Optimal Design of Experiments Group

GR DOE

BIOKMOD

USER MANUAL

English version. Translated from Spanish Manual Rev 2

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https://diarium.usal.es/guillermo/biokmod/

INDEX

1 INTRODUCTION

BIOKMOD is an application oriented to modelling, particularly compartmental modelling and its application to internal dosimetry. It includes the ICRP (International Commission on Radiological Protection) and OIR (Occupational Intakes of Radionuclides) models most commonly used in occupational internal dosimetry, although it also includes some specific isotopes for application in Nuclear Medicine.

The app can be accessed in two ways:

a) From the Mathematica program in which the application has previously been installed.

b) As a web application that we call BIOKMODWEB. In this case, the application is on a web server that has Java, Tomcat, and Mathematica.

In what follows we refer to BIOKMODWEB. In the case of the examples in this manual, the one installed on the OED server of the University of Salamanca has been used. It should work the same on other servers with the same configuration.

To access the application, go to the web address: http://oed.usal.es/webMathematica/Biokmod/ (or to a web address with the application installed).

It can be used on any device (PC, computer, tablet, or mobile with a large enough screen).

When accessing the application, a bar similar to the one shown below will appear, which gives access to the different modules:

In this manual we are going to refer to the menu options: *Compartmental Mod*, *OIR Models* and *Bioassay Evaluation*.

The following convention applies to inputs or outputs where numerical values appear: Point (.), Log (natural logarithm), E (number), *a^b* (*a* to the power of *b*) is used as a decimal separator

Inputs and results can be printed directly from the browser (if you have the corresponding plugin, outputs can be generated in pdf). In addition, some numerical outputs are in table format so that they can be copied directly into a spreadsheet or text editor.

Some of the calculation methods used in the programming of the application have been published in relevant journals ([Sánchez-León 2022], [Moraleda 2020], [Rodríguez-Díaz 2019a], [Rodríguez-Díaz 2019b], [Lopez-Fidalgo 2019], [Rodríguez-Díaz 2014], [Sánchez-León 2007]).

In the cases that are available, the data obtained by BIOKMOD have been compared with other sources, in particular the outputs for one-off additions in the OIR models have been contrasted with those given by the ICRP 2022 Electronic Annex.

2 CONSTRUCTION AND RESOLUTION OF COMPARTMENTAL MODELS

A compartment model is usually represented by a block diagram, where compartments are represented by rectangles or circles and by arrows the compartment exchanges with each other and compartments with the outside. The retention as a function of time for compartment *i* is denoted by *xi*(*t*) and the transfer coefficient from compartment *i* to compartment *j* by *kij* (some authors prefer *kji*). Sometimes, when there is no ambiguity about the target compartment, ki is written. The outside of the compartment system is represented by "0", so the transfer coefficient from *i* to the outside is *ki0*. Radioactive decay is an outward transfer with a transfer coefficient λ, i.e. *kio* = λ, which is the decay constant. If there are transfers from compartment i to several, the total transfer coefficient of *i* will be *Ki*, which corresponds to the sum of each of the individual coefficients. The input from the outside to compartment *i* is denoted by *bi*(*t*), if there are *m* inputs to the same compartment *i* then $bi(t) = \sum_k bki(t)$ with $k = \{1, ..., m\}$. The evolution of a compartmental system is described mathematically by a system of first-order differential equations. Specifically, the general formulation for n-compartment systems with constant transfer coefficients is given by (1).

$$\mathbf{x'}(t) = \mathbf{A}\,\mathbf{x}(t) + \mathbf{b}(t), \text{ with } t \geq 0 \text{ and with initial condition } \mathbf{x}(0) = \mathbf{x0} \qquad (1)$$

A is the compartmental (square) matrix formed by the constant terms {*aij*} with $aij = \sum_j (-kij + kji)$. We will assume that the *kij* are all different from each other.

$$\mathbf{x'}(t) = [x'_1(t), x'_2(t), \ldots, x'_n(t)]^T$$

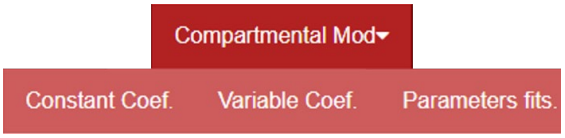
$$\mathbf{x}(t) = [1(t), 2(t), \ldots, Xn(t)]^T$$

$$\mathbf{b}(t) = [B1(t), B2(t), \ldots, Bn(t)]^T$$

$$\mathbf{x0} = [1(0), 2(0), \ldots, Xn(0)]^T$$

(*T* indicates transposed matrix)

BIOKMOD gives the user the option to build his compartmental model, by means of a simple menu, internally transforms the input into a system of differential equations in the way that has been described. To do this, from the toolbar we access the *Compartmental Mod option*,



It has several options, the Constant *Coef module.* when the transfer coefficients are constant, *kij*, *Variable Coef.* when they are variable over time, *kij*(*t*), and the *Parameters Fits* module when a transfer coefficient is left as a parameter to be adjusted from measurements in a compartment.

The *Constant Coef.*shows a screen like the one in Figure 2.1 on which the user constructs the compartment model including the initial conditions.

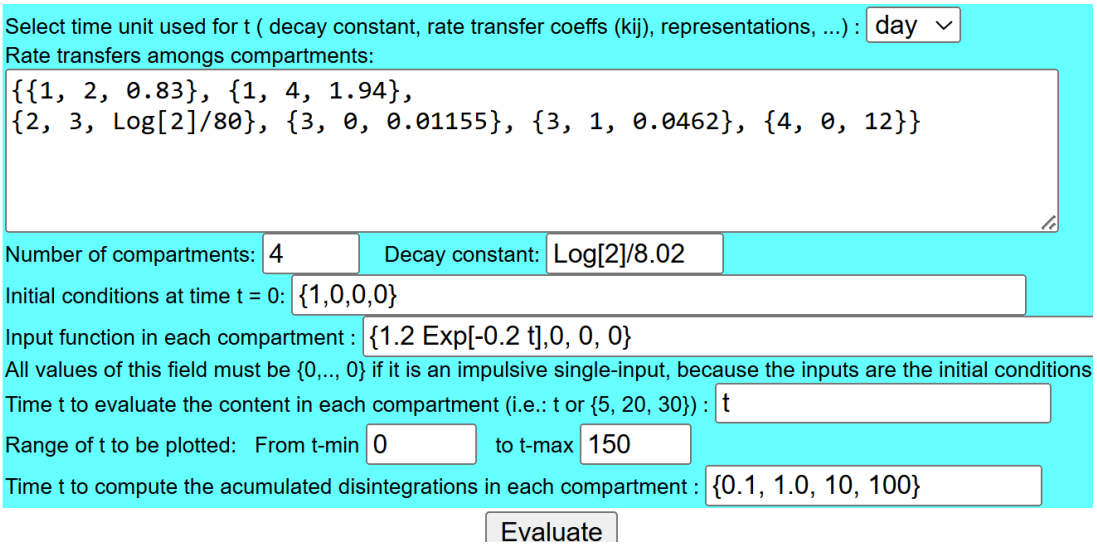


Figure 2.1. Access screen to *Compartmental Modeling*.

The input data is:

- *Compartmental Matrix*.- Compartmental matrix, in which we enter the transfer rates *kij* between the origin, i, and destination compartments, j, in format: {i, j, k_{ij}}.
- *Number of compartments*.- Number (n) of compartments in the system.
- *Decay constant*.- Decay constant, λ.
- *Initial conditions*: {$x_1(0)$, $x_2(0)$,..., $x_n(0)$}.
- *Input function*.- Input function in each compartment: {$b1(t)$, $b2(t)$,..., $bn(t)$}. If it is a case of point inputs, 0 is entered in all compartments, that is, {0, ..., 0}. Note that a *point* input $bi(0)$ is equivalent to an initial condition $bi(0) = xj(0)$}.
- *Time to evaluate*.- Values for which you want the calculations to be made. You can choose to leave the solution depending on the time *t*.
- *Range to be plotted*.- Time range for graphical representation.
- *Time to compute the accumulated disintegrations (TIC)*. -The days for which we want the accumulated Us disintegrations in each compartment to be shown are specified.

Example.- I-131 model

Consider the biokinetic model of I-131 given in the publication ICRP 78 [ICRP 1997] (it has been replaced by that of ICRP 137 [ICRP 2017], we use it here for teaching purposes because of its simplicity) and shown in Figure 2.2, where compartment 1 is the blood, compartment 2 is the thyroid, compartment 3 is the rest of the body, and compartment 4 is the urinary bladder. We denote with "0" the output outside the system. The BIOKMOD input is shown Figure 2.1.

The *transfer rates* values or *clearance* given in ICRP 78, at day^{-1}, k_{10} = 1.9404, k_{12} = 0.8316, k23 = Log[2]/80, k_{30} = 0.01155, k_{31} = 0.0462, k30 = 0.01155 and k40 = 12.

The compartmental matrix is defined with the format: {{1, 2, 0.83}, {1, 4, 1.94}, {2, 3, log[2]/80}, {3, 0, 0.01155}, {3, 1, 0.0462}, {4, 0, 12}}

The decay constant used for I-131 is Log[2]/8.02 days^{-1}.

