**OAK RIDGE
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LOCKHEED MARTIN

**SAFETY EVALUATION REPORT
FOR THE TENNESSEE VALLEY
AUTHORITY'S PLAN TO
DECOMMISSION ITS LOW-LEVEL
RADIOACTIVE WASTE BURIAL SITE
AT MUSCLE SHOALS, ALABAMA**

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FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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FOR THE TENNESSEE VALLEY AUTHORITY'S PLAN
TO DECOMMISSION ITS LOW-LEVEL RADIOACTIVE
WASTE BURIAL SITE AT MUSCLE SHOALS, ALABAMA**

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ACRONYMS AND ABBREVIATIONS

ALARA	as low as reasonably achievable
ALI	annual limit on intake
Ag	silver
Am	americium
Au	gold
Ba	barium
Bi	bismuth
$\beta\gamma$	beta and/or gamma radiation
C	carbon
Cd	cadmium
Ce	cerium
CFR	<i>Code of Federal Regulations</i>
Cl	chlorine
Co	cobalt
cm	centimeter (10^{-2} meter)
Cs	cesium
d	day
EN	multiplied by 10 to the <i>N</i> power ($2E-3 = 2 \times 10^{-3}$)
Eu	europium
FR	<i>Federal Register</i>
ft	feet
g	gram
gal	gallon
H	hydrogen
h	hour
ha	hectare (10^4 square meters)
HEPA	high-efficiency particulate air (filter)
in.	inch
K	potassium
kg	kilogram (10^3 gram)
km	kilometer (10^3 meter)
L	liter
lb	pound
LLRWBS	Low-Level Radioactive Waste Burial Site
m	meter
Mn	manganese
mr	milliroentgen (10^{-3} roentgen, now usually written mR)
mrem	millirem (10^{-3} rem)
mSv	millisievert (10^{-3} sievert)
μ Ci	microcurie (10^{-6} curie)
Na	sodium
nCi	nanocurie (10^{-9} curie)
NFERC	National Fertilizer Environmental Research Center
NRC	Nuclear Regulatory Commission

ORNL	Oak Ridge National Laboratory
Pb	lead
pCi	picocurie (10^{-12} curie)
Po	polonium
Ra	radium
RESRAD	code system to implement RESidual RADioactive material guidelines
Rn	radon
Ru	ruthenium
s	second
Sb	antimony
SER	Safety Evaluation Report
Sr	strontium
TEDE	total effective dose equivalent
Th	thorium
TVA	Tennessee Valley Authority
U	uranium
y	year
Zn	zinc

EXECUTIVE SUMMARY

From 1966 to 1981, the Tennessee Valley Authority (TVA) operated a burial site, licensed under the former 10 CFR 20.304, for low-level radioactive waste on its Muscle Shoals, Alabama, reservation. TVA submitted a decommissioning plan for the burial site and requested approval for unrestricted use of the site. The Nuclear Regulatory Commission requested Oak Ridge National Laboratory (ORNL) to evaluate this plan to determine if the site meets the radiological requirements for unrestricted use as specified in 10 CFR 20.1402; that is, an average member of the critical group would not receive more than 25 mrem/y from residual radioactivity at the TVA Low-Level Radioactive Waste Burial Site and the radioactivity has been reduced to levels as low as reasonably achievable (ALARA).

ORNL reviewed information on the geohydrology of the site, inventory and burial records, and environmental sampling in the area, as well as the TVA analysis of the projected impacts of decommissioning the site. ORNL modeled the projected doses from the burial site using the RESRAD model and a range of modeling assumptions about future conditions and uses of the site. All the RESRAD simulations began in 1981, the year of the last burial, and assumed a particular scenario for a 1000-y period. ORNL chose a set of alternative geohydrologic parameters from within an appropriate range of values to ensure a conservative, yet potentially realistic, estimate of future dose rates assuming the burial area is not located over conduits in the groundwater zone. Each scenario was examined with both the TVA and ORNL geohydrologic parameters. ORNL also reviewed TVA's estimate of dose from radioisotopes not included in the RESRAD model.

The estimated maximum annual doses calculated using RESRAD ranged from 0.6 to 20.4 mrem/y. These hypothetical doses would have occurred 0–3.6 y after burials ceased, or around 1981–1985. The dose from C-14 through the water pathway was the principal contributor to the larger annual doses. The projected annual doses decrease fairly quickly after reaching their maximum. By 16 years (1997), the projected dose rates ranged from $\sim 10^{-6}$ to 0.2 mrem/y. At 100 y (2081), the range was $\sim 10^{-7}$ to 0.04 mrem/y. There is a small, secondary dose rate peak in some scenarios at around 300 y (2281) attributed to Am-241, although the highest value obtained at 300 y was less than 0.2 mrem/y; the annual doses decrease again before the end of the 1000-y period considered.

The ORNL-estimated geohydrologic parameters slow the movement of the contaminants out of the area, producing somewhat higher future doses and higher concentrations in the water from a well at the boundary of the contaminated area than those calculated with the TVA parameters. All the dose estimates are thought to be conservative. The peak annual doses estimated would not have occurred, because many of the scenario assumptions about the condition and use of the site did not occur during the time period between 1981 and the present.

The projected future annual dose rates would be less than 25 mrem/y, considering both the doses modeled with RESRAD and the conservative estimate of dose from the remaining radionuclides. The site meets the radiological requirements for unrestricted use. To maintain radiation exposures ALARA, ORNL suggests that TVA continue to maintain and restrict access to the site until it has another use for the land. If the land should be transferred or leased to another party,

TVA should provide information on the site and original inventory to reduce the probability of unplanned disturbance of the burial site.

1. INTRODUCTION

1.1 BACKGROUND

The Tennessee Valley Authority (TVA) operated a burial site for low-level radioactive waste on the Muscle Shoals reservation from 1966 until 1981. The site was operated under the regulatory requirements of 10 CFR 20.304 and license number 01-06113-02 issued by the Atomic Energy Commission [predecessor to the Nuclear Regulatory Commission (NRC)] to the TVA Office of Agricultural and Chemical Development on July 15, 1964. The burial site was closed after January 1981 because 10 CFR 20.304 was no longer in effect after January 29 of that year (Johnson 1998). After that time, the small quantities of new radioactive wastes produced at Muscle Shoals were shipped to other TVA facilities for disposal with their wastes.

In 1995, TVA notified the NRC that it no longer intended to use this site for burial of low-level radioactive materials and, as required by 10 CFR 30.36(d), would develop a decommissioning plan for the site (Williams 1995). In September 1997, TVA submitted an assessment of the environmental effects of the site and requested release for "unrestricted access" for the site (Sorrelle 1997). The NRC then requested Oak Ridge National Laboratory (ORNL) to provide an independent evaluation of the plan by preparing a Safety Evaluation Report (SER).

This SER reviews TVA's environmental assessment to determine if the plan for releasing the site meets the radiological requirements for unrestricted use set by 10 CFR 20.1402:

A site will be considered acceptable for unrestricted use if the residual radioactivity that is distinguishable from background radiation results in a TEDE to an average member of the critical group that does not exceed 25 mrem (0.25 mSv) per year, including that from groundwater sources of drinking water, and the residual radioactivity has been reduced to levels that are as low as reasonably achievable (ALARA). Determination of the levels which are ALARA must take into account consideration of any detriments, such as deaths from transportation accidents, expected to potentially result from decontamination and waste disposal.

1.2 SITE DESCRIPTION

The TVA Environmental Research Center is located on a 1,050-ha (2,600-acre) reservation south of the Tennessee River (downstream of Wilson Dam) and north of the city of Muscle Shoals, Alabama. While diversified environmental research is now performed, the reservation was once the site for government nitrate plants that manufactured explosives for use in World War I. After TVA was created, the munitions plants were converted to produce phosphate fertilizers (TVA 1998a). Until recently, the site was known as the National Fertilizer Environmental Research Center (NFERC).

