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Tritium and VOC Fluxes to the Water Table from the Mixed Waste Management Facility (U)

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Executive summary

The Environmental Restoration Department is investigating the source of tritium and volatile organic compound (VOC) plumes emanating from the Mixed Waste Management Facility (MWMF)/Low Level Radioactive Waste Disposal Facility (LLRWDF), in part through the use of saturated groundwater flow and solute contaminant transport models. For input to these models, future fluxes of tritium and VOCs from the MWMF/LLRWDF to the water table are estimated in this study using COBRA records, prior containment and leachability studies, and analytical solutions of vadose zone transport. The analytical solutions developed in the report consider the waste containment, leaching, advection through the vadose zone, and radioactive decay. Except for the Mound Special Burial, tritium is assumed to leach immediately to the vadose zone (no containment) and migrate to the water table with a 5 yr travel time (pre-cap infiltration). Ultimately 86% of the initial inventory leaches to the vadose zone and 65% enters the water. The Mound Special Burial is assumed to be contained for 50 yr and have a 50 yr travel time through the vadose zone (post-cap infiltration). With these assumptions, 94% decays within the waste form before the container is breached, 5% leaches to the vadose zone, and only 0.3% reaches the water table. VOC contaminant migration is similar to tritium under default conditions, except that no decay is assumed to occur. As a result, all of the initial buried VOC inventory eventually migrates to the vadose zone.

Table of Contents

Executive summary iii
Tables v
Figures vi
Introduction 1
Model of vadose zone leaching and transport 1
Analytical solution for flux to the water table 3
Unit release calculations under MWMF/LLRWDF conditions 5
COBRA burial records 5
Computer software, verification and electronic output 7
Summary and conclusions 7
References 8
Appendix A A-1
Appendix B B-1
Appendix C C-1
Appendix D D-1

Tables

Table 1 Unit release calculations for default tritium burial 9
Table 2 Unit release calculations for Mound Special Burial 10
Table 3 Unit release calculations for VOC burial 11
Table 4 Parameter settings for tritiated waste burials 12
Table 5 Summary information for flux to the water table 12

Figures

Figure 1 Conceptual model and nomenclature for vadose zone leaching and transport 13
Figure 2 Definition of activity balances and fluxes for vadose zone transport 13
Figure 3 Summary of parameter settings for the MWMF/LLRWDF 14
Figure 4 Unit release curves using default tritium parameters 15
Figure 5 Unit release curves using the Mound Special Burial parameters 16
Figure 6 Unit release curves for VOCs (non-decaying contaminant) 17

Introduction

The Environmental Restoration Department is investigating the source of tritium and volatile organic compound (VOC) plumes emanating from the Mixed Waste Management Facility (MWMF)/Low Level Radioactive Waste Disposal Facility (LLRWDF), in part through the use of saturated groundwater flow and solute contaminant transport models. The purpose of this study is to estimate the past and future fluxes of tritium and VOCs to the water table as input to these models. The primary input to this study is the extensive analysis of buried inventory and contaminant leachability for the MWMF/LLRWDF provided by WSRC (2000). An analytical approach is used to quantify leaching and decay rates for contaminant release and transport in the vadose zone.

Model of vadose zone leaching and transport

Contaminant flux to the water table is envisioned to be the result of two processes shown conceptually in Figure 1. The first is leaching from and decay within the solid waste form. The second process is transport through and decay within the unsaturated sediment between the solid waste and water table. These processes are identified in Figure 1 as occurring in the "waste zone" and "vadose zone". Nomenclature for the various fluxes and activity associated with the two regions is also defined in the figure.

Radioactive decay is a first-order process described by

$$F_{decay} = \lambda Q \tag{1}$$

where

$F_{decay} \equiv$ decay rate (Ci/yr)

$Q \equiv$ activity present (Ci)

$\lambda \equiv$ decay coefficient (1/yr)

The decay coefficient is related to the half-life by

$$\lambda = \frac{\ln 2}{\tau} \tag{2}$$

where

$\tau \equiv$ half-life (yr)

For tritium, τ = 12.3 yr and λ = 0.0564 yr^{-1}.

WSRC (2000, Appendix E) concluded that tritium leaching data for spent melt crucibles ("spent melts") could be well represented by a first-order model, analogous to radioactive decay

$$F_{leaching} = kQ \tag{3}$$

where

$F_{leaching} \equiv$ decay rate (Ci/yr)

$k \equiv$ leaching coefficient (1/yr)

Lysimeter data suggest an initial activity of 133 Ci per Line 2 spent melt and a leaching coefficient of 0.34 yr^{-1} (approximately 2 yr leaching half-life) (WSRC, 2000, Appendix E). Burial records assign 200 Ci to a Line 2 double melt, so approximately 2/3 is available for leaching. The remainder is imbedded deep within the Al-Li matrix and inaccessible due to an extremely low rate of molecular diffusion.

WSRC (2000) determined that leaching rates for other tritiated waste forms would likely be similar to spent melts because the same dissolution/diffusion processes would be involved, and any packaging would provide no significant containment of tritium. The latter assumption is based on the ability of tritium to diffuse rapidly through many materials and the likelihood of container degradation due to backfilling and subsequent dynamic compaction in preparation for RCRA covers. The full inventory would be available for leaching because contamination would be on the surface of the waste form in general.

An exception to the above assumptions for non-spent melts is the Mound Special Burial which contained over 1 million Curies of tritium (WSRC, 2000). These off-site wastes were packaged in nested steel drums that effectively contain tritium prior to container degradation. Because the trench location of the Mound Special Burial was bypassed during dynamic compaction, container degradation was assumed by WSRC (2000) to result from sequential failure of the steel drums due to corrosion. The time between burial and container breaching is uncertain, but estimated to be on the order of 50 years by WSRC (2000, Appendix E).

Burial records contain no quantitative information about TCE and PCE burial amounts. However, VOC contamination of this type is probably associated with job control waste, containing items such as rags and protective clothing. Therefore job control waste records can be used as a surrogate for VOC burials to define relative spatial and temporal variability. Groundwater model calibration to historical plume data could then be used to define a scaling/conversion factor to convert ft^3 of job control waste to grams of TCE or PCE. Leaching rates for TCE and PCE are unknown. For simplicity and consistency, leaching is assumed to occur via the same first-order process as tritium (i.e. 2 yr leaching half-life).

The average travel time between waste form and the water table can be estimated from the distance and average pore velocity. The speed of water movement through the vadose zone has been measured in the field to be approximately 7 ft/yr under natural recharge conditions (Horton, 1975; Haskell and Hawkins, 1964; Horton and Hawkins, 1964). The field estimate is consistent with the pore velocity associated with 15 in/yr of recharge flowing through sediment with 40% total porosity at 45% water saturation:

$$\frac{15\,\text{in/yr}}{(0.4)(0.45)} \times \frac{\text{ft}}{12\,\text{in}} = 7\ \text{ft/yr} \tag{4}$$

Under RCRA cap conditions the infiltration rate and pore velocity would be reduced by roughly an order of magnitude (e.g. Bell and Brewer, 2001). Assuming a ground elevation of 285 ft, trench depth of 20 ft, and water table elevation of 235 ft, the average distance between solid waste burials and the water table would be approximately 35 ft. The travel time would then be 5 yrs under pre-cap conditions, and 50 yrs with post-cap infiltration.

