# RESIDUAL RADIOACTIVE MATERIAL GUIDELINES: METHODOLOGY AND APPLICATIONS*

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## ABSTRACT

A methodology to calculate residual radioactive material guidelines was developed for the U.S. Department of Energy (DOE). This methodology is coded in a menu-driven computer program, RESRAD, which can be run on IBM or IBM-compatible microcomputers. Seven pathways of exposure are considered: external radiation, inhalation, and ingestion of plant foods, meat, milk, aquatic foods, and water. The RESRAD code has been applied to several DOE sites to calculate soil cleanup guidelines. This experience has shown that the computer code is easy to use and very user-friendly.

## INTRODUCTION

The U.S. Department of Energy (DOE) has established radiological protection guidelines for the cleanup of residual radioactive material at sites administered under the Formerly Utilized Sites Remedial Action Program (FUSRAP) and the Surplus Facilities Management Program (SFMP) (1). The guidelines establish radionuclide concentrations or radioactivity levels that are acceptable if the site is to be used without radiological restrictions. Guidelines can be categorized as either (1) generic (or site-independent), i.e., taken from existing radiation protection standards, or (2) site-specific, i.e., derived from basic dose limits using site-specific models and data. Generic guidelines for radium-226, radium-228, thorium-230, and thorium-232 are presented in Ref. 1. For other radionuclides, the procedures and data for deriving site-specific soil guidelines are provided in Ref. 2, and have also been coded in a microcomputer program called RESRAD. This program can be run on IBM or IBM-compatible computers, is menu-driven, and is extremely user-friendly.



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This paper describes the concepts and procedures underlying the RESRAD program. A set of selected input screens for a sample application is also provided, along with a sample results display, to demonstrate the use of the program.

## PROCEDURES TO DERIVE SITE-SPECIFIC GUIDELINES

Site-specific soil guidelines are based on the requirement that the 50-year committed effective dose-equivalent for a hypothetical individual who lives or works on the site or in its immediate vicinity should not exceed 100 mrem/yr following decontamination of the site. The derivation of soil guidelines is generally based on a presumed worst-case plausible-use scenario of the site. It is assumed that, after decontamination, the site will be used without radiological restrictions. Although the soil cleanup guidelines are derived based on a dose limit of 100 mrem/yr, the dose incurred by a potential future user will be far below 100 mrem/yr because all sites will be decontaminated to a level that is as low as reasonably achievable (2). Two general exposure scenarios used are on-site resident and industrial worker scenarios. Once the exposure scenario is defined by the user based on the potential future use of the site, there are three steps to derive site-specific soil guidelines: (1) exposure pathways determination, (2) pathway factors calculations, and (3) guidelines calculations. These steps are discussed below.

### Exposure Pathways Determination

The determination of exposure pathways for the exposure scenario considered depends on the specific conditions of the site. Seven pathways are considered in the program: (1) direct exposure to external radiation from the contaminated soil materials, (2) internal radiation from inhalation, (3) internal radiation from ingestion of plant foods grown on-site and irrigated with water drawn from an on-site well or pond, (4) internal radiation from ingestion of meat from livestock fed with fodder grown on-site and water drawn from an on-site well or pond, (5) internal radiation from ingestion of milk from livestock fed with fodder grown on-site and water drawn from an on-site well or pond, (6) internal radiation from ingestion of aquatic food (fish) from a nearby pond, and (7) internal radiation from drinking water from an on-site well or pond. These pathways are illustrated in Fig. 1. If certain pathways are considered to be negligible or not contributing to the total dose, they can be eliminated by setting certain parameters to zero in the RESRAD code (2).

