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Program for Determination of Coefficients of the Standard 5098

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Abstract

All building products made of materials extracted from the Earth crust (sand, stones, cement, bricks etc.) contain natural radioactive elements that emit radiation. The main radioisotopes in the building materials are potassium-40 (^{40}K), radium-226 (^{226}Ra) and its products that are part of the uranium-238 chain and therefore the effect of all of the radioisotopes in this chain must be considered, and thorium-232 (^{232}Th) that also decays into a chain of radioisotopes. Typical activity concentrations of these radioinuclides in building materials are within a few to hundreds of Becquerel per kilogram (Bq/kg). The radiation dose from these radionuclides consists of the external (gamma) radiation and internal (inhalation) radiation (produced by radon gas and its decay products which results from the decay of radium).

The program described in the current work is a development of the Block program published by Soreq Nuclear Research Center 5 years ago.

The program enables to calculate the annual radiation dose (based on occupancy time of 7000 hours/year inside the building), which is absorbed in a certain location in the room of given dimensions built of the materials with given density and radionuclides content. In addition, the program enables the calculations of maximum activity concentrations of the radionuclides in building products, assuming a given annual radiation dose obtained in the center of the room.

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Contents

Introduction

All building products made of materials extracted from the Earth crust (sand, stones, cement, bricks etc.) contain natural radioactive elements that emit radiation. The main radioisotopes in the building materials are: potassium-40 (^{40}K), radium-226 (^{226}Ra) and its decay products that are part of the uranium- 238 chain and therefore the effect of all of the radioisotopes in this chain must be considered, and thorium-232 (^{232}Th) that also decays into a chain of radioisotopes. Typical activity concentrations of these radionuclides in building materials are within a few to hundreds of Becquerel per kilogram (Bq/kg). The radiation dose from these radionuclides consists of the external (gamma) radiation and internal (inhalation) radiation (produced by radon gas and its decay products, which are part of the decay of radium).

The program described in the current work is a development of the Block program published by Soreq Nuclear Research Center a few years ago, which is used as a basis for the current study[1] (leading to its name Block2.0).

Block2.0 program divides the problem into a sum of very small sources, to the point that they can be considered as a point by dividing the entire wall into three dimensional boxes (voxels) of any desired size.

This program considers the absorption in that box and all those infront of it, including their angle of incidence, includes the buildup of the dose on its way in the absorber, and includes all of the known gamma lines above 20 keV whose abundance exceeds 1%.

The program enables to calculate the annual radiation dose (based on occupancy time of 7000 hours/year inside the building), which is absorbed in a certain location in the room of the given dimensions built of the materials with given density and radioanuclides content. In addition, the program enables calculations of maximum activity concentrations of the radioanuclides in building products, assuming a given annual radiation dose obtained in the center of the room [1].

1. Calculation of exposure rate and radiation dose at a certain distance from the wall

In order to calculate the rate of exposure that is received from radioisotopes in a certain wall, we divide the wall (three dimensionally) into a large number of small boxes, so that from the viewpoint of the detector, each box is a point source.

The general formula for calculating the rate of exposure from a shielded point source is:

(1.1)
$$X(\frac{R}{h}) = \frac{A \cdot \Gamma_\gamma}{D^2} \cdot B \cdot e^{-\mu d}$$

Each argument in formula (1.1) may be calculated in the following manner:

(1.2)
$$A = \frac{C \cdot \rho \cdot \Delta V}{3.7 \cdot 10^{10}}$$

A [Ci] – Activity

C [Bq/kg] – Concentration of the specific radioisotope in the box ρ [kg/m^3] – Density

3.7*10^{10} – Conversion factor from [Bq] to [Ci]

ΔV [m^3] – Box volume

(1.3) $$\Delta V = \Delta L \cdot \Delta b \cdot \Delta h$$

ΔV [m^3] – box volume

ΔL [m] – box length

Δb [m] – box width

Δh [m] – box height

(1.4) $$\Gamma_{\gamma j} = 0.52 \cdot f_j \cdot E_j$$

$\Gamma_{\gamma j}$[R.m^2/Ci.h] = Gamma constant. This value is calculated in advance, according to the equation above and is presented in Appendix 1 (formula taken from [2])

f_j – Probability of the gamma ray for each decay (fraction) – this value appears in study [1].

E_j[MeV] – The energy of the gamma photon – this value is presented in Appendix 1.

* f_j and E_j are taken from 7.

0.52 – Units conversion factor $\left[\frac{R \cdot m^2}{Ci \cdot h}\right]$

(1.5) $$\mu = \frac{\mu}{\rho} \cdot \rho = \mu_m \cdot \rho$$

μ [1/m] – linear attenuation factor

μ/ρ [m^2/kg] = μ_m - mass attenuation factor – this value appears in Appendix 1 and is taken from source [7].

ρ [kg/m^3] – density of the building product

(1.6) $$B(E, R)$$

B – Buildup factor – this constant depends on the photon energy and the number of average free paths that a certain photon passes until it comes out of the wall. Appendix 2 contains expanded tables of the Buildup Factor constant, which are based on Table 6.5.1 from source [7] and on study [3].

(1.7) $$R(mfp) = \mu \cdot d = \mu_m \cdot \rho \cdot d$$

R – The number of average free paths

μ – The attenuation factor, calculated by formula 1.5

d – Length of the path in the wall, calculated by formula 1.9

(1.8) $$D_i^2 = (l_d - l_s)^2 + (m_d - m_s)^2 + (n_d - n_s)^2$$

D_i [m^2] – the distance between the "point of interest" (the "detector") and the center of the box of origin.

(l_d,m_d,n_d) = P_d – This point indicates the "point of interest" relative to the coordinate system.

(l_s,m_s,n_s) = P_s – This point indicates the location of a point source in the center of a specific cube in a wall, relative to the coordinate system.

- A detailed explanation about how to calculate this distance appears in study [1].

(1.9) $$d = \frac{D_i \cdot l_s}{l_s + l_d}$$

d [m] – The distance between a point source at the center of a specific cube in a wall, and the point of exit from the wall.

- A detailed explanation about how to calculate this distance ais presented in Appendix 1.

After assigning all of the arguments that appear in formula (1.1), the following equation results:

Rate of exposure from a certain point source in a given wall:

(1.10) $$X(\frac{R}{h}) = \frac{C \cdot \rho \cdot \Delta V}{D_i^{\,2} \cdot 3.7 \cdot 10^{10}} \sum_{j=1}^{N} \Gamma_\gamma \cdot B \cdot e^{-\mu_m \cdot \rho \cdot d}$$

N – The number of emissions of gamma radiation out of the total radioisotopes in the entire chain.

- The arguments in the equation that vary as a function of j are: μ_m, and Γ_γ.

We wish to comment here that, in order to take into account the emanation of radon when calculating the gamma dose, it must be recognized that the emanation reduces the concentration of the radon daughters in the wall. Meaning, an equilibrium doesn't exist in the wall. Therefore the dose from the radium chain should be multiplied by (1-e), in which e is the emanation factor.

The rate of exposure that will be received from the entire wall will be:

(1.11)
$$X\left(\frac{R}{h}\right)=\sum_{i=1}^{M}\frac{C\cdot\rho\cdot\Delta V}{D_i^2\cdot 3.7\cdot 10^{10}}\sum_{j=1}^{N}\Gamma_\gamma\cdot B\cdot e^{-\mu_m\cdot\rho\cdot d}$$

M – The number of boxes that constitute the wall.

The rate of exposure that will be received from the entire wall with the opening correction factor will be:

(1.12)
$$X\left(\frac{R}{h}\right)=\left[\sum_{i=1}^{M}\frac{C\cdot\rho\cdot\Delta V}{D_i^2\cdot 3.7\cdot 10^{10}}\sum_{j=1}^{N}\Gamma_\gamma\cdot B\cdot e^{-\mu_m\cdot\rho\cdot d}\right]\cdot F_k$$

F_k – The opening correction factor. This factor is to be used when the wall is not “full” (window, door). This constant is a number between 0 and 1 and is calculated by the following formula:

(1.13)
$$F_k=1-\frac{S_g}{S_k}$$

S_g [m^2] – The area of the windows and doors in that wall

S_k [m^2] – The area of the wall

The annual external dose that will be received from the radioactive elements K-40, Th-232 and its daughters and Ra-226 and its daughters (assuming that Th-232 and Ra-226 are in equilibrium with their daughters), which are in the building materials, in a specific room will be:

(1.14)
$$D\left(\frac{mSv}{Y}\right)=\sum_{k=1}^{6}\left\{\left[\sum_{i=1}^{M}\frac{C_k\cdot\rho_k\cdot\Delta V}{D_i^2\cdot 3.7\cdot 10^{10}}\sum_{j=1}^{N}\Gamma_\gamma\cdot B\cdot e^{-\mu_m\cdot\rho\cdot d}\right]\cdot 4.263\cdot 10^4\cdot F_k\right\}$$

K=1,…,6: The six faces that the room is made of.

* The multiplication by the number 4.263 x 10^4 results from conversion of units:

$$\frac{R}{h}\cdot 0.87\frac{Rad}{R}\cdot 0.7\frac{rem}{Rad}\cdot 10\frac{mSv}{\mathrm{Re}\,m}\cdot 7000\frac{h}{y}=4.263\cdot 10^4\frac{mSv}{y}$$

- This number embodies the assumption that the person occupies the building for 7000 hours per year (see source [4]).
- The number 0.87 was taken from [5].