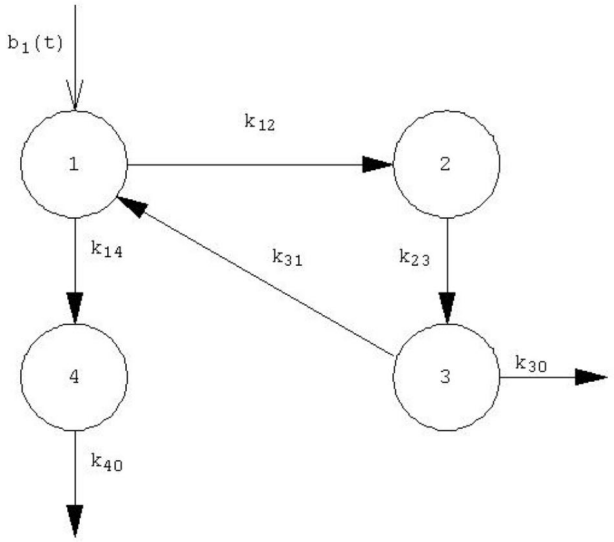


Figure 2.2. Biokinetic model of iodine (ICRP 78)

A continuous input from the outside into compartment 1 given by the function b1 (t)= 1.2 Exp[-0.2 t] is assumed. Then the input function in BIOKMOD format is: {1.2 Exp[-0.2 t], 0, 0, 0}. Also, 1 Bq of I-131 at t= 0, in compartment 1 is assumed, this is equivalent to taking as an initial condition: 1, 0, 0, 0}.

In the Figure 2.3. The output given by the program is shown: the differential equations of the model, the analytical solution (retention in each compartment), the graphical representation for the chosen period and the total disintegrations in each compartment.

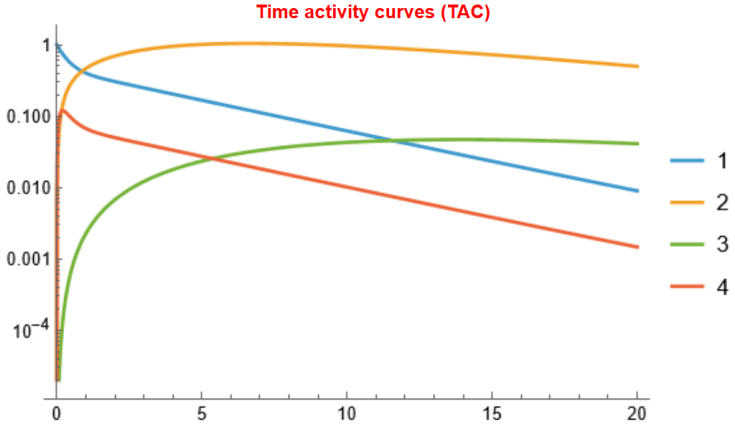
Differential equation

$$x_1'(t) = -2.85643\, x_1(t) + 0.0462\, x_3(t) + 1.2\, e^{-0.2\,t} + 0.$$
$$x_2'(t) = 0.83\, x_1(t) - 0.0950917\, x_2(t) + 0.$$
$$x_3'(t) = 0.00866434\, x_2(t) - 0.144177\, x_3(t) + 0.$$
$$x_4'(t) = 1.94\, x_1(t) - 12.0864\, x_4(t) + 0.$$
$$x_1(0) = 1$$
$$x_2(0) = 0$$
$$x_3(0) = 0$$
$$x_4(0) = 0$$

Solution

$$x_1(t) \to 0.548276\, e^{-2.85638\,t} + 0.461593\, e^{-0.2\,t} - 0.019723\, e^{-0.146559\,t} + 0.00985456\, e^{-0.0927539\,t}$$
$$x_2(t) \to -0.164803\, e^{-2.85638\,t} - 3.65197\, e^{-0.2\,t} + 0.318064\, e^{-0.146559\,t} + 3.49871\, e^{-0.0927539\,t}$$
$$x_3(t) \to 0.000526475\, e^{-2.85638\,t} + 0.566829\, e^{-0.2\,t} - 1.15685\, e^{-0.146559\,t} + 0.589497\, e^{-0.0927539\,t}$$
$$x_4(t) \to -0.188965\, e^{-12.0864\,t} + 0.115238\, e^{-2.85638\,t} + 0.0753372\, e^{-0.2\,t} - 0.0032046\, e^{-0.146559\,t} + 0.00159399\, e^{-0.0927539\,t}$$

Time activity curves (TAC)



Acumulated disintegrations in each compartment, in Bq s

	0.1*day	1.*day	10*day
1	7984.75	51005.7	185612.
2	338.942	23576.6	745083.
3	0.0988922	71.5684	19181.7
4	549.294	7708.09	29720.6

Figure 2.3. Output of the program corresponding to the case entered in the

3 ICRP/OIR CONCEPTUAL MODEL

The modelling of radioactive substances in the body is described in different ICRP publications and in all cases compartment modelling is used.

In the case of BIOKMOD, some of the OIR biokinetic models described in the documents ICRP134 [ICRP 2016], ICRP137 [ICRP 2017], ICRP141 [ICRP 2019] and ICRP 151 [ICRP 2022] have been incorporated. For the routes of incorporation involving the respiratory tract (HRTM), the one described in the publication ICRP130 [ICRP 2015] is used. The model of the food system (HATM) is the one described in ICRP100 [ICRP 2006], although each element has specific characteristics described in the corresponding ICRP documents. Systemic compartments are usually element-specific, although sometimes there are sets of elements that are modeled using the same systemic compartments.

The general conceptual model used is shown in Figure 3.1.

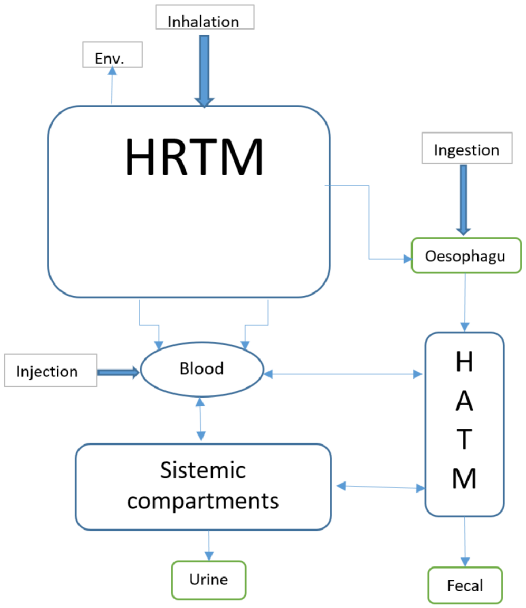


Figure 3.1. Modelling of the body in compartmentalised subsystems.

The OIR models for inhalation ingestions use the model of the respiratory tract shown in the diagram in Figure 3.2. The model contemplates a stage of dissolution and subsequent absorption into blood, which can occur at different speeds.

The HRTM is divided into two regions: the extrathoracic and the thoracic. The process followed by inhaled aerosols is as follows: After inhalation, a fraction of the contaminant is deposited in the regions of the respiratory tract from where it can reach the blood and the rest of the body. The amount of material deposited in each region depends mainly on the particle size of the inhaled material, which is represented by the Medium Aerodynamic Diameter of Activity (AMAD). Two mechanisms are responsible for the removal of deposited particles: the transport of material to other regions and absorption into the blood. Particle transport rates are considered to be the same for all materials and regardless of age and sex. Absorption into the blood depends on the physical and chemical form of the deposited material and occurs in all compartments except the anterior

nose, ET1. The absorption process has been mathematically represented by two subsystems: one for the fraction fr that dissolves rapidly (at a rate sr) and another for the remaining part that dissolves slowly (at a *rate ss*), *sr* and *ss* represent the rate of transfer of each compartment from the thoracic region to the blood. Three basic types of metabolism are considered (Fast (F), Medium (M) and Slow (S)). In addition, in some cases, intermediate metabolisms associated with certain chemical forms of some elements are added.

