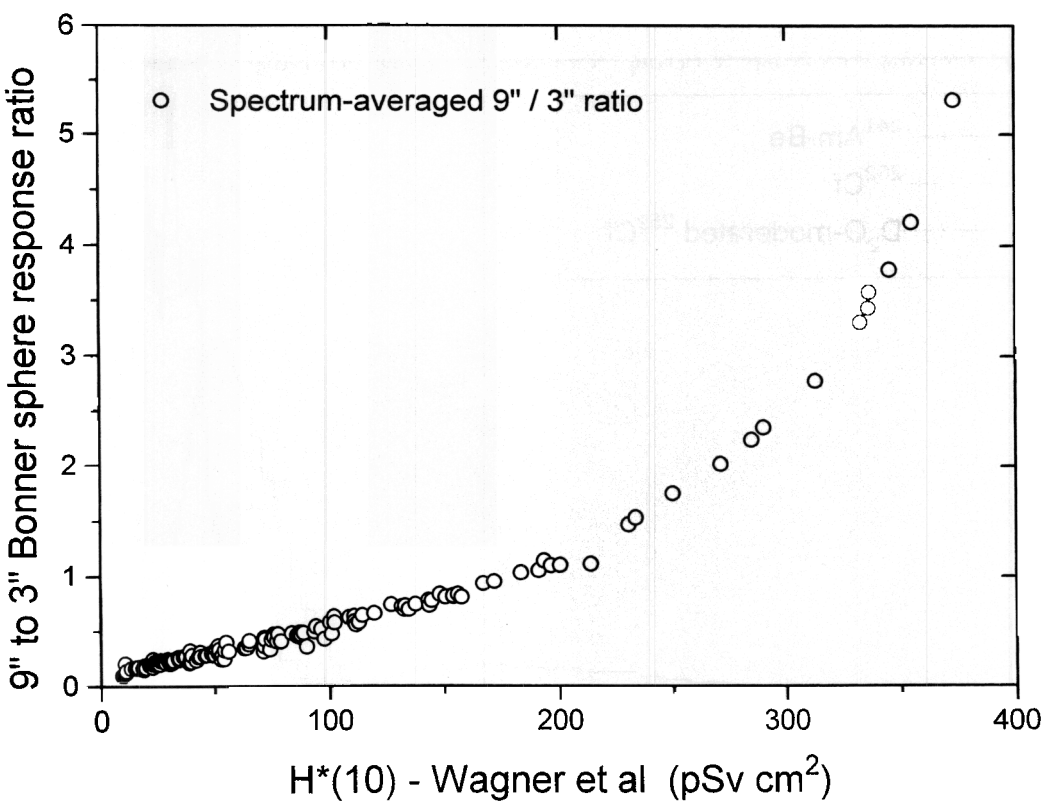


Figure 6. 9" to 3" Bonner sphere response ratio as a function of ambient dose equivalent for 'workplace' fission spectra.

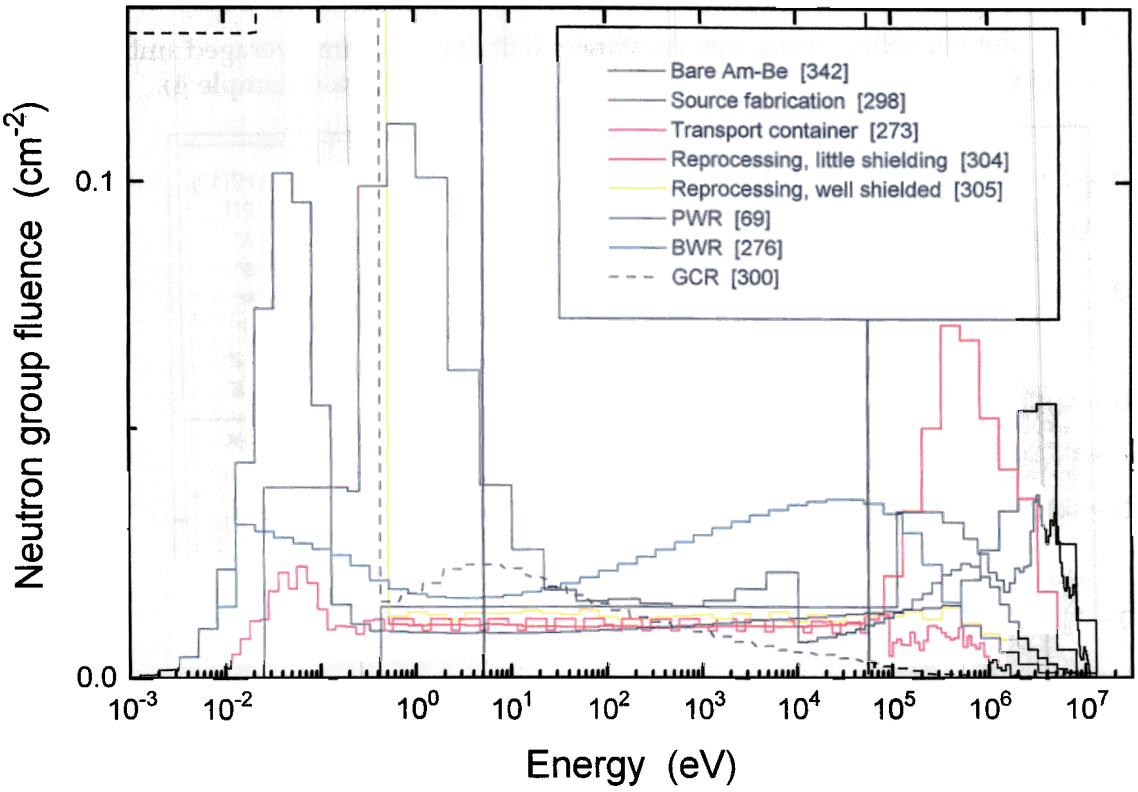


Figure 7. Neutron spectra for Example 3. The lines define the energy boundaries used for the calculation.