As we commented above, the concentration of the radium isotope should be multiplied by 1-e owing to the partial escape of radon from the wall.

<u>The annual internal dose that will be received from the radioactive element Ra-226 and its daughters (assuming an equilibrium), which is in the building materials, in a certain room will be:</u>

(1.15) $$D(Rn) = 0.017 \cdot C(Rn)$$

D(Rn) [mSv/y] – the contribution of radon to the annual effective radiation dose[4].

0.017 [(mSv/y)/(Bq/m^3)] – the dose factor. A number expressing the committed effective dose that will be received from breathing air with radon at a concentration of 1 Bq/m^3.

C(Rn) [Bq/m^3] – the contribution of the six faces in the room to the concentration of radon gas in the room.

(1.16) $$C(Rn) = \sum_{k=1}^{6} \frac{S_k}{V} \cdot e_m \cdot C_k(Ra) \cdot \lambda \cdot \rho_k \cdot \frac{b_k}{2} \cdot \frac{1}{vent}$$

e_m – emanation (as defined in SI 5098) – the fraction of the total radon that is generated inside a building product, which finds its way out of the product.

λ – The decay constant of radon $\left(\lambda = 7.6 \cdot 10^{-3} \frac{1}{h}\right)$

ρ_k [kg/m^3] – The density of a certain wall

b_k [m] – the thickness of a certain wall

C_k(Ra) [Bq/kg] – Ra concentration in a certain wall

vent [1/h] – The number of air exchanges in the building per hour.

Sk [m^2] – The area of a certain wall

V [m^3] – The volume of the room

- This equation stems from an equilibrium between the amount of radon that is being produced in the wall and diffuses into the room, and the quantity that leaks from the room due to the air exchange (as long as the room is not highly sealed and thus the loss rate due to radon decay is negligible compared to the removal due to air exchange). In addition it is assumed that half of the amount of radon that is emitted from the wall enters the room and half is emitted out of the room [6].

After assigning equation (1.16) in equation (1.15), and assigning the radon decay constant, we get:

(1.17) $$D(Rn) = \sum_{k=1}^{6} 6.46 \cdot 10^{-5} \cdot \frac{S_k}{V} \cdot e_m \cdot \rho_k \cdot b_k \cdot C_k(Ra) \cdot \frac{1}{vent}$$

2. Calculation of the maximum concentration of radioactive elements in a residential building

At the beginning, the Professional Advisory Committee on the control of radiation in Israel recommended that the maximum additional annual effective dose, that is received in a residential building from the building materials, as a result of both gamma radiation and radon, would not exceed 0.3 mSv/y. This value is in addition to the annual effective dose that is received from a reference product.

The annual effective radiation dose that is received in a typical room made of concrete (home shelter) is 1.1 mSv/y (calculated by the formulas above). It is composed of 0.25 mSv/y of gamma radiation and 0.85 mSv/y of radon radiation.

The standard room that has been recommended for standard-calculations is of an area of 3*3 m^2, 2.7 m height and general opening correction factor of 0.94.

Radon background dose value is a result of long term measurements performed by the Soreq Nuclear Research Center in home shelters located on top floors of buildings, showing the average radon concentration is approximately 50 Becquerel per m^3. Gamma dose value depends on the concentrations of the radioactive elements in the building materials and on the thickness of the walls, particularly. As for an example let us take a home shelter that is being used as a bedroom. As known, home shelter is built of massive concrete in all of the faces of its shell – the walls, ceiling and floor. We Assume concrete density of 2,400 kg per m^3, and the openings (window and door) are 6% of the shell area. Assuming the concentrations of radium, thorium and potassium in concrete are 30, 15 and 50 Becquerel per kg, respectively, and 0.2 m average thickness of the walls of the shell, The dose from gamma radiation (calculated with our developed tool described in this document), in the room equals 0.2 mSv/y. When the concentration of radium reaches 50 Becquerel per kg, or when the thickness of the walls equals 0.25 m, the gamma radiation dose increases to 0.25 mSv/y. As a basis for our calculations further on, we will assume an annual effective radiation dose of 1.1 mSv/y in a typical room made of concrete (home shelter), composed of 0.25 mSv/y gamma radiation and 0.85 mSv/y of radiation from radon. This dose will be used as a “reference dose”.

The values of the annual dose can be changed in the program according to the following equation:

(2.1) $$D_{total} = D_{ref} + D_b$$

D_{total} [mSv/y] – The annual effective radiation dose that is received in a residential building as a result of gamma radiation and radon combined.

D_{ref} [mSv/y] – The annual effective radiation dose that is received in a room built of the reference product.

D_b [mSv/y] – The maximum additionnal annual effective radiation dose from gamma radiation and radon combined, received from any building product.

The calculation of annual external dose received in a room (four walls, floor and ceiling), as a result of the radioisotopes Th-232, K-40 and Ra-226, will be performed by assigning a concentration of 1 Bq/kg in equation 1.14. In this way we get the argument $D_{ext}(1\frac{Bq}{kg})$

The maximum concentration of Th-232, K-40 or Ra-226 in building materials is:

(2.2) $$C_l\left(\frac{Bq}{kg}\right)=\frac{D_{total}}{D_{ext}\left(1\frac{Bq}{kg}\right)}$$

C_1 [Bq/kg] – The maximum concentration of radioisotope 1, in building materials.

The calculation of the annual internal dose that is received in a room (four walls, floor and ceiling), as a result of the radioisotope Rn-222, will be performed by assigning a concentration of 1 Bq/kg and by assigning an emanation factor e_m of 100% in equation 1.17. This yields the member $D_{in}\left(1\frac{Bq}{kg}\right)$.

The maximum concentration of Rn-222 in building materials is:

(2.3) $$C_l\left(\frac{Bq}{kg}\right)=\frac{D_{total}}{D_{in}\left(1\frac{Bq}{kg},100\%\right)}$$

3. General description of the Block2.0 program

Program Objectives

1. Finding the annual effective radiation dose (external + internal) that is received in any position in the room, according to the equations in chapter 1.
2. Finding the maximum concentration of the radioactive elements: Rn-222, K-40, Th-232

and Ra-226 in building materials according to the equations in chapter 2.

Structured data that is in the program's database

1. Tables summarizing data that are used of gamma-ray energies, attenuation factors (μ_m) and gamma constants (Γ_γ) are presented in Appendix 1 and are based on studies [7,8].
2. B.F factors tables are presented in Appendix 2. The tables appearing in this appendix, for gamma energy above 100 keV, are expansions of tables that were generated by ANSI/ANS 6.4.3. In the case of gamma energies below 100 keV we used source [3].

Input data

1. Room dimensions: length (y), width (x), height (z).
2. Number of divisions of the room faces (creating small boxes - voxels).
3. Location of the point of interest in the room.
4. Concentration (C_m) of radioisotope m in the wall (Bq/kg).
5. Number of air exchanges per hour.
6. The emanation factor (e) in percent, (comment: the definition of this term is taken from Israeli standardization, which is not the exact scientific definition of the term. "The part of the gas generated in the material that finds its way out of the wall").
7. F_k - Opening correction factor (a fraction that indicates which part of the wall is full, expressing the presence of openings).

   When choosing the first objective, each room face can get different opening correction factor. When choosing the second target, all six faces get the same opening correction factor.
8. D_{ref} – The annual effective radiation dose that will be used as a reference dose, above it the program will allow a constant addition (see below). Later in this work (Appendix 4) are shown examples for calculating this dose from dose rate calculations of several reference products in a typical room.
9. D_b – The maximum addition of annual effective radiation dose from gamma radiation and radon combined, that can be received from any building product, above the annual reference effective dose (mSv/y).

4. The stages of the program

Choosing the first objective

The program receives all of the data and starts to calculate the radiation dose that is received from a single wall (the "southern" wall). For this purpose, the program divides the wall into a large number of boxes, as defined by the user, and according to the equations in Chapter 1 it calculates the radiation dose that is received from the three radioisotopes and their daughters. The result is saved in the southern wall register r.south. Thereafter, the program repeats these stages for the rest of the walls + floor + ceiling, and at the end of each wall, the radiation dose is saved in the appropriate register. The final output of the program is a combination of the four walls registers + the floor register + the ceiling register.

In this objective, it is possible to calculate the radiation dose of a room with walls and a floor that are identical in their properties (density, thickness, radionuclides concentrations), or alternatively to do it for a single wall with specific properties.

Selection of the second objective

The program works as in the first objective, when the differences are:

A. The user cannot set the concentration of the radioisotopes, but the program automatically assigns a concentration of 1 Bq/kg for the three radioisotopes and their daughters.

B. The radiation doses received from each radioisotope and their daughters are saved in three different registers: D(Th), D(K), D(Ra) (there is no accumulation at the wall level, but throughout all the walls, the floor and the ceiling, for each radioisotope separately).

C. After the program finds the relative contribution of each radioisotope and its daughters to the annual effective radiation dose in the center of the room, it uses the formulas in Chapter 2 in order to find the maximum concentration of each radioisotope in the building materials.

5. Determination of voxel size

It is necessary to select optimal dimensions for a single voxel. The smaller it is, the better the precision of calculation.