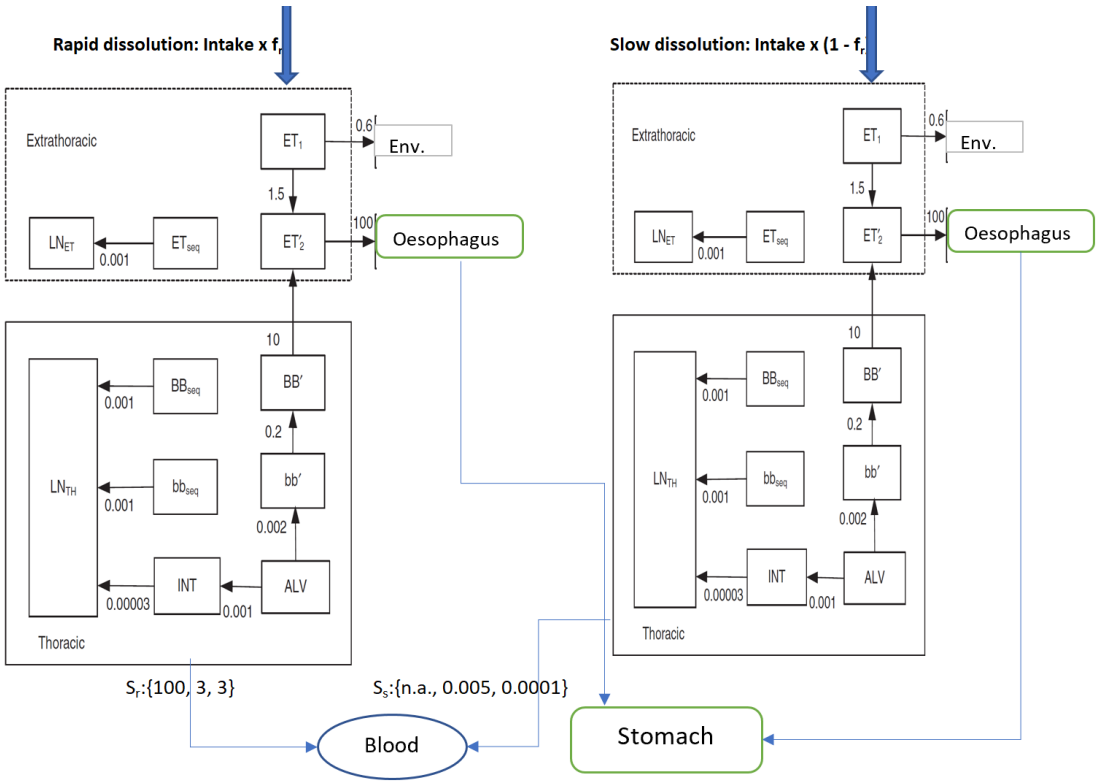


Figure 3.2. HRTM respiratory tract model. The aerosols, when inhaled, are deposited in different fractions, according to their AMAD, in the compartments: {ALV, bb', bbseq, BB', BBseq, ET2', ETseq, ET1}.

The general model for absorption factors {f_r, Sr, S_s) is shown in Figure 3.3. If f_b=0 does not apply the *Bound Material* compartment, as is the case with the elements Co, Cs, I, U, F. In some cases (such as lanthanides), fb>0 and then the compartment for the bound fraction (*bound material*) and the factor Sb are taken into account.

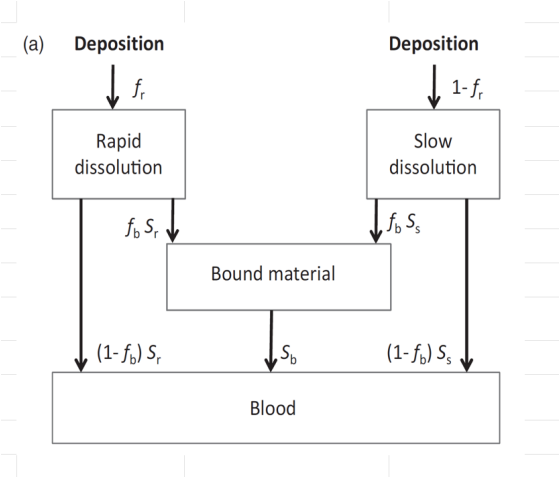


Figure 3.3. General diagram of transfer to the blood.

4 SOLVING ICRP/OIR MODELS

In the initial toolbar, by clicking on the ***OIR models*** tab, we can choose between several elements on which the application will provide us with different types of information depending on the type of output we choose.

Lanthanides includes all lanthanides listed in ICRP 141 made up of five subgroups: Lutetium: {Lu, Tb, Dy, Ho, Er, Tm, Yb}; Europium:{Eu}; Gadolinium: {Gd}; Lanthanum: {La, Ce, Pr}; Neodymium:{Nd, Pm, Sm} [All lanthanides have the same biokinetic pattern, and elements belonging to the same subgroup have the same absorption parameters]

The first step is to choose the item. Clicking on it will display the corresponding screen in which we can enter the input data (Figure 4.1).

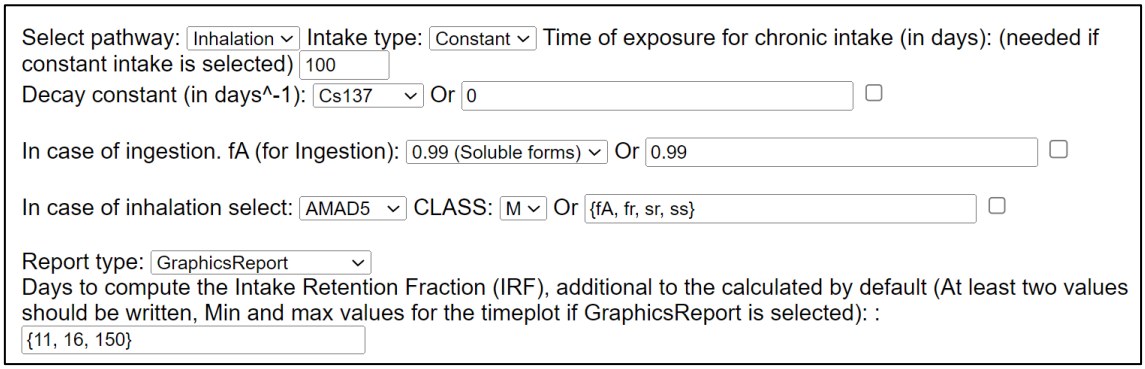


Figure 4.1. Data entry for the chosen isotope. The example shows the case of incorporation of Cs-137 by inhalation, but it is similar for other elements and isotopes except for F-18.

The input data:

- *Select Pathway*.- Allows you to choose the type of incorporation route (usually): Inhalation, Ingestion, Injection (in the case of F-18 only the injection option is offered).
- *Intake type*.- Allows you to choose between *Acute* or *Constant* incorporation. If Acute is chosen , the program considers a single incorporation at t=0 of 1 Bq, if Constant is chosen, a chronic incorporation of 1 Bq/d is assumed.
- *Time of exposure for chronic intake*.- Applies if constant *has been chosen* as *Intake type*. The number of days during which the individual has been exposed to a chronic incorporation of 1 Bq/day is entered.
- *Decay constant*.- Decay constant ($days^{-1}$). You can choose from the drop-down menu or enter it manually in the box. It also allows simple calculations, for example, if for Cs-137 the half-life is 30.167 years, the decay constant can be written as: Log[2]/(30.167*365.242)), (Log is natural logarithm and the argument is bracketed). In addition, it is necessary to check the validation box to indicate that a value has been entered externally and the default value is not used, if any.
- *fA* (for ingestion).- It is the absorption factor from the alimentary tract and in this option, it only applies in case of ingestion (to introduce the fA for cases of inhalation see CLASS

below). If *Select Pathway* is chosen Ingestion, the default values of *fA* will be displayed, but the user has the option to enter a different value. In the case of lanthanides, for ingestion, the value 5.0 *10^-4 is always used, which is the one recommended by ICRP 141.

- *AMAD* (inhalation cases only).- Refers to the aerodynamic size of inhaled particles as defined in ICRP 130. Select from the drop-down menu, by default it is recommended to choose AMAD5 (corresponding to a 5 μm AMAD). When choosing this value, the program internally uses the corresponding deposition factors (Figure 3.2).
- *CLASS* (only in cases of inhalation).- It refers to the type of metabolization that depends on the chemical species in which the aerosol is incorporated, it is chosen from a menu among the types of metabolism associated with the chosen element. Normally the forms F, M, S and others that depend on the element are considered. When you choose this option, the program enters the corresponding {fA, fr, sr, ss} values internally. The user has the option to enter these values manually.
- *Report type.*- This is the type of output you want to get: *BiossayReport, GraphicsReport, CompartmentContent, ResponseFunction* and TIA (Accumulated *Disintegrations).* In the case of choosing *BiossayReport* for a one-off incorporation, it will provide us with a table similar to the one that can be obtained from the OIR_Data_Viewer software (Electronic Annex - Publication 151) although with more decimal places. The program allows us to obtain other types of results that OIR_Data_Viewer does not provide, in particular we can obtain analytical expressions that can be used in different types of studies.
- *BioassayReport* offers whole body (WB) retention fraction (IRF) results and fecal and urinary 24-hour excretion (Fec24h and Urine24h). Depending on the element and route of incorporation chosen, other organs or regions may also be included (e.g., in the case of U, pulmonary retention is included, and for iodine, retention in the thyroid). The output will show the IRFs for the most frequently used days, but the user can add more days by completing the entry that follows. For example, if {11, 16, 150} is entered, in addition to the default values, the IRFs for days 11, 16, and 150 will be displayed.
- *GraphicsReport* graphically shows the temporal evolution of the results of the bioassays. To choose the range to be represented, the user must fill in the same cell as in the *BioassayReport* option, in this case the minimum and maximum values entered will be chosen, the rest of the values, if any, are not used. For example: If {11, 16, 150} is entered, the graph for IRFs ranging from 11 to 150 will be displayed.
- *CompartmentContents* displays the retention in each compartment.
- *ResponseFunction* is the response function in analytic expression (although it shows all terms in practice, from day one, only 4 or 5 terms are affected)

Once you have chosen the type of report, you must press the ***Evaluate*** key to obtain the OUTPUT.