Figure 3 summarizes the parameter settings discussed above for the MWMF/LLRWDF. For simplicity, and to accommodate an analytical solution, vadose zone transport for a particular burial is assumed to occur entirely under either pre- or post-cap conditions. The default is pre-cap infiltration (i.e. 5 yr travel time) under the assumption that most transport will occur prior to caps being installed in 1991. The exception is the Mound Special Burial, which has a 50 yr breech time before vadose zone migration occurs.

Analytical solution for flux to the water table

The activity balance for the waste zone in differential form is

$$\begin{aligned} dQ_{waste}/dt &= -F_{vz}(t) - F_{wd}(t) \\ &= -kQ - \lambda Q \\ &= -(k+\lambda)Q \end{aligned} \tag{5}$$

where the flux terms are defined by first-order models, i.e. equations (1) and (3). Equation (5) is a first-order ordinary differential equation that can be readily solved with an analytical methods, as shown in Appendix A. The flux results are summarized by

$$dQ_{waste}/dt = -Q_0(k+\lambda)e^{-(k+\lambda)t} \tag{6}$$

$$F_{vz}(t) = Q_0 k e^{-(k+\lambda)t} \tag{7}$$

$$F_{wd}(t) = Q_0 \lambda e^{-(k+\lambda)t} \tag{8}$$

where

Q_0 ≡ initial buried activity (Ci)

The corresponding cumulative and residual amounts of activity are summarized by

$$Q_{waste}(t) = Q_0 e^{-(k+\lambda)t} \tag{9}$$

$$Q_{vz}(t) = Q_0 \frac{k}{k+\lambda}\left[1 - e^{-(k+\lambda)t}\right] \tag{10}$$

$$Q_{wd}(t) = Q_0 \frac{\lambda}{k+\lambda}\left[1 - e^{-(k+\lambda)t}\right] \tag{11}$$

The activity balance for the vadose zone in differential form is

$$dQ_{vadose}/dt = F_{vz}(t) - F_{vd}(t) - F_{wt}(t) \tag{12}$$

where F_{wt} is zero for $t < \Delta t$ where

Δt ≡ travel time through the vadose zone (yr)

As shown in Appendix A, equation (12) also leads to separate first-order differential equations for the time periods $t < \Delta t$ and $t > \Delta t$. Both can be readily solved with analytical methods. For $t < \Delta t$ the flux results are

$$dQ_{vadose}/dt = Q_0(k+\lambda)e^{-(k+\lambda)t} - Q_0\lambda e^{-\lambda t} \tag{13}$$

$$F_{vz}(t) = Q_0 k e^{-(k+\lambda)t} \tag{14}$$

$$F_{vd}(t) = Q_0\lambda\left[e^{-\lambda t} - e^{-(k+\lambda)t}\right] \tag{15}$$

and the corresponding cumulative and residual activities are

$$Q_{vadose}(t) = Q_0\left[e^{-\lambda t} - e^{-(k+\lambda)t}\right] = Q_0 e^{-\lambda t}\left[1 - e^{-kt}\right] \tag{16}$$

$$Q_{vz}(t) = Q_0 \frac{k}{k+\lambda}\left[1 - e^{-(k+\lambda)t}\right] \tag{17}$$

$$Q_{vd}(t) = Q_0\left[1 - e^{-\lambda t}\right] - Q_0 \frac{\lambda}{(k+\lambda)}\left[1 - e^{-(k+\lambda)t}\right] \tag{18}$$

The water table flux is zero of course. For $t > \Delta t$ the flux results are

$$dQ_{vadose}/dt = -Q_0(k+\lambda)\left[e^{k\Delta t} - 1\right]e^{-(k+\lambda)t} \tag{19}$$

$$F_{vz}(t) = Q_0 k e^{-(k+\lambda)t} \tag{20}$$

$$F_{vd}(t) = Q_0 \lambda \left[e^{k\Delta t} - 1 \right] e^{-(k+\lambda)t} \tag{21}$$

$$\boxed{F_{wt}(t) = Q_0 k e^{k\Delta t} e^{-(k+\lambda)t} = Q_0 k e^{-\lambda\Delta t} e^{-(k+\lambda)(t-\Delta t)}} \tag{22}$$

and the cumulative and residual activities are

$$Q_{vadose}(t) = Q_0 \left[e^{k\Delta t} - 1 \right] e^{-(k+\lambda)t} = Q_0 e^{-\lambda t} \left[e^{-k(t-\Delta t)} - e^{-kt} \right] \tag{23}$$

$$Q_{vz}(t) = Q_0 \frac{k}{k+\lambda} \left[1 - e^{-(k+\lambda)t} \right] \tag{24}$$

$$Q_{vd}(t) = Q_0 \frac{k}{k+\lambda} \left[1 - e^{-\lambda\Delta t} \right] + Q_0 \frac{\lambda}{k+\lambda} \left[1 - e^{k\Delta t} \right] e^{-(k+\lambda)t} \tag{25}$$

$$\boxed{Q_{wt}(t) = Q_0 \frac{k}{k+\lambda} e^{k\Delta t} \left[e^{-(k+\lambda)\Delta t} - e^{-(k+\lambda)t} \right]} \tag{26}$$

The primary input to groundwater modeling would be equation (22) or equation (26).

Unit release calculations under MWMF/LLRWDF conditions

Except for the Mound Special Burial, tritium is assumed to leach immediately to the vadose zone (no containment) and migrate to the water table with a 5 yr travel time (pre-cap infiltration). Table 1 and Figure 4 illustrate the flux and activity transients associated with a 1 Ci burial under these default conditions. Note that ultimately 86% of the initial inventory leaches to the vadose zone and 65% enters the water. Table 2 and Figure 5 provides the analogous information for the Mound Special Burial, which is assumed to be contained for 50 yr and have a 50 yr travel time through the vadose zone. Here 94% decays within the waste form before the container is bereted, 5% leaches to the vadose zone, and only 0.3% reaches the water table. VOC contaminant migration is similar to tritium under default conditions, except that no decay is assumed to occur. Table 3 and Figure 6 define the release curves. Note in Table 3 that the no decay condition is practically implemented by setting the radioactive half-life to one million years. Note that all of the initial buried inventory eventually migrates to the vadose zone in the absence of decay.

COBRA burial records

The Computerized Burial Record Analysis (COBRA) database comprises a record of virtually all unclassified solid waste disposals at the MWMF/LLRWDF (WSRC, 2000).

The primary focus of COBRA was to record radiological quantities being buried. Information about other materials of current interest, such as VOCs, is generally lacking. Detailed analysis and discussion of tritium and VOC burials are available in Appendix E and D, respectively, of WSRC (2000). Table 5 provides summary information about each group of COBRA records discussed below.

Records pertaining to tritiated waste burials were extracted from the COBRA database as part of WSRC (2000) and placed in a project database. For this study, data were exported from the WSRC (2000) database and organized by the following groups of records:

No. records	*Description*
123	known reactive beds
632	known spent melts
274	suspect beds and melts
240	burials of off-site origin
7528	other
8797	total

These groupings were further subdivided as follows:

No. records	*Description*
123	known reactive beds
632	known spent melts
32	suspect beds
242	suspect melts
25	Mound Special Burial
215	other off-site
7528	other
8797	total

Table 4 summarizes the parameter settings appropriate for each type of waste. The breech time and travel time values have been discussed previously. Some COBRA records do not identify the quantity of tritium, or the value is zero. In these cases, a default value is assigned depending on the type of waste. Reactive bed records typically indicate an activity of 500 Ci, and this value is taken as the default for records that do not indicate quantity. For spent melts, the default quantity is set to 400 Ci under the assumption that the typical burial involved 2 double-melt crucibles per shipment. This assumption is based on inspection of the COBRA database, which indicates that 200 Ci was assigned to each double-melt, and personal communication (11/15/00 e-mail) with Don Zecha who stated

> "The transport truck from Tritium had 2 shielded containers attached to its bed. Count on 2 crucibles per shipment. For the MWMF, consider each crucible to have 2 melts when shipped."