The Low-Level Radioactive Waste Burial Site (LLRWBS) is located near the southwest corner of the reservation (Fig. 1), about 2.3 km (1.4 miles) from the Tennessee River. The land surface elevation at the LLRWBS is about 163 m (525 ft) above mean sea level. Surface water runoff from the vicinity of the LLRWBS reaches the Tennessee River via a small, unnamed stream that flows north-northwest and collects drainage from the western part of the reservation. Several

Fig. 1. Location of radioactive waste burial site within southwestern corner of TVA's Muscle Shoals, Alabama, reservation. Insets show (left) approximate location of the Muscle Shoals site and (right) arrangement of burial holes within the fenced area. The coordinates on the map are in feet; the distance between tick marks is 1000 ft. *Sources:* "Monitoring Well Locations and Inactive Low-Level Radioactive Waste Burial Site Plant Map, Muscle Shoals, Al.," Drawing No. B23350ARO, Western Engineering Design, Muscle Shoals, Ala., June 25, 1996, Sheet 1 of 2; H. E. Julian, S. C. Young, C. Lu, J. C. Herweijer, and K. E. Richter, *NFERC Regional Groundwater Investigation*, WR28-1-520-191, Tennessee Valley Authority Engineering Laboratory, Norris, Tenn., April 1993, Fig. 1-1; and *Description of a Low-Level Radioactive Material Burial Site on the Tennessee Valley Authority Reservation in Muscle Shoals, Alabama*, Tennessee Valley Authority, Muscle Shoals, Ala., 1995, Fig. 2.

other large industrial sites adjoin the Environmental Research Center to the east, and these facilities lie in a generally upgradient region with respect to the regional groundwater flow system.

The area around the LLRWBS is not densely populated, but development is occurring. Strip development has occurred along the highways bordering the reservation near the burial area, and the LLRWBS could be subject to development pressure. TVA has said that it is committed to future industrial use of the reservation and has no plans at this time for any other activity at the LLRWBS. Municipal water is available in the area, so that new development is not likely to rely on wells for drinking water.

The material buried at the site was generated by organizations within TVA under several licenses. The inventory of the site originally included over 50 different radionuclides; only 22 of the longer-lived radionuclides remained in TVA's August 1995 inventory. Most of the materials buried were contaminated with radioactive by-product materials used in agricultural experiments and nearby laboratories. There is a small quantity of a special nuclear material, enriched uranium, thought to be waste from quality control checks of reactor fuel pellets (TVA 1995).

The LLRWBS is about 30 m $\times$ 30 m (100 ft $\times$ 100 ft) and surrounded by a 3-m (10-ft) exclusion fence. Less than one third of the fenced area was used for disposal. Forty-two holes, located in five rows, were dug at the site (see inset in Fig. 1). Holes in the first three rows were spaced about 2 m (7 ft) apart, while the spacing is greater in the last two rows. Each hole is 0.6 m (2 ft) in diameter and 3 m (10 ft) deep. The holes were filled to a depth of 1.8 m (6 ft) with waste and capped with 1.2 m (4 ft) of clay. Two holes (41 and 42) were never used and were eventually filled with clean cover material. Each hole is currently marked with a metal pole and tag (TVA 1995).

Transfers of radioactive waste material for disposal at the site were generally documented by internal memoranda. In some cases, there are only notations of activity, radionuclide, and date. In one transfer, the radionuclides were not specified. There are a few cases where the physical nature of the buried material is described (e.g., soil, plant material, planchets, HEPA filter, etc.), but, in most cases, only the radionuclide and its activity are given (TVA 1998b). These records were used to prepare an August 1995 inventory for each hole (TVA 1995, Appendix 3) and the total inventory for the LLRWBS (TVA 1995, Appendices 1 and 2).

1.3 REPORTS AND RECORDS REVIEWED

The NRC provided ORNL copies of the materials that TVA had submitted (Williams 1995; Sorrelle 1997). These materials included an inventory of the burial site (TVA 1995), a report on groundwater in the area (Julian et al. 1993), and TVA's assessment of the impact of the LLRWBS (TVA 1997). TVA provided copies of the appendices to the groundwater study and a report providing additional information on the geohydrology of the reservation (Julian 1998a). ORNL performed an initial review of this material before a site visit on June 29–30, 1998.

During the site visit, TVA provided additional records and materials. These included maps of the site, copies of memoranda documenting transfer of materials for disposal (TVA 1998b), and a well-installation record for a sampling well near the site (TVA 1996). Following the site visit,

TVA sent the NRC the results of radiological analyses of soil samples taken within the LLRWBS (Dillard 1996) and water samples from the downgradient sampling well (Frederick 1996a,b; 1997). The additional materials were reviewed and incorporated into the ORNL analysis.

2. REVIEW OF LICENSEE'S DATA AND ANALYSIS

2.1 INVENTORY RECORDS

TVA had originally provided a description of the burial site that listed only the quantities of the individual radionuclides buried in each hole (TVA 1995). No information was provided on the physical nature (volume, density, etc.) of the material buried. During the site visit, TVA provided a collection of internal memoranda and handwritten notes documenting transfers of material for burial. These documents were reviewed to learn more about the nature of the material buried; information in the original memos, particularly that on longer-lived radionuclides, was checked against the summary data. There were some discrepancies in the two sets of materials, which were resolved by checking the original documentation. Corrections were made to the inventory quantities when warranted. These adjustments are described in Table 1.

The internal TVA transfer memos often listed the activities being transferred as "less than" some value (TVA 1998b). The "less than" was dropped in the inventory (TVA 1995), so that the activities are listed at the maximum value for the analysis, adding conservatism to the assessment.

2.2 TVA SAMPLING DATA

During the site visit, ORNL learned that TVA had taken soil samples around the LLRWBS and had drilled one monitoring well downgradient of the burial site. TVA agreed to provide the results from the analysis of the samples.

Surface and subsurface soil samples were collected to a depth of 49 m (16 ft) at 7 soil boring locations within the LLRWBS and one designated "background" location at the site perimeter. The soil analyses showed only naturally occurring radionuclides above detection limits, with the exception of Cs-137, which was detected in surface soil samples (Dillard 1996). The Cs-137 was detected in the designated "background" soil sample, as well as in all of the surface soil samples from the site (Dillard 1996). Therefore, this cesium was attributed to global fallout from historic atmospheric testing of nuclear weapons.

One groundwater monitoring well was installed at the estimated downgradient location, based on the available regional hydrogeologic data. The results of analysis of a water sample from this well (taken November 4, 1996) for H-3 and C-14 indicate that neither of these potential contaminants was present in the well water at detection limits of 795 and 652 pCi/L, respectively (Frederick 1996a). Similar results were obtained on a sample taken May 5, 1997 (Frederick 1997). Gamma spectroscopy of a water sample reported "only naturally occurring isotopes" (Frederick 1996b). No results from a radioisotopic analysis were included.