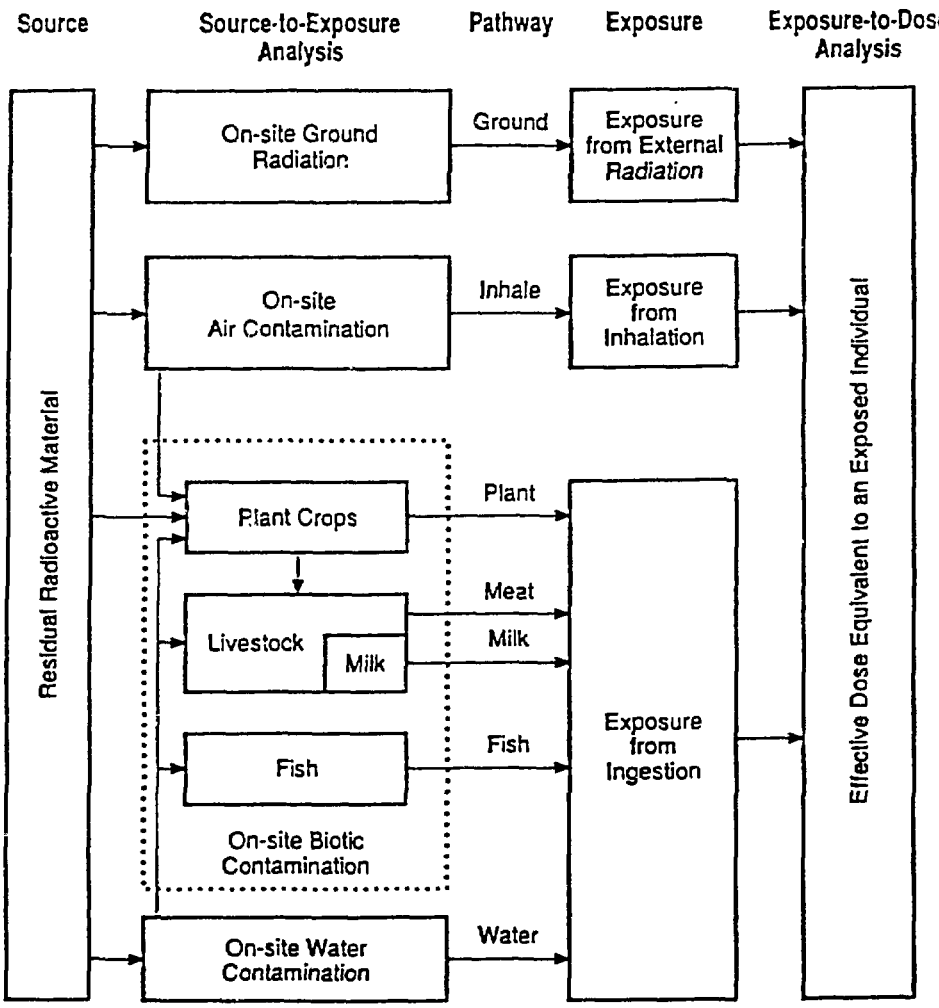


Fig. 1 Exposure Pathways Considered in the RESRAD Code

## Pathway Factors Calculations

For each pathway considered, pathway factors must then be calculated. These factors relate pathway compartments in the environment between which radionuclides can be transported or radiation can be transmitted. Most pathway factors are concentration ratios in adjoining compartments. Some are factors for converting a radionuclide concentration to a radiation level or radiation dose, and some are use and occupancy factors that affect exposure. The radiation dose to an individual is expressed as a pathway sum consisting of a sum of products of pathway factors.

The calculation of pathway factors is discussed in detail in Ref. 2, but is summarized below.

External Radiation Pathway. The dose due to external gamma radiation is first calculated for an individual exposed continuously to radiation from an infinite contaminated zone at a distance of 1 m from the ground surface. Correction factors are then applied for the (1) finite area and thickness of the contaminated zone, (2) shielding by a cover of uncontaminated soil, (3) an irregular shape, (4) shielding by the floors and walls of a house, and (5) less-than-continuous occupancy.

Inhalation Pathway. An inhalation pathway consists of two segments: (1) an airborne exposure segment linking the source (the contaminated zone) with the airborne radionuclides at an exposure location and (2) an inhalation segment linking the airborne radionuclides with the exposed individual. The latter segment is characterized by an occupancy factor (equivalent fraction of time during which an individual inhales contaminated air) and an inhalation rate. The first segment is characterized by an area and depth factor and a mass loading factor, defined as the ratio of the airborne concentration of a radionuclide at a human exposure location to the concentration in the soil.

Ingestion Pathways. Ingestion pathways include the ingestion of plant foods, meat, milk, aquatic food, and drinking water from the site (see Fig. 1). These ingestion pathways may be classified as water-independent or water-dependent, in reference to water that has been contaminated by radionuclides leached from the contaminated zone. The direct root uptake and foliar deposition pathways for plant food, meat, and milk are water-independent. The water-dependent pathways are (1) the irrigation water pathway for plant food, meat, and milk, (2) the livestock water pathway for meat and milk, (3) the aquatic food pathway, and (4) the drinking water pathway. In regions where natural rainfall is the only source of water used in raising crops, only the last three of these water-dependent pathways are applicable. If ditch irrigation is used, there will be an additional contribution from root uptake of contaminated irrigation water by plant foods and fodder. If overhead irrigation is used, the contribution from the subpathways for foliar and root uptake from irrigation water must be added.