Figure 4.2 shows the output corresponding to the input in Figure 4.1 (Report type: *GraphicsReport*). Figure 4.3 shows the output corresponding to the input Figure 4.1 by choosing *BioassayReport* as Report type. In this case, the output is a table that can be copied into a spreadsheet and operated with (in the case that the output includes values expressed exponentially in the spreadsheet, the format must be modified (e.g.,10^{-8} →E-08)].

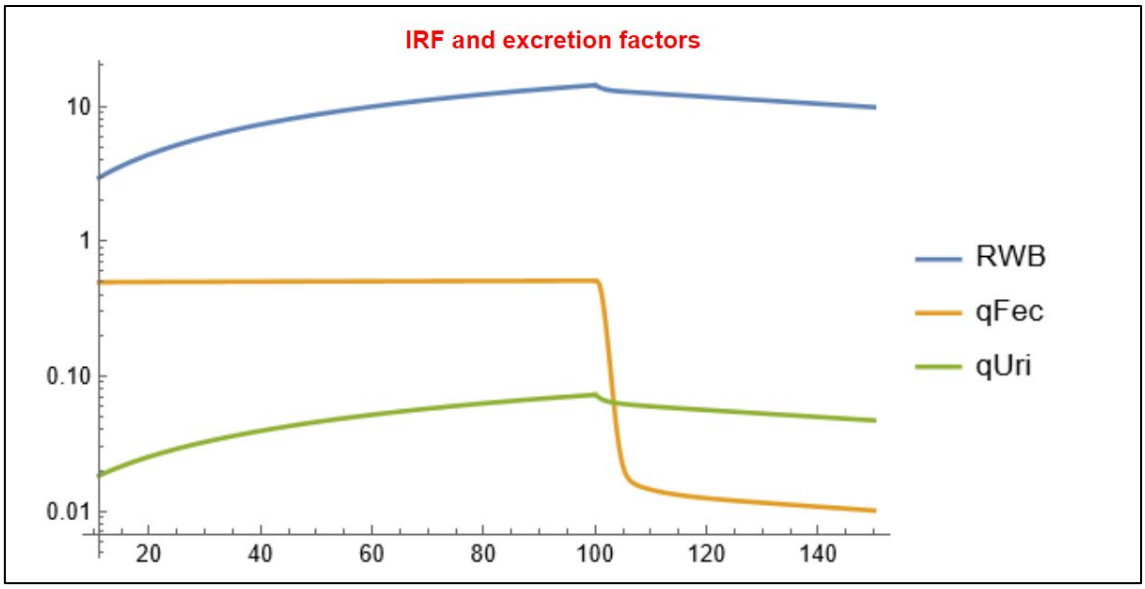


Figure 4.2. GraphicsReport output for the data entry in Figure 4.1

IRF and excretion factors

days	Wb	Fec24h	Urine24h
1	0.718752	0.07282	0.00505568
2	1.21978	0.286768	0.00813628
3	1.52699	0.421771	0.0100462
4	1.74285	0.47187	0.0114868
5	1.92773	0.486659	0.0126923
6	2.10301	0.490847	0.0137618
7	2.27471	0.492308	0.0147456
8	2.44439	0.493085	0.0156723
9	2.61249	0.493657	0.0165591
10	2.77919	0.494135	0.0174172
11	2.94457	0.494552	0.0182536
14	3.43354	0.495558	0.0206732
15	3.59429	0.495836	0.0214578
16	3.75398	0.496093	0.0222338
20	4.38262	0.496981	0.025267
30	5.88847	0.498745	0.0324743
40	7.30709	0.500282	0.0392484
45	7.98549	0.501006	0.0424886
50	8.64413	0.501705	0.0456355
60	9.90441	0.503037	0.0516599
70	11.0924	0.504283	0.057342
80	12.2123	0.505449	0.0627002
90	13.268	0.506541	0.0677524
100	14.2634	0.507564	0.0725153
120	11.7043	0.0124374	0.0559689
150	9.807	0.0100734	0.046884
180	8.22412	0.00826783	0.0392515

Figure 4.3. Output (partial) corresponding to Fig. 4.1, choosing *Report type: BioassayReport.*

A special case is the F-18 which has a specific input and output, especially aimed at medical applications. The model described in the [*EURADOS 2021]* report, and in ICRP 151 [1CRP 2022] is applied.

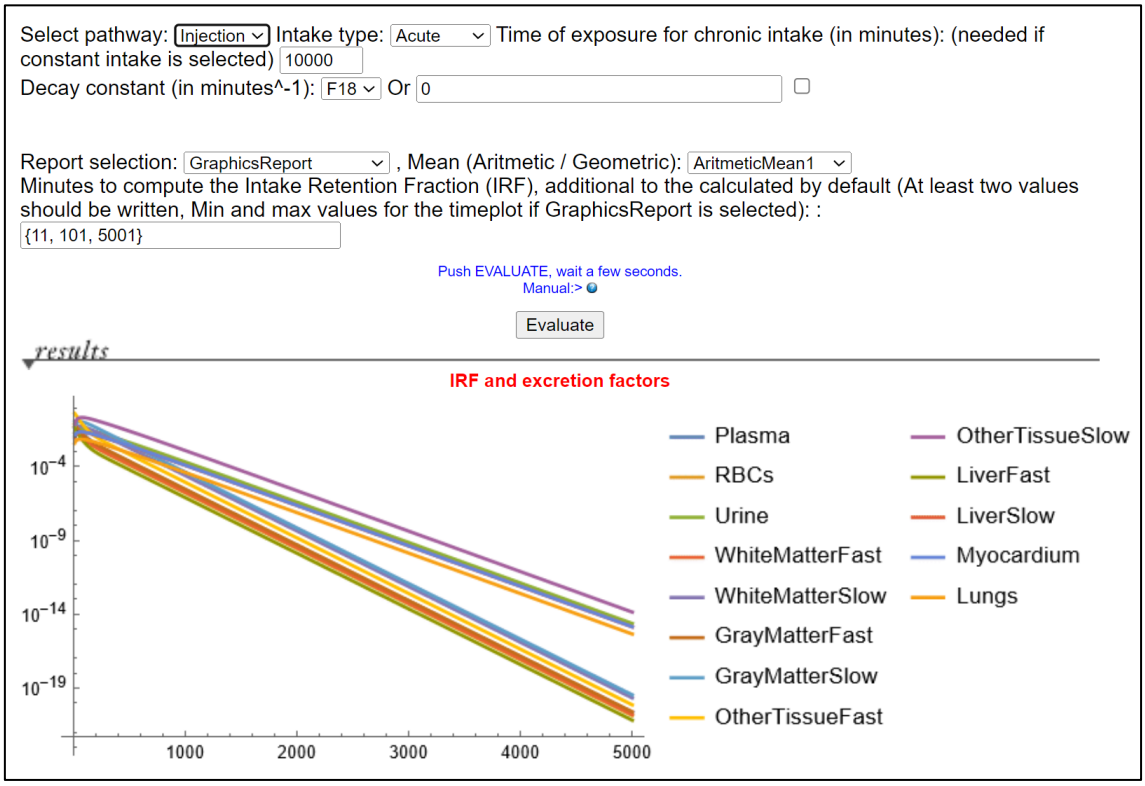
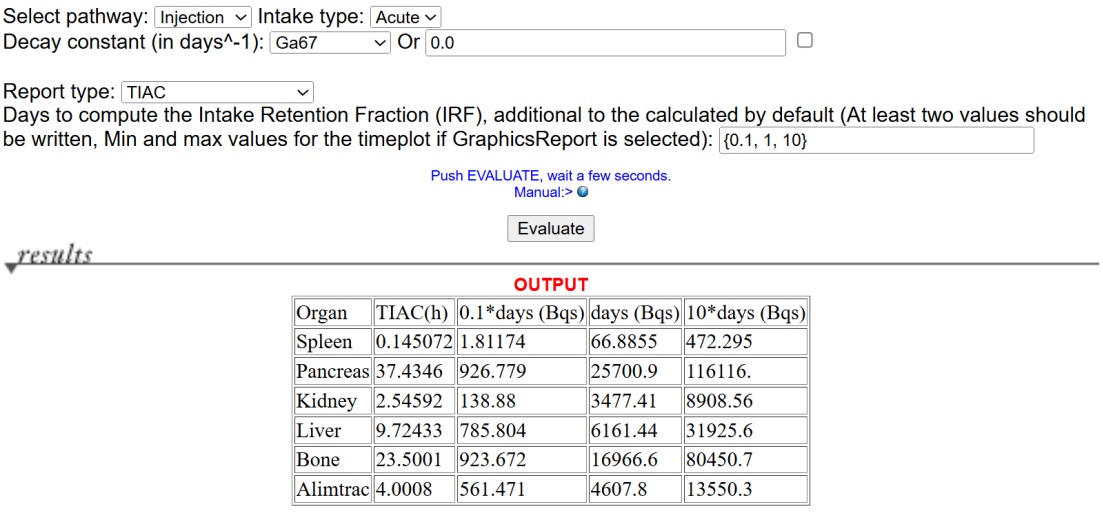


Figure 4.4. Example of F-18



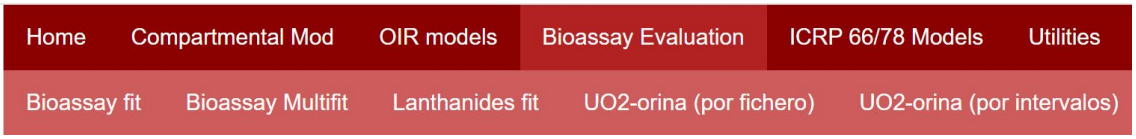
Organ	TIAC(h)	0.1*days (Bqs)	days (Bqs)	10*days (Bqs)
Spleen	0.145072	1.81174	66.8855	472.295
Pancreas	37.4346	926.779	25700.9	116116.
Kidney	2.54592	138.88	3477.41	8908.56
Liver	9.72433	785.804	6161.44	31925.6
Bone	23.5001	923.672	16966.6	80450.7
Alimtrac	4.0008	561.471	4607.8	13550.3

Figure 4.5. Example of input and output for Ga 67. The output shows the TIAC and the accumulated disintegration or TIA for 0.1, 1 and 10 days after one single intake of Bq at t= 0, The table can be copy and paste in other programs.