Table 1. Discrepancies in inventory

Problem	Approach taken
Unidentified bags of waste. Memo dated August 18, 1969 ^a , describes seven small plastic bags of waste, "each the size of the watermelon." Six bags are identified as having 1-4 mr $\beta\gamma$ at 1 in., while the seventh is said to contain less than 0.1 μCi of unspecified $\beta\gamma$ emitters. This material was omitted from the inventory of Hole 8.	ORNL assumed that the material in bags was similar in composition and quantity to that buried in Holes 6, 7, 9, 10, and 11 (October 1968-August 1970) ^b and selected the largest quantity of the longer-lived radionuclides in any one of these holes. The addition of 0.2 μCi of C-14, 0.007 μCi of Co-60, 0.0658 μCi of Cs-137, 0.024 μCi of H-3, and 0.55 μCi of Sr-90 (August 1995 activities) to the inventory does not make a significant change to the original radionuclide input to RESRAD, so the material in the bags was neglected.
Closure date of Hole 14. Closure date of Hole 14 should be June 1972, not April 1972, as listed in Appendix 1 ^b . The second and third of three transfers for that hole occurred in June (the first was in April).	This error does not impact the inventory.
Omission of Ba-133. Burials of Ba-133 in some holes were omitted from Appendix 1 ^b . These omissions included 0.0386 μCi (August 1995 activity) in Hole 26, 0.690 μCi in Hole 31, and 1.034 μCi in Hole 33 (as shown in Appendix 3 ^b).	The Appendix 3 ^b values are supported by transfer memos dated October 21, 1977; December 13, 1977; September 14, 1978; and January 23, 1979 ^a . The total Ba-133 activity buried was adjusted to 6.63 μCi , and the August 1995 inventory increased to 2.36 μCi instead of 0.605 μCi .
Omission of Po-208. Appendix 3 ^b shows 0.0021 μCi Po-208 buried in Hole 39 (in two transfers), with an August 1995 activity of 0.000065 μCi , while Appendix 1 ^b shows only 0.000034 μCi Po-208 in that hole.	The higher activity is supported by memos dated September 25 and November 20, 1980. ^a The total August 1995 inventory of Po-208 was increased to 0.000153 μCi .
Omission of Cs-137. The August 1995 quantity of Cs-137 in Hole 12 was 0.114 μCi in Appendix 3 ^b , instead of 0.0114 μCi shown in Appendix 1 ^b .	The higher activity is supported by a January 29, 1971, transfer memo. ^a The total August 1995 Cs-137 inventory was increased to 39.315 μCi .
Summing of uranium radionuclides. The Appendix 1 ^b listing of uranium radionuclides contains several inconsistencies with Appendix 3 ^b and the transfer memos. ^a These include the following: (1) Hole 31 contains 0.1 μCi natural uranium instead of 0.1 μCi U-235; (2) Hole 33 contains 0.081 μCi natural uranium instead of 0.081 μCi U-238; and (3) 0.39 μCi U-235 were omitted from Hole 34.	The corrected sums would be 0.3945 μCi U-235, 2.388 μCi U-238, and 3.7622 μCi natural uranium. Using the specific activity of natural uranium and the relative abundance of radionuclides in natural uranium, the activity of the natural uranium can be assigned to the constituent radionuclides. ^c The total August 1995 activities for U-235 and U-238 are then 0.477 μCi and 4.167 μCi , respectively, plus 1.9 μCi U-234 from the natural uranium.

^aDescription of a Low-Level Radioactive Material Burial Site on the Tennessee Valley Authority Reservation in Muscle Shoals, Alabama, enclosure in letter from R. J. Williams, Environmental Research Center, Tennessee Valley Authority, Muscle Shoals, Ala., to D. Heim, Material Licensing Section, U.S. Nuclear Regulatory Commission, Atlanta, Ga., Sept. 5, 1995.

^b"Record of Radioactive Wastes Buried in Each Hole at the Burial Ground, OACD, Muscle Shoals, Alabama" (collection of internal TVA memoranda), provided by P. Llewellyn, Tennessee Valley Authority, Muscle Shoals, Ala., to K. S. Gant, Oak Ridge National Laboratory, Oak Ridge, Tenn., June 30, 1998.

^cEach gram (0.705 μCi) of natural uranium contains 0.992739 g U-238 (0.336 $\mu\text{Ci/g}$), 0.007204 g U-235 (2.16 $\mu\text{Ci/g}$), and 0.000057 g U-234 (6250 $\mu\text{Ci/g}$).

2.3 SITE AND REGIONAL ENVIRONMENTAL DATA

Several documents relevant to the Muscle Shoals area geologic and hydrogeologic setting were provided by the licensee. A key document for the site is the 1993 *NFERC Regional Groundwater Investigation* (Julian et al. 1993), prepared by the TVA Engineering Laboratory. The report also includes a large amount of descriptive information on the site soils, their hydrologic properties, and aquifer conditions throughout the reservation. The reservation is located between two or three other industrial facilities and the towns of Muscle Shoals, Sheffield, and Tuscumbia. The area groundwater flow system has been well defined by hydrogeologic investigations that have been performed in the area by consultants to industrial facilities and by the State of Alabama.

Residual silty clay soils that range in thickness from about 15 to 25 m (50 to 90 ft) lie beneath the reservation (Julian et al. 1993). The soils were formed by natural weathering of the underlying Tuscumbia Limestone. Bedrock formations that outcrop in the site area include the Tuscumbia Limestone and the underlying Fort Payne Chert. Weathering of these formations has created a system of interconnected conduits in the bedrock that are collectively called the Tuscumbia-Fort Payne aquifer system.

Groundwater enters the Tuscumbia-Fort Payne aquifer as recharge through the overlying soils and as direct inflow through sinkholes and storm water injection drains. The water table generally occurs in the residual soil somewhat above the bedrock surface. A shallow monitoring well adjacent to the LLRWBS has a depth to water of about 16.5 m (54 ft) below ground surface (Julian 1998b). This well had a total depth of about 19 m (61.5 feet) and did not penetrate bedrock. Julian et. al. (1993) documented the vertical hydraulic gradient measurements at a number of well locations and found that gradients vary considerably across the site. In some areas a water table is relatively persistent in the overburden, while in other areas there is little differential between the hydraulic head levels in the overburden and the bedrock.

Groundwater in the Tuscumbia-Fort Payne aquifer is withdrawn from wells and discharges into local surface water bodies through springs in the area. The most significant spring in the area is Tuscumbia Spring, located about 6 km (3.75 miles) southwest of the Muscle Shoals reservation. Tuscumbia Spring discharges an average of 159,000 m³/d (42 million gal/d)(Julian et al. 1993) and serves as a potable water supply for the town of Tuscumbia. Other springs in the area have much lower discharge volumes.

Groundwater tracing has been used in the Tuscumbia-Sheffield-Muscle Shoals area to identify flow pathways from various points of tracer injection into the Tuscumbia-Fort Payne aquifer to area wells and springs. Tracer tests have been performed from locations on the neighboring upgradient industrial sites and from two wells on the reservation. Tracer test results typically show movement of groundwater from injection areas upgradient of the reservation and the LLRWBS to Tuscumbia Spring and to springs along the Tennessee River northwest of the burial site.

2.4 LICENSEE'S ANALYSIS

TVA's approach to the analysis followed the Branch Technical Position screening methodology (61 FR 56716). TVA completed its records review and prepared an inventory of the

radionuclides known to be in the LLRWBS (TVA 1995), which satisfied Step 1. The inventory could not pass Step 2 in the screening (Sorrelle 1997), and Step 3 could not be used because there were radionuclides with atomic numbers greater than 88 in the inventory. A more detailed analysis was therefore required.

Twenty-seven of the radionuclides in the Muscle Shoals inventory were not included in RESRAD (ANL 1997), the computer model used to estimate future doses. A separate analysis was performed on these radionuclides.

Radionuclides Not Included in RESRAD. TVA performed a conservative estimate of the dose from the radionuclides that were not included in RESRAD. TVA assumed that the entire 1997 inventory was consumed by one person in a single year and estimated the dose that year. The 1997 inventory, in this case, was reached by assuming that the total inventory buried represented the 1981 value (no decay before 1981) and calculating the decay of each radionuclide for the following 16 y.

TVA did not find a published annual limit on intake (ALI) value for Po-208. (Po-208 is not included in RESRAD.) TVA had estimated the ALI of Po-208 by adjusting the ALI of Po-210 based on the differences in radioactive half-life and the energy of the alpha emitted by the two radionuclides (TVA 1997). ORNL confirmed that neither ALI nor ingestion dose conversion factor for Po-208 were included in two commonly accepted sources (Eckerman et al. 1988; RSL 1996). Other professionals contacted (McKenna 1998; Goans 1998) were also unable to find a published value, but they confirmed that the TVA approach seemed to be a reasonable way to approximate the value.