The analysis shows that the most effective dimension in calculating radiation dose is the vosel thickness, since significant amount of radiation is absorbed in the wall material, and the more we divide into smaller thicknesses, the higher is the precision.

In order to examine this issue, calculations of annual dose values per unit activity concentration were performed, and in Figure 1 are the differences among selection of different thicknesses.

It can be seen that the values converge at around 1 cm voxel thickness (for example, the change among the values of the factors between 1 cm and 0.5 cm is less than 0.4%), therefore the thickness selected for the following calculations is set at 1 cm.

In the same manner it was checked that for the other dimensions of the walls, which, as noted, are a few meters themselves, the sensitivity to the voxel dimensions is low, so we chose a size of 5 cm.

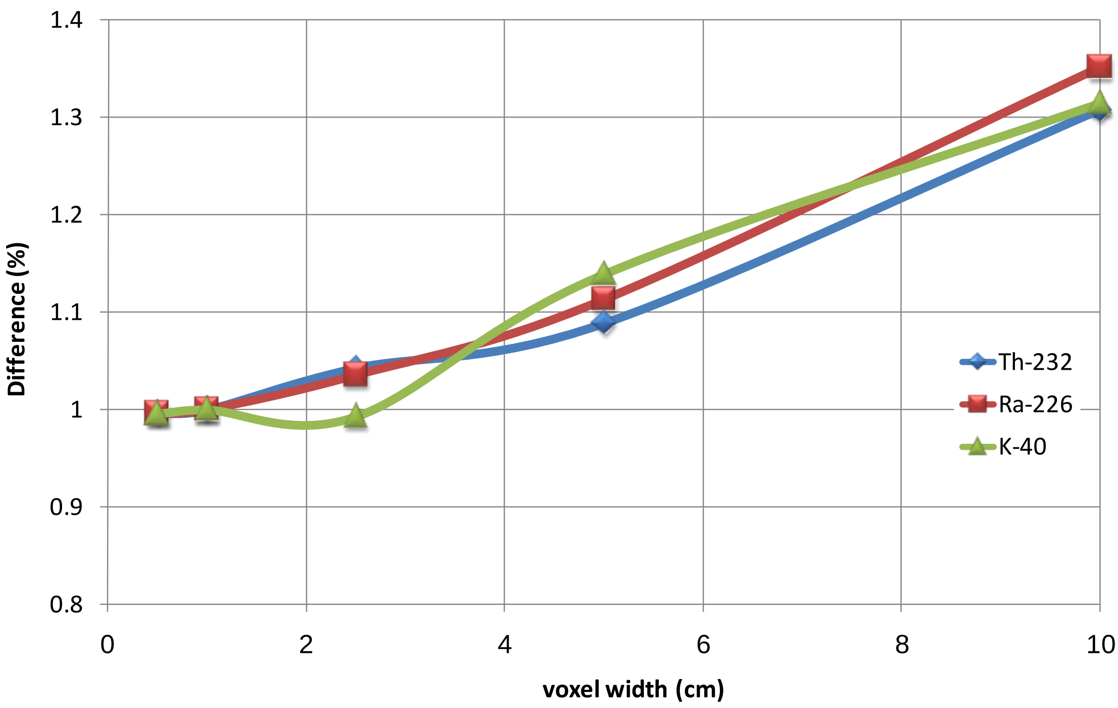

Figure 1 – Change in the annual dose values per unit activity concentration of Ra-226, Th-232 and K-40 is one, versus voxel thickness.

6. Determination of basic wall thickness for calculating the coefficients for the standard

To save on tables and calculations, it is common to use thickness units that are expressed in weight per unit area. However, it turns out there is some difference between precise calculation, for each width (in linear units) and each density (in weight per unit volume), and a calculation of thickness that is expressed in weight per unit area (Table 1). As a result of a comparison between the coefficient values for a wall thickness which varies between 1…20 cm, it can be determined that selecting 10 cm as wall thickness is a reasonable compromise and gives differences of up to 2% relative to the extremes of the thickness variability range (1 cm and 20 cm). Therefore, the selected wall thickness is 10 cm.

Table 1- activity concentrations of radium Ra-226, thorium Th-232 and potassium K-40 for unit of annual dose, as a function of wall thickness.

Wall length, cm	Potassium	Relative to 10 cm, %	Radium	Relative to 10 cm, %	Thorium	Relative to 10 cm, %
1	1419.4	97.96	157.61	98.13	112.01	98.07
10	1449.0	100.00	160.62	100.00	114.21	100.00
20	1481.8	102.26	164.00	102.10	116.67	102.15

7. Program quality control

For control purposes, two checks were performed: (A) a manual check for a single box (voxel) and (B) a check against a previous program (Block)[1].

Manual check for a single voxel

This problem shows a case of a single voxel with small dimensions (point source) that is located at a large distance and on a direct line of sight (without deviation angle) from the point of the dose measurement.

Data

- Cube dimensions: 0.01 * 0.01 * 0.01 m.
- Location of "point of interest" relative to the cube: P_d (1, $5\cdot10^{-3}$, $5\cdot10^{-3}$) m
- Concentration of the three radioisotopes and their daughters: C_m = 100 Bq/kg
- Wall density: ρ = 1000 kg/m^3
- Wall correction factor: F_k = 1

* Because the calculation is performed for a small cube and not for a room, radon contribution is not considered.

Purpose:

Finding the annual effective exposure dose that will be received at a distance of one meter, using manual calculation and the Block program.

Manual calculation:

Location of a "point of interest" relative to the intersection of the axes: P_d (l_d, m_d, n_d) = (1, $5\cdot10^{-3}$, $5\cdot10^{-3}$)

Location of a point source at the center of a specific cube in the wall, relative to the intersection of the axes:

$$P_s = (-\frac{\Delta b}{2}, \frac{\Delta L}{2}, \frac{\Delta h}{2}) = (l_s, m_s, n_s) = (-5\cdot10^{-3}, 5\cdot10^{-3}, 5\cdot10^{-3})$$

Volume of a single voxel:

$$\Delta V = \Delta L \cdot \Delta b \cdot \Delta h = (0.01)^3 = 1\cdot10^{-6}\ m^3$$

$$A = \left(\frac{C_m \cdot \rho \cdot \Delta V \cdot 4.263\cdot10^4}{3.7\cdot10^{10}} \right) = 1.152\cdot10^{-7}$$

$$D_i^2 = (l_d - l_s)^2 + (m_d - m_s)^2 + (n_d - n_s)^2 = (1+5\cdot10^{-3})^2 = 1.010025\ m^2$$

d = $5\cdot10^{-3}$ m

Finding the contribution of K-40 to the effective exposure dose:

$$\boldsymbol{R(mfp) = \mu_m \cdot \rho \cdot d} = 0.0264$$

B (1.461, 0.0264) = 1.0204

$$D(k-40) = \frac{A}{D_i^{\,2}} \sum_{j=1}^{N} \Gamma_\gamma \cdot B \cdot e^{-\mu_m \cdot \rho \cdot d}$$ = $9.1941 \cdot 10^{-9}$ mSv/Y

The contribution of Th-232 and of Ra-226 and their daughters to the effective exposure dose by manual calculation is shown in Table 2 and in Table 3, respectively.

Table 2 – Manual calculation of the contribution of Th-232 and its daughters to the effective dose.

N	E(MeV)	R(mfp)	B(E, R)	Γ_γ	$\Gamma_\gamma \cdot B \cdot e^{-R}$
1	7.5520E-01	0.0365	1.0337	4.1060E-03	4.0922E-03
2	9.9450E-02	0.0854	1.1496	6.6890E-04	7.0602E-04
3	7.7220E-01	0.0361	1.0331	6.1880E-03	6.1662E-03
4	1.0500E-01	0.085	1.1505	8.7450E-04	9.2413E-04
5	8.3550E-01	0.0348	1.0308	7.5320E-03	7.4984E-03
6	1.6300E+00	0.025	1.0188	1.5680E-02	1.5580E-02
7	8.9950E-02	0.0925	1.1181	9.9100E-04	1.0101E-03
8	4.0950E-01	0.0475	1.0566	4.5120E-03	4.5462E-03
9	1.2910E-01	0.0762	1.1316	1.8470E-03	1.9367E-03
10	3.2760E-01	0.052	1.0699	5.4390E-03	5.5243E-03
11	9.3350E-02	0.0899	1.1301	1.6800E-03	1.7353E-03
12	1.5880E+00	0.0253	1.0192	2.9090E-02	2.8908E-02
13	2.7020E-01	0.0562	1.0818	5.0270E-03	5.1410E-03
14	9.4780E-01	0.0328	1.0274	2.0160E-02	2.0044E-02
15	2.0930E-01	0.0617	1.0971	4.7920E-03	4.9427E-03
16	4.6300E-01	0.0452	1.0493	1.0600E-02	1.0631E-02
17	7.9470E-01	0.0356	1.0323	1.8990E-02	1.8918E-02
18	9.6460E-01	0.0325	1.0270	2.5950E-02	2.5798E-02
19	3.3830E-01	0.0514	1.0681	1.9850E-02	2.0140E-02
20	9.6910E-01	0.0324	1.0269	8.3210E-02	8.2724E-02
21	9.1110E-01	0.0353	1.0299	1.3040E-01	1.2964E-01
22	8.4260E-02	0.0997	1.0992	5.2670E-04	5.2401E-04
23	2.4100E-01	0.0588	1.0890	4.9170E-03	5.0488E-03
24	3.0010E-01	0.0535	1.0748	5.2810E-03	5.3803E-03
25	8.7300E-02	0.0945	1.1082	3.6240E-03	3.6540E-03
26	7.4880E-02	0.1094	1.0587	4.1360E-03	3.9250E-03
27	7.7110E-02	0.1053	1.0677	7.1710E-03	6.8912E-03
28	2.3860E-01	0.059	1.0896	5.5040E-02	5.6536E-02
29	7.8550E-01	0.0358	1.0326	7.9910E-03	7.9613E-03
30	1.6210E+00	0.0251	1.0189	2.3020E-02	2.2874E-02
31	7.2720E-01	0.0372	1.0346	4.4440E-02	4.4299E-02