5. EVALUATION OF BIOASSAYS

A typical internal dosimetry problem is to estimate the intake, and the corresponding committed dose, by a person exposed to radioactive substances from the results of bioassay measurements (urinary excretion, whole body, ...). BIOKMOD uses two adjustment methods: a) the maximum likelihood method or ML-Method according to the procedure described in [EURADOS 2013] and b) the least squares method which consists of obtaining the adjustment given by the smallest Chi-Square.

To perform these calculations on the toolbar, the ***Bioassay Evaluation tab*** gives access to several options for evaluating bioassays.



5.1 BIOASSAY TUNING AND LANTHANIDE TUNING

Bioassay fit and **Lanthanides fit** are applied when only one type of bioassay is available. Bioassay fit applies to the isotopes of Cs, Co, I and U. **Lanthanides fit** applies to the lanthanide elements formed by Lutetium subgroups: {Lu, Tb, Dy, Ho, Er, Tm, Yb}; Europium:{Eu}; Gadolinium: {Gd}; Lanthanum: {La, Ce, Pr}; Neodymium:{nd, pm, sm}

Input data

Selecting ***Bioassay fit*** (**Lanthanides fit** is similar) menu displays the data entry screen as shown in Figure 5.1.

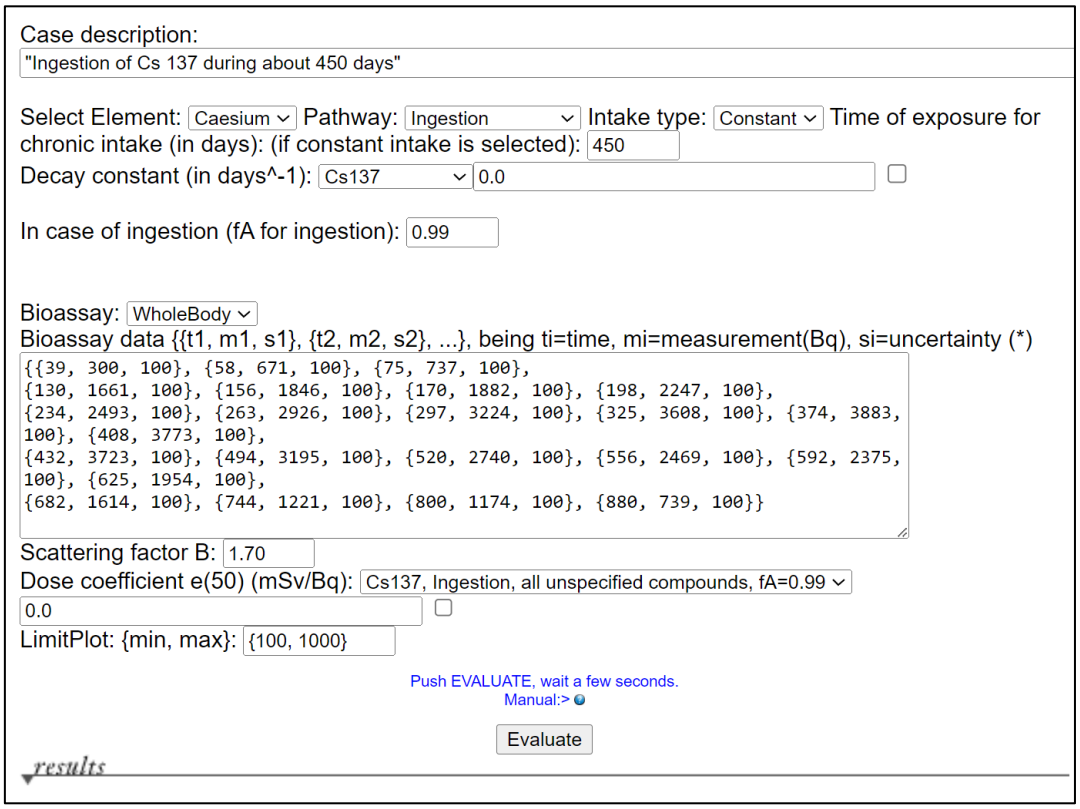


Figure 5.1. Bioassay Fit *data entry screen*. Corresponding to a case of contamination by ingestion of Cs-137 with whole-body measurements in a Body Radioactivity Counter

The user will specify:

- *Element*.- Element to which the bioassay corresponds (the isotope will be specified later).
- *Route*.- Route of incorporation: *Injection, Ingestion* or *Inhalation*.
- *Intake type*.- Type of incorporation: Punctual (*Acute*) or chronic (*Constant*). If Constant is chosen, you must specify the number of days of constant onboarding.
- *Decay Constant*.- Several isotopes associated with the chosen element are deployed, the program will use the decay constant of the chosen isotope. If the isotope we want is not available, we will manually enter the decay constant, at $^{d-1}$.
- AMAD and CLASS.- Select the desired type. This option only applies if the route of incorporation is inhalation.
- *fA*.- Enter the applicable value (only if the incorporation is by ingestion).
- *Bioassay*.- Select the type of bioassay for which we have measurements.
  - *Bioassa data*.- We have a window in which we will enter the measurements: {{t1, m1, s1}, {t2, m2, s2}, ...} where: t: is the time elapsed in days from the time of incorporation (if it is acute exposure) or from the beginning of it (if it is constant); m is the result of the measurement, in Bq if it is a retention measurement by means of a Body Radioactivity Counter, and Bq/d if it is excretion.; s: uncertainty of the measurement (normally calculated with 1 sigma, if 2 s are used in that case the result will also be expressed with 2 s)
- *Scattering factor* B (SFB).- Scattering factor B (typically the geometric standard deviation). If this is already incorporated in s, write 1 and it will not be taken into account.

- *Dose coefficient* e(50) (mSv/Bq).- Coefficient of Effective Dose in mSv/Bq. The program gives us the option to choose between several, if the one we want is not available, we will enter it manually.

- *LimitPlot*: {min, max}: Minimum and maximum values, in days, in which we want to show the curve that the program will obtain from the information entered. The output will show the theoretical adjustment function obtained and the determinations made {{t1, m1, s1}, ...}. The program will use all the values entered and not just those of the represented range.

The values for *Decay Constant*, fA and e(50) can be obtained from the ICRP 2022 Electronic Annex.

The values of fA, fr, sr, and sr that are used are shown in Table 5.1.

Table 5.1. Values of the parameters f_A, f_r, sr and sr used in BIOKMOD by default

	ago	Fr	MR	Ff
CesioF	0.99	1	100	n.a
CesioM	0.2	0.2	3	0.005
CesioS	0.01	0.01	3	0.0001
Cobalt	0.1	1	1	n.a
Cobalt	0.02	0.2	1	0.005
Cobalt	0.001	0.01	1	0.0001
IodineF	0.99	1	100	N.A.
IodoM	0.2	0.2	3	0.005
Iodine	0.01	0.01	3	0.0001
UraniumF	0.02	1	10	n.a
UraniumM	0.004	0.2	3	0.005
Uranium	0.0002	0.01	3	0.0001
LaSoluble (*)	2.5E-4	0.5	1	0.0015
LaDioxise (*)	5E-7	0.001	1	0.001
LaTypeF(*)	5E-4	1	1	1E-8
LaTypeM(*)	1E-4	0.2	1	0.005
LaTypeS(*)	5E-6	0.01	1	1E-4

(*) Applies to all lanthanides.

Example 1.- Ingestion of Cs-137 and whole-body measurements

The data for this example have been obtained from EURADOS 2000.