As discussed earlier, lysimeter data suggest an available activity of 133 Ci per spent melt, or 2/3 of 200 Ci. Therefore, all spent melt quantities are scaled down by a factor of 2/3 as indicated in Table 4.

The coordinates of the Mound Special Burial in COBRA are incorrect according to WSRC (2000). The correct location in SRS coordinates is N75180, E58600, and this change was made before the records were processed to compute water table flux.

For use as a surrogate for VOC burials, job control waste information was also extracted from the COBRA data compiled in WSRC (2000). There are 150,623 records in total. Job control waste burials are quantified by volume in ft^3. The COBRA data can be translated into a water table "flux" of job control waste in ft^3/yr using the analytical solutions developed earlier in this report. A conversion/scaling factor, with units such as g/ft^3, should then be applied to produce a flux of VOC contaminant. Such a conversion factor would have to be determined through groundwater model calibration to historical plume data. As an illustrative example, Flach and others (1996) estimated 0.1 g of TCE and 0.03 g of PCE per ft^3 of job control waste at the Old Radioactive Waste Burial Ground.

Computer software, verification and electronic output

Computer software is required to process the large number of COBRA records under consideration (8797 for tritium and 150,623 for job control waste). Appendix B lists the Fortran90 source code for processing tritium records, and verification runs that reproduce the Excel calculations shown in Tables 1 and 2. Appendix C lists a similar Fortran90 code for processing job control waste, and a verification case that matches Table 3. Each code produces a **`*.out`** file that echoes the input **`*.txt`** file, a **`*.log`** file providing summary level information, and a **`*.flx`** file that provides the water table flux information. Table 5 provides summary information about each group of COBRA records. Note that the percentage of buried activity is consistent with the unit release calculations presented in Tables 1 through 3. The input and output files associated with the software in Appendices B and C are far too large to provide in printed form. However, the CDROM in Appendix D provides a complete electronic archive of the source code, and input and output files.

Summary and conclusions

Future fluxes of tritium and VOCs from the MWMF/LLRWDF to the water table have been estimated using COBRA records, containment and leachability studies, and analytical solutions of vadose zone transport. The estimates were developed as input to saturated groundwater flow and solute contaminant transport models. The analytical solutions developed in the report consider the waste containment, leaching, advection through the vadose zone, and radioactive decay. Except for the Mound Special Burial, tritium is assumed to leach immediately to the vadose zone (no containment) and migrate

to the water table with a 5 yr travel time (pre-cap infiltration). Ultimately 86% of the initial inventory leaches to the vadose zone and 65% enters the water. The Mound Special Burial is assumed to be contained for 50 yr and have a 50 yr travel time through the vadose zone (post-cap infiltration). With these assumptions, 94% decays within the waste form before the container is breached, 5% leaches to the vadose zone, and only 0.3% reaches the water table. VOC contaminant migration is similar to tritium under default conditions, except that no decay is assumed to occur. As a result, all of the initial buried VOC inventory eventually migrates to the vadose zone.

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Table 1 Unit release calculations for default tritium burial.

Input parameters

2	τ_k, leaching half-life (yr)		
12.3	τ_λ, radioactive half-life (yr)		
5	Δt, travel time to water table (yr)	5	50
0	$\Delta\tau$, time to breech containment (yr)	0	50
0.1	starting Δt		
2	scale factor for time progression		

Derived parameters

0.346574	$k=\ln 2/\tau_k$, leaching rate constant (yr^{-1})
0.056353	$\lambda=\ln 2/\tau_\lambda$, radioactive decay constant (yr^{-1})
0.402927	$k+\lambda$, composite rate constant (yr^{-1})
1	$e^{-\lambda\Delta\tau}$, relative decay of activity/mass while in containment