32	8.4900E-02	0.0963	1.0987	2.4170E-04	2.4118E-04
33	7.6310E-01	0.0364	1.0334	2.3330E-03	2.3247E-03
34	7.2800E-02	0.1131	1.0494	2.7620E-04	2.5885E-04
35	7.4970E-02	0.1091	1.0590	4.8050E-04	4.5626E-04
36	2.7740E-01	0.0555	1.0800	3.5170E-03	3.5933E-03
37	8.6040E-01	0.0343	1.0299	2.0000E-02	1.9903E-02
38	5.1080E-01	0.0435	1.0443	2.0500E-02	2.0497E-02
39	5.8310E-01	0.041	1.0411	9.1770E-02	9.1704E-02
40	2.6150E+00	0.0199	1.0134	4.8700E-01	4.8380E-01
				total	1.1765E+00

$$\sum_{j=1}^{40}\Gamma_\gamma \cdot B\cdot e^{-R} = 1.1765$$

$$D(Th-232) = \frac{A}{D_i^2}\cdot\sum_{j=1}^{40}\Gamma_\gamma \cdot B\cdot e^{-R} = 1.3421\cdot 10^{-7}\ \text{mSv/Y}$$

Table 3 – Manual calculation of the contribution of Ra-226 and its daughters to the annual effective dose.

N	E(MeV)	R(mfp)	B(E, R)	Γ_γ	$\Gamma_\gamma\cdot B\cdot e^{-R}$
1	1.86E-01	0.0645	1.1045	3.16E-03	3.2670E-03
2	7.86E-01	0.0358	1.0326	4.45E-03	4.4315E-03
3	5.32E-02	0.1663	1.0000	3.04E-04	2.5734E-04
4	8.73E-02	0.0945	1.1082	2.11E-03	2.1224E-03
5	7.48E-02	0.1091	1.0582	2.40E-03	2.2781E-03
6	2.15E-01	0.0612	1.0957	8.32E-03	8.5750E-03
7	7.71E-02	0.1055	1.0679	4.17E-03	4.0044E-03
8	2.95E-01	0.0525	1.0739	2.94E-02	2.9907E-02
9	3.52E-01	0.0507	1.0659	6.77E-02	6.8543E-02
10	1.66E+00	0.0248	1.0186	9.91E-03	9.8451E-03
11	2.12E+00	0.0219	1.0154	1.29E-02	1.2765E-02
12	8.06E-01	0.0355	1.0320	5.14E-03	5.1165E-03
13	1.40E+00	0.0271	1.0211	1.01E-02	1.0008E-02
14	1.28E+00	0.0285	1.0225	9.80E-03	9.7340E-03
15	2.45E+00	0.0203	1.0139	1.97E-02	1.9592E-02
16	6.66E-01	0.0388	1.0372	5.39E-03	5.3817E-03
17	1.16E+00	0.0300	1.0238	1.01E-02	1.0065E-02
18	1.85E+00	0.0246	1.0179	2.00E-02	1.9834E-02
19	1.51E+00	0.0260	1.0199	1.73E-02	1.7201E-02
20	1.41E+00	0.0271	1.0211	1.81E-02	1.7978E-02
21	1.73E+00	0.0243	1.0180	2.65E-02	2.6369E-02

22	9.34E-01	0.0330	1.0277	1.55E-02	1.5392E-02
23	1.16E+00	0.0300	1.0238	2.10E-02	2.0845E-02
24	1.38E+00	0.0274	1.0214	2.92E-02	2.9039E-02
25	2.20E+00	0.0216	1.0151	5.67E-02	5.6366E-02
26	7.68E-01	0.0362	1.0332	2.00E-02	1.9949E-02
27	1.24E+00	0.0290	1.0228	3.80E-02	3.7755E-02
28	1.12E+00	0.0304	1.0243	8.77E-02	8.7102E-02
29	1.77E+00	0.0240	1.0177	1.44E-01	1.4347E-01
30	6.09E-01	0.0402	1.0399	1.46E-01	1.4554E-01
31	4.65E-02	0.2152	1.0000	9.73E-04	7.8453E-04
				total	8.4352E-01

$$\sum_{j=1}^{31}\Gamma_\gamma \cdot B \cdot e^{-R} = 0.84352$$

$$D(Ra-226) = \frac{A}{D_i}\cdot\sum_{j=1}^{31}\Gamma_\gamma \cdot B \cdot e^{-R} = 9.6223\cdot 10^{-8} \text{ mSv/Y}$$

The total effective dose calculated manually is:

D_t = D(K-40) + D(Th- 232) + D(Ra-226) = $2.3963\cdot 10^{-7}$ mSv/Y

Table 4 shows a comparison between the manual calculation and the results of the Block program

Table 4 – Comparison of the results of the manual calculation and the results of Block software.

The annual effective exposure dose from the cube that will be absorbed by the detector [mSv/y]		
Radionuclide	Manual calculation	Block software
K – 40	9.1941×10^{-9}	9.1940×10^{-9}
Th – 232	1.3421×10^{-7}	1.3421×10^{-7}
Ra – 226	9.6223×10^{-8}	9.6224×10^{-8}
K, Th, Ra	2.3962×10^{-7}	2.3962×10^{-7}

In conclusion, the match between the manual calculation and the program is perfect, down to the fourth digit after the decimal point. The error results from inaccuracy in the manual calculation (rounding of the fourth digit after the decimal point).

Check against previous program (Block)

The check was performed under the same conditions as in study [1].

Five calculations were made based on 0.03 emanation factor for several values of mass per unit area (from 50 to 250 kg per m^2) and their results are shown in Table 5.

Table 5 – Comparison of the two program versions

Mass per unit area	Ra-226 radium		Dev.	Th-232 thorium		Dev.	K-40 potassium		Dev.
[kg/m^3]	Block 2.0	Block	%	Bloc k 2.0	Block	%	Block 2.0	Block	%
50	340	337	-0.87	350	347	-0.93	5157	5129	-0.55
100	176	175	-0.76	185	183	-0.98	2713	2701	-0.44
150	123	122	-0.74	132	131	-0.40	1915	1907	-0.42
200	97	96	-0.75	106	105	-0.90	1527	1520	-0.45
250	81	81	-0.32	91	91	-0.27	1303	1296	-0.51

It can be seen that the deviations do not exceed 1%. In our opinion the deviations are a result of different interpolation methods that were performed for the buildup factor. In the last version of the program, quadratic interpolation was performed.

8. Summary

The Block program that was developed at Soreq Nuclear Research Center in 2004 for calculating the radiation dose from natural radioactive materials in building materials[1], has been upgraded. In the program model the problem is divided into a sum of small sources in small cells that constitute the volume of all of the walls (voxels), taking into consideration the absorption and buildup in the passage of photons through the wall, including all the exit angles.

The program was written in a manner that allows calculation of doses in a room made of any desired composition, at any desired thickness and any location of test point. In addition, the program allows to calculate for each radioactive element the maximum concentration in the building materials of the wall, which are determined according to the maximum doses that can be set as input for the program.

Appendix 1 – Data Summary Table

K - 40

	E_γ [MeV]	μ/ρ (Concrete) [kg/cm^2)	Γ(E) [Ci-hr/R-m^2]
1	1.461E+00	5.280E-03	8.110E-02

Th - 232

	E_γ [MeV]	μ/ρ(Concrete) [Kg/m^2]	Γ(E) [Ci-hr/R-m^2]
1	7.552E-01	7.310E-03	4.106E-03
2	9.945E-02	1.708E-02	6.689E-04
3	7.722E-01	7.220E-03	6.188E-03
4	1.050E-01	1.700E-02	8.745E-04
5	8.355E-01	6.960E-03	7.532E-03
6	1.630E+00	5.000E-03	1.568E-02
7	8.995E-02	1.850E-02	9.910E-04
8	4.095E-01	9.500E-03	4.512E-03
9	1.291E-01	1.525E-02	1.847E-03
10	3.276E-01	1.039E-02	5.439E-03
11	9.335E-02	1.799E-02	1.680E-03
12	1.588E+00	5.060E-03	2.909E-02
13	2.702E-01	1.123E-02	5.027E-03
14	9.478E-01	6.560E-03	2.016E-02
15	2.093E-01	1.233E-02	4.792E-03
16	4.630E-01	9.040E-03	1.060E-02
17	7.947E-01	7.110E-03	1.899E-02
18	9.646E-01	6.490E-03	2.595E-02
19	3.383E-01	1.027E-02	1.985E-02
20	9.691E-01	6.480E-03	8.321E-02
21	9.111E-01	7.070E-03	1.304E-01
22	8.426E-02	1.994E-02	5.267E-04
23	2.410E-01	1.176E-02	4.917E-03
24	3.001E-01	1.070E-02	5.281E-03
25	8.730E-02	1.890E-02	3.624E-03
26	7.488E-02	2.187E-02	4.136E-03
27	7.711E-02	2.105E-02	7.171E-03
28	2.386E-01	1.180E-02	5.504E-02
29	7.855E-01	7.160E-03	7.991E-03
30	1.621E+00	5.020E-03	2.302E-02
31	7.272E-01	7.440E-03	4.444E-02
32	8.490E-02	1.925E-02	2.417E-04