A person who has been exposed to Cs-137 for 450 days and has had Whole Body measurements taken at the following values:

{d, m_i, u_i}, with d days from the start of the exposure, my measurement in Bq, associated uncertainty u_i: {{39, 300, 100}, {58, 671, 100}, {75, 737, 100}, {130, 1661, 100}, {156, 1846, 100}, {170, 1882, 100}, {198, 2247, 100}, {234, 2493, 100}, {263, 2926, 100}, {297, 3224, 100}, {325, 3608, 100}, {374, 3883, 100}, {408, 3773, 100}, {432, 3723, 100}, {494, 3195, 100}, {520, 2740, 100}, {556, 2469, 100}, {592, 2375, 100}, {625, 1954, 100}, {682, 1614, 100}, {744, 1221, 100}, {800, 1174, 100}, {880, 739, 100}}

This entry corresponds to the data entered in Figure 5.1. The result are shown in Figure 5.2. The output with the results is shown in Figure 5.6. It is observed that the worker incorporated 122 kBq (according to the least squares method) and an effective dose of 2.07 mSv or 120 kBq (according to the ML method) and an effective dose of 2.03 mSv.

Dosimetry report

Input data

Name -> Pepe Garcia Sanchez
Description -> Ingestion of Cs 137 during about 500 days taken with a whole body control
Caesium
Decay constant -> 0.000063133
Pathway -> Ingestion
Type of intake -> Constant
fA -> 0.99
Bioassay -> WholeBody
Scattering B-factor -> 1.7
Dose coefficient e(50) (mSv/Bq) -> 0.000014

Estimated intake and E(50) doses by fitting

I (Bq or Bq/day) Sd-method -> 29.7596	sd -> 0.264843	Chi2 -> 33.6179	(I(Bq or Bq/day) using ML -> 35.1721	Chi2 ML -> 31.9761
Using I(Sd-method):>	Total Intake (Bq):>	13391.8*Bq	E(50):>	0.187485*mSv
Using I (ML-method):>	Total Intake (Bq):>	15827.4*Bq	E(50):>	0.221584*mSv

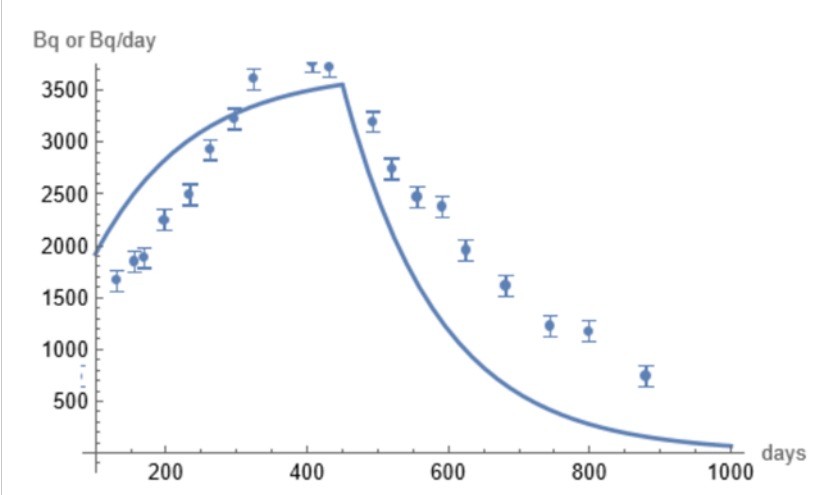


Figure 5.2. Result of the dosimetric report corresponding to the case of an incorporation by ingestion of Cs-137 in Figure 5.1.

Example 2.- Inhalation of uranium oxide aerosols and measurements of U in urine

Consider a worker who has been consistently exposed to aerosols of UO2 (type M/S) and AMAD 5 μm. It is assumed that during all that time he has been working in the same job and the average conditions of exposure can be considered approximately constant.

The following measurements have been made on 24-h urine samples that have been taken on weekdays (i.e. there have been no exposure-free times between exposure and sample collection) {d (day), U-234 (Bq), sd (Bq}):

{{10765, 1.48 10^-2, 1.29 10^-3}, {10989, 1.22 10^-2, 9.40 10^-4},{11211, 8.14 10^-3, 7.8 10^-4},{11423, 1.63 10^-2,1.24 10^-3}, {11709, 8.24 10^-3,7.60 10^-4},{11892, 1.21 10^-2,1.85 10^-3 }, {12065, 7.53 10^-3, 7.30 10^-4}}.

Consider for urine 24 h SFB = 1.7 and that the dose coefficient e(50) is 5.4*10^-3 Bq/mSv (corresponding to UO2 enriched to 4% wt). The worker has been exposed until day 12100 from the start of the job.

The data entry screen (**Bioassay fit**) will be completed as shown in Figure 5.3. The corresponding output can be seen in Figure 5.4.

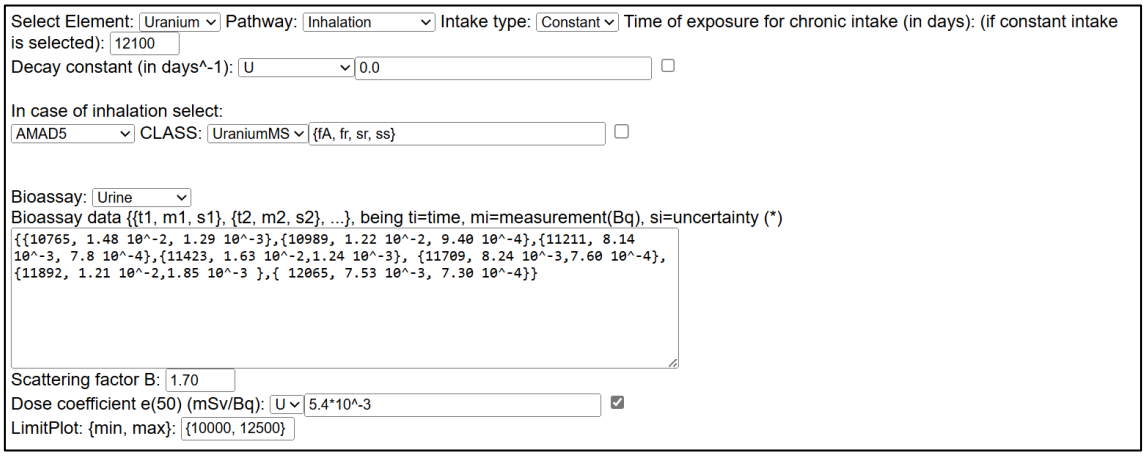


Figure 5.3. Input data for a case of U inhalation for estimation of incorporation from urine measurements ()

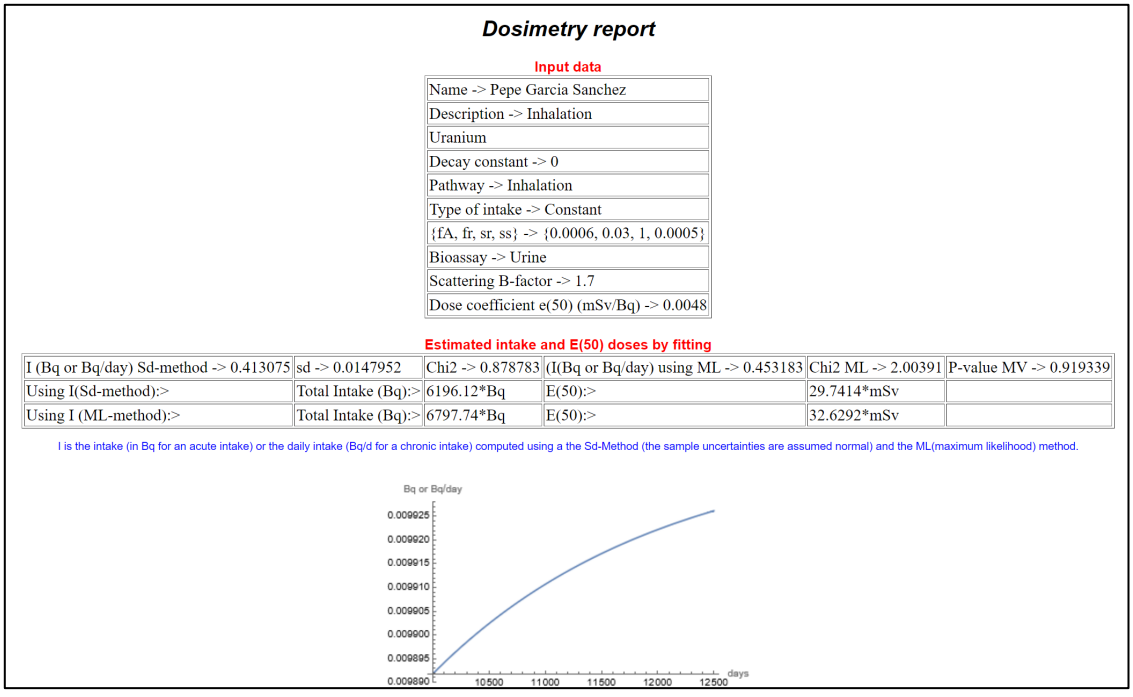


Figure 5.4. Result of the dosimetric report corresponding to the case of an incorporation by inhalation of U in Figure 5.3.

Example 3.- Accidental exposure of I-131

A worker who worked for 3 days with I-131 in the form of steam had the I-131 content measured in his thyroid according to the details shown in Table 5.2.