Of the 27 radionuclides in the inventory, only Ba-133 and Po-208 remained in sufficient quantity to contribute to a dose in 1997. The TVA estimate for this dose was about 1.8 mrem (TVA 1997).

RESRAD Analysis. TVA analyzed the projected dose using RESRAD, Ver. 5.75. TVA RESRAD calculations were based on the August 1995 inventory included in the site description (TVA 1995). The 1995 inventory was determined by calculating the decay of each radionuclide in each hole from the time the hole was closed until August 1995 (TVA 1995, Appendix 3) and summing the activity of each radionuclide in the burial site at that time (TVA 1995, Appendix 1). All RESRAD calculations began at 1981, the date the LLRWBS was closed, and extended for 1000 y.

Isotopic activities used as input to RESRAD were taken from the 1995 inventory (TVA 1995) and increased to their equivalent activity level in 1981. The radionuclides were assumed to be uniformly distributed in the soil within the disposal area (i.e., mixed with the soil between the burial holes). The disposal area was modeled with a 1.22-m (4-ft) cover of clean dirt. The radon pathway was suppressed based on the small quantities of radon parents in the burial site (TVA 1997). RESRAD default parameters were used for the ingestion and exposure assumptions. The TVA calculations (TVA 1997) projected a maximum annual dose of 0.55 mrem at 1.6 y (about 1983).

3. ORNL ANALYSIS

3.1 RADIONUCLIDES NOT INCLUDED IN RESRAD

TVA's conservative estimate of the dose from 27 radionuclides in the inventory that were not included in RESRAD assumed that the entire 1997 inventory of these radionuclides was consumed by one person in a single year. ORNL corrected the Ba-133 and Po-208 activities to eliminate the summing errors previously noted (Table 1) and repeated the calculations.

The 1997 Ba-133 activity would be about $2.07\mu\text{Ci}$. This activity would increase the conservative dose estimate (TVA 1997, Table A-1) from Ba-133 from 1.4 mrem to 5.1 mrem. In 1997, the Po-208 activity would have been about $0.000095\mu\text{Ci}$. This activity would reduce the dose estimate from Po-208 to 0.02 mrem. The total estimated dose contribution from the radionuclides not included in RESRAD would be about 5.12 mrem, instead of 1.8 mrem, as shown in Table A-1 of TVA's assessment (TVA 1997).

3.2 RESRAD ANALYSIS

ORNL performed additional RESRAD analysis of the LLRWBS using different scenarios and assumptions. This analysis is based upon the information on inventory and burial practices supplied by TVA.

3.2.1 Comparison RESRAD Runs

ORNL used version 5.70 of RESRAD (ANL 1997) for its analysis. To verify that ORNL could reproduce the TVA calculation and to check for any difference resulting from the use of a more recent version of the computer model, ORNL reran RESRAD using the TVA data. The results were virtually identical. RESRAD 5.70 predicted a maximum annual dose of 0.59 mrem at 1.5 y, as compared to 0.55 mrem at 1.6 y.

Once the corrections were made to the inventory, ORNL did another comparison run. The maximum projected dose and time of occurrence did not change (to two significant digits), showing that the inventory discrepancies did not have any significant impact on the RESRAD dose projections.

3.2.2 Conceptual Model

Figure 2 shows a conceptual model of the LLRWBS with auger holes constructed in the site soil and potential contaminant migration or exposure pathways. This model provides the general basis for the evaluation of potential radiological exposure from the LLRWBS. In this model the groundwater pathway is conceptualized as (1) release of contaminants from the disposal wells with geochemical attenuation of radionuclides in the residual soil, (2) potential migration of some radionuclides to a water table aquifer in the soil, and (3) withdrawal of groundwater from a well constructed in the shallow groundwater at the edge of the disposal site. The direct exposure,

Fig. 2. Conceptual model of groundwater flow and exposure pathways from LLRWBS.

inhalation, and ingestion pathways will be more important if one assumes that the waste would be disturbed or excavated at some time in the future and spread in a layer on the ground surface where direct exposure, inhalation, and uptake by garden vegetables could occur.

3.2.3 Alternative Geohydrologic Parameters

Assessment of the potential exposure to radionuclides in the groundwater pathway considers the waste solubility, geochemical retardation in the soil mass, and hydrologic properties of the site aquifer. The LLRWBS lies in an area where solution conduits (see Fig. 2) may or may not exist in the Tuscumbia Limestone beneath the site. The presence of such conduits that would be interconnected with the Tuscumbia-Fort Payne aquifer would result in rapid groundwater movement, with substantial dilution along the flow path, to the spring or to pumped wells. This approach was used by TVA. If conduits are not present beneath the site, well water for a domestic water supply is assumed to be withdrawn from the lower part of the soil overburden zone. Radionuclide concentrations would then be higher because less mixing and dilution would occur beneath the site. Therefore, to provide a more conservative, yet potentially realistic, assessment of the higher exposure level that would occur in the absence of conduit flow, the ORNL evaluation also modeled groundwater use from the soil profile rather than from a conduit.

Hydraulic Conductivity of the Saturated Zone. The exposure scenario examined by TVA assumed a high horizontal groundwater flow velocity representative of the presence of a conduit [53.4 km/y (33.2 miles/y) for the hydraulic conductivity of the saturated zone] (Julian 1998c). ORNL chose a much lower hydraulic conductivity for this analysis, where the well of use is assumed to be at the boundary of the LLRWBS. Saturated hydraulic conductivities of 0.3–30 m/y (1–98 ft/y) were selected, based on the descriptions in the *NFERC Regional Groundwater Investigation* (Julian et al. 1993). The upper end of this range produced the largest doses, so a saturated zone conductivity of 30 m/y (98 ft/y) was chosen for the ORNL analysis. [Sensitivity studies suggest that a maximum annual dose would occur at a saturated hydrologic conductivity of 100–200 m/y (330–660 ft/y), but conductivities in this range are well outside the range consistent with the site data.]

Hydraulic Gradient of the Saturated Zone. A hydraulic gradient of 0.001–0.02 is suggested by the groundwater data (Julian et al. 1993). TVA used 0.003 in their analysis; ORNL chose the upper end of this range for conservatism.

Unsaturated Zone Hydraulic Conductivity. Data from direct measurement of the unsaturated zone hydraulic conductivity are not available for the site, so an estimated range for this parameter was used to evaluate its influence on the potential dose. The unsaturated zone conductivity depends on the moisture content of the soil (percent saturation) and the pressure head on the soil. Under conditions of low moisture content and low head, unsaturated conductivity may be less than 10% of the saturated conductivity value for a soil material, and the movement of water and dissolved constituents through the soil is much slower than under saturated conditions. As moisture content and pressure head increase, the soil becomes saturated, and, at that point, water and dissolved constituents move under a saturated flow regime. Initial dose estimates using an unsaturated conductivity parameter range of 10–25% of the saturated conductivity did not show a sensitivity to this parameter at the LLRWBS. ORNL selected a value of 3 m/y (9.8 ft/y) or 10% saturated conductivity.

3.2.4 Scenarios Examined

ORNL used RESRAD to project doses for several scenarios, which are described briefly below. These scenarios were run using both the TVA-selected and ORNL's alternative geohydrologic parameters. They represent three sets of radioisotopic concentrations, based on how much soil was mixed with the waste and the assumed density of the soil. The radon pathway was suppressed based on 62 FR 39057. The NRC recognizes that, in most cases, the radon from the licensee's activities will be indistinguishable from that from natural background, and that showing that the precursors to radon meet the requirements for unrestricted release is generally sufficient.

For consistency with TVA estimates, calculations were begun at site closure in 1981. The results of these efforts are shown in Table 2. Detailed information on data input to these scenarios is contained in the appendix.