33	7.631E-01	7.270E-03	2.333E-03
34	7.280E-02	2.262E-02	2.762E-04
35	7.497E-02	2.182E-02	4.805E-04
36	2.774E-01	1.110E-02	3.517E-03
37	8.604E-01	6.870E-03	2.000E-02
38	5.108E-01	8.700E-03	2.050E-02
39	5.831E-01	8.200E-03	9.177E-02
40	2.615E+00	3.970E-03	0.487E+00

Ra - 226

	E_γ [MeV]	**μ/ρ(Concrete) [kg/m^2]**	**Γ(E) [Ci-hr/ R-m^2]**
1	1.862E-01	1.291E-02	3.155E-03
2	7.859E-01	7.160E-03	4.448E-03
3	5.323E-02	3.326E-02	3.039E-04
4	8.730E-02	1.890E-02	2.105E-03
5	7.482E-02	2.182E-02	2.401E-03
6	2.150E-01	1.223E-02	8.320E-03
7	7.711E-02	2.109E-02	4.167E-03
8	2.952E-01	1.050E-02	2.935E-02
9	3.519E-01	1.014E-02	6.765E-02
10	1.661E+00	4.960E-03	9.908E-03
11	2.119E+00	4.380E-03	1.285E-02
12	8.062E-01	7.090E-03	5.137E-03
13	1.402E+00	5.420E-03	1.007E-02
14	1.281E+00	5.710E-03	9.795E-03
15	2.448E+00	4.060E-03	1.972E-02
16	6.655E-01	7.750E-03	5.394E-03
17	1.155E+00	6.000E-03	1.013E-02
18	1.847E+00	4.920E-03	1.997E-02
19	1.509E+00	5.190E-03	1.731E-02
20	1.408E+00	5.420E-03	1.809E-02
21	1.730E+00	4.860E-03	2.654E-02
22	9.341E-01	6.600E-03	1.548E-02
23	1.158E+00	6.000E-03	2.098E-02
24	1.378E+00	5.480E-03	2.922E-02
25	2.204E+00	4.310E-03	5.674E-02
26	7.684E-01	7.240E-03	2.002E-02
27	1.238E+00	5.800E-03	3.800E-02
28	1.120E+00	6.080E-03	8.766E-02
29	1.765E+00	4.810E-03	1.444E-01
30	6.093E-01	8.040E-03	1.457E-01
31	4.650E-02	4.303E-02	9.729E-04

Appendix 2 – B.F. Tables

	Energy(MeV)										
R(mfp)	0.02	0.05	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.5	1	1	1.89	1.81	1.73	1.65	1.57	1.55	1.52	1.5	1.47
1	1.15	1.89	2.78	2.65	2.53	2.4	2.27	2.21	2.15	2.1	2.04
2	1.22	2.58	4.63	4.48	4.33	4.18	4.03	3.87	3.71	3.56	3.4
3	1.28	3.26	6.63	6.54	6.45	6.35	6.26	5.95	5.64	5.34	5.03
4	1.34	3.93	8.8	8.84	8.89	8.93	8.97	8.46	7.95	7.44	6.93
5	1.4	4.61	11.1	11.38	11.65	11.93	12.2	11.43	10.65	9.88	9.1
6	1.45	5.44	13.6	14.18	14.75	15.33	15.9	14.8	13.7	12.6	11.5
7	1.5	6.28	16.3	17.28	18.25	19.23	20.2	18.7	17.2	15.7	14.2
8	1.55	7.11	19.2	20.65	22.1	23.55	25	23.04	21.08	19.12	17.16
10	1.64	8.78	25.6	28.3	31	33.7	36.4	33.26	30.12	26.98	23.84
15	1.87	16.24	44.9	52.58	60.25	67.92	75.6	67.92	60.24	52.56	44.88
20	2.1	23.7	69.1	84.58	100.05	115.53	131	116.22	101.44	86.66	71.88
25	2.32	37.95	97.9	124.18	150.45	176.73	203	178.42	153.84	129.26	104.68
30	2.53	52.2	131	170.75	210.5	250.25	290	253.2	216.4	179.6	142.8
35	2.74	78.1	170	227.25	284.5	341.75	399	346	293	240	187
40	2.95	104	214	291.25	368.5	445.75	523	451.2	379.4	307.6	235.8

	Energy(MeV)										
R(mfp)	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2
0.5	1.45	1.44	1.43	1.426	1.418	1.41	1.402	1.394	1.386	1.378	1.37
1	1.98	1.96	1.94	1.917	1.896	1.875	1.854	1.833	1.812	1.791	1.77
2	3.24	3.18	3.12	3.063	3.004	2.945	2.886	2.827	2.768	2.709	2.65
3	4.72	4.61	4.5	4.384	4.272	4.16	4.048	3.936	3.824	3.712	3.6
4	6.42	6.24	6.06	5.877	5.696	5.515	5.334	5.153	4.972	4.791	4.61
5	8.33	8.07	7.8	7.535	7.27	7.005	6.74	6.475	6.21	5.945	5.68
6	10.4	10.04	9.68	9.32	8.96	8.6	8.24	7.88	7.52	7.16	6.8
7	12.7	12.23	11.75	11.281	10.808	10.335	9.862	9.389	8.916	8.443	7.97
8	15.2	14.6	14	13.394	12.792	12.19	11.588	10.986	10.384	9.782	9.18
10	20.7	19.8	18.9	18	17.1	16.2	15.3	14.4	13.5	12.6	11.7
15	37.2	35.34	33.48	31.62	29.76	27.9	26.04	24.18	22.32	20.46	18.6
20	57.1	53.99	50.88	47.77	44.66	41.55	38.44	35.33	32.22	29.11	26
25	80.1	75.48	70.86	66.24	61.62	57	52.38	47.76	43.14	38.52	33.9
30	106	99.62	93.24	86.86	80.48	74.1	67.72	61.34	54.96	48.58	42.2
35	134	125.69	117.38	109.07	100.76	92.45	84.14	75.83	67.52	59.21	50.9
40	164	153.58	143.16	132.74	122.32	111.9	101.48	91.06	80.64	70.22	59.8

	Energy(MeV)									
R(mfp)	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3
0.5	1.366	1.362	1.358	1.354	1.35	1.346	1.342	1.338	1.334	1.33
1	1.76	1.75	1.74	1.73	1.72	1.71	1.7	1.69	1.68	1.67
2	2.623	2.596	2.569	2.542	2.515	2.488	2.461	2.434	2.407	2.38
3	3.549	3.498	3.447	3.396	3.345	3.294	3.243	3.192	3.141	3.09
4	4.533	4.456	4.379	4.302	4.225	4.148	4.071	3.994	3.917	3.84
5	5.573	5.466	5.359	5.252	5.145	5.038	4.931	4.824	4.717	4.61
6	6.66	6.52	6.38	6.24	6.1	5.96	5.82	5.68	5.54	5.4
7	7.793	7.616	7.439	7.262	7.085	6.908	6.731	6.554	6.377	6.2
8	8.965	8.75	8.535	8.32	8.105	7.89	7.675	7.46	7.245	7.03
10	11.401	11.102	10.803	10.504	10.205	9.906	9.607	9.308	9.009	8.71
15	18.05	17.5	16.95	16.4	15.85	15.3	14.75	14.2	13.65	13.1
20	25.17	24.34	23.51	22.68	21.85	21.02	20.19	19.36	18.53	17.7
25	32.76	31.62	30.48	29.34	28.2	27.06	25.92	24.78	23.64	22.5
30	40.72	39.24	37.76	36.28	34.8	33.32	31.84	30.36	28.88	27.4
35	49.05	47.2	45.35	43.5	41.65	39.8	37.95	36.1	34.25	32.4
40	57.56	55.32	53.08	50.84	48.6	46.36	44.12	41.88	39.64	37.4