		Waste									Vadose zone												
time progression	*time after release*	*rate*				*cumulative*					*rate*					*cumulative*						In Scientific Notation	
Δt	t	dQ_{waste}/dt	F_{vz}	F_{wd}	chk sum = 0	$Q_{<breech}$	Q_{waste}	Q_{vz}	Q_{wd}	chk sum = 1	dQ_{vadose}/dt	F_{vz}	F_{vd}	F_{wt}	chk sum = 0	Q_{vadose}	Q_{vz}	Q_{vd}	Q_{wt}	chk sum = 0	Q_d	F_{wt}	Q_{wt}
	0.01953	-0.3998	0.3439	0.0559	0	0	0.9922	0.0067	0.0011	1	0.3435	0.3439	0.0004	0.0000	1E-17	0.0067	0.0067	0.0000	0.0000	4E-19	0.0011	0.00E+00	0.00E+00
	0.03906	-0.3966	0.3412	0.0555	0	0	0.9844	0.0134	0.0022	1	0.3404	0.3412	0.0008	0.0000	3E-17	0.0134	0.0134	0.0000	0.0000	4E-19	0.0022	0.00E+00	0.00E+00
	0.07813	-0.3904	0.3358	0.0546	0	0	0.9690	0.0267	0.0043	1	0.3343	0.3358	0.0015	0.0000	4E-18	0.0266	0.0267	0.0001	0.0000	9E-19	0.0044	0.00E+00	0.00E+00
	0.15625	-0.3783	0.3254	0.0529	0	0	0.9390	0.0525	0.0085	1	0.3225	0.3254	0.0029	0.0000	2E-17	0.0522	0.0525	0.0002	0.0000	0	0.0088	0.00E+00	0.00E+00
	0.3125	-0.3553	0.3056	0.0497	-6E-17	0	0.8817	0.1018	0.0165	1	0.2999	0.3056	0.0057	0.0000	3E-17	0.1009	0.1018	0.0009	0.0000	0	0.0175	0.00E+00	0.00E+00
	0.625	-0.3132	0.2694	0.0438	0	0	0.7774	0.1915	0.0311	1	0.2588	0.2694	0.0106	0.0000	5E-17	0.1880	0.1915	0.0035	0.0000	7E-18	0.0346	0.00E+00	0.00E+00
	1.25	-0.2435	0.2094	0.0341	0	0	0.6043	0.3403	0.0553	1	0.1910	0.2094	0.0185	0.0000	3E-18	0.3277	0.3403	0.0127	0.0000	3E-17	0.0680	0.00E+00	0.00E+00
	2.5	-0.1471	0.1266	0.0206	0	0	0.3652	0.5460	0.0888	1	0.0982	0.1266	0.0284	0.0000	-7E-18	0.5034	0.5460	0.0426	0.0000	8E-17	0.1314	0.00E+00	0.00E+00
0	5	-0.0537	0.0462	0.0075	0	0	0.1334	0.7454	0.1212	1	-0.2503	0.0462	0.0350	0.2615	0	0.6211	0.7454	0.1243	0.0000	-6E-17	0.2456	2.61E-01	0.00E+00
0.1	5.1	-0.0516	0.0444	0.0072	0	0	0.1281	0.7500	0.1219	1	-0.2404	0.0444	0.0336	0.2511	0	0.5966	0.7500	0.1278	0.0256	0	0.2497	2.51E-01	2.56E-02
0.2	5.2	-0.0496	0.0426	0.0069	0	0	0.1230	0.7543	0.1227	1	-0.2309	0.0426	0.0323	0.2412	0	0.5730	0.7543	0.1311	0.0502	0	0.2537	2.41E-01	5.02E-02
0.4	5.4	-0.0457	0.0393	0.0064	0	0	0.1135	0.7625	0.1240	1	-0.2130	0.0393	0.0298	0.2226	0	0.5286	0.7625	0.1373	0.0966	0	0.2613	2.23E-01	9.66E-02
0.8	5.8	-0.0389	0.0335	0.0054	0	0	0.0966	0.7770	0.1263	1	-0.1813	0.0335	0.0254	0.1894	0	0.4499	0.7770	0.1483	0.1788	0	0.2746	1.89E-01	1.79E-01
1.6	6.6	-0.0282	0.0243	0.0039	0	0	0.0700	0.7999	0.1301	1	-0.1313	0.0243	0.0184	0.1372	0	0.3260	0.7999	0.1656	0.3084	0	0.2957	1.37E-01	3.08E-01
3.2	8.2	-0.0148	0.0127	0.0021	0	0	0.0367	0.8285	0.1347	1	-0.0689	0.0127	0.0096	0.0720	0	0.1711	0.8285	0.1873	0.4702	0	0.3220	7.20E-02	4.70E-01
6.4	11.4	-0.0041	0.0035	0.0006	0	0	0.0101	0.8514	0.1384	1	-0.0190	0.0035	0.0027	0.0198	0	0.0471	0.8514	0.2046	0.5997	0	0.3431	1.98E-02	6.00E-01
12.8	17.8	-0.0003	0.0003	0.0000	0	0	0.0008	0.8595	0.1398	1	-0.0014	0.0003	0.0002	0.0015	0	0.0036	0.8595	0.2107	0.6452	0	0.3505	1.51E-03	6.45E-01
25.6	30.6	0.0000	0.0000	0.0000	0	0	0.0000	0.8601	0.1399	1	0.0000	0.0000	0.0000	0.0000	0	0.0000	0.8601	0.2112	0.6489	0	0.3511	8.66E-06	6.49E-01
51.2	56.2	0.0000	0.0000	0.0000	0	0	0.0000	0.8601	0.1399	1	0.0000	0.0000	0.0000	0.0000	0	0.0000	0.8601	0.2112	0.6489	0	0.3511	2.87E-10	6.49E-01
102.4	107.4	0.0000	0.0000	0.0000	0	0	0.0000	0.8601	0.1399	1	0.0000	0.0000	0.0000	0.0000	0	0.0000	0.8601	0.2112	0.6489	0	0.3511	3.15E-19	6.49E-01
204.8	209.8	0.0000	0.0000	0.0000	-1E-53	0	0.0000	0.8601	0.1399	1	0.0000	0.0000	0.0000	0.0000	0	0.0000	0.8601	0.2112	0.6489	0	0.3511	3.80E-37	6.49E-01
409.6	414.6	0.0000	0.0000	0.0000	0	0	0.0000	0.8601	0.1399	1	0.0000	0.0000	0.0000	0.0000	0	0.0000	0.8601	0.2112	0.6489	0	0.3511	5.52E-73	6.49E-01
819.2	824.2	0.0000	0.0000	0.0000	0	0	0.0000	0.8601	0.1399	1	0.0000	0.0000	0.0000	0.0000	0	0.0000	0.8601	0.2112	0.6489	0	0.3511	########	6.49E-01
	100	0.0000	0.0000	0.0000	0	**0**	0.0000	**0.8601**	**0.1399**	1	0.0000	0.0000	0.0000	0.0000	0	0.0000	0.8601	0.2112	**0.6489**	0	**0.3511**	6.22E-18	6.49E-01
	1	-0.2693	0.2316	0.0377	0	0	0.6684	0.2853	0.0464	1	0.2160	0.2316	0.0156	0.0000	-5E-18	0.2768	0.2853	0.0084	0.0000	-7E-18	0.0548	0.00E+00	0.00E+00

Table 2 Unit release calculations for Mound Special Burial of tritium.

Input parameters

2	τ_K, leaching half-life (yr)		
12.3	τ_λ, radioactive half-life (yr)		
50	Δt, travel time to water table (yr)	5	50
50	$\Delta\tau$, time to breech containment (yr)	0	50
0.1	starting Δt		
2	scale factor for time progression		

Derived parameters

0.346574 $k=\ln 2/\tau_K$, leaching rate constant (yr^{-1})

0.056353 $\lambda=\ln 2/\tau_\lambda$, radioactive decay constant (yr^{-1})

0.402927 $k+\lambda$, composite rate constant (yr^{-1})

0.059745 $e^{-\lambda\Delta\tau}$, relative decay of activity/mass while in containment