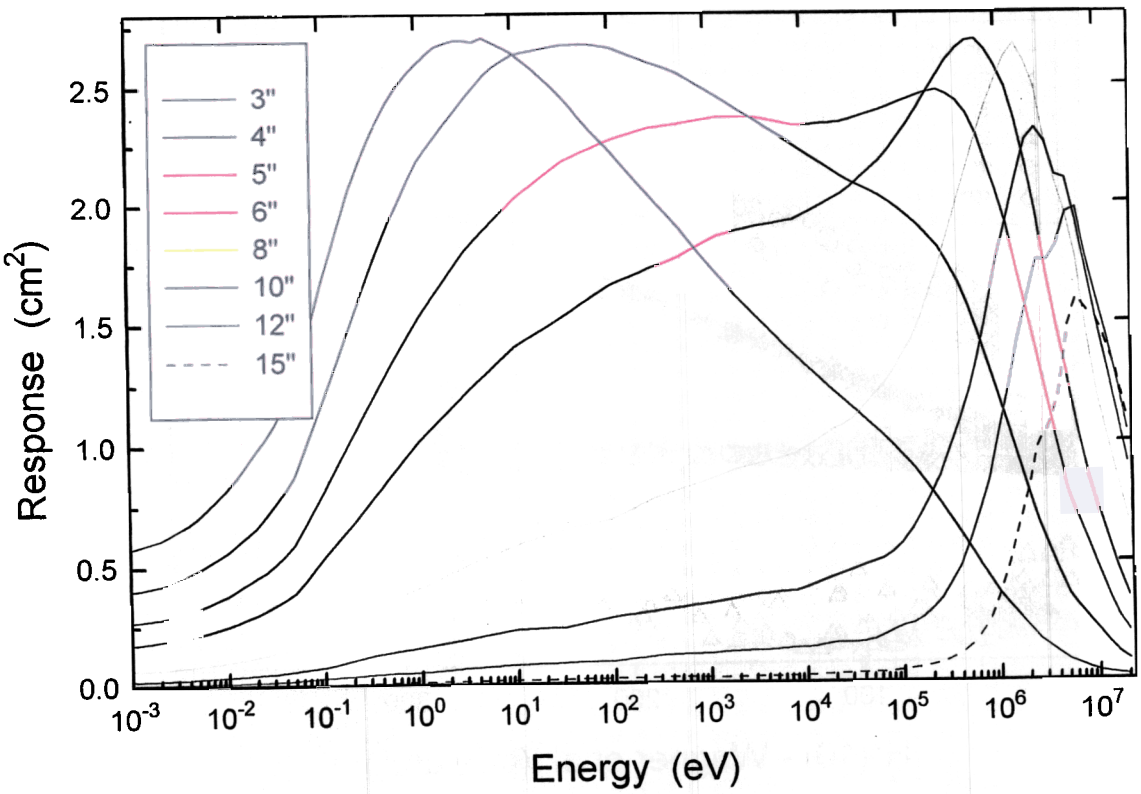
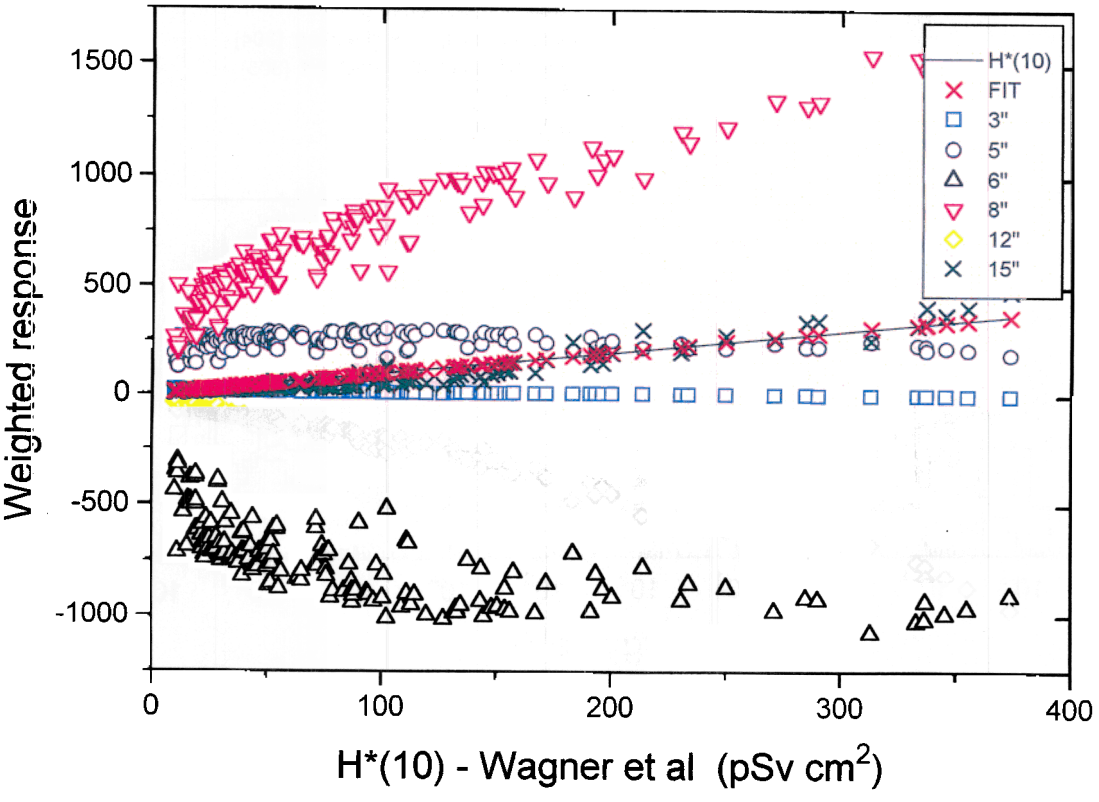
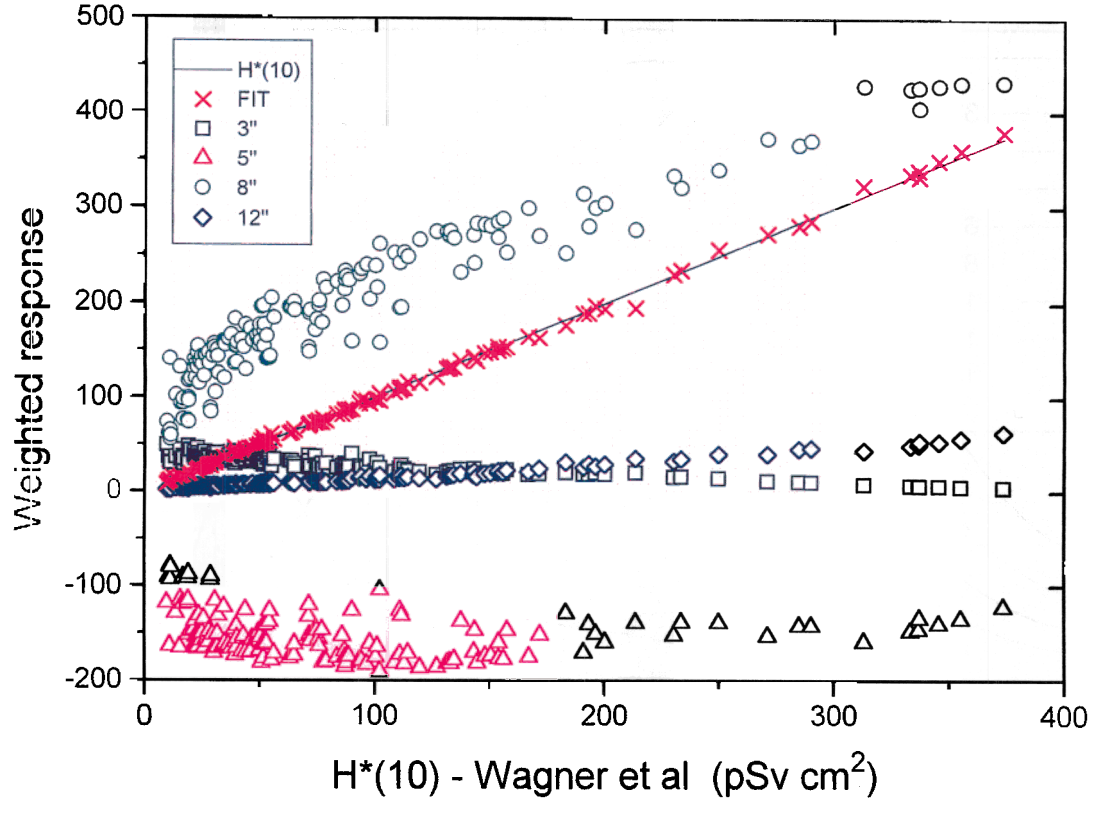


Figure 8. Bonner sphere response functions used in Examples 4 and 5.