Appendix 3 – Block2.0 Program

The main text of the program including 6 functions that it uses as follows:

```
% Main of Block2.0
% התוכנה מחשבת ריכוזים גבוליים של היסודות הר"א בחומרי המבנה, בהינתן מנה
שנתית מרבית מוגדרת, במרכז החדר.%
clc
clear all
close all
t0=fix(clock);     % זמן תחילת ההרצה
fid=fopen('BLOCK2_Results.out','w');     % יצירת קובץ תוצאות
fprintf(fid,'Date: %2i.%2i.%2i       Time: %2i:%2i:%2i\n',t0);
disp('****************************************')
disp('*          Program BLOCK2.0            *')
fprintf('* Date: %2i.%2i.%2i      Time: %2i:%2i:%2i *\n',t0);
disp('****************************************')
disp(' ')
disp('Dimensions of room:')
L=input('enter length [m] :');     % מידות החדר.
B=input('enter width  [m] :'); % רוחב
H=input('enter height [m] :');   % גובה
disp(' ')
Xs=L/2;  % "קואורדינטות "נקודת ההתעניינות
Ys=B/2;   % במערכת הגלובלית
Zs=H/2;

disp('What do you want to calculate?')
disp('For dose from a whole room - press "d"')
disp('For dose from a single wall - press "w"')
disp('For calculation of coefficients - press "c"')
choice=input(' ', 's');
while (choice~='c'  && choice~='d' && choice~='w')   % בדיקת קלט
    disp(' ')
    disp('Error. Please enter "c" or "w" or "d"')
    disp('For dose from specific room - press "d"')
    disp('For dose from a single wall - press "w"')
    disp('For calculate of coefficients - press "c"')
    choice=input(' ', 's');
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%

if (choice=='d' || choice=='w')      % חישוב מנה מקיר או מחדר שלם
   b=input('enter average thickness of walls/floor [cm]  : ');
   b=b/100;    % מעבר למטרים
   % גודל תיבה בודדת
   disp('Default size of single voxel is 5x5xthickness/10 [cm]')
   ans1=input('Do you want to change default settings of single voxel press
"y"/"n"  : ','s');
   if ans1=='y'
       Lvoxel=input('enter length of voxel [cm]  :')/100;    % מידות voxel
       Hvoxel=input('enter height of voxel [cm]  :')/100;   % גובה
       bvoxel=input('enter width of voxel [cm]  :')/100; % רוחב
   else
        Lvoxel=0.05;  % אורך תיבה
        Hvoxel=0.05; % גובה תיבה
        bvoxel=b/10;   % עובי תיבה
```

```
   end
   CmRa=input('enter concentration of Ra-226 [bq/kg]           : ');% ריכוז
נמדד של רדיואיזוטופ ספציפי, בקיר (Bq/kg)
   CmTh=input('enter concentration of Th-232 [bq/kg]           : ');
   CmK= input('enter concentration of K-40 [bq/kg]             : ');
   e=input('enter emanation rate [%]                 : ')/100;
%  מקדם אמנציה
   ro=input('enter average density of walls [kg/m^3]         : ');          %
צפיפות
   disp('Default value of reduction coefficient of openings is 94%')
% מקדם פתחים
   ans1=input('Do you want to change it? press "y"/"n"  : ','s');
   if ans1=='y'
       Fk=input('enter reduction coefficient of openings [%]  : ');
   else
       Fk=0.94;
   end

   if (choice=='d')
        fprintf('\nworking...\n\n');

[D_K,D_Ra,D_Th]=Droom(L,B,H,b,Xs,Ys,Zs,Lvoxel,Hvoxel,bvoxel,ro,CmK,CmRa,CmT
h,Fk);    % חישוב מנת הקרינה בחדר מכל אחד מהרדיואיזוטופים
        disp('            Room dose   ')
        fprintf(fid,'\n        Room dose:\n');
        Sk=2*(L*H+B*H+L*B);          %  שטח מעטפת החדר
   else     %    wall dose
       L=input('enter length of wall[m] : ');     % אורך
       H=input('enter height of wall[m] : ');   % גובה
       Sk=L*H;                             % שטח קיר
       fprintf('\nworking...\n\n')

[D_k,D_ra,D_th]=Dside(B,H,b,Xs,Ys,Zs,Lvoxel,Hvoxel,bvoxel,ro,CmK,CmRa,CmTh)
;
       D_K=4*D_k*42630*Fk ;   % 4 רבע קיר כפול
       D_Ra=4*D_ra*42630*Fk;   % ההנחות הן מטעמי סימטריה
       D_Th=4*D_th*42630*Fk;
       disp('           Wall/floor dose')
       fprintf(fid,'\n       Wall/floor dose \n');
   end

   V=L*B*H;                           % נפח החדר
   vent=0.5;                         % מספר  החלפות אוויר בשעה
   D_Rn=0.0000646*(Sk/V)*e*ro*b*CmRa/vent;      %  1.17 נוסחא
   D_Ra=(1-e)*D_Ra;                 %   הפחתת האמנציה
   D_total=D_K+D_Ra+D_Th;
   disp(' ')
   fprintf(fid,'Total gamma dose  : %10.5f [mSv/yr] \n', D_total);
   fprintf(fid,'Dose from Ra-226      : %10.5f [mSv/yr] \n', D_Ra);
   fprintf(fid,'Dose from Th-232      : %10.5f [mSv/yr] \n', D_Th);
   fprintf(fid,'Dose from K-40            : %10.5f [mSv/yr] \n', D_K);
   fprintf(fid,'Dose from Rn-222        : %10.5f [mSv/yr] \n', D_Rn);
   fprintf('Total gamma dose      : %10.5f [mSv/yr] \n', D_total)
   fprintf('Dose from Ra-226      : %10.5f [mSv/yr] \n', D_Ra)
   fprintf('Dose from Th-232      : %10.5f [mSv/yr] \n', D_Th)
   fprintf('Dose from K-40        : %10.5f [mSv/yr] \n', D_K)
   fprintf('Dose from Rn-222        : %10.5f [mSv/yr] \n', D_Rn)
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%
```

```
if (choice=='c')       % חישוב מנה מחדר הנקלט
   disp('Default size of single voxel is 5x5x1 [cm]  (for thickness of
walls of 10cm)')       % גודל תיבה בודדת
   b=0.1;      % עובי הקיר
   ans1=input('Do you want to change default settings of single voxel press
"y"/"n"  : ','s');
   if ans1=='y'
       Lvoxel=input('enter length of voxel [cm]  :')/100;     % voxel מידות
       Hvoxel=input('enter height of voxel [cm]  :')/100;    % גובה
       bvoxel=input('enter width of voxel [cm]  :')/100; % רוחב
   else
        Lvoxel=0.05;  % אורך תיבה
        Hvoxel=0.05; % גובה תיבה
        bvoxel=b/10;    % עובי תיבה
   end

CmK= 1;     % ריכוז נמדד של רדיואיזוטופ ספציפי, בקיר (Bq/kg)
CmRa=1;
CmTh=1;

disp('Default value of reduction coefficient of openings is 94 %')
% מקדם פתחים
   ans1=input('Do you want to change it? press "y"/"n"  : ','s');
   if ans1=='y'
       Fk=input('enter reduction coefficient of openings [%]  : ');
   else
       Fk=0.94;
   end

   Dref=1.1;   % מנת קרינת הרקע גאמה+רדון
   disp('Default value of reference dose is 1.1 mSv/y')         %  מקדם
פתחים
   ans1=input('Do you want to change it? press "y"/"n"  : ','s');
   if ans1=='y'
       Dref=input('enter reference dose [mSv/y] : ');
   end
Db=0.3;   %  התוספת המרבית של מנת הקרינה האפקטיבית השנתית מקרינת גמא ורדון
שאפשר לקבל ממוצר בניה כלשהו, בהשוואה למנת הקרינה האפקטיבית המתקבלת ממוצר
הייחוס (mSv/y).
disp('Default value of extra dose is 0.3 mSv/y')         % מקדם פתחים
ans1=input('Do you want to change it? press "y"/"n"  : ','s');
if ans1=='y'
    Dref=input('enter extra dose [mSv/y] : ');
end

D_total=Dref+Db;   % סה"כ המנה המותרת

ro=[100,200,300,400,500,1000,1500,2000,2500,3000,3500,4000,4500,5000,5500,6
000,7000,8000,9000,10000];
    n=length(ro);
    fprintf(fid,'        Coefficients:\n');
    fprintf('\n       Coefficients:\n');
    for i=1:n

[D_K,D_Ra,D_Th]=Droom(L,B,H,b,Xs,Ys,Zs,Lvoxel,Hvoxel,bvoxel,ro(i),CmK,CmRa,
CmTh,Fk);    % חישוב מנת הקרינה בחדר מכל אחד מהרדיואיזוטופים
        Cmax_K(i)=D_total/D_K;          % ריכוזים מקסימליים מותרים
        Cmax_Ra(i)=D_total/D_Ra;
        Cmax_Th(i)=D_total/D_Th;
```

```
        V=L*B*H;                      % נפח החדר
        vent=0.5;                    % מספר  החלפות אוויר בשעה
        Sk=2*(L*H+B*H+L*B);         %  שטח מעטפת החדר
        e=1;
        D_Rn=0.0000646*(Sk/V)*e*ro(i)*b*CmRa/vent;      %  1.17 נוסחא
        Cmax_Rn(i)=D_total/D_Rn;
        masa_per_sqr_mtr(i)=ro(i)*b;             % שטח מסה ליחידת
        fprintf('density   density/area     K-40           Ra-226
Th-232      Rn-222    \n')
        format short g
        [,masa_per_sqr_mtr(i),Cmax_K(i),Cmax_Ra(i),Cmax_Th(i),Cmax_Rn(i)]
    end
    masa_per_sqr_mtr1=masa_per_sqr_mtr';   % שחלוף
    Cmax_Ra1=Cmax_Ra';
    Cmax_K1=Cmax_K';
    Cmax_Th1=Cmax_Th';
    Cmax_Rn1=Cmax_Rn';
    fprintf(fid,' density/area      K-40                   Ra-226
Th-232          Rn-222 \n');
    fprintf('density/area     K-40           Ra-226          Th-232
Rn-222    \n')
    for i=1:n
      fprintf(fid,'           %8i               %8g    %20g          %10g
%10g
\n',masa_per_sqr_mtr1(i),Cmax_K1(i),Cmax_Ra1(i),Cmax_Th1(i),Cmax_Rn1(i));
      fprintf('     %5i          %8g    %10g        %10g       %10g
\n',masa_per_sqr_mtr1(i),Cmax_K1(i),Cmax_Ra1(i),Cmax_Th1(i),Cmax_Rn(i))
    end
end

 t1=fix(clock)      % זמן\ סוף ההרצה
dt=t1-t0                 % משך ההרצה
 pause
fclose(fid);
```