		Waste									**Vadose zone**												
time progression	*time after release*	*rate*				*cumulative*					*rate*					*cumulative*						In Scientific Notation	
Δt	t	dQ_{waste}/dt	F_{vz}	F_{wd}	chk sum = 0	$Q_{<breech}$	Q_{waste}	Q_{vz}	Q_{wd}	chk sum = 1	dQ_{vadose}/dt	F_{vz}	F_{vd}	F_{wt}	chk sum = 0	Q_{vadose}	Q_{vz}	Q_{vd}	Q_{wt}	chk sum = 0	Q_d	F_{wt}	Q_{wt}
	0.19531	-0.0223	0.0191	0.0031	0	0.94026	0.0552	0.0039	0.0006	1	0.0189	0.0191	0.0002	0.0000	-4E-19	0.0039	0.0039	0.0000	0.0000	2E-19	0.9409	0.00E+00	0.00E+00
	0.39063	-0.0206	0.0177	0.0029	-4E-18	0.94026	0.0510	0.0075	0.0012	1	0.0173	0.0177	0.0004	0.0000	3E-19	0.0074	0.0075	0.0001	0.0000	3E-20	0.9416	0.00E+00	0.00E+00
	0.78125	-0.0176	0.0151	0.0025	0	0.94026	0.0436	0.0139	0.0023	1	0.0144	0.0151	0.0008	0.0000	-2E-19	0.0136	0.0139	0.0003	0.0000	1E-18	0.9428	0.00E+00	0.00E+00
	1.5625	-0.0128	0.0110	0.0018	-2E-18	0.94026	0.0318	0.0240	0.0039	1	0.0097	0.0110	0.0013	0.0000	9E-19	0.0229	0.0240	0.0011	0.0000	4E-18	0.9453	0.00E+00	0.00E+00
	3.125	-0.0068	0.0059	0.0010	0	0.94026	0.0170	0.0368	0.0060	1	0.0040	0.0059	0.0019	0.0000	0	0.0331	0.0368	0.0037	0.0000	5E-18	0.9499	0.00E+00	0.00E+00
	6.25	-0.0019	0.0017	0.0003	0	0.94026	0.0048	0.0472	0.0077	1	-0.0004	0.0017	0.0021	0.0000	4E-19	0.0372	0.0472	0.0101	0.0000	7E-18	0.9580	0.00E+00	0.00E+00
	12.5	-0.0002	0.0001	0.0000	0	0.94026	0.0004	0.0511	0.0083	1	-0.0015	0.0001	0.0016	0.0000	0	0.0291	0.0511	0.0219	0.0000	7E-18	0.9705	0.00E+00	0.00E+00
	25	0.0000	0.0000	0.0000	0	0.94026	0.0000	0.0514	0.0084	1	-0.0008	0.0000	0.0008	0.0000	0	0.0146	0.0514	0.0368	0.0000	0	0.9854	0.00E+00	0.00E+00
0	50	0.0000	0.0000	0.0000	-6E-27	0.94026	0.0000	0.0514	0.0084	1	-0.0014	0.0000	0.0002	0.0012	0	0.0036	0.0514	0.0478	0.0000	-7E-18	0.9964	1.24E-03	0.00E+00
0.1	50.1	0.0000	0.0000	0.0000	0	0.94026	0.0000	0.0514	0.0084	1	-0.0014	0.0000	0.0002	0.0012	0	0.0034	0.0514	0.0478	0.0001	1E-18	0.9965	1.19E-03	1.21E-04
0.2	50.2	0.0000	0.0000	0.0000	0	0.94026	0.0000	0.0514	0.0084	1	-0.0013	0.0000	0.0002	0.0011	0	0.0033	0.0514	0.0479	0.0002	-3E-18	0.9965	1.14E-03	2.38E-04
0.4	50.4	0.0000	0.0000	0.0000	0	0.94026	0.0000	0.0514	0.0084	1	-0.0012	0.0000	0.0002	0.0011	0	0.0030	0.0514	0.0479	0.0005	-4E-18	0.9965	1.05E-03	4.57E-04
0.8	50.8	0.0000	0.0000	0.0000	0	0.94026	0.0000	0.0514	0.0084	1	-0.0010	0.0000	0.0001	0.0009	0	0.0026	0.0514	0.0480	0.0008	7E-18	0.9966	8.96E-04	8.46E-04
1.6	51.6	0.0000	0.0000	0.0000	0	0.94026	0.0000	0.0514	0.0084	1	-0.0008	0.0000	0.0001	0.0006	0	0.0019	0.0514	0.0481	0.0015	0	0.9967	6.49E-04	1.46E-03
3.2	53.2	0.0000	0.0000	0.0000	-2E-27	0.94026	0.0000	0.0514	0.0084	1	-0.0004	0.0000	0.0001	0.0003	0	0.0010	0.0514	0.0482	0.0022	0	0.9968	3.41E-04	2.22E-03
6.4	56.4	0.0000	0.0000	0.0000	0	0.94026	0.0000	0.0514	0.0084	1	-0.0001	0.0000	0.0000	0.0001	0	0.0003	0.0514	0.0483	0.0028	0	0.9969	9.39E-05	2.84E-03
12.8	62.8	0.0000	0.0000	0.0000	0	0.94026	0.0000	0.0514	0.0084	1	0.0000	0.0000	0.0000	0.0000	0	0.0000	0.0514	0.0483	0.0031	0	0.9969	7.12E-06	3.05E-03
25.6	75.6	0.0000	0.0000	0.0000	-2E-31	0.94026	0.0000	0.0514	0.0084	1	0.0000	0.0000	0.0000	0.0000	0	0.0000	0.0514	0.0483	0.0031	0	0.9969	4.10E-08	3.07E-03
51.2	101.2	0.0000	0.0000	0.0000	0	0.94026	0.0000	0.0514	0.0084	1	0.0000	0.0000	0.0000	0.0000	0	0.0000	0.0514	0.0483	0.0031	-3E-18	0.9969	1.36E-12	3.07E-03
102.4	152.4	0.0000	0.0000	0.0000	0	0.94026	0.0000	0.0514	0.0084	1	0.0000	0.0000	0.0000	0.0000	0	0.0000	0.0514	0.0483	0.0031	-6E-18	0.9969	1.49E-21	3.07E-03
204.8	254.8	0.0000	0.0000	0.0000	0	0.94026	0.0000	0.0514	0.0084	1	0.0000	0.0000	0.0000	0.0000	0	0.0000	0.0514	0.0483	0.0031	-6E-18	0.9969	1.80E-39	3.07E-03
409.6	459.6	0.0000	0.0000	0.0000	0	0.94026	0.0000	0.0514	0.0084	1	0.0000	0.0000	0.0000	0.0000	0	0.0000	0.0514	0.0483	0.0031	-6E-18	0.9969	2.61E-75	3.07E-03
819.2	869.2	0.0000	0.0000	0.0000	0	0.94026	0.0000	0.0514	0.0084	1	0.0000	0.0000	0.0000	0.0000	0	0.0000	0.0514	0.0483	0.0031	-6E-18	0.9969	########	3.07E-03
	100	0.0000	0.0000	0.0000	0	**0.94026**	0.0000	**0.0514**	**0.0084**	1	0.0000	0.0000	0.0000	0.0000	0	0.0000	0.0514	0.0483	**0.0031**	0	**0.9969**	2.20E-12	3.07E-03
	1	-0.0161	0.0138	0.0023	0	0.94026	0.0399	0.0170	0.0028	1	0.0129	0.0138	0.0009	0.0000	8E-19	0.0165	0.0170	0.0005	0.0000	-1E-18	0.9435	0.00E+00	0.00E+00

Table 3 Unit release calculations for VOC burial.

Input parameters

2	τ_k, leaching half-life (yr)		
1.00E+06	τ_λ, radioactive half-life (yr)		
5	Δt, travel time to water table (yr)	5	50
0	$\Delta\tau$, time to breech containment (yr)	0	50
0.1	starting Δt		
2	scale factor for time progression		

Derived parameters

0.346574	$k=\ln 2/\tau_k$, leaching rate constant (yr^{-1})
6.93E-07	$\lambda=\ln 2/\tau_\lambda$, radioactive decay constant (yr^{-1})
0.346574	$k+\lambda$, composite rate constant (yr^{-1})
1	$e^{-\lambda\Delta\tau}$, relative decay of activity/mass while in containment