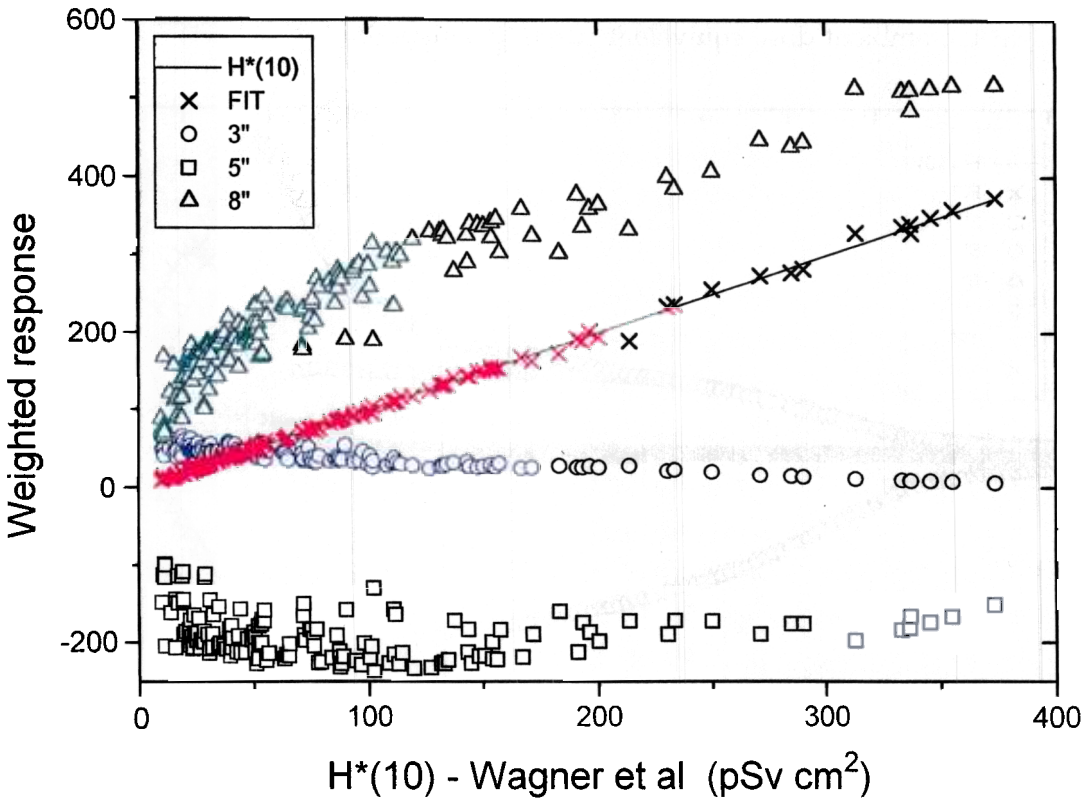
Figure 9. Bonner sphere responses, combined to fit the spectrum-averaged ambient dose equivalent for a variety of workplace fission spectra (Example 4).



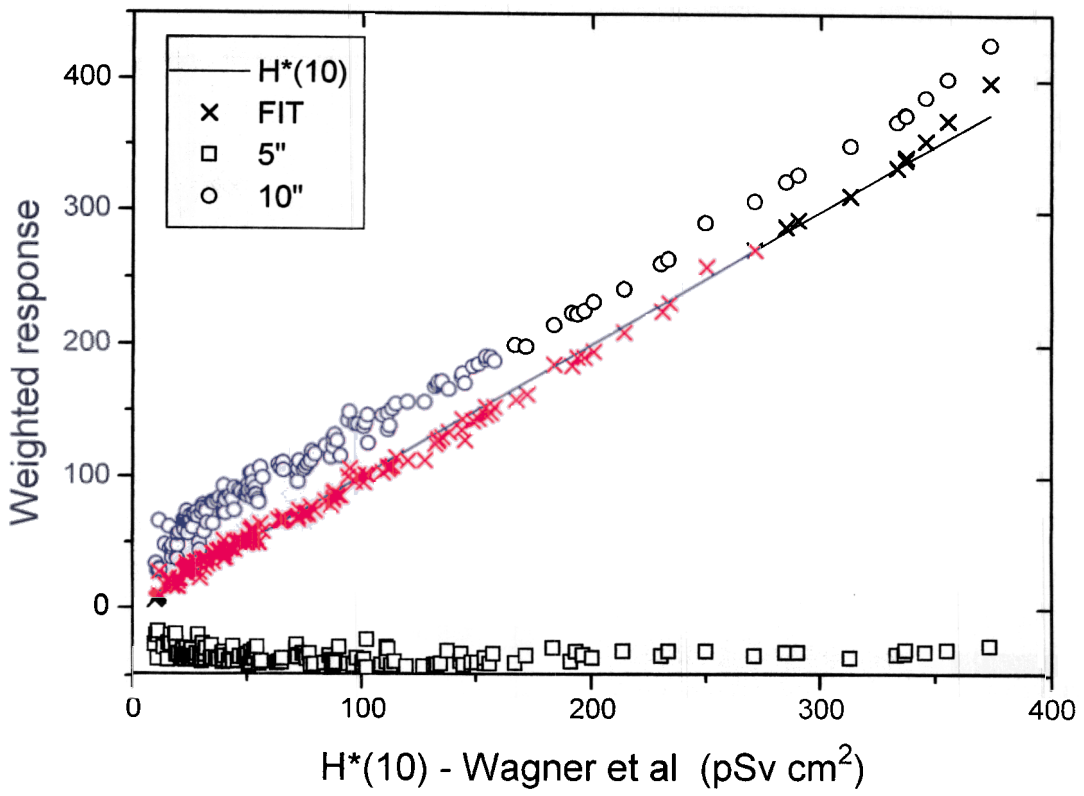
(a) Six sphere combination: 3", 5", 6", 8", 12" and 15"



(b) Four sphere combination: 3", 5", 8" and 12"

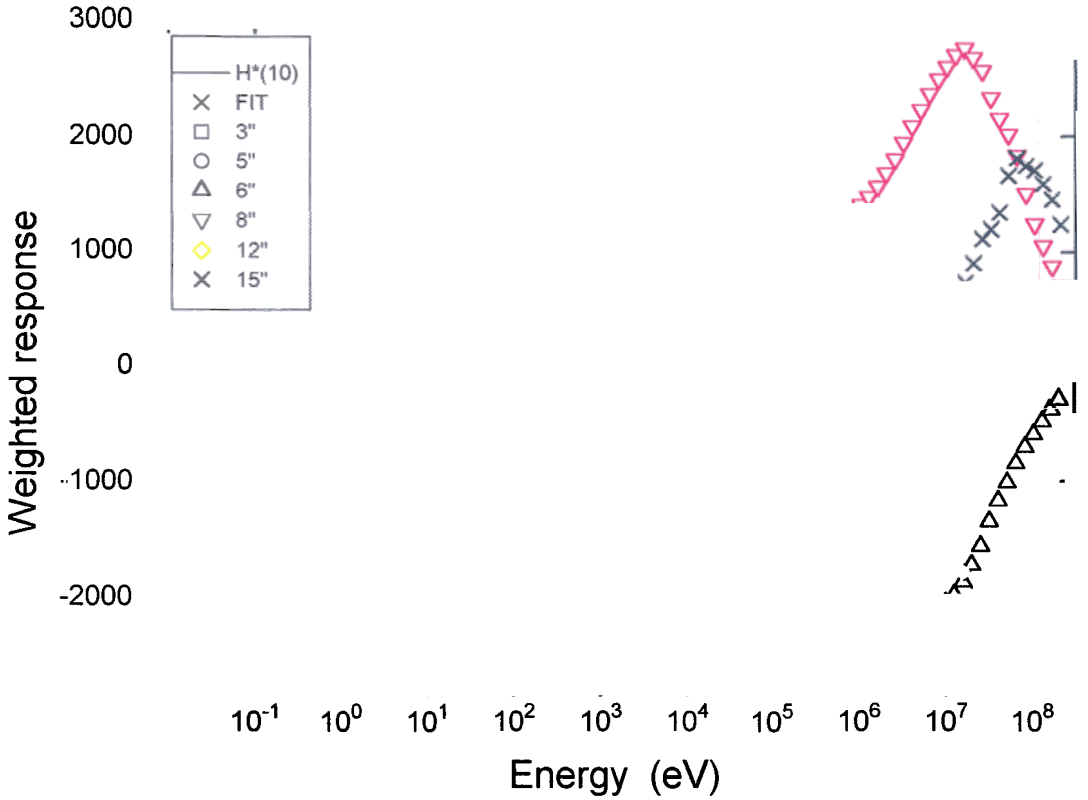


(c) Three sphere combination: 3", 5" and 8"