Table 5.2. Thyroid I-131 Activity Measurements Performed on a Worker

Week days (d)	Time after the first day of handling (d)	Thyroid activity of ^{131}I (Bq)	Comment
Tuesday	0		1st day of handling
Wednesday	1		2nd day of handling
Thursday	2		3rd day of handling
Friday	3		
Saturday	4		
Sunday	5		
Monday	6	2.1E+04	1st day of measurement
Tuesday	7	2.5E+04	2nd day of measurement
Wednesday	8	1.5E+04	3rd day of measurement

We are going to assume that the worker has been exposed to continuous incorporation for 3 days, days 7, 8 and 9 (we assume these moments because in the absence of other information we consider that the measure is taken at the end of days 6, 7 and 8). In all cases we will estimate that the uncertainty of the measure is 10^-3 Bq.

The results of the measurements in the previous table are written as follows:

{{7, 2.1*10^4, 10^3}, {8, 2.5*10^4, 10^3}, {9, 1.5*10^4, 10^3}}

The data entry (**Bioassay fit**) is shown in Figure 5.5. The output with the results is shown in Figure 5.6. It is observed that the worker incorporated 122 kBq (according to the least squares method) and an effective dose of 2.07 mSv or 120 kBq (according to the ML method) and an effective dose of 2.03 mSv.

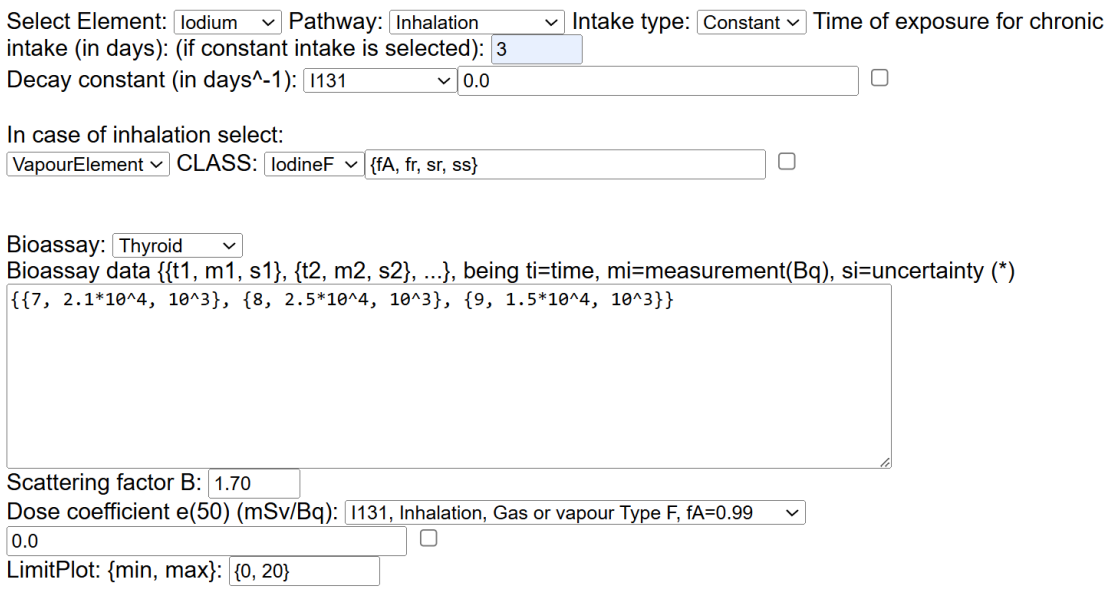


Figure 5.5. Input data for estimation of I-131 inhalation incorporation from thyroid measurements.

Dosimetry report

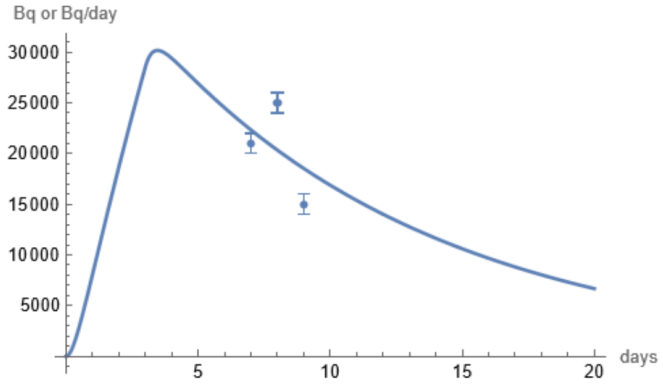
Input data

Name -> Pepe Garcia Sanchez
Description -> Iodine 131, inhalalation as vapour
Iodium
Decay constant -> 0.086371
Pathway -> Inhalation
Type of intake -> Constant
{fA, fr, sr, ss} -> {0.99, 1, 100, N.A}
Bioassay -> Thyroid
Scattering B-factor -> 1.7
Dose coefficient e(50) (mSv/Bq) -> 0.000017

Estimated intake and E(50) doses by fitting

I (Bq or Bq/day) Sd-method -> 40681.9	sd -> 1148.34	Chi2 -> 0.0923593	(I(Bq or Bq/day) using ML -> 39827.1	Chi2 ML -> 0.314845
Using I(Sd-method):>	Total Intake (Bq):>	122046.*Bq	E(50):>	2.07478*mSv
Using I (ML-method):>	Total Intake (Bq):>	119481.*Bq	E(50):>	2.03118*mSv

I is the intake (in Bq for an acute intake) or the daily intake (Bq/d for a chronic intake) computed using a the Sd-Method (the sample uncertainties are assumed normal) and the ML(maximum likelihood) method.



Observed	Predicted	Standard Error	Confidence Interval
21000.	22323.9	630.142	{19612.6, 25035.2}
25000.	20335.	574.	{17865.2, 22804.7}
15000.	18525.4	522.92	{16275.4, 20775.3}

Figure 5.6. Result of the dosimetric report corresponding to the case of an inhalation incorporation of I-131 in Figure 5.4.

Example 4.- Accidental puncture with Lu-177

A laboratory analyst accidentally suffered a finger prick with a syringe that had been in contact with a 2 ml vial of lutetium chloride with an activity of 162.5 GBq of Lu-177. Two measurements have been made with a full-body counter that have given the following results:

m1 = 563.0 ± 93.1 kBq (2σ) Lu-177 – 3 days after the incident

m2 = 359.0 ± 59.5 kBq (2σ) Lu-177 – 7 days after the incident

We chose the ***Lanthanides fit option.*** We enter the data as shown in Figure 5.7. The result can be seen in Figure 5.8. The analyst incorporated 963 kBq (both methods are almost the same) and an effective dose of 0.23 mSv.

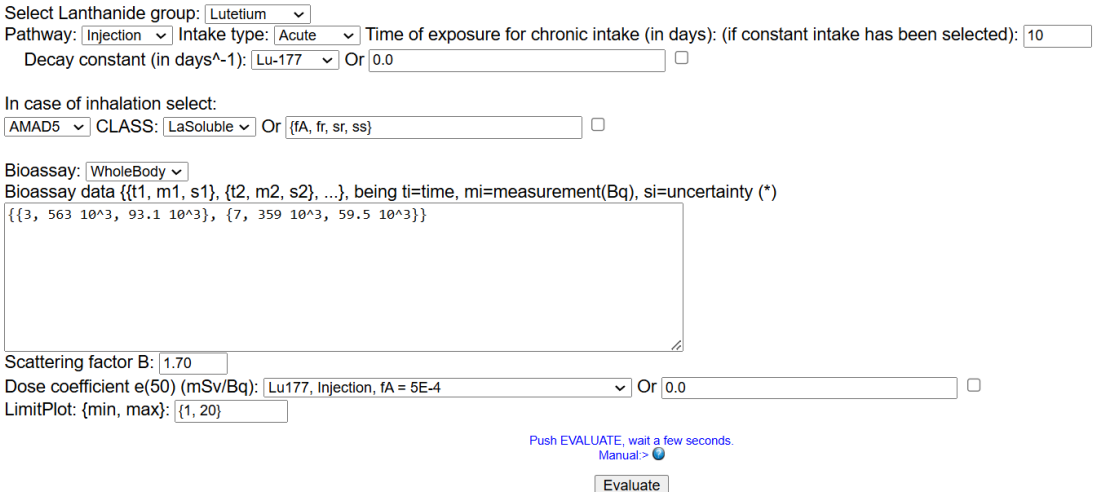


Figure 5.7. Data entry for a Lu-177 injection case. Note: For any of the lanthanides formed by Lu, Tb, Dy, Ho, Er, Tm and Yb we must choose: Select Element: Lutetium. It has been decided to program it this way because all these elements of this group have all the common parameters. If the program does not provide the decay constant or the dose coefficient (e(50)) for the desired isotope, enter it manually by checking the corresponding box