		Waste									Vadose zone												
time progression	*time after release*	*rate*					*cumulative*				*rate*					*cumulative*						In Scientific Notation	
Δt	t	dQ_{waste}/dt	F_{vz}	F_{wd}	chk sum = 0	$Q_{<breech}$	Q_{waste}	Q_{vz}	Q_{wd}	chk sum = 1	dQ_{vadose}/dt	F_{vz}	F_{vd}	F_{wt}	chk sum = 0	Q_{vadose}	Q_{vz}	Q_{vd}	Q_{wt}	chk sum = 0	Q_d	F_{wt}	Q_{wt}
	0.01953	-0.3442	0.3442	0.0000	5E-17	0	0.9933	0.0067	0.0000	1	0.3442	0.3442	0.0000	0.0000	-4E-17	0.0067	0.0067	0.0000	0.0000	-4E-19	0.0000	0.00E+00	0.00E+00
	0.03906	-0.3419	0.3419	0.0000	2E-17	0	0.9866	0.0134	0.0000	1	0.3419	0.3419	0.0000	0.0000	-8E-18	0.0134	0.0134	0.0000	0.0000	-5E-19	0.0000	0.00E+00	0.00E+00
	0.07813	-0.3373	0.3373	0.0000	-3E-17	0	0.9733	0.0267	0.0000	1	0.3373	0.3373	0.0000	0.0000	4E-17	0.0267	0.0267	0.0000	0.0000	-7E-19	0.0000	0.00E+00	0.00E+00
	0.15625	-0.3283	0.3283	0.0000	1E-17	0	0.9473	0.0527	0.0000	1	0.3283	0.3283	0.0000	0.0000	-1E-17	0.0527	0.0527	0.0000	0.0000	-7E-18	0.0000	0.00E+00	0.00E+00
	0.3125	-0.3110	0.3110	0.0000	2E-17	0	0.8974	0.1026	0.0000	1	0.3110	0.3110	0.0000	0.0000	-5E-17	0.1026	0.1026	0.0000	0.0000	-1E-17	0.0000	0.00E+00	0.00E+00
	0.625	-0.2791	0.2791	0.0000	3E-17	0	0.8052	0.1948	0.0000	1	0.2791	0.2791	0.0000	0.0000	-3E-17	0.1948	0.1948	0.0000	0.0000	-3E-17	0.0000	0.00E+00	0.00E+00
	1.25	-0.2247	0.2247	0.0000	2E-17	0	0.6484	0.3516	0.0000	1	0.2247	0.2247	0.0000	0.0000	-2E-17	0.3516	0.3516	0.0000	0.0000	-2E-18	0.0000	0.00E+00	0.00E+00
	2.5	-0.1457	0.1457	0.0000	2E-17	0	0.4204	0.5796	0.0000	1	0.1457	0.1457	0.0000	0.0000	-9E-18	0.5796	0.5796	0.0000	0.0000	-1E-17	0.0000	0.00E+00	0.00E+00
0	5	-0.0613	0.0613	0.0000	8E-19	0	0.1768	0.8232	0.0000	1	-0.2853	0.0613	0.0000	0.3466	0	0.8232	0.8232	0.0000	0.0000	2E-16	0.0000	3.47E-01	0.00E+00
0.1	5.1	-0.0592	0.0592	0.0000	-2E-18	0	0.1708	0.8292	0.0000	1	-0.2756	0.0592	0.0000	0.3348	0	0.7952	0.8292	0.0000	0.0341	1E-16	0.0000	3.35E-01	3.41E-02
0.2	5.2	-0.0572	0.0572	0.0000	-6E-19	0	0.1649	0.8351	0.0000	1	-0.2662	0.0572	0.0000	0.3234	0	0.7681	0.8351	0.0000	0.0670	2E-16	0.0000	3.23E-01	6.70E-02
0.4	5.4	-0.0533	0.0533	0.0000	-1E-18	0	0.1539	0.8461	0.0000	1	-0.2484	0.0533	0.0000	0.3017	0	0.7167	0.8461	0.0000	0.1294	0	0.0000	3.02E-01	1.29E-01
0.8	5.8	-0.0464	0.0464	0.0000	2E-18	0	0.1340	0.8660	0.0000	1	-0.2162	0.0464	0.0000	0.2627	0	0.6239	0.8660	0.0000	0.2421	0	0.0000	2.63E-01	2.42E-01
1.6	6.6	-0.0352	0.0352	0.0000	5E-18	0	0.1015	0.8985	0.0000	1	-0.1639	0.0352	0.0000	0.1991	0	0.4728	0.8985	0.0000	0.4256	0	0.0000	1.99E-01	4.26E-01
3.2	8.2	-0.0202	0.0202	0.0000	3E-18	0	0.0583	0.9417	0.0000	1	-0.0941	0.0202	0.0000	0.1143	0	0.2716	0.9417	0.0000	0.6701	0	0.0000	1.14E-01	6.70E-01
6.4	11.4	-0.0067	0.0067	0.0000	3E-19	0	0.0192	0.9808	0.0000	1	-0.0310	0.0067	0.0000	0.0377	0	0.0896	0.9808	0.0000	0.8912	0	0.0000	3.77E-02	8.91E-01
12.8	17.8	-0.0007	0.0007	0.0000	-2E-20	0	0.0021	0.9979	0.0000	1	-0.0034	0.0007	0.0000	0.0041	0	0.0097	0.9979	0.0000	0.9882	0	0.0000	4.10E-03	9.88E-01
25.6	30.6	0.0000	0.0000	0.0000	7E-22	0	0.0000	1.0000	0.0000	1	0.0000	0.0000	0.0000	0.0000	0	0.0001	1.0000	0.0000	0.9999	0	0.0000	4.86E-05	1.00E+00
51.2	56.2	0.0000	0.0000	0.0000	2E-25	0	0.0000	1.0000	0.0000	1	0.0000	0.0000	0.0000	0.0000	0	0.0000	1.0000	0.0000	1.0000	0	0.0000	6.81E-09	1.00E+00
102.4	107.4	0.0000	0.0000	0.0000	2E-33	0	0.0000	1.0000	0.0000	1	0.0000	0.0000	0.0000	0.0000	0	0.0000	1.0000	0.0000	1.0000	0	0.0000	1.34E-16	1.00E+00
204.8	209.8	0.0000	0.0000	0.0000	3E-49	0	0.0000	1.0000	0.0000	1	0.0000	0.0000	0.0000	0.0000	0	0.0000	1.0000	0.0000	1.0000	0	0.0000	5.18E-32	1.00E+00
409.6	414.6	0.0000	0.0000	0.0000	1E-79	0	0.0000	1.0000	0.0000	1	0.0000	0.0000	0.0000	0.0000	0	0.0000	1.0000	0.0000	1.0000	0	0.0000	7.74E-63	1.00E+00
819.2	824.2	0.0000	0.0000	0.0000	-1E-141	0	0.0000	1.0000	0.0000	1	0.0000	0.0000	0.0000	0.0000	0	0.0000	1.0000	0.0000	1.0000	0	0.0000	########	1.00E+00
	100	0.0000	0.0000	0.0000	6E-33	**0**	0.0000	**1.0000**	**0.0000**	1	0.0000	0.0000	0.0000	0.0000	0	0.0000	1.0000	0.0000	**1.0000**	0	**0.0000**	1.74E-15	1.00E+00
	1	-0.2451	0.2451	0.0000	1E-17	0	0.7071	0.2929	0.0000	1	0.2451	0.2451	0.0000	0.0000	-3E-17	0.2929	0.2929	0.0000	0.0000	-2E-17	0.0000	0.00E+00	0.00E+00

Table 4 Parameter settings for tritiated waste burials.

Description	*No. records*	*Breech time (yr)*	*Travel time (yr)*	*Default quantity (Ci)*	*Scaling factor*
Mound Special Burial	25	50	50	0	1
Other off-site	215	0	5	0	1
Known beds	123	0	5	500	1
Suspect beds	32	0	5	500	1
Known melts	632	0	5	400	0.67
Suspect melts	242	0	5	400	0.67
Other	7528	0	5	0	1

Table 5 Summary information for flux to the water table.

Description	*Total no. records*	*Quantity unknown records*	*Cumulative buried activity (Ci or ft^3)*	*Cumulative activity entering WT (Ci or ft^3)*	*Cumulative activity entering WT (%)*
Tritium					
Mound Special Burial	25	0	1,191,468	3,658	0.3
Other off-site	215	68	262,828	170,557	65
Known beds	123	6	64,575	41,905	65
Suspect beds	32	0	48,519	31,485	65
Known melts	632	7	247,447×0.67*	107,587	65
Suspect melts	242	1	55,491×0.67*	24,126	65
Other	7528	6930	519,886	337,370	65
Job control waste	150,623	2	12,855,841	12,855,841	100

* Reflects over-estimate in COBRA database (200 Ci recorded versus 133 Ci estimated from lysimeter studies).