RESRAD Resident Farmer Scenario (Cases 1 and 2). This scenario represents a resident farmer scenario and uses RESRAD defaults to describe the ingestion and exposure pathways. The radon pathway was suppressed. The radionuclide inventory is assumed to be evenly distributed through a mixture of waste and soil between the holes in the burial area. The density of all soil and of the waste-soil mixture is assumed to be 1.5 g/cm^3 (94 lb/ft^3). The contaminated volume is a 308.5-m^2 ($3,320\text{-ft}^2$) circular area, 1.83 m (6 ft) deep. The length parallel to the aquifer flow (a RESRAD input parameter) is that chosen by TVA, 17.6 m (58 ft). There is a cover layer of clean soil 1.22 m (4 ft) deep.

Case 1 represents the RESRAD resident farmer scenario using the geohydrologic parameters chosen by TVA. The ORNL geohydrologic parameters (Case 2) produced a higher maximum dose (15.1 mrem/y instead of 0.6 mrem/y) at about 2 y later. The principal contributor to the peak annual dose is C-14 through the water pathway.

Modified PG-8-08 Resident Farmer Scenario (Cases 3–6). The NRC *Policy and Guidance Directive PG-8-08: Scenarios for Assessing Potential Doses Associate with Residual Radioactivity* (NRC 1994) presents a slightly different scenario (Scenario C) to estimate the exposure of a resident farmer, the maximum reasonably exposed individual. The assumptions about the volume of contaminated material are the same. The length parallel to the aquifer was increased to 19.82 m (65 ft), the diameter of the hypothetical circular contaminated area. The density of the soil was assumed to be the PG-8-08 default value, 1.63 g/cm^3 (102 lb/ft^3), and the concentrations of the radionuclides were decreased to reflect the heavier soil.

PG-8-08 values for inhalation rate, inhalation shielding factor, fraction of time inside and outside, and quantities of food consumed were used. The RESRAD default value for soil ingestion, 36.5 g/y (0.08 lb/y), was higher than that in PG-8-08. The result was not very sensitive to this parameter and a higher value may be appropriate to this area, so the RESRAD default value was used. The RESRAD default external gamma shielding factor of 0.7 was also used, as PG-8-08 states that the building is assumed to reduce exposure by 33%. This value produced a higher external dose, but it did not have much impact on the maximum annual dose in this scenario. Typical agricultural irrigation in the Muscle Shoals area averages about 0.2 m/y (8 in./y) (Curtis 1998), so that number was used instead of the 0.76 m/y (30 in./y) value in PG-8-08. RESRAD reduced the fraction of contaminated plant food from 50% to about 15%,

Table 2. Projected annual doses and principal pathways from ORNL RESRAD analysis^{a,b}
[All doses are in mrem/y.]

Scenario ^c	Case ^d	Maximum annual dose			Annual dose at 16 y			Annual dose at 100 y			Annual dose at 300 y		
		TVA ^{e,f}	ORNL ^f		TVA	ORNL		TVA	ORNL		TVA	ORNL	
RESRAD resident farmer ^g	1,2	0.6 (w)	15.1 (w)		~10 ⁻⁶ (w)	~10 ⁻⁴ (w)		~10 ⁻⁷ (w)	~10 ⁻⁵ (w)		~10 ⁻⁴ (w)	0.001 (w)	
Mod. PG-8-08 resident farmer (with soil cover) ^g	3,4	0.9 (w)	19.2 (w)		~10 ⁻⁶ (w)	~10 ⁻⁴ (w)		~10 ⁻⁷ (w)	~10 ⁻⁴ (w)		0.002 (w)	0.2 (w)	
Mod. PG-8-08 resident farmer (no soil cover) ^g	5,6	4.1 (p,g)	20.4 (w)		0.4 (g)	0.5 (g)		0.04 (g,p)	0.04 (g,p)		0.01 (g,p)	0.2 (w)	
Mod. PG-8-08 worker ^{g,h}	7	—	0.5 (g)		—	0.1 (g)		—	0.007 (g,i)		—	0.002 (g,i)	
Mod. PG-8-08 resident farmer (contamination spread on surface) ⁱ	8,9	4.6 (p,g)	4.6 (p,g)		0.2 (g)	0.2 (g)		0.004 (g)	0.004 (g)		~10 ⁻⁶ (w)	0.02 (w)	

^a RESRAD: Code System to Implement Residual Radioactive Material Guidelines, Ver. 5.70, Argonne National Laboratory, Argonne, Ill., January 1997.

^b The TVA-chosen geohydrologic parameters, representing epicarst formations, used in the analysis were as follows: saturated zone hydraulic conductivity, 53,400 m/y; saturated zone hydraulic gradient, 0.003; unsaturated layer hydraulic conductivity, 0.3 m/y. ORNL chose the following geohydrologic parameters: saturated zone hydraulic conductivity, 30 m/y; saturated zone hydraulic gradient, 0.02; unsaturated layer hydraulic conductivity, 3 m/y.

^c Scenarios are described in Sect. 3.2.4 and in greater detail in the appendix.

^d Case numbers are shown for reference to detailed tables in the appendix.

^e The predominant exposure pathway is shown in parentheses after the projected dose: w = water pathway, p = water-independent plant pathway, g = direct exposure from ground, and i = inhalation (excluding radon). When two pathways are shown, the first had the larger impact, but the second was also significant.

^f With the TVA parameters, the maximum annual dose occurs at 1.5 y for Cases 1 and 3 and at 0 y for Cases 5 and 8. With the ORNL parameters, the maximum annual dose occurs at 3.6 y for Cases 2, 4, and 6 and at 0 y for Cases 7 and 9.

^g Radionuclide inventory is assumed to be evenly distributed through mixture of waste and soil between the holes in the burial area. In Cases 1 and 2, the soil density is assumed to be 1.5 g/cm³. In all other cases, the soil density is assumed to be 1.63 g/cm³.

^h The choice of geohydrologic parameters has no noticeable impact on the doses for this scenario, because the ingestion and water pathways are suppressed.

ⁱ Radionuclide inventory is assumed to be evenly distributed through mixture of waste, soil between the holes in the burial area, and cover material. The soil density is assumed to be 1.63 g/cm³.

based on the small area of the LLRWBS. The fractions of contaminated meat and milk were also reduced.

This scenario was run four times. The first calculations (Cases 3 and 4) assumed that the cover layer remained in place, while the remaining two runs (Cases 5 and 6) assumed that the cover layer of clean soil had been removed.

When the cover layer was in place, the maximum annual dose was 0.94 mrem/y at 1.5 y with the TVA parameters (Case 3) and 19.2 mrem/y at 3.6 y when the ORNL parameters were used (Case 4). Without a cover layer of clean soil, the values were 4.1 mrem/y at 0 y with the TVA parameters (Case 5) and 20.4 mrem/y at 3.6 y. The principal contributor to the maximum annual dose was C-14 through the water pathway in Cases 3, 4, and 6. In Case 5, the principal contributors to the peak annual dose were the water-independent plant pathway (C-14) and direct exposure to the ground (Co-60). The differences in pathways in Cases 5 and 6 at the time of the maximum dose appear to be due to the differences in the time at which those doses occurred (0 and 3.6 y, respectively). The small, secondary dose rate peak around 300 y is attributable to Am-241 and its decay products in the water pathway.

Modified PG-8-08 Industrial Worker Scenario (Case 7). Because the likely future use of the site is for industrial development, ORNL considered an industrial worker scenario, based on PG-8-08 (NRC 1994) Scenario A. The radioisotope inventory was assumed to be evenly distributed through a mixture of waste and the soil between the holes in the burial area. The contaminated volume was a 308.5-m² (3,320-ft²) circular area, 3.05 m (6 ft) deep, with a density of 1.63 g/cm³ (102 lb/ft³). There was no cover layer. This scenario considered only the external gamma and inhalation (excluding radon) pathways. The RESRAD default external gamma shielding factor of 0.7 was kept.