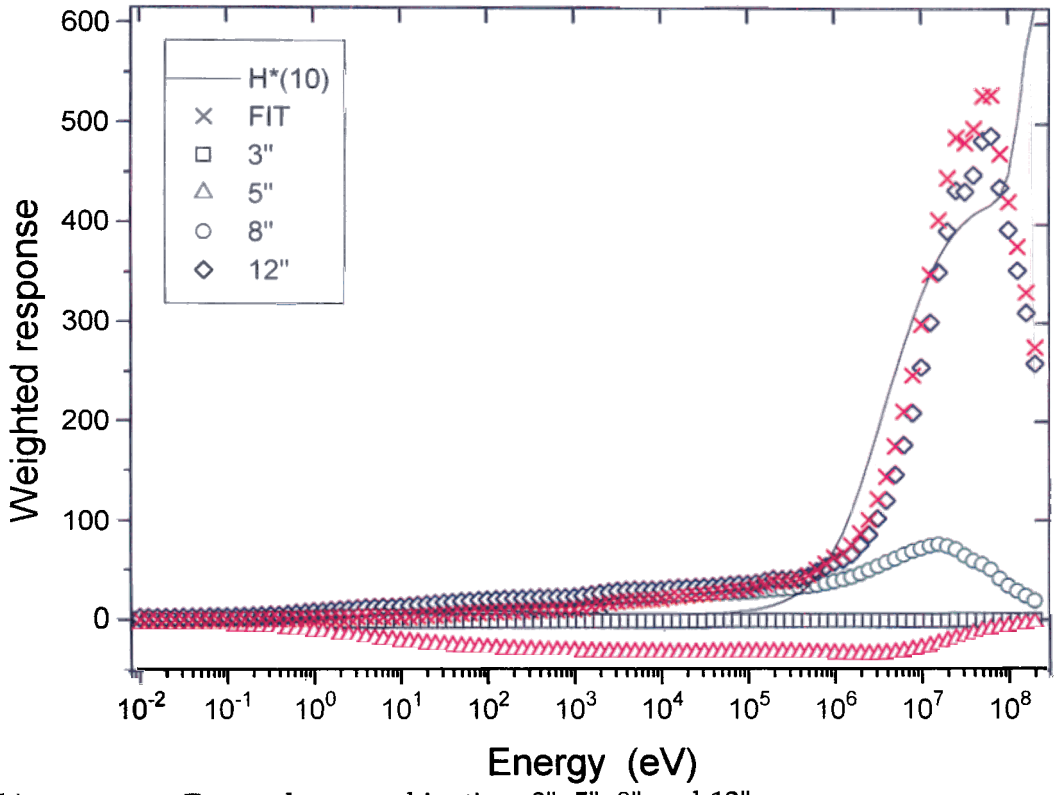


(d) Two sphere combination: 5" and 10"

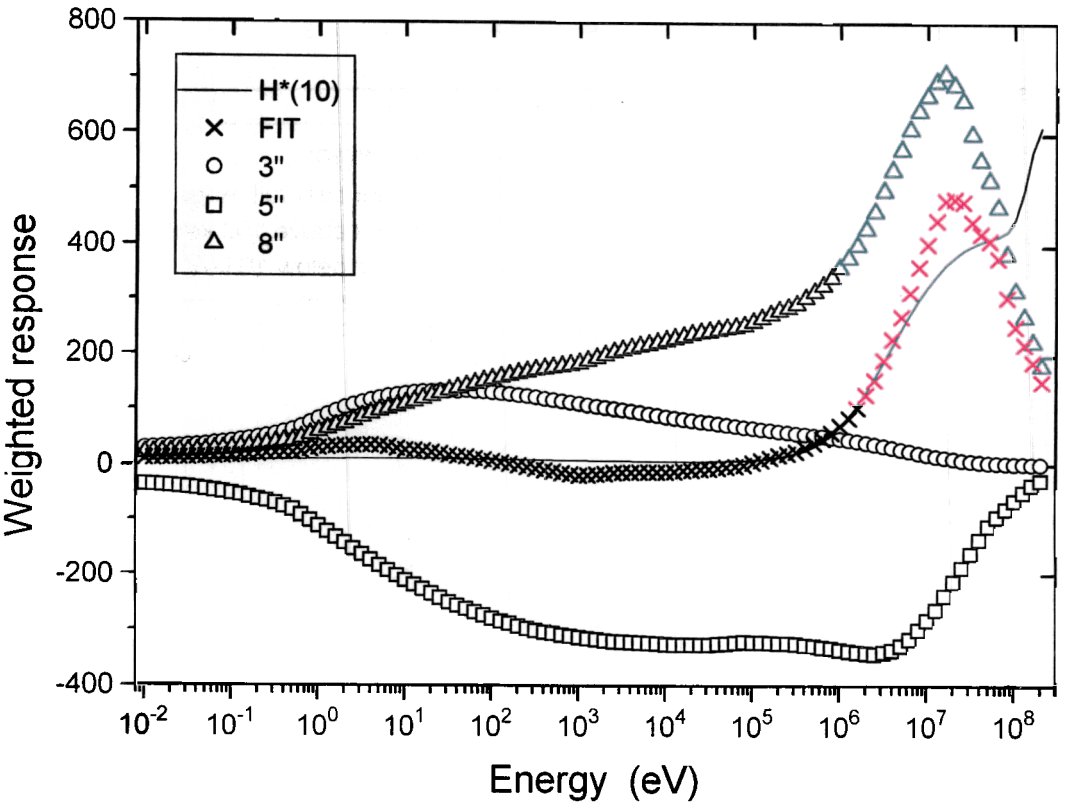
Figure 10 Weighted least squares combinations of Bonner sphere response functions to fit the ambient dose equivalent curve (Example 5).



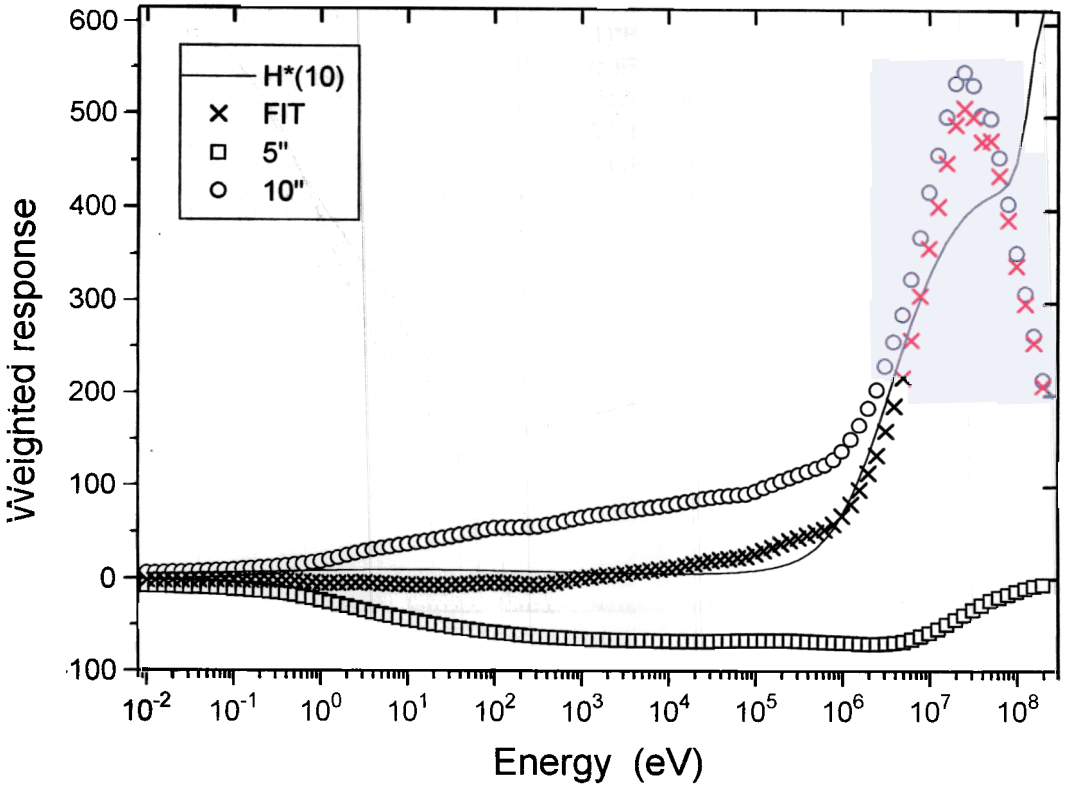
(a) Six sphere combination: 3", 5", 6", 8", 12" and 15"



(b) Four sphere combination: 3", 5", 8" and 12"