פונקציה 1:

```
function
[D_K,D_Ra,D_Th]=Droom(L,B,H,b,Xs,Ys,Zs,Lvoxel,Hvoxel,bvoxel,ro,CmK,CmRa,CmT
h,Fk)
  % חישוב מנת הקרינה בחדר ע"י זימון פונקציה של פאה בודדת תוך התאמת פרמטרים
  % רצפה. הפונציית מחזירה את מנות הקרינה לפי כל אחד משלושת\תקרה\לקיר
  % היסודות הר"א
   % קיצור דרך קטן  שאני עושה כדי להאיץ את התוכנית
   % אני מניח שהקירות סימטריים ביחס למרכז וכך גם התקרה והרצפה

[D_k(1),D_ra(1),D_th(1)]=Dside(B,H,b,Xs,Ys,Zs,Lvoxel,Hvoxel,bvoxel,ro,CmK,C
mRa,CmTh);              % west wall
  t_first_wall=fix(clock)
  %[D_k(2),D_ra(2),D_th(2)]=Dside(B,H,b,L-Xs,B-
Ys,Zs,Lvoxel,Hvoxel,bvoxel,ro,CmK,CmRa,CmTh);     % east wall
  %t_second_wall=fix(clock)
  [D_k(3),D_ra(3),D_th(3)]=Dside(L,H,b,Ys,L-
Xs,Zs,Lvoxel,Hvoxel,bvoxel,ro,CmK,CmRa,CmTh);         % south wall
  t_third_wall=fix(clock)
  %[D_k(4),D_ra(4),D_th(4)]=Dside(L,H,b,B-
Ys,Xs,Zs,Lvoxel,Hvoxel,bvoxel,ro,CmK,CmRa,CmTh);          % north wall
   %t_fourth_wall=fix(clock)

[D_k(5),D_ra(5),D_th(5)]=Dside(B,L,b,Zs,Xs,Ys,Lvoxel,Hvoxel,bvoxel,ro,CmK,C
mRa,CmTh);               % bottom
    t_floor=fix(clock)
```

```
  %[D_k(6),D_ra(6),D_th(6)]=Dside(B,L,b,H-
Zs,Ys,Xs,Lvoxel,Hvoxel,bvoxel,ro,CmK,CmRa,CmTh);          % top
   %t_top=fix(clock)

  % סכימה של כל המנות והכפלה במקדם פתחים ומעבר יחידות
  D_K=8*(D_k(1)+D_k(3)+D_k(5))*42630*Fk ;    %  רבע קיר כפול 4 וכפול 2
(הקירות), רבע רצפה כפול 4 כפול 2 (התקרה)
  D_Ra=8*(D_ra(1)+D_ra(3)+D_ra(5))*42630*Fk;    % ההנחות הן מטעמי סימטריה
  D_Th=8*(D_th(1)+D_th(3)+D_th(5))*42630*Fk;
End

פונקציה 2:
% הפונקציה מקבלת מידות של פאה בחדר, צפיפות, גודל קוביה בודדת, "נקודת %
% ההתעניינות" מקדם פתחים ואת כמויות הרדיואיזוטופים לפי ב"אה
function
[D_K,D_Ra,D_Th]=Dside(L,H,b,Xs,Ys,Zs,Lvoxel,Hvoxel,bvoxel,ro,CmK,CmR,CmTh)
   sqr = @(a) a.^2;    % "הגדרת פונקציה בריבוע"
   K=40;
   D_K=0;
   Ra=226; % סימון מוסכם שלי לרדיום
   D_Ra=0;
   Th=232;
   D_Th=0;
   dV=Lvoxel*Hvoxel*bvoxel;  % נפח תיבה
   for x=(-b+bvoxel/2):bvoxel:(-bvoxel/2)     % לולאה שרצה על עומק הקיר
       fprintf('.')
      for y=(Lvoxel/2):Lvoxel:(L/2-Lvoxel/2)       % לולאה שרצה על אורך הקיר
          for z=(Hvoxel/2):Hvoxel:(H/2-Hvoxel/2)    %  לולאה שרצה על גובה
הקיר
                Dsqr=sqr(Xs-x)+sqr(Ys-y)+sqr(Zs-z);   % חישוב D בריבוע
                d=(sqrt(Dsqr)*(-x))/(Xs-x);       % חישוב d
                D_K=D_K+((CmK*ro*dV )/(Dsqr*3.7*10^10))*SigmaGamma(K,ro,d);
% חישוב מנת הקרינה המתקבלת מכל אחד מהיסודות הרדיואקטיביים

D_Ra=D_Ra+((CmRa*ro*dV)/(Dsqr*3.7*10^10))*SigmaGamma(Ra,ro,d);

D_Th=D_Th+((CmTh*ro*dV)/(Dsqr*3.7*10^10))*SigmaGamma(Th,ro,d);
          end
      end
   end
end

פונקציה 3:
function [Sigma]=SigmaGamma(RadioIzotop,ro,d)     % פונקציה  שמחשבת סך הכל
פליטות האנרגיה מקרינת גמא מסך כל הרדיואיזוטופים בכל שרשרת של רדיואיזוטופ
מסוים ומרחק נתון של מסלול בתוך הקיר
    load B_ER.txt
   if RadioIzotop==40                                     %  סימון מוסכם שלי
לאשלגן
       load Gamma_B_mium_K.txt                       %  טעינת קובץ הקבועים של
אשלגן
       Gamma_B_mium=Gamma_B_mium_K;   % הצבת נתוני האשלגן בנתונים הכללים
   end
   if RadioIzotop==226                                   %  סימון מוסכם שלי
לרדיום
       load Gamma_B_mium_Ra.txt
       Gamma_B_mium=Gamma_B_mium_Ra;
   end
   if RadioIzotop==232                                   %  סימון מוסכם שלי
לטוריום
     load Gamma_B_mium_Th.txt
```

```
        Gamma_B_mium=Gamma_B_mium_Th;
    end
    Sigma=0;
    [N,m]=size(Gamma_B_mium);
    for i=1:N  % סכימת מכפלות קבועי ונתוני רדיואיזוטופ ספציפי
        R=Gamma_B_mium(i,3)*ro*d;  % calculation of R
        B=B_E_R(RadioIzotop,i,R,B_ER);                % calculation of B
        Sigma=Sigma+Gamma_B_mium(i,1)*B*exp(-R);
    end
end
```

:4 פונקציה

```
 function [B]=B_E_R(RadioIzotop,i,R,B_ER)
  if RadioIzotop==40                                  % סימון מוסכם של
לאשלגן
        load E_K.txt                                   % טעינת קובץ
הקבועים של אשלגן
         E=E_K(i);                                    % הצבת נתוני האשלגן
בנתונים הכללים
    end
    if RadioIzotop==226                               % סימון מוסכם של
לרדיום
        load E_Ra.txt
        E=E_Ra(i);
    end
    if RadioIzotop==232                               % סימון מוסכם של
לטוריום
        load E_Th.txt
        E=E_Th(i);
    end
    [m,n]=size(B_ER);  % גבוליים R מציאת ערכי
    j=3;
    for j=3:m
        if R<=B_ER(j,1)
            break
        end
    end
    R1=j-1;
    R2=j;
    R3=j+1;
    l_R=B_ER(R2,1)-B_ER(R1,1);
    l_Ry=R-B_ER(R1,1);
    j=3;
     for j=3:n   % מציאת ערכי אנרגיה גבוליים
        if E<=B_ER(1,j)
            break
        end
     end
    E1=j-1;
    E2=j;
    l_E=B_ER(1,E2)-B_ER(1,E1);
    l_Ex=E-B_ER(1,E1);
    if R3<=18

B1=square_interpolation(R,B_ER(R1,1),B_ER(R1,E1),B_ER(R2,1),B_ER(R2,E1),B_E
R(R3,1),B_ER(R3,E1));

B2=square_interpolation(R,B_ER(R1,1),B_ER(R1,E2),B_ER(R2,1),B_ER(R2,E2),B_E
R(R3,1),B_ER(R3,E2));
    else
```

```
       B1=linear_interpolation(B_ER(R1,E1),B_ER(R1,E2),l_R,l_Ry);      %
בעזרת אינטרפולציה ליניארית B מציאת
       B2=linear_interpolation(B_ER(R2,E1),B_ER(R2,E2),l_R,l_Ry);
   end

   B=linear_interpolation(B1,B2,l_E,l_Ex);
  if B<1
       B=1;
   End
```