Suppressing the water pathways minimized the impact of the different geohydrologic parameters, so only one case was run. The maximum projected annual dose is 0.5 mrem/y at 0 y, the time of site closure. The principal contributor to the maximum annual dose was Co-60 through the direct exposure to the ground.

Modified PG-8-08 Resident Farmer Scenario (Contamination Spread) (Cases 8 and 9). This scenario was chosen to represent an extreme disturbance of the area. In this case, the contaminated volume and cover material are excavated, mixed, and spread in a circle 0.15 m (5.9 in.) deep on the surface of an undisturbed adjacent area. This depth was chosen so that the material would be plowed and have an opportunity to enter the food ingestion pathways. The surface area of the contaminated zone was increased to about 6,270 m² (1.5 acres) to maintain the same volume of contaminated material, and the length parallel to the aquifer was increased accordingly. The larger surface area permitted a higher fraction of contaminated food in the diet. The other scenario assumptions of Cases 3–6 were used.

Both sets of geohydrologic parameters produce maximum annual doses of 4.6 mrem/y at 0 y. The water-independent plant pathway (C-14) and direct exposure to Co-60 in the ground contributed significantly to the maximum annual dose.

3.3 SUMMARY OF ANALYSIS

The ORNL analysis is based upon the information on inventory and burial practices supplied by TVA. All the RESRAD dose projections began in 1981 and assumed a particular scenario for an entire 1000-y period. Many of the assumptions in the scenarios (e.g., resident farmer, water supply from well at edge of site) are known to have not occurred for the time period between 1981 and the present. The fenced burial site has been maintained and remains undisturbed. Scenarios that ignored the cover layer of clean soil produced higher maximum doses because of larger contributions from direct exposure to the ground and the water-independent plant pathway. As long as the existing cover remains in place, these doses should not occur.

The results of the analysis are conservative. No credit was taken for packaging of the materials. Although any packaging was assumed to fail immediately in the analysis, it would, in reality, delay the release of the radionuclides to the environment and allow for additional decay in place. Because of the large amount of C-14 in the inventory and its 5730-y radioactive half life, the total activity of the inventory would decay only from 1.70 nCi to 1.45 nCi over the 1000-y period. In the scenarios where the peak dose was delivered through the water pathway, C-14 was responsible for almost all the peak dose (over 98% in Case 4). C-14 moves quickly through the environment, producing its peak dose within a few years of release, and its contribution to the annual dose then begins to decrease. If any packaging has not yet failed, there could be some increase in the annual dose as the C-14 is released into the groundwater. All packaging, when present, would not be expected to fail at the same time, so the peak annual doses should be a small fraction of that calculated here.

The ORNL geohydrologic parameters produced greater or equal maximum doses in all cases, as compared to those resulting from use of the TVA parameters. The ORNL parameters were selected from within an appropriate range of values to ensure a conservative, yet potentially realistic, estimate. The high hydraulic conductivity of the saturated zone selected by TVA represents a condition in which the radionuclides move with the groundwater to karst flow conduits interconnected with the Tusculumbia-Fort Payne aquifer, where the contaminants are rapidly diluted and carried away. The alternative ORNL parameters represent a case where the burial area is not located over the conduits in the groundwater zone. These parameters slow the movement of the contaminants out of the area, producing higher future doses and higher concentrations in the water from a well at the boundary of the contaminated area. However, if the assumed alternative parameters were an accurate representation, it is unlikely that a well would produce enough water to be a satisfactory water supply. The availability of municipal water also makes well water an unlikely source of drinking water in the foreseeable future.

The scenarios examined covered a range of modeling assumptions and possible uses of the site from 1981 to 2981. The maximum annual doses calculated by RESRAD ranged from 0.6 to 20.4 mrem/y. These hypothetical doses would have occurred 0–3.6 y after burial. However, because the site was controlled at that time, those doses never occurred. Soil and groundwater samples taken at the LLRWES in the 1996 and 1997 showed no evidence of contaminant release from the burial holes at that time.

The projected annual doses decrease fairly quickly after reaching their peak. By 16 years (1997), the projected dose rates ranged from $\sim 10^{-6}$ to 0.4 mrem/y. At 100 y (2081), the range was $\sim 10^{-7}$ to 0.04 mrem/y. There is a small, secondary dose rate peak in some scenarios at around 300 y

(2281), although the highest value obtained at 300 y was less than 0.2 mrem/y. This secondary peak was due to the Am-241 in the original inventory and its radioactive progeny in the water pathway. The mean annual doses decrease again before the end of the 1000-y period.

The extremely conservative estimate of the dose from Ba-133 and Po-208, two isotopes in the inventory that are not included in RESRAD, would be at most 5.1 mrem in 1997 (assuming someone ingested the entire inventory of Ba-133 and Po-208 in that year.) Any actual dose would be a small fraction of this dose, which is almost all attributed to Ba-133. Ba-133 has a half-life of 10.74 y. Before 2025, the extremely conservative dose would be less than 1 mrem/y, based on radioactive decay alone. These two isotopes would not be expected to contribute much to a future annual dose.

4. CONCLUSIONS AND RECOMMENDATIONS

Based on the review of the burial records, sampling data, and computer modeling, an average member of the critical group should, in the future, receive less than 25 mrem/y from the Muscle Shoals LLRWBS. This conclusion considers both the doses modeled with RESRAD and the very conservative estimate of dose from the radionuclides not considered in the model. As previously discussed, the greatest portion of the estimated dose in 1997 (5.1 mrem) would be from Po-208 and Ba-133 which is assumed to be consumed in 1 y by a single individual. This is clearly a very conservative assumption, and the contribution from these isotopes would be much smaller.

The conservative RESRAD modeling shows the peak annual dose rate (20.4 mrem/y in Case 6) occurring about 3.6 y after release of all the radionuclides. The higher hypothetical doses in the early years after the LLRWBS closed are based on assumptions of use (i.e., resident farmer, drinking water from well) and condition (loss of cover layer) which have not occurred. The area remains fenced, unused, and under TVA control. The water and soil samples taken at the burial site in recent years, while limited in number, show no evidence of radionuclide migration from the buried waste. While all radionuclides would not be released at the same and may contribute to the annual dose at a later time than under the model assumptions, any future annual doses should be well below the calculated peak. Consequently, the site would meet the radiological requirements for unrestricted use (10 CFR 20.1402).

ORNL suggests that TVA should continue to maintain the site in its current fenced state until some other use is determined for the land to reduce any radiation exposure to levels as low as reasonably achievable. If the land should be transferred or leased to another party, TVA should make full disclosure of the original inventory and burial information to the new owner or leaseholder to reduce the probability of unplanned disturbance of the area.

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APPENDIX CALCULATIONAL DETAILS

This appendix contains additional details about input parameters for the RESRAD calculations. It is provided for reference and to allow the calculations to be repeated, if necessary. Table A-1 contains brief descriptions of the cases considered. The cases are numbered for ease in associating the following input information with the appropriate cases. Table A-2 lists the isotopic concentrations used as input to RESRAD. The concentrations depend on both the volume of material mixed with the radionuclides and the density assumed for the mixture. Table A-3 summarizes the remaining RESRAD input for each of the cases considered. The case numbers correspond to the descriptions in Table A-1.