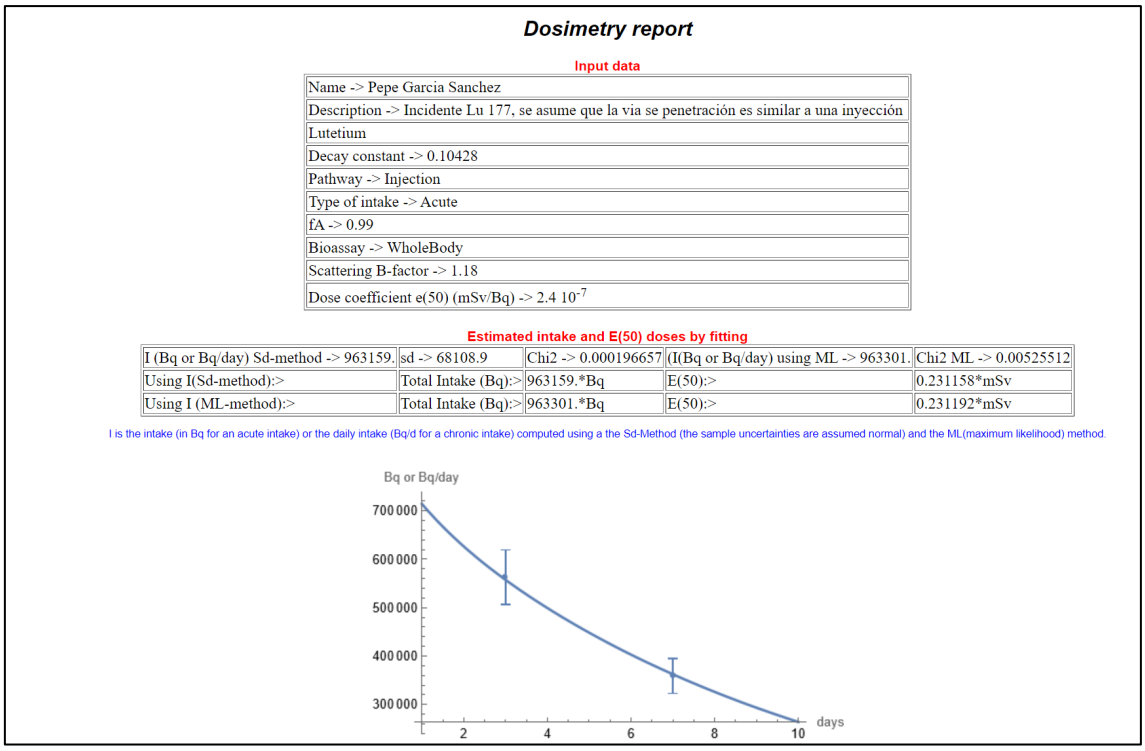


Figure 5.8. Dosimetric result of the Lu-177 injection case in Figure 5.7.

5.2. MULTIFIT BIOASSAY

If we have two types of bioassays and we want to estimate the incorporation from these bioassays, we choose from the menu: ***Bioassay Multifit.***

Example 5. Accidental incorporation of Co-60 aerosols

A worker who has been exposed to a single incorporation by inhalation of Co-60 in the form of oxide. Measurements shown in Table 5.3 have been taken.

Table 5.3. Whole-body and urine Co-60 activity measurements performed on a worker

Type of monitoring measurment	Isotope	Time after intake (d)	Type of measurement	Activity measurement (Bq)	Percentage uncertainty (± 2 SD)
SPECIAL	Co-60	1	Whole body	18500	±4%
SPECIAL	Co-60	10	Whole body	1875	±5%
SPECIAL	Co-60	30	Whole body	1470	±5%
SPECIAL	Co-60	1	Urine (spot)	11.2	±10%
SPECIAL	Co-60	10	Urine (true 24 h)	0.3	±15%

Note two types of bioassays are performed. The data for entering the program corresponds to Fig. 5.9. Figure 5.10 shows the output with the corresponding results.

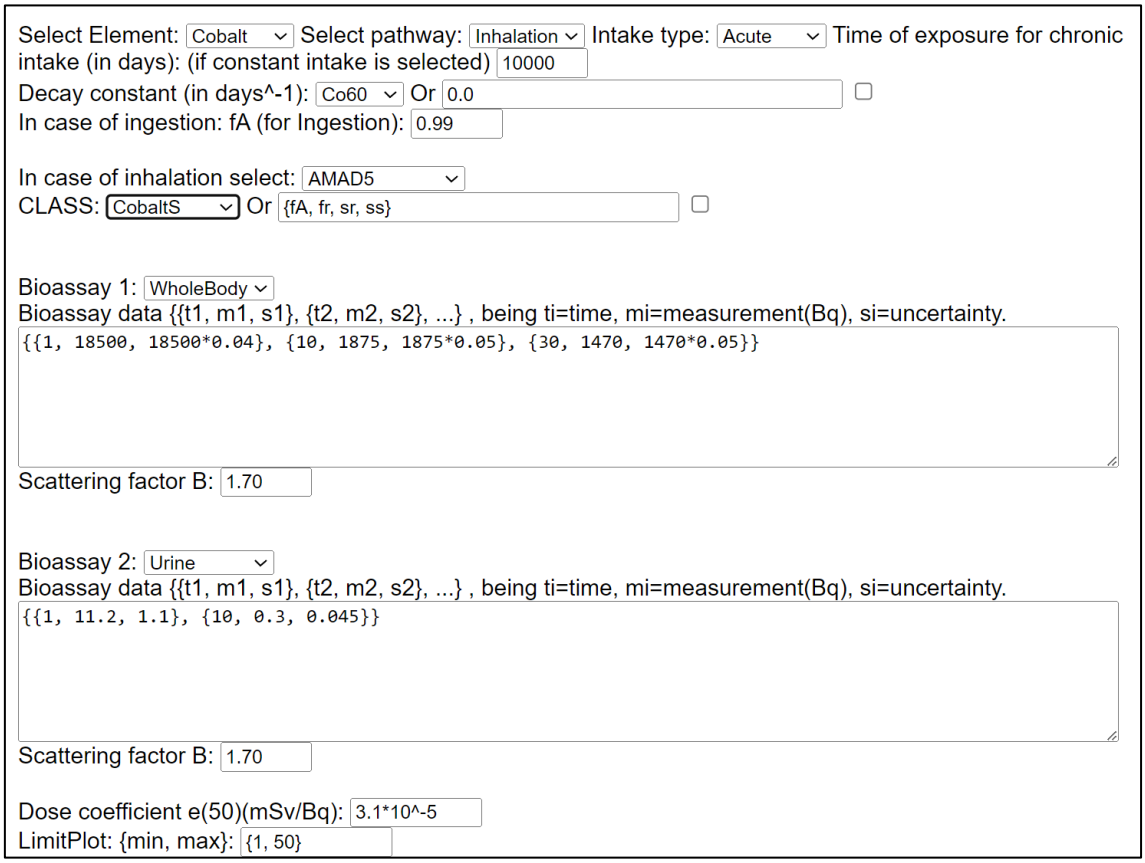


Figure 5.9. Data entry, incorporation estimation with 2 bioassay measures (*Bioassay Multifit*).

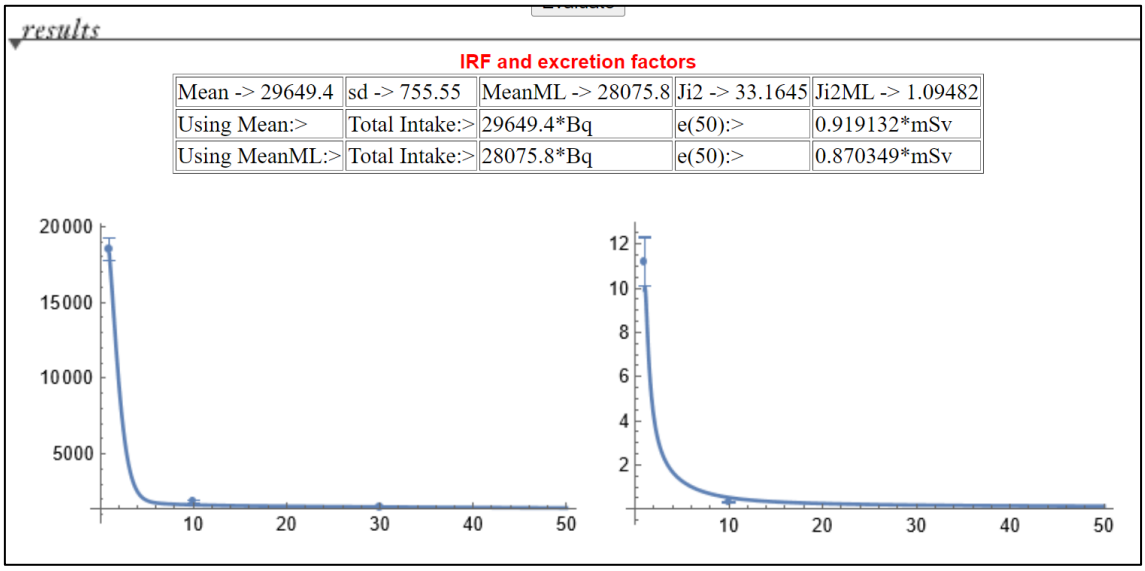


Figure 5.10. Dosimetric result for the case of Co-60 inhalation in Figure 5.9.

The worker has incorporated 29.7 kBq (least squares method) resulting in an effective dose of 0.92 mSv or 28 kBq (ML method) with an effective dose of 0.87 mSv.

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