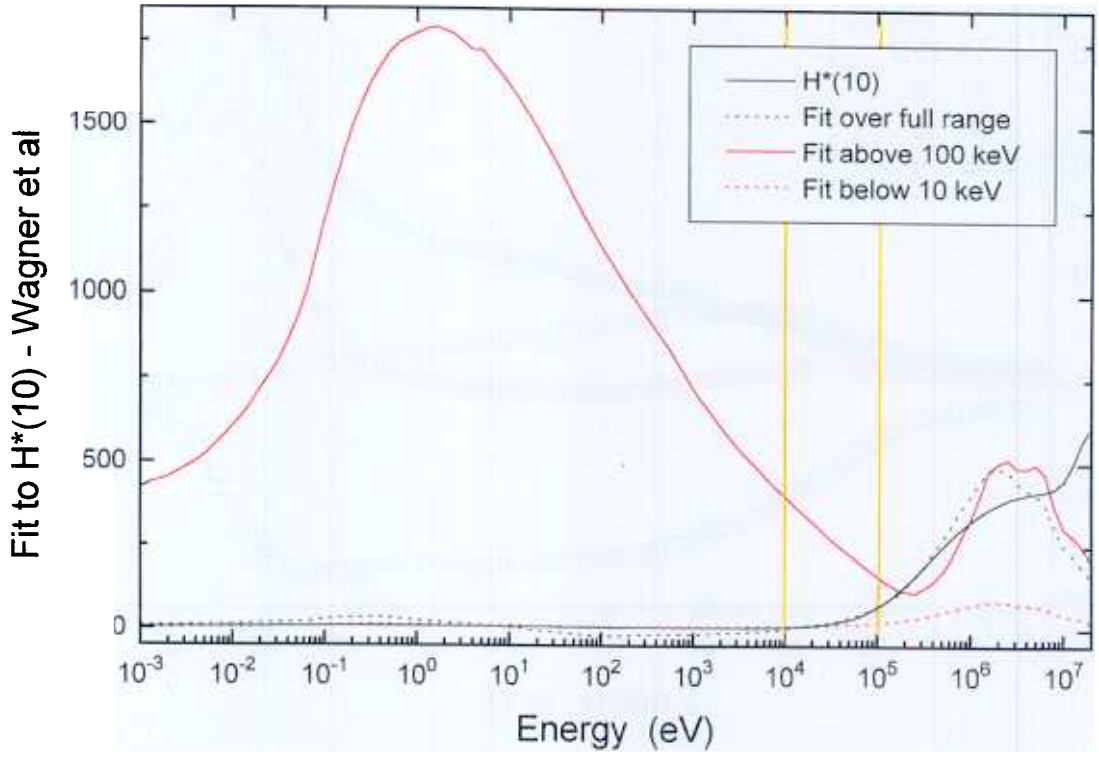


(c) Three sphere combination: 3", 5" and 8"

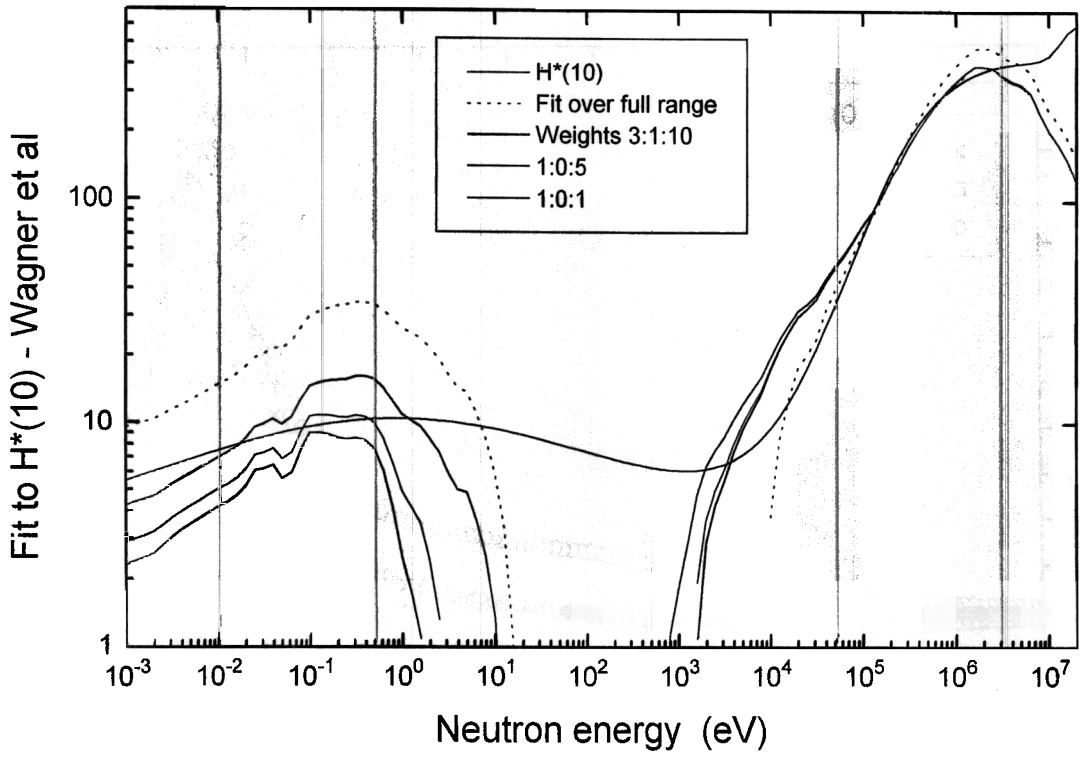


(d) Two sphere combination: 5" and 10"

Figure 11. Weighted least squares combination of three Bonner sphere response functions to fit ambient dose equivalent (Example 5).



(a) Calculation over two discrete energy ranges: low energy and high energy.



(b) Calculation with spectrum divided into thermal, intermediate and fast energy regions, with varying weights applied to each interval. Vertical lines define the boundaries of the three energy ranges.

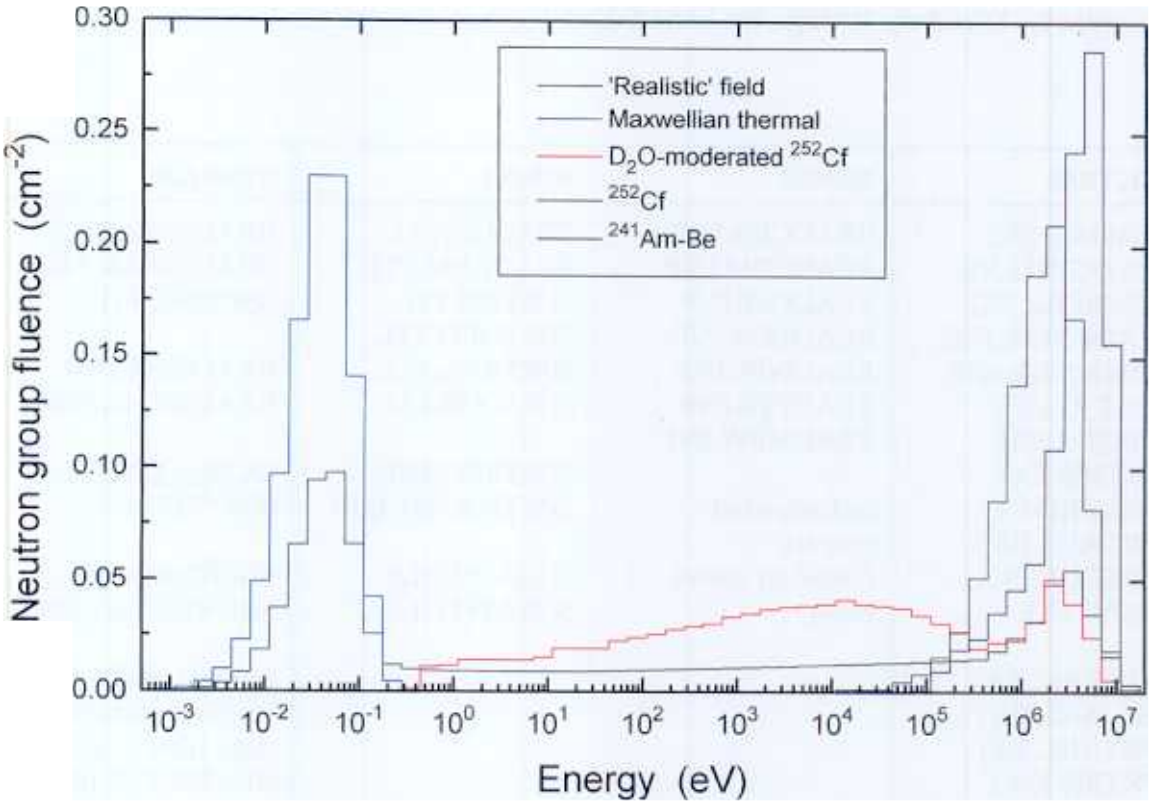


Figure 12. Calibration and 'realistic' spectra used for Example 6.