The water-independent pathways are assumed to contribute to the dose as soon as a family establishes a residence and garden on the site. The time dependence of these pathways is determined by the time dependence of the cover depth and the radionuclide concentration in the contaminated zone. The contribution from water-dependent pathways is delayed until radionuclides transported by groundwater reach a point of water withdrawal. The time dependence of these pathways is determined by the time dependence of the radionuclide concentration in the contaminated water, as determined by the hydrological model used for the groundwater pathway segment. A fraction of a radionuclide will have been leached from the root zone before the radionuclide first reaches a point of water withdrawal in above-background concentrations; hence, the contributions to the dose from the water-independent and water-dependent pathways will occur at different times.

Radionuclide transport through the food pathways will be determined by the quantities of different foods consumed (dietary factors), the fraction of the diet from food that is contaminated by radionuclides from the contaminated zone (the area factor), the cover and contaminated zone thicknesses relative to the root zone of the plants (the cover and depth factors), the various transfer factors from root or foliage to plants and from fodder or water to meat or milk, and the concentrations of radionuclides in water that has percolated through the contaminated zone.

### Guideline Calculations

The pathway factors are used to calculate the dose-to-source concentration ratios, which are then used to calculate the guidelines. The dose-to-source concentration ratio for each pathway can be calculated by multiplying the pathway factors by the dose conversion factor and the source factor (primarily a correction factor for radioactive ingrowth and decay). The total dose-to-source concentration ratio is the sum of the ratios for each pathway. The residual radioactive material guideline is calculated by dividing the basic dose limit of 100 mrem/yr by the total dose-to-source ratio.

## SAMPLE APPLICATION

Figure 2 shows the RESRAD main menu (R010), which is the starting point for using the RESRAD code. User selections from the data and function categories listed bring up the appropriate menus for entering the data needed for a given application. Output reports are also accessible from the main menu. As an example, Figs. 3-7 show the RESRAD menus corresponding to categories 1, 3, 6, 7, and 8 on the main menu. The input data shown were taken from the deep-well exposure scenario (a plausible scenario) used to derive the uranium and cesium-137 residual radioactive material guidelines for the Niagara Falls Storage Site (3).

Once all the parameter values are entered (or modified), the RESRAD program can be executed by selecting function category 9 on the main menu (see Fig. 2). The pathway factors, dose-to-source concentration ratios, guidelines, and intermediate computational results are saved and can be reviewed through the RESRAD file-review utility (function category 10 on the main menu). Figure 8 shows a printout of results containing the dose-to-source ratios and guidelines calculated for the sample application shown in Figs. 3-7.

```
RESRAD: Residual Radioactivity Program                          (R010)
-------------------------------------------------------------------------
                        RESRAD Main Menu
-------------------------------------------------------------------------
   You may now access specific RESRAD data, or you may run the RESRAD code.

            ---------- Major Data and Function Categories ----------

     1. Title, user data files, and contaminated zone parameters
     2. Initial concentrations of principal radionuclides
     3. Contaminated and saturated zone hydrological data
     4. Uncontaminated and unsaturated strata hydrological data
     5. Distribution coefficients for transport by groundwater
     6. External gamma and dust inhalation parameters
     7. Ingestion pathway data, dietary parameters
     8. Ingestion pathway data, non-dietary parameters

     9. Execute the code

    10. View latest RESRAD output (or any ASCII file)
-------------------------------------------------------------------------
   Enter 1-10 from above list to select data or function category: 1
   Or press "F1" or "F2" for HELP, or "Esc" to EXIT from RESRAD system.

Input a number from 1 through 10, and press "Enter" key to continue.
```

Fig. 2 RESRAD Main Menu

```
RESRAD: Residual Radioactivity Program                          (R011)
-------------------------------------------------------------------------
              Title, User Data Files, and Contaminated Zone Parameters
-------------------------------------------------------------------------
   You may now view or modify any of the following non-hydrological data.

Title: NFSS uranium and Cs-137 (deep aquifer)

Site-specific data file (initial): NFSSDEEP.DAT
Site-specific data file (final):   NFSSDEEP.DAT
Printer output (LPT1 or file):     LPT1

                  Area of contaminated zone:  37000      square meters
                                 Cover depth:  0         meters
            Thickness of contaminated zone:  6           meters
          Length parallel to aquifer flow:  120         meters
                                Erosion rate:  0         meters/year
              Basic radiation dose limit:  100           millirem/year

Times for calculations:    1   10   100   250   500   750  1000     0     0
                (years since initial time, 32767 is maximum)
-------------------------------------------------------------------------
Press "F1" or "F2" for HELP, or "Esc" to IGNORE CHANGES and return to main menu.
                  Press "F10" to SAVE DATA AND CONTINUE.
What title should be used in the output of this program?
```