פונקציה 5: אינטרפולציה ליניארית:

```
function  [x]=linear_interpolation(a,b,l,l_a)    %  הפונקציה מקבלת 2 ערכים
ביהנהם ומרחק עד נקודת הבינים המבוקשת ומבצעת אינטפולציה ליניארית  את המרחק
לערך הביניים המבוקש
   x=a+l_a*(b-a)/l;                                % משולשים דומים
```

פונקציה 6: אינטרפולציה ריבועית:

```
function [Y]=square_interpolation(X,x1,y1,x2,y2,x3,y3)
Y=y1+((y2-y1)/(x2-x1))*(X-x1)+((y3-y2)/(x3-x2)-(y2-y1)/(x2-x1))*(X-x1)*(X-
x2)/(x3-x1);
end
```

Appendix 4 – Examples for Calculation of Background Radiation (Model Reference Dose)

Examples of concentrations of radioactive elements which are common in building products in Israel are presented in the following table:

Building material	Density	Ra-226	Th-232	K-40
Units	kg/m^3	Bq/kg	Bq/kg	Bq/kg
Cellular concrete block – autoclave	500	10	6	97
Hollow concrete block	1250	45	6	75
Hollow concrete block	1600	45	6	75
Hollow pumice block	750	53	60	866
Concrete	2350	30	15	50
Concrete including terrazzo finishing	2350	30	15	50
Ceramics	2300	243	76	1130
Cement	2000	66	40	140
Compacted sand	1600	12	4	51

Based on these values and **on alternatives for a reference room** shown in Appendix 5, using the program described here, the background radiation doses in standard rooms were calculated based on these alternatives. For example, the values of the gamma radiation dose are presented in the following table:

Alternative number	Alternative description	Exterior walls	Interior walls	Floor/ ceiling	Annual gamma radiation dose [mSv/y]
1	Corner room with exterior walls made of cellular concrete cured by autoclave	E1	I1	FC2	1.1607
2	Corner room with exterior walls made of hollow concrete blocks (1250 kg per m^3)	E2	I1	FC2	1.1862
3	Corner room with exterior walls made of hollow concrete blocks with pumice aggregate (750 kg per m^3)	E3	I1	FC2	0.2405
4	Non-corner room with pumice block exterior walls	E3	I1	FC2	0.2210
5	Corner room with exterior walls as per alternative E4	E4	I1	FC2	0.1902
6	Corner room with exterior walls as per alternative E5	E5	I1	FC2	0.1928
7	Home shelter with 20 cm thick walls*	20 cm concrete	20 cm concrete	FC2	0.1877

* Alternative for home shelter rooms was added to the alternatives cited in Appendix 5

It is noted that the radiation dose depends on the concentration values in the material and on the thickness of the product. For examples, dose values in a shelter room made of concrete walls of 25 cm average thickness, with radium, thorium and potassium content of 50, 15 and 50 Becquerel per kg and an emanation factor of 10%, are presented in the following table:

Dose from radium [mSv/y]	Dose from thorium [mSv/y]	Dose from potassium [mSv/y]	Dose from radon [mSv/y]	Total background dose [mSv/y]
0.16	0.07	0.02	0.80	1.1

Assuming the background dose is 1.1 mSv/y, the coefficients for calculating the radiation index I in the standard

$$I = (1-e)\frac{\left[{}^{226}Ra\right]}{A({}^{226}Ra)} + \frac{e\left[{}^{226}Ra\right]}{A({}^{226}Ra)} + \frac{\left[{}^{232}Th\right]}{A({}^{232}Th)} + \frac{\left[{}^{40}K\right]}{A({}^{40}K)}$$

will be as follows:

Mass per unit area ρδ (kg/m^2)	$A({}^{40}K)$	$A({}^{232}Th)$	$A({}^{222}Rn)$	$A({}^{226}Ra)$
10	109290	7483	522.4	10437
20	55088	3760	261.2	5243
30	37038	2522	174.1	3516
40	28026	1905	130.6	2656
50	22630	1537	104.5	2142
100	11906	811	52.2	1130
150	8403	577	34.8	804
200	6701	465	26.1	649
250	5717	400	20.9	560
300	5089	359	17.4	504
350	4665	332	14.9	466
400	4365	312	13.1	440
450	4148	298	11.6	421
500	3986	287	10.4	407
550	3865	279	9.5	397
600	3772	272	8.7	389
700	3645	264	7.5	378
800	3568	258	6.5	371

Appendix 5 – Alternatives for Standard Room in Israel

January 7, 2004

To: Members of the Central Committee for Building

Re: alternatives for reference room for the experts committee work for SI 5098

A proposal for alternatives for a standard room, for the experts committee work for SI 5098, which will define the most common alternatives currently existing in ordinary construction in Israel, is attached.

The proposal was prepared with Association Professor Konstantin Kovler, who is a member of this committee. For these alternatives to be acceptable to all members of the committee, I would be grateful if you could forward your comments by fax or by email.

Best regards,

Assoc. Prof. Rachel Becker

Standard room:

Dimensions: length – 3.0 m, width – 3.0 m, height – 2.7 m (inner envelope area: 50.4 m^2).

Window: 1.2×1.2 (area: 1.44 m^2), will be deducted from the area of walls with a cross-section as per exterior wall.

Door: 2.0×0.8 (area: 1.6 m^2), will be deducted from the area of walls with a cross-section as per interior wall.

Every alternative of components below should be checked for:

A. Room that includes one exterior wall with a window, one interior wall with a door, and 2 interior walls without openings.

B. Room that includes one exterior wall with a window, one exterior wall without a window, one interior wall with a door, and one interior wall without openings.

The structure of the alternative elements

<u>Exterior walls:</u>

Alternative no. E1:

Exterior wall (from inside outward) for 85% of the wall area: 1 cm cement-lime interior rendering (1800 kg/m^3), 20 cm autoclaved aerated concrete blocks (500 kg/m^3), 2 cm of exterior cementitious rendering (2000 kg/m^3).

Concrete components in the exterior walls for 15% of the wall area: 1 cm cement-lime interior rendering (1800 kg/m^3), 20 cm concrete (2350 kg/m^3), 2 cm exterior cementitious rendering (2000 kg/m^3).

Alternative no. E2:

Exterior wall (from inside outward) for 85% of the wall area: 1 cm cement-lime interior rendering (1800 kg/m^3), 20 cm hollow-core concrete blocks (1250 kg/m^3), 2 cm exterior cementitious rendering (2000 kg/m^3).

Concrete components in the exterior walls for 15% of the wall area: 1 cm cement-lime interior rendering (1800 kg/m^3), 20 cm concrete (2350 kg/m^3), 2 cm exterior cementitious rendering (2000 kg/m^3).

Alternative no. E3:

Exterior wall (from inside outward) for 85% of the wall area: 1 cm cement-lime interior rendering (1800 kg/m^3), 20 cm hollow-core concrete blocks with pumice aggregate (750 kg/m^3), 2 cm exterior cementitious rendering (2000 kg/m^3).

Concrete components in the exterior walls for 15% of wall area: 1 cm cement-lime interior rendering (1800 kg/m^3), 20 cm concrete (2350 kg/m^3), 2 cm exterior cementitious rendering (2000 kg/m^3).

Alternative no. E4:

Exterior wall (from inside outward) 100% of the wall area: 12 cm concrete (2350 kg/m^3), 3 cm expanded polystyrene, 5 cm concrete (2350 kg/m^3), 2 cm limestone (2600 kg/m^3).

Alternative no. E5:

Exterior wall (from inside outward) 100% of wall area: 1.25 cm plasterboard (1000 kg/m^3), 5 cm glass wool, 15 cm concrete (2350 kg/m^3), 2 cm limestone (2600 kg/m^3).

Interior walls:

Alternative no. I1:

Interior wall for 85% of the wall area: 1 cm cement-lime interior rendering (1800 kg/m^3), 7 cm hollow-core concrete block (1600 kg/m^3), 1 cm cement-lime interior rendering (1800 kg/m^3).

Concrete components in the interior wall: for 15% of interior and exterior wall area: 1 cm cement-lime interior rendering (1800 kg/m^3), 20 cm concrete (2350 kg/m^3), 1 cm cement-lime interior rendering (1800 kg/m^3).

Alternative no. I2:

Interior wall for 100% of the wall area: 0.3 cm interior cementitious rendering (2000 kg/m^3), 7 cm autoclaved aerated concrete block (2350 kg/m^3), 0.3 cm interior cementitious rendering (2000 kg/m^3).

<u>Floor / ceiling elements:</u>

(All data is for floor – top down. For the ceiling, same layers must be taken, but in a reverse order):

Alternative FC1:

Floor: 4 cm concrete (2350 kg per m^3, including terrazzo finish), 2 cm cementitious mortar (2000 kg/m^3), 6 cm compacted sand (1600 kg/m^3), 14 cm concrete (2350 kg/m^3), 1 cm cement-lime rendering (1800 kg/m^3).

Option FC2:

Floor: 0.8 cm ceramic tiles (2300 kg/m^3), 2 cm cementitious mortar (2000 kg/m^3), 6 cm compacted sand mixed with cement (1800 kg/m^3), 14 cm concrete (2350 kg/m^3), 1 cm cement-lime rendering (1800 kg/m^3).

These are the most common alternatives. In reality any combination of them may be found.

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