Table A-1. Description of RESRAD cases considered

No.	Name	Description
1	RESRAD resident farmer/TVA	Resident farmer scenario using RESRAD defaults to describe the ingestion and exposure pathways. The radionuclide inventory is assumed to be evenly distributed through mixture of waste and soil between the holes in the burial area. There is a cover layer of clean soil. All soils were assumed to have a density of 1.5 g/cm ³ . The radon pathway was suppressed. TVA-selected geohydrologic parameters were used.
2	RESRAD resident farmer/ORNL	Case 2 is identical to Case 1, except that the alternative ORNL-selected geohydrologic parameters were used.
3	Modified PG-8-08 resident farmer (with cover)/TVA	This resident farmer scenario is based on Scenario C from the NRC <i>Policy and Guidance Directive PG-8-08: Scenarios for Assessing Potential Doses Associate with Residual Radioactivity</i> . The radionuclide inventory was assumed to be evenly distributed through mixture of waste and soil between the holes in the burial area. The cover layer is in place. All soils were assumed to have a density of 1.63 g/cm ³ . All exposure pathways except radon were considered; some inhalation, consumption, and exposure assumptions differed from those in Cases 1–2. TVA-selected geohydrologic parameters were used.
4	Modified PG-8-08 resident farmer (with cover)/ORNL	Case 4 is identical to Case 3, except that the alternative ORNL-selected geohydrologic parameters were used.
5	Modified PG-8-08 resident farmer (no cover)/TVA	Case 5 is identical to Case 3, except that no cover layer was assumed. The dimensions of the contaminated volume remained the same. TVA-selected geohydrologic parameters were used.
6	Modified PG-8-08 resident farmer (no cover)/ORNL	Case 6 is identical to Case 5, except that the alternative ORNL-selected geohydrologic parameters were used.
7	Modified PG-8-08 industrial worker/ORNL	This industrial worker scenario is based primarily on Scenario A from the NRC <i>Policy and Guidance Directive PG-8-08: Scenarios for Assessing Potential Doses Associate with Residual Radioactivity</i> . The radionuclide inventory was assumed to be evenly distributed through mixture of waste and the soil between the holes in the burial area. All soils were assumed to have a density of 1.63 g/cm ³ . This scenario considers only the external gamma and inhalation (excluding radon) pathways. Because the water pathway was suppressed, the geohydrologic parameters had no impact; only one case was run.

Table A-1. (continued)

No.	Name	Description
8	Modified PG-8-08 resident farmer (contamination spread)/TVA	This scenario represents an extreme disturbance of the area, where the contaminated volume and cover material are excavated, mixed, and spread in a circle 0.15 m deep (5.9 in) on the surface of an undisturbed adjacent area. This scenario considered all exposure pathways except radon and used the inhalation, consumption, and exposure assumptions from Cases 3–6. All soils were assumed to have a density of 1.63 g/cm ³ . TVA-selected geohydrologic parameters were used.
9	Modified PG-8-08 resident farmer (contamination spread)/ORNL	Case 9 is identical to Case 8, except that the alternative ORNL-selected geohydrologic parameters were used.

Table A-2. Radionuclide inventory and concentrations

Radionuclide	Aug 1995 activity ^a (μ Ci)	Half-life (y)	Decay factor for -14 y	1981 activity (μ Ci)	Conc. Cases 1-2 ^b (pCi/g)	Conc. Cases 3-7 ^c (pCi/g)	Conc. Cases 8-9 ^d (pCi/g)
Ag-110m	2.2E-7	0.684	1.44E+8	0.318	3.76E-4	3.46E-4	2.08E-4
Am-241	14.3	432.2	1.02	14.7	0.0173	0.0159	9.57E-3
Au-195	7.7E-13	0.501	2.57E+8	1.98E-4	2.34E-7	2.15E-7	1.29E-7
Bi-207	8.44	38.0	1.29	10.9	0.0129	0.0118	7.11E-3
C-14	1.63E+4	5730	1.00	1.63E+4	19.2	17.7	10.6
Cd-109	0.1	1.27	2078	208	0.245	0.226	0.136
Ce-144	6E-6	0.778	2.60E+5	1.56	1.85E-3	1.70E-3	1.02E-3
Cl-36	1.20	3.01E+5	1.00	1.20	1.42E-3	1.30E-3	7.83E-4
Co-57	1E-5	0.742	4.77E+5	4.77	5.63E-3	5.19E-3	3.11E-3
Co-60	18.6	5.271	6.30	117	0.139	0.128	0.0765
Cs-134	0.0972	2.062	110	10.7	0.0127	0.0117	7.01E-3
Cs-137	39.3	30	1.38	54.3	0.0641	0.0591	0.0354
Eu-152	40.8	13.33	2.07	84.6	0.0999	0.0920	0.0552
H-3	39.0	12.35	2.19	85.6	0.101	0.0931	0.0559
K-40	0.308	1.28E+9	1.00	0.308	3.64E-4	3.35E-4	2.01E-4
Mn-54	1E-5	0.856	83600	0.836	9.87E-4	9.09E-4	5.46E-4
Na-22	7.4E-5	2.602	41.6	3.08E-3	3.64E-6	3.35E-6	2.01E-6
Pb-210	0.745	22.3	1.54	1.15	1.36E-3	1.25E-3	7.51E-4
Ra-226	1.89	1600	1.01	1.90	2.25E-3	2.07E-3	1.24E-3
Ra-228	5.2E-5	5.75	5.40	2.81E-4	3.32E-7	3.06E-7	1.83E-7
Ru-106	2.00E-4	1.01	14800	2.97	3.51E-3	3.23E-3	1.94E-3
Sb-125	0.374	2.77	33.2	12.4	0.0147	0.0135	8.10E-3
Sr-90	69.6	2.912	1.40	97.1	0.115	0.106	0.0633
Th-230	0.780	77000	1.00	0.780	9.21E-4	8.48E-4	5.09E-4
U-234 ^e	1.90	245000	1.00	1.90	—	2.07E-3	1.24E-3
U-235	0.477	7.04E+8	1.00	0.477	5.64E-4	5.19E-4	3.12E-4
U-238	4.17	4.468E+9	1.00	4.17	4.92E-3	4.53E-3	2.72E-3
Zn-65	5E-6	0.668	2.03E+6	10.2	0.0120	0.0110	6.62E-3

^a Activity in 1981 taken from *Description of a Low-Level Radioactive Material Burial Site on the Tennessee Valley Authority Reservation in Muscle Shoals, Alabama*, Tennessee Valley Authority, Muscle Shoals, Ala., 1995, and adjusted for inventory discrepancies.

^b Activity in 1981 divided by mass of waste and soil in 4-10-ft layer between burial holes (8.5E+8 g). Density is assumed to be 1.5 g/cm³.

^c Activity in 1981 divided by mass of waste and soil in 4-10-ft layer between burial holes (9.2E+8 g). Density is assumed to be 1.63 g/cm³.

^d Activity in 1981 divided by mass of waste, soil in 4-10-ft layer between burial holes, and 4-ft cover layer (1.5E+9 g). Density is assumed to be 1.63 g/cm³.

^e U-234 was not included in original inventory. After corrections were made in amount of natural uranium, U-234 was included as one of the radionuclides found in natural uranium. U-234 was included in Cases 3-9, and the activities of U-235 and U-238 were decreased accordingly.

Table A-3. RESRAD input values

Variable	Value	Case
<i>Contaminated zone parameters</i>		
Area of contaminated area (m ²)	308.5	1-7
	6272.8	8-9
Thickness of contaminated zone (m)	1.83	1-7
	0.15	8-9
Length parallel to aquifer flow (m)	17.6	1-2
	19.82	3-7
	89.4	8-9
<i>Cover and contaminated zone hydrologic data</i>		
Cover depth (m)	1.22	1-4
	0 ^a	5-9
Density of cover material (g/cm ³)	1.5 ^b	1-2
	1.63 ^a	3-4
	Not used ^a	5-9
Cover erosion rate (m/y)	0.001 ^b	1-4
	Not used ^a	5-9
Density of contaminated zone (g/cm ³)	1.5 ^b	1-2
	1.63 ^a	3-9
Contaminated zone erosion rate (m/y)	0.001 ^{a,b}	1-9
Contaminated zone total porosity	0.4 ^b	1-9
Contaminated zone effective porosity	0.06	1-9
Contaminated zone hydraulic conductivity (m/y)	0.3	1-9
Contaminated zone b parameter	7.75	1-9
Humidity in air (g/m ³)	8.0 ^b	1-9
Evapotranspiration coefficient	0.5 ^{a,b}	1-9
Precipitation (m/y)	1.32	1-9
Irrigation (m/y)	0.2 ^b	1-9
Irrigation mode (overhead or ditch)	Overhead	1-9
Runoff coefficient	0.2 ^b	1-9
Watershed area for nearby stream or pond (m ²)	2.18E8	1-9
Accuracy for soil/water calculations	0.001 ^b	1-9