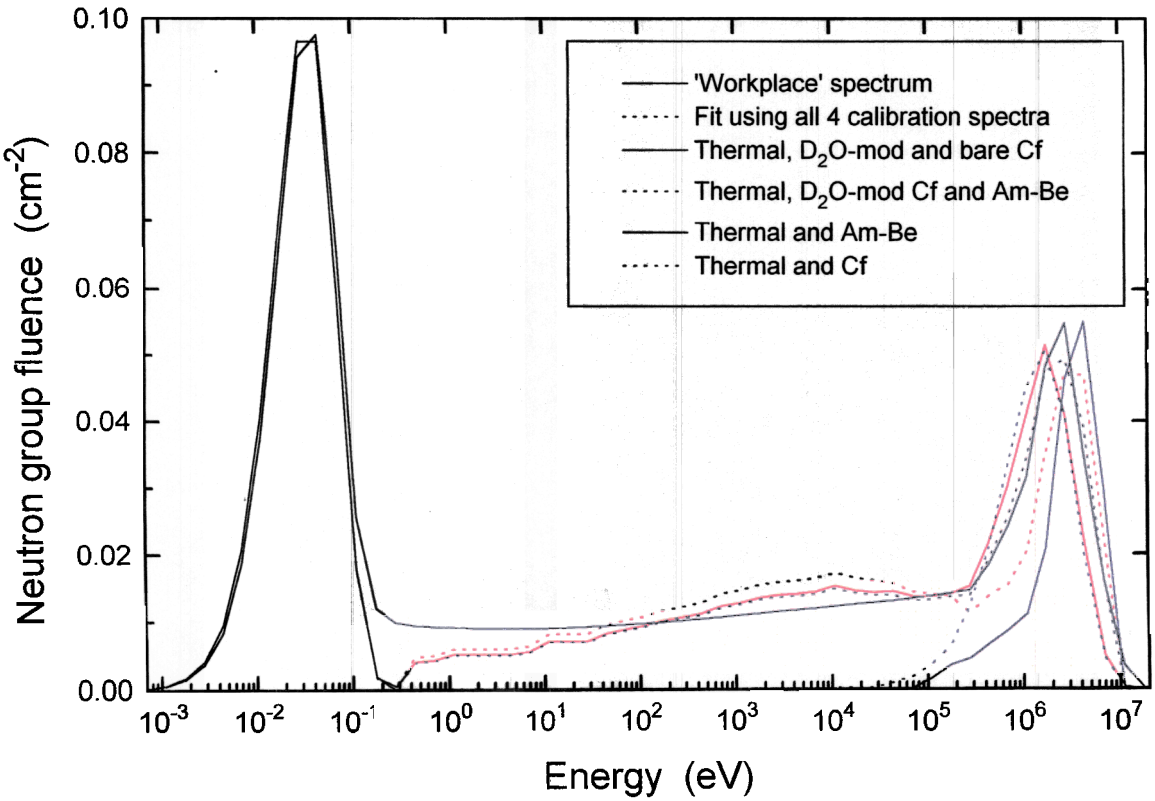
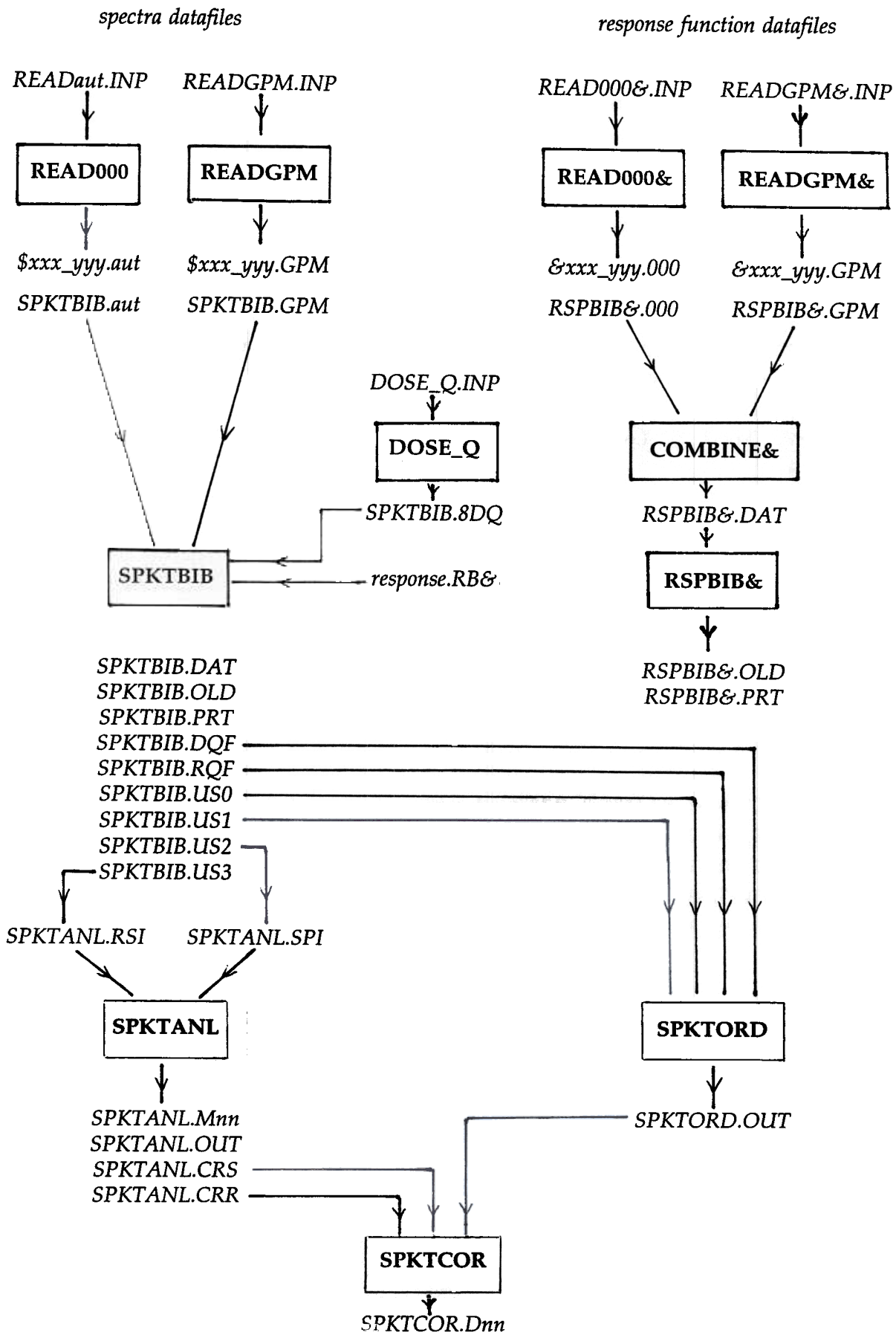


Figure 13. Simulation of a 'realistic' field using combinations of calibration spectra.