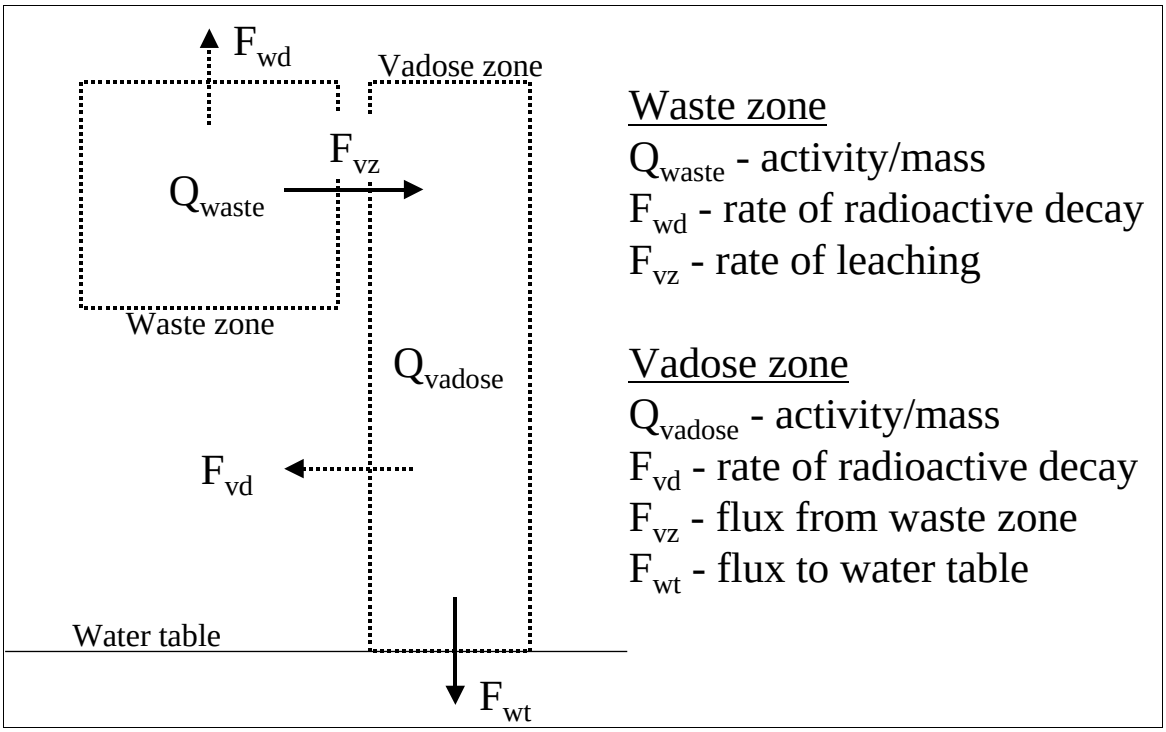

Figure 1 Conceptual model and nomenclature for vadose zone leaching and transport.

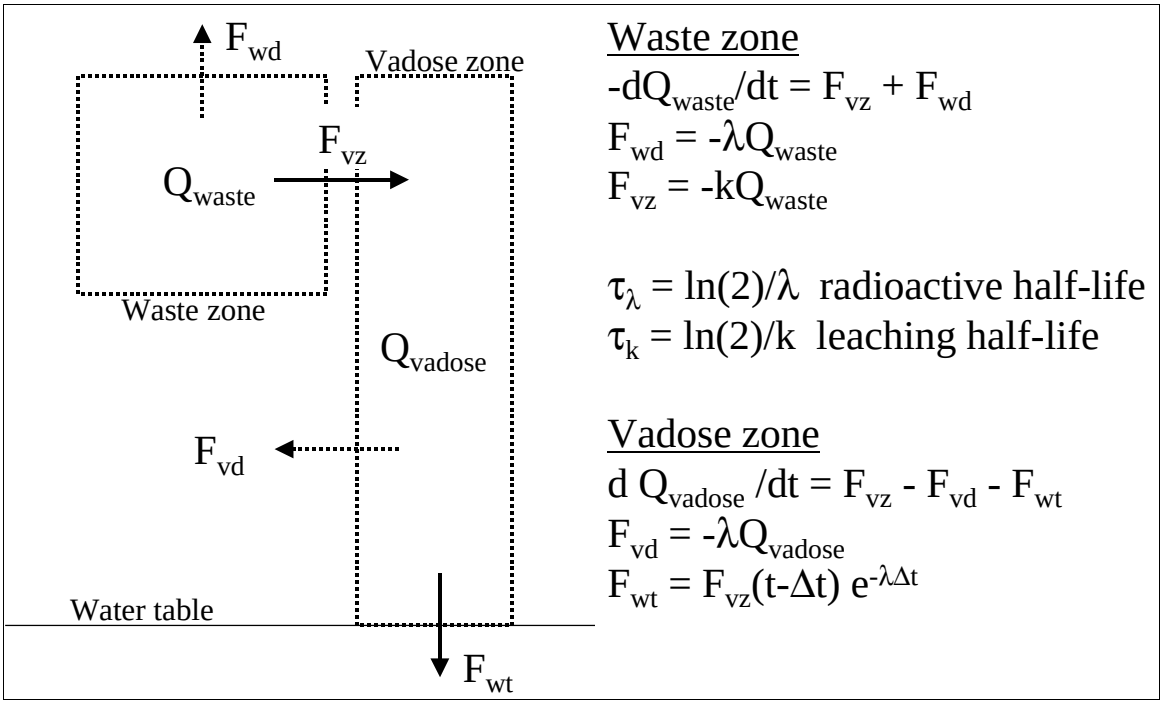

Figure 2 Definition of activity balances and fluxes for vadose zone transport.

Depth to water		*Half-lives (based on lysimeter)*	
Ground elevation	285 ft	Radioactive (τ_λ)	12.3 yr
Trench bottom depth	20 ft	Leaching (τ_k)	2 yr
Water table elev.	235 ft		
Depth to water	30+ ft	*Breach time (SAIC-Mayberry)*	
		Default	0 yr
Pore velocity (data and HELP)		Mound Special Burial	50 yr
w/o cap	7 ft/yr		
w/ cap (10%)	0.7 ft/yr	*Timing*	
		RCRA cap	1991
Travel time (Δt)		Default	w/o cap
No cap	5 yr	Mound Special Burial	w/ cap
RCRA cap	50 yr		

Figure 3 Summary of parameter settings for the MWMF/LLRWDF.