Fig. 3 RESRAD Menu 1

```
RESRAD: Residual Radioactivity Program                              (R013)
-------------------------------------------------------------------------
                Contaminated and Saturated Zone Hydrological Data
-------------------------------------------------------------------------
        You may now modify any of the following hydrological input data.

            Density of contaminated zone:  1.8          grams/cubic centimeters
               Density of saturated zone:  1.7          grams/cubic centimeters
                  Well pump intake depth:  4            meters below water table
       Effective saturated zone porosity:  .1
  Contaminated zone waterosity/porosity:  .4
         Evapotranspiration coefficient:  .85
  Saturated zone hydraulic conductivity:  72.1         meters/year
      Hydraulic gradient at water table:  .0016
                          Precipitation:  .89          meters/year
                             Irrigation:  .2           meters/year
                        Irrigation mode:  0        (0 for overhead; 1 for ditch)
                     Runoff coefficient:  .2
Watershed area for nearby stream or pond:  100000      square meters
    Distance from surface to water table:  15          meters
    Crossover area (for model selection):  1000        square meters
         Individual's use of groundwater:  500         cubic meters/year
Press "F1" or "F2" for HELP, or "Esc" to IGNORE CHANGES and return to main menu.
                    Press "F10" to SAVE DATA AND CONTINUE.
What is the density of the site's contaminated zone?
```

Fig. 4 RESRAD Menu 3

```
RESRAD: Residual Radioactivity Program                              (R016)
-------------------------------------------------------------------------
                External Gamma and Dust Inhalation Parameters
-------------------------------------------------------------------------

            You may now modify any of the following input data.

                                Inhalation rate:  8400        cubic meters/year

                      Mass loading for inhalation:  .0002     grams/cubic meter

Occupancy and shielding factor (external gamma):  .6

                     Occupancy factor (inhalation):  .5

                     Shape factor (external gamma):  1

Height of mixing for airborne dust (inhalation):  3          meters


Press "F1" or "F2" for HELP, or "Esc" to IGNORE CHANGES and return to main menu.
                    Press "F10" to SAVE DATA AND CONTINUE.
What is the inhalation rate?
```

Fig. 5 RESRAD Menu 6

```
RESRAD: Residual Radioactivity Program                              (R017)
-------------------------------------------------------------------------
                  Ingestion Pathway Data, Dietary Parameters
-------------------------------------------------------------------------
                  You may now modify any of the following input data.

    Fruits, vegetables and grain consumption:  160        kilograms/year
                  Leafy vegetable consumption:  14        kilograms/year

                          Milk consumption:  92           liters/year

                 Meat and poultry consumption:  63        kilograms/year

                          Fish consumption:  5.4          kilograms/year
                 Other seafood consumption:  .9           kilograms/year

                      Drinking water intake:  410         liters/year

    Fraction of drinking water from site:  1              (0-1)
      Fraction of aquatic food from site:  .5             (0-1)
-------------------------------------------------------------------------

Press "F1" or "F2" for HELP, or "Esc" to IGNORE CHANGES and return to main menu.
                  Press "F10" to SAVE DATA AND CONTINUE.
How much fruits, vegetables and grain products does a human eat?
```

Fig. 6 RESRAD Menu 7

```
RESRAD: Residual Radioactivity Program                              (R018)
-------------------------------------------------------------------------
              Ingestion Pathway Data, Non-Dietary Parameters
-------------------------------------------------------------------------
                  You may now modify any of the following input data.

    Livestock fodder intake for meat:  68         kilograms/day
                  "       "     "  " milk:  55     kilograms/day

    Livestock water intake for meat:  50          liters/day
                  "       "     "  " milk:  160    liters/day

    Mass loading for foliar deposition:  .0001    grams/meter**3
                  Depth of soil mixing layer:  .15  meters

---------- Ground Water Fractional Usage (balance from surface water) ----------

                          Drinking water:  1      (0-1)
                          Livestock water:  1     (0-1)
                              Irrigation:  1      (0-1)
-------------------------------------------------------------------------

Press "F1" or "F2" for HELP, or "Esc" to IGNORE CHANGES and return to main menu.
                  Press "F10" to SAVE DATA AND CONTINUE.
How much fodder does a "meat" cow eat?
```