Appendix 1: Directory listings for installation

SPKTBIB	BIB000	BIB$$$	BIB&&&
READ000.EXE READGPM.EXE READ000&.EXE READGPM&.EXE COMBINE&.EXE DOSE_Q.EXE RSPBIB&.EXE SPKTBIB.EXE SPKTORD.EXE SPKTANL.EXE SPKTCOR.EXE SHOW.EXE USE_RAM.BAT USE_ANL.BAT SPKTANL.TXT SPKTBIB.DAT COURB.FON HELVB.FON GRAPH.INC SGRAPH.HLP	READCEA.INP READGPM.INP READGSF.INP READI&M.INP READNPL.INP READPTB.INP READNEW.INP unformatted spectra (listed in above files)	READ000.TTL READGPM.TTL SPKTBIB.TTL SPKTORD.TTL SPKTANL.TTL SPKTCOR.TTL SPKTBIB.MNU SPKTBIB.H01-H10 SGRAPH.HLP SGRAPH.HLF	READ000&.TTL READGPM&.TTL RSPBIB&.TTL READ000&.INP READGPM&.INP DOSE_Q.INP SPKTBIB.8DQ RSPBIB&.MNU RSPBIB&.H01-H06 unformatted response function data (listed on READ&.INP files)

Appendix 2: Flow chart of the system



Appendix 3: Sample datafile for energy spectra

13	*No. comment lines*
Nuclear fuel (used & unused) handling, reprocessing area, Bonner spheres.	*HEAD(1)*
1: Reprocessing, plutonium finishing plant, little shielding.	*HEAD(2)*
2: Reprocessing, plutonium finishing plant, well shielded area.	" "
3: Fuel pin assembly, little shielding.	" "
4: Reprocessing, plutonium finishing plant, little shielding.	" "
5: Reprocessing, plutonium finishing plant, little shielding.	" "
A.G. Bardell, D.T. Bartlett, & D.J. Thomas	*AUTHOR*
NPL Teddington and NRPB Chilton, UK.	*INSTITUTION*
Measurements at a variety of sites where nuclear fuel is handled and	
stored with varying degrees of shielding depending on the dose rates.	
Quantity given is fluence per bin, lower bound first.	
Spectra normalized to unit total fluence.	

Energy eV	Loc 1	Loc 2	Loc 3	Loc 4	Loc 5	
38 5 0 0						*No. bins, no. spectra, data representation *, energy units †*
1.0000E-3	**3.2502E-1**	**5.8558E-1**	**1.4847E-1**	**1.0841E-1**	**1.0358E-1**	*1*
5.0120E-1	**1.0909E-2**	**1.2402E-2**	**9.7954E-3**	**1.8866E-2**	**8.3468E-3**	*2*
7.9430E-1	**1.0628E-2**	**1.3311E-2**	**1.0653E-2**	**1.4326E-2**	**8.0506E-3**	*3*
1.2590E0	**1.0764E-2**	**1.2685E-2**	**1.0519E-2**	**1.5450E-2**	**8.1960E-3**	*4*
1.9950E0	**1.0796E-2**	**1.1653E-2**	**1.0378E-2**	**1.5417E-2**	**8.3037E-3**	*5*
3.1620E0	**1.0660E-2**	**1.3067E-2**	**1.0944E-2**	**1.3917E-2**	**8.0883E-3**	*6*
1.2590E6	**4.2076E-2**	**7.8143E-3**	**9.1424E-2**	**9.6307E-2**	**5.2046E-2**	*34*
1.9950E6	**3.6195E-2**	**6.0410E-3**	**9.1031E-2**	**4.4280E-2**	**5.0242E-2**	*35*
3.1620E6	**1.7570E-2**	**2.7623E-3**	**9.5201E-2**	**7.4580E-3**	**4.4830E-2**	*36*
5.0120E6	**5.7603E-3**	**5.2357E-4**	**6.4862E-2**	**4.9159E-4**	**2.5619E-2**	*37*
7.9430E6	**1.0169E-3**	**1.2955E-4**	**4.6507E-3**	**7.1744E-6**	**1.3419E-2**	*38*
1.2590E7						*39*

0 = group fluence
1 = fluence per unit lethargy

† 0 = eV
6 = MeV

Appendix 4: Sample datafile for response functions

```
19                                                          No. comment lines
Bonner sphere responses (5"-8") PTB-C system: MCNP calculation   HEAD(1)
5" Bonner sphere - PTB-C system: MCNP calculation           HEAD(2)
6" Bonner sphere - PTB-C system: MCNP calculation
7" Bonner sphere - PTB-C system: MCNP calculation
8" Bonner sphere - PTB-C system: MCNP calculation
B. Wiegel, A.V. Alevra and B.R.L. Siebert                   AUTHOR
PTB, Braunschweig                                           INSTITUTION

  3He pressure:          200 kPa  ==  4.9418E+19 atoms/cm^3
  PE density  :          0.946 g/cm^3
  direction of irradiation: 0 degree  ==  irradiation onto the 'nose'
                            or the opposite side of the 'stem'

10 bins per decade: energy value (MeV) is logarithmic midpoint of a bin.
In the energy region from 2 to 10 MeV the carbon resonances have been
resolved for the 4.5", 8", 12" and 15" spheres. The integral over this bin
is equal to the integral within the bin limits of the linear interpolation
of the original data in a lin-log (response vs. energy) representation.

105   4                                          No. energy points, no. response functions
1.000E-03  2.714E-01  1.760E-01  1.127E-01  6.922E-02   1
1.259E-03  2.769E-01  1.818E-01  1.161E-01  7.088E-02   2
1.585E-03  2.824E-01  1.877E-01  1.194E-01  7.254E-02   3
1.995E-03  2.880E-01  1.936E-01  1.228E-01  7.422E-02   4
2.512E-03  2.969E-01  1.997E-01  1.262E-01  7.704E-02   5
3.162E-03  3.075E-01  2.058E-01  1.300E-01  8.046E-02   6

1.000E+07  4.690E-01  7.335E-01  9.637E-01  1.198E+00   101
1.259E+07  3.612E-01  5.957E-01  8.079E-01  1.020E+00   102
1.585E+07  2.677E-01  4.660E-01  6.631E-01  8.482E-01   103
1.995E+07  2.046E-01  3.540E-01  5.258E-01  6.806E-01   104
2.000E+07  2.039E-01  3.528E-01  5.244E-01  6.789E-01   105
```

Appendix 5a: Graphics menu

The plot is initially displayed according to the default parameters assigned in the file GRAPH.INC. On pressing the <ENTER> key, the user is taken to a graphics menu where the plotting parameters can be altered.

The menu consists of a number of green boxes containing the parameter values, the contents of which can be changed. Movement between boxes is achieved using the cursor keys. The existing entry will be overwritten unless the <INSERT> key is pressed. No distinction is made between capital and small letters, and abbreviations are tolerated as long as they are distinct from all other entries in the field (e.g. "y" is acceptable for "yellow", but "b" could be "blue" or "brown"). Press <ENTER> to confirm the change.

Parameter	Description
	Text for heading; and x- and y-coordinates (on a 100 x 100 grid) for positioning of first letter.
x-Axis	Minimum and maximum values of horizontal axis (energies will be in eV) - default values are the smallest and largest data points; "log" or "lin" for logarithmic or linear scale; and text for axis heading.
y-Axis	As for x-axis.
	x-coordinate (i.e. energy in eV) at which a vertical line is to be drawn - for use with SPKTANL. Two entries can be inserted into each of the six boxes.
	Presence of coordinate grid on plot: "yes" or "no'
Text height	Font-size of lettering for title, axis headings, and titles for curves: 2-6.
Curve *n*	Representation of data for curve *n*:
blank :	data not plotted
Poly :	points joined by straight line
Hist :	histogram
Sym 1 :	cross (×)
Sym 2 :	circle
Sym 3 :	cross (+)
Sym 4 :	square
Sym 5 :	diamond
Sym 6 :	triangle
Sym 7 :	inverted triangle
Sym 8 :	star
Sym 9 :	dash
Color:	Colour of curve *n*: blue, green, cyan, red, magenta, brown, white, l'blue, l'green, l'cyan, l'red, l'magenta, yellow, l'white.
Var:	Colour of error bars for curve *n*: as above.
Text:	Label for curve *n*, and x- and y-coordinates of its position on a 100 x 100 grid.

The red boxes are command fields, and are carried out on pressing <RETURN> whilst the cursor is located in the appropriate box:

Plot — Displays the plot according to the plotting parameters defined at that time.