Table A-3. (continued)

Variable	Value	Case
<i>Saturated zone hydrologic data</i>		
Density of saturated zone (g/cm ³)	1.5 ^b	1-2
	1.63 ^a	3-9
Saturated zone total porosity	0.3 ^b	1-9
Saturated zone effective porosity	0.14	1-9
Saturated zone hydraulic conductivity (m/y)	53,400	1, 3, 5, 8
	30	2, 4, 6, 7, 9
Saturated zone hydraulic gradient	0.003	1, 3, 5, 8
	0.02 ^{a,b}	2, 4, 6, 7, 9
Saturated zone b parameter	Not used	1-9
Water table drop rate	0 ^a	1-9
Well pump intake depth (m below water table)	10 ^{a,b}	1-9
Model for water transport parameters (nondispersion or mass-balance)	Nondispersion ^b	1-9
Well pumping rate (m ³ /y)	250 ^b	1-9
<i>Uncontaminated unsaturated zone parameters</i>		
Thickness of unsaturated zone (m)	15.25	1-7
	18.15	8-9
Density of unsaturated zone (g/cm ³)	1.5 ^b	1-2
	1.63 ^a	3-6, 8-9
	Not used	7
Total porosity of unsaturated zone	0.4 ^b	1-6, 8-9
	Not used	7
Effective porosity of unsaturated zone	0.06	1-6, 8-9
	Not used	7
Hydraulic conductivity of unsaturated zone (m/y)	0.3	1, 3, 5, 8
	3.0	2, 4, 6, 9
	Not used	7
Uncontaminated zone b parameter	10.4	1-6, 8-9
	Not used	7

Table A-3. (continued)

Variable	Value	Case
<i>Occupancy, inhalation, and external gamma data</i>		
Inhalation rate (m ³ /y)	8400 ^b	1-2
	10512 ^a	3-9
Mass loading for inhalation (g/m ³)	2E-4 ^{a,b}	1-9
Dilution length for airborne dust (m)	3 ^{a,b}	1-9
Exposure duration (y)	30 ^b	1-9
Inhalation shielding factor	0.4 ^b	1-2
	0.5 ^a	3-9
External gamma shielding factor	0.7 ^b	1-9
Indoor time fraction	0.18 ^a	7
	0.5 ^b	1-2
	0.55 ^a	3-6, 8-9
Outdoor time fraction	0.05 ^a	7
	0.21 ^a	3-6, 8-9
	0.25 ^b	1-2
Shape flag of the contaminated zone (1 = circular)	1 ^b	1-9
<i>Ingestion pathway, dietary data</i>		
Fruit, vegetable, and grain consumption (kg/y)	160 ^b	1-2
	166 ^a	3-6, 8-9
	Not used	7
Leafy vegetable consumption (kg/y)	11 ^a	3-6, 8-9
	14 ^b	1-2
	Not used	7
Milk consumption (kg/y)	92 ^b	1-2
	100 ^a	3-6, 8-9
	Not used	7
Meat and poultry consumption (kg/y)	63 ^b	1-6, 8-9
	Not used	7
Fish consumption (kg/y)	5.4 ^b	1-6, 8-9
	Not used	7
Other seafood consumption (kg/y)	0.9 ^b	1-6, 8-9
	Not used	7
Soil ingestion (g/y)	36.5 ^b	1-6, 8-9
	Not used	7

Table A-3. (continued)

Variable	Value	Case
Drinking water intake	510 ^b	1-2
	730 ^a	3-6, 8-9
	Not used	7
Contamination fraction—drinking water	1 ^{a,b}	1-6, 8-9
	Not used	7
Contamination fraction—household water	Not used	1-9
Contamination fraction—livestock water	1 ^b	1-6, 8-9
	Not used	7
Contamination fraction—irrigation water	1 ^b	1-6, 8-9
	Not used	7
Contamination fraction—aquatic food	0.5 ^b	1-6, 8-9
	Not used	7
Contamination fraction—plant food	0.154 ^c	1-6
	0.5 ^c	8-9
	Not used	7
Contamination fraction—meat	0.0154 ^c	1-6
	0.314 ^c	8-9
	Not used	7
Contamination fraction—milk	0.0154 ^c	1-6
	0.314 ^c	8-9
	Not used	7
<i>Ingestion pathway, non-dietary data</i>		
Livestock fodder intake for meat (kg/s)	68 ^{a,b}	1-6, 8-9
	Not used	7
Livestock fodder intake for milk (kg/d)	55 ^{a,b}	1-6, 8-9
	Not used	7
Livestock water intake for meat (L/d)	50 ^{a,b}	1-6, 8-9
	Not used	7
Livestock water intake for milk (L/d)	160 ^{a,b}	1-6, 8-9
	Not used	7
Livestock intake of soil (kg/d)	0.5 ^b	1-6, 8-9
	Not used	7
Mass loading from foliar deposition (g/m ³)	1E-4 ^{a,b}	1-6, 8-9
	Not used	7
Depth of soil mixing layer (m)	0.15 ^{a,b}	1-9
Drinking water fraction from groundwater	1 ^{a,b}	1-9

Table A-3. (continued)

Variable	Value	Case
Household water fraction from groundwater	1 ^b Not used	1-6, 8-9 7
Livestock water fraction from groundwater	1 ^{a,b} Not used	1-6, 8-9 7
Irrigation water fraction from groundwater	1 ^{a,b} Not used	1-6, 8-9 7
<i>Storage times before use</i>		
Storage time before use—fruits, non-leafy vegetables, and grain (d)	14 ^b Not used	1-6, 8-9 7
Storage time before use—leafy vegetables (d)	1 ^b Not used	1-6, 8-9 7
Storage time before use—milk (d)	1 ^b Not used	1-6, 8-9 7
Storage time before use—milk (d)	1 ^b Not used	1-6, 8-9 7
Storage time before use—meat (d)	20 ^b Not used	1-6, 8-9 7
Storage time before use—fish (d)	7 ^b Not used	1-6, 8-9 7
Storage time before use—crustacea and mollusks (d)	7 ^b Not used	1-6, 8-9 7
Storage time before use—well water (d)	1 ^b Not used	1-6, 8-9 7
Storage time before use—surface water (d)	1 ^b Not used	1-6, 8-9 7
Storage time before use—livestock fodder (d)	45 ^b Not used	1-6, 8-9 7

Table A-3. (continued)

Variable	Value	Case
<i>Carbon-14 data</i>		
C-12 concentration in local water (g/cm ³)	2E-5 ^b	1-9
C-12 concentration in contaminated soil (g/cm ³)	3E-2 ^b	1-9
Fraction of vegetation carbon absorbed from soil	2E-2 ^b	1-9
Fraction of vegetation carbon absorbed from air	0.98 ^b	1-9
Thickness of evasion layer of C-14 in soil (m)	0.3 ^b	1-9
C-14 evasion flux from soil (1/s)	7E-7 ^b	1-9
C-12 evasion flux from soil (1/s)	1E-10 ^b	1-9
Grain fraction in livestock feed—beef cattle	0.8 ^b	1-9
Grain fraction in livestock feed—milk cattle	0.2 ^b	1-9

^a Values from scenarios in *Policy and Guidance Directive PG-8-08: Scenarios for Assessing Potential Doses Associated with Residual Radioactivity*, U.S. Nuclear Regulatory Commission, Washington, D.C., May 1994.

^b RESRAD default value.

^c Calculated by RESRAD based on size of contaminated area.