Fig. 7 RESRAD Menu 8

Residual Radioactivity Program, Version 2.11 01/16/89 16:35 Page 14
Summary : NFSS uranium and Cs-137 (deep aquifer) File: NFSSDEEP.DAT

Dose/Source Ratios Summed Over All Pathways, (mrem/yr)/(pCi/g)

| Nuclide (i) | t= 0 | 1 | 10 | 100 | 250 | 500 | 750 | 1000 |
|---|---|---|---|---|---|---|---|---|
| Cs-137 | 3.016E+00 | 1.709E+00 | 1.378E-02 | 3.315E-10 | 5.461E-02 | 7.456E-06 | 0.000E+00 | 0.000E+00 |
| U-234 | 1.892E-01 | 1.840E-01 | 1.439E-01 | 1.465E-02 | 3.188E-03 | 5.278E-03 | 6.211E-03 | 6.538E-03 |
| U-235 | 7.054E-01 | 6.200E-01 | 2.366E-01 | 1.850E-02 | 3.739E-03 | 9.960E-04 | 2.472E-04 | 5.612E-05 |
| U-238 | 2.443E-01 | 2.349E-01 | 1.677E-01 | 1.257E-02 | 3.578E-04 | 4.393E-06 | 5.559E-06 | 8.282E-06 |

Single Radionuclide Soil Guidelines G(i,t) in pCi/g
Basic Radiation Dose Limit = 100 mrem/yr

| Nuclide (i) | t= 0 | 1 | 10 | 100 | 250 | 500 | 750 | 1000 |
|---|---|---|---|---|---|---|---|---|
| Cs-137 | 3.316E+01 | 5.852E+01 | 7.259E+03 | 3.017E+11 | 1.831E+03 | 1.341E+07 | *8.653E+13 | *8.653E+13 |
| U-234 | 5.287E+02 | 5.435E+02 | 6.952E+02 | 6.827E+03 | 3.137E+04 | 1.895E+04 | 1.610E+04 | 1.529E+04 |
| U-235 | 1.418E+02 | 1.613E+02 | 4.227E+02 | 5.404E+03 | 2.674E+04 | 1.004E+05 | 4.045E+05 | 1.782E+06 |
| U-238 | 4.094E+02 | 4.257E+02 | 5.963E+02 | 7.956E+03 | 2.794E+05 | *3.360E+05 | *3.360E+05 | *3.360E+05 |

*At specific activity limit

Summed Dose/Source Ratios DSR(i,t) in (mrem/yr)/(pCi/g)
and Single Radionuclide Soil Guidelines G(i,t) in pCi/g
at tmin = time of minimum single radionuclide soil guideline
and at tmax = time of maximum total dose = 0 years

| Nuclide (i) | Initial pCi/g | tmin (years) | DSR(i,tmin) | G(i,tmin) (pCi/g) | DSR(i,tmax) | G(i,tmax) (pCi/g) |
|---|---|---|---|---|---|---|
| Cs-137 | 1.000E+00 | 0 | 3.016E+00 | 3.316E+01 | 3.016E+00 | 3.316E+01 |
| U-234 | 1.000E+00 | 0 | 1.892E-01 | 5.287E+02 | 1.892E-01 | 5.287E+02 |
| U-235 | 4.600E-02 | 0 | 7.054E-01 | 1.418E+02 | 7.054E-01 | 1.418E+02 |
| U-238 | 1.000E+00 | 0 | 2.443E-01 | 4.094E+02 | 2.443E-01 | 4.094E+02 |

Fig. 8 RESRAD Guideline Summary Results

## CONCLUSIONS

A pathways analysis computer program called RESRAD has been developed for DOE to calculate site-specific residual radioactive material guidelines for FUSRAP and SFMP sites. The code considers the potential radiation doses resulting from seven exposure pathways: (1) direct exposure to external radiation, (2) inhalation, (3) ingestion of plant foods, (4) ingestion of meat, (5) ingestion of milk, (6) ingestion of aquatic food, and (7) ingestion of water.

The RESRAD code has been applied to derive soil cleanup guidelines for several FUSRAP sites being decontaminated. The experience gained indicates that a comprehensive set of site-specific hydrogeological and geochemical input parameters must be used for a realistic pathway analysis. The RESRAD code is easy to use and very user-friendly.

## REFERENCES

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