Save — Outputs data points and plotting parameters to a file. A filename must be entered in the adjacent green field. The plot can subsequently be displayed using the program SHOW.

Textblock — Aligns left-hand position of all curve-headings to match the x-coordinate of curve 1

Help — Accesses on-line help-facility.

German / English : The menu can be written in German or English. In both cases the input can be in either language.

End — Exits the graphics and returns to the main program.

The above commands can also be carried out using the key-combination <ALT> with the initial letter of the command:

e.g. <ALT> + P = Plot

N.B. <ESCAPE> = End

Appendix 5b: Graphics routines

The plotting routines are common to all programs, and are accessed by the command

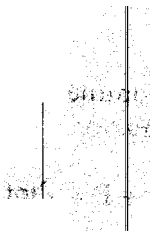
CALL GRAPH(x,y,dy,k,n)

x(k,n) and y(k,n) are the arrays of x- and y-coordinate data for curve n, and dy(k,n) the uncertainties, where n≤8. k, the number of data points, is restricted only by the available storage space.

The default parameters, e.g. axis range, symbol type, colour, etc., are defined by variables in a common-block. They can be changed interactively from within the graphics menu (as described in Appendix 5a) once the graph has been plotted.

Alternatively, the default parameter set can be edited. The variables are defined in the file GRAPH.INC, and the common-block for the graphics is printed below:

```
c  Common-block for screenplot
c
      real          xa, xe, x1, xt, ya, ye, y1, yt, xfak, yfak
      integer       htit, hatx, hktx
      real          mark(12), ttx(8), tty(8), tix, tiy
      logical       gn
      integer*2     art(8), fk(8), ff(8), lg(8)
      character*24  xax, yax
      character*12  text(8)
      character*58  titel
      character*1   sprache, xoy
      common /py_sc/  xa, xe, x1, xt, ya, ye, y1, yt, xfak, yfak, htit, hatx, hktx,
     *                sprache, xoy, mark, ttx, tty, tix, tiy,
     *                gn, art, fk, ff, lg, xax, yax, text, titel
```



Definition of variables:

xa, xe — Range of the x-axis:
xa=1e30 is replaced by the smallest value of the field xf, and xe=-1e30 by the largest.

xt — Scale of the x-axis:
Default xt>0 - linear; xt=0 - logarithmic.

ya, ye, yt — As above, for y-axis.

titel — Title for the plot

tix, tiy — Coordinates for positioning title, defined on a 100 x 100 grid.

htit — Font size for title. There are five sizes, characterised by integers 2 to 6.

xax, yax — Axis headings.

hatx — Font size for axis headings.

text(k) — Label for each curve.

ttx(k), tty(k) — Coordinates of curve headings (see tix, tiy).

hktx — Font size of headings.

mark(i) x-coordinates of any vertical marking lines added to plot. A value of 1e30 signifies that lines have not been specified.

gn The plot may have an underlying coordinate grid
gn=.true. : with grid (default).
gn=.false. : without grid.

art(k) Curve representation:
art(k) = 0: curve excluded
= 1-9: see symbols in Appendix 5a
= 10: polygon
= 11: histogram

Colour of the curve:

fk(k)=	0: black	fk(k)=	8: grey
	1: blue		9: light blue
	2: green		10: light green
	3: cyan		11: light cyan
	4: red		12: light red
	5: magenta		13: light magenta
	6: brown		14: y%llow
	7: white		15: bright white

Colour of the error-bars:
ff(k)=0 : no error-bars
ff(k)>0 : values as for fk

Number of data-points in each curve. For each curve, a number less than k can be specified, and only the first lg(k) points will be plotted.

sprache The graphics menu can be in either English or German
sprache='e' : English (default)
sprache='d' : German

The common-variables not defined above are only used internally in the program.

A similar routine has been used for plotting data without the use of the interactive graphics menu:

CALL GRAPH_0 (x, y, dy, k, n)

This differs from the routine GRAPH in that the graphics menu cannot be accessed, and <ENTER> returns the user to the main program.

Appendix 6: Description of dosimetric parameters and spectrum-folding procedure for instrument response functions[2].

Name, abbrev.	Units	Equation	Meaning of symbols	Comments
Fluence mean energy, $\bar{E}$	eV	$\bar{E} = \frac{\int_{E_{max}}^{E_{min}} E\ \Phi_E\ dE}{\int_{E_{max}}^{E_{min}} \Phi_E\ dE}$		Usually called mean energy.
Mean neutron fluence to absorbed dose conversion factor, d*(10)	Gy cm^2	$\overline{d^*}(10) = \frac{\int_{E_{max}}^{E_{min}} d^*(10)\ \Phi_E\ dE}{\int_{E_{max}}^{E_{min}} \Phi_E\ dE}$	d*(10)=D*(10)/Φ is expressed by the unified analytical expressions given by Wagner et al[9]	
Mean neutron fluence to ambient dose equivalent conversion factor, h*(10)	Sv cm^2	$\overline{h^*}(10) = \frac{\int_{E_{max}}^{E_{min}} h^*(10)\ \Phi_E\ dE}{\int_{E_{max}}^{E_{min}} \Phi_E\ dE}$	h*(10)=H*(10)/Φ is the neutron fluence to ambient dose equivalent conversion factor[9,10]	Also applicable to neutron personal dose equivalent[11], MADE[8], effective dose, etc.
Spectrum-averaged fluence response of a detector, R_Φ	cm^2	$\overline{R_\Phi} = \frac{\int_{E_{max}}^{E_{min}} R_\Phi\ \Phi_E\ dE}{\int_{E_{max}}^{E_{min}} \Phi_E\ dE}$		

Appendix 7: SPKTBIB.RQF - Personal dose equivalent in the ICRU slab phantom and personal dosemeter responses folded with a number of different 'workplace' neutron spectra.

```
RESPONSES: Personal dose equivalent and dosemeter responses
  13     6  COR / ORD - FORMAT
<E>≡(mean)    - - - -    column headings
Hp(10) A-P
Np on-body
PADC (1)
PADC (2)
NTA IAEA
 342  4.154E+06  4.880E+02  1.631E+03  3.426E-05  3.666E-05  6.258E-04
 340  2.129E+06  4.824E+02  1.412E+03  3.996E-05  4.390E-05  4.318E-04
 341  5.389E+05  1.331E+02  3.730E+02  9.224E-06  9.924E-06  1.000E-04
 298  7.564E+05  1.411E+02  4.272E+02  1.037E-05  1.081E-05  1.281E-04
 304  4.199E+05  1.712E+02  3.774E+02  1.381E-05  1.404E-05  8.940E-05
 305  7.311E+04  4.421E+01  1.049E+02  3.085E-06  2.503E-06  1.472E-05
 350  1.134E+05  1.073E+02  1.200E+02  5.884E-06  5.701E-06  1.645E-05
 273  1.098E+05  7.980E+01  1.656E+02  5.501E-06  5.104E-06  2.194E-05
  69  2.375E+05  1.156E+02  2.336E+02  8.908E-06  8.714E-06  5.132E-05
  62  5.697E+04  6.076E+01  6.606E+01  2.523E-06  2.044E-06  4.866E-06
 276  6.343E+04  5.043E+01  1.313E+02  2.724E-06  2.337E-06  1.030E-05
 302  1.682E+04  2.659E+01  7.077E+01  1.365E-06  7.461E-07  2.071E-06
 300  2.821E+03  1.590E+01  4.828E+01  8.955E-07  1.168E-07  2.662E-07
```

Spectrum number:

342 ^{241}Am-Be ISO spectrum[18]
340 ^{252}Cf ISO spectrum[18]
341 D_2O-moderated ^{252}Cf ISO spectrum[18]
298 ^{241}Am-Be source in glove box - neutron source fabrication plant[19]
304 Nuclear fuel reprocessing area - little shielding[20]
305 " " " " " - well shielded[20]
350 Fuel transport cask[21]
273 " " " [22]
69 PWR - within containment[6]
62 " " " " [6]
276 BWR - inside containment[23]
302 GCR[20]
300 " [24]