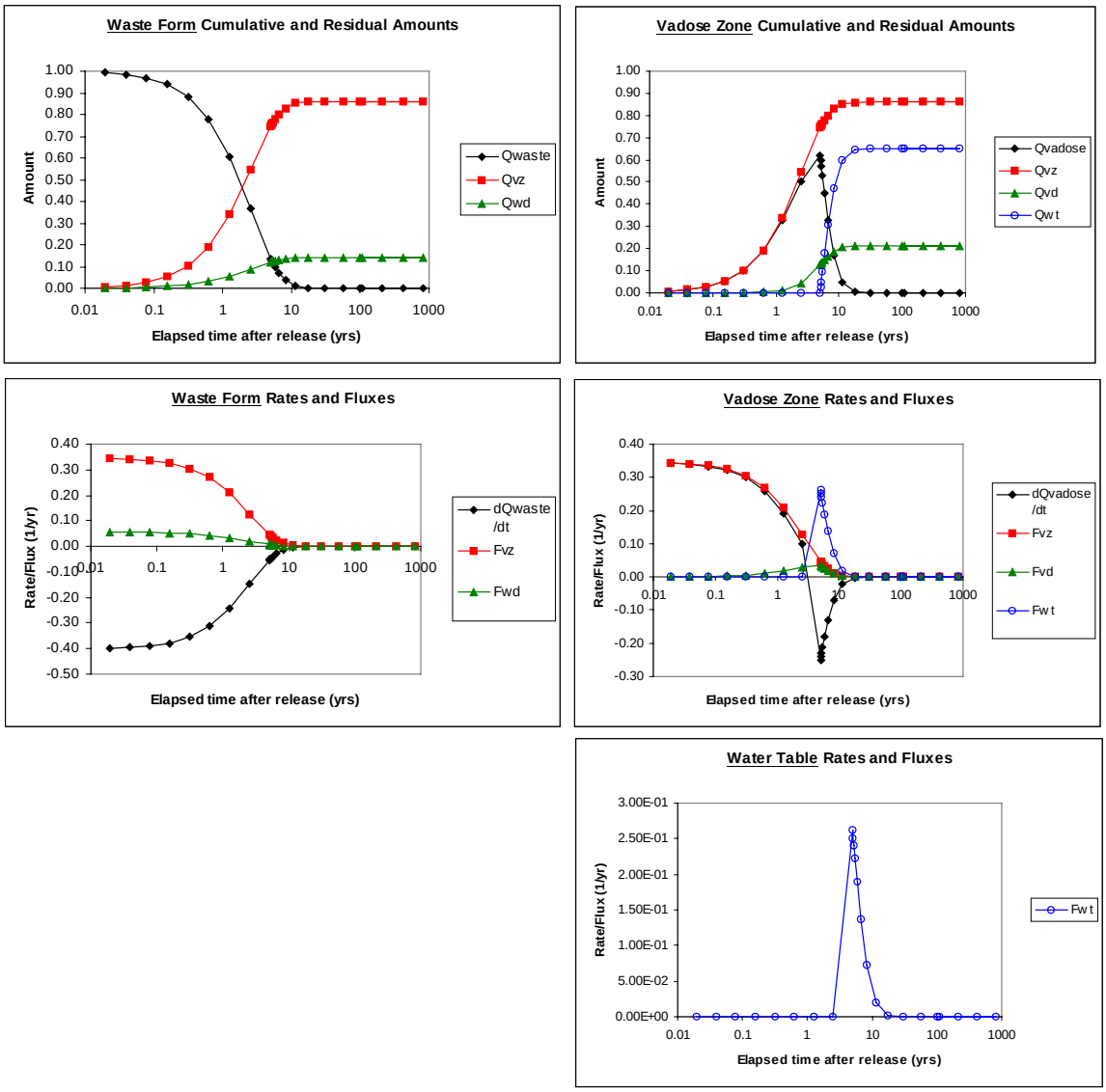

Figure 4 Unit release curves using default tritium parameters.

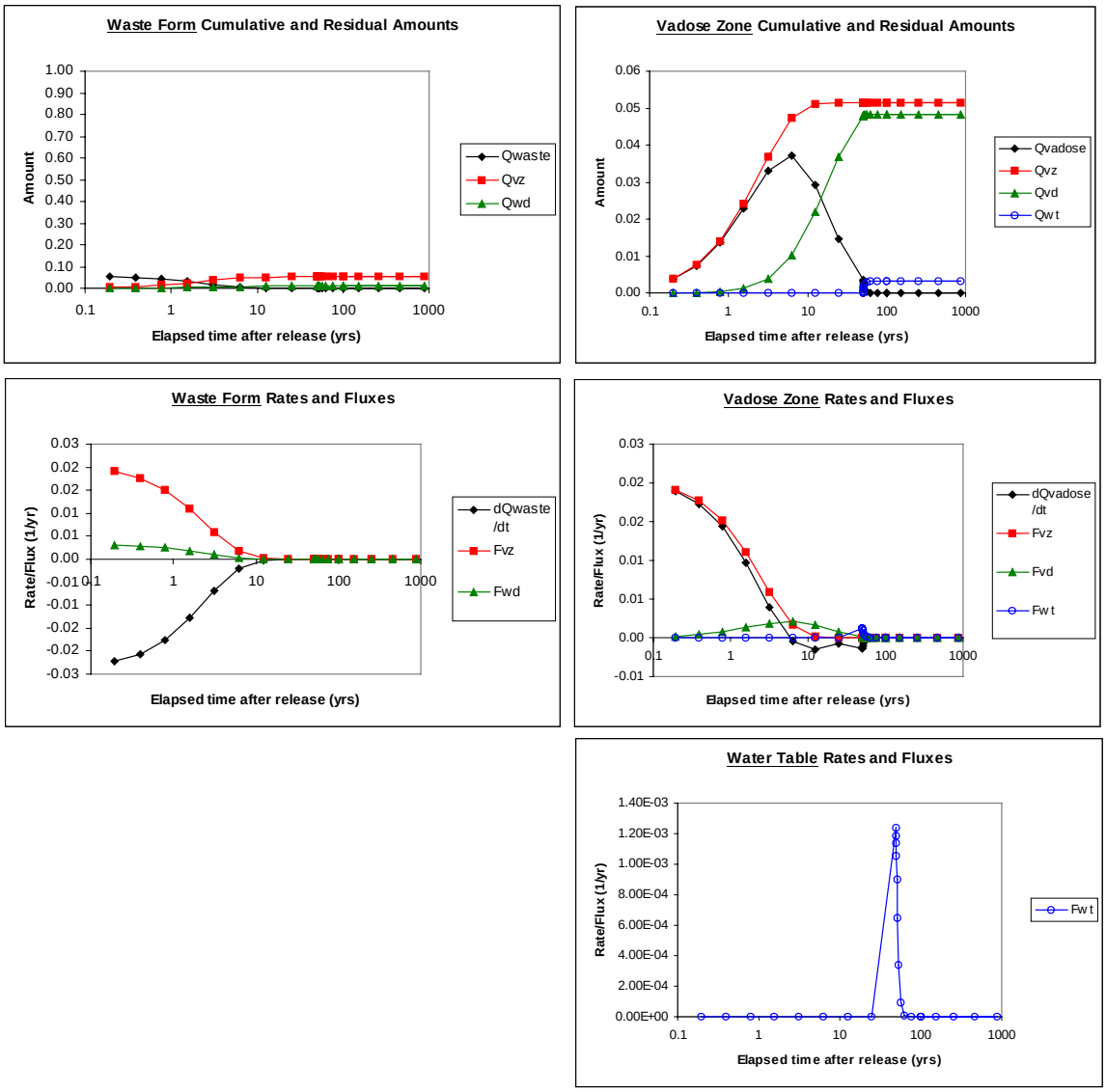

Figure 5 Unit release curves using the Mound Special Burial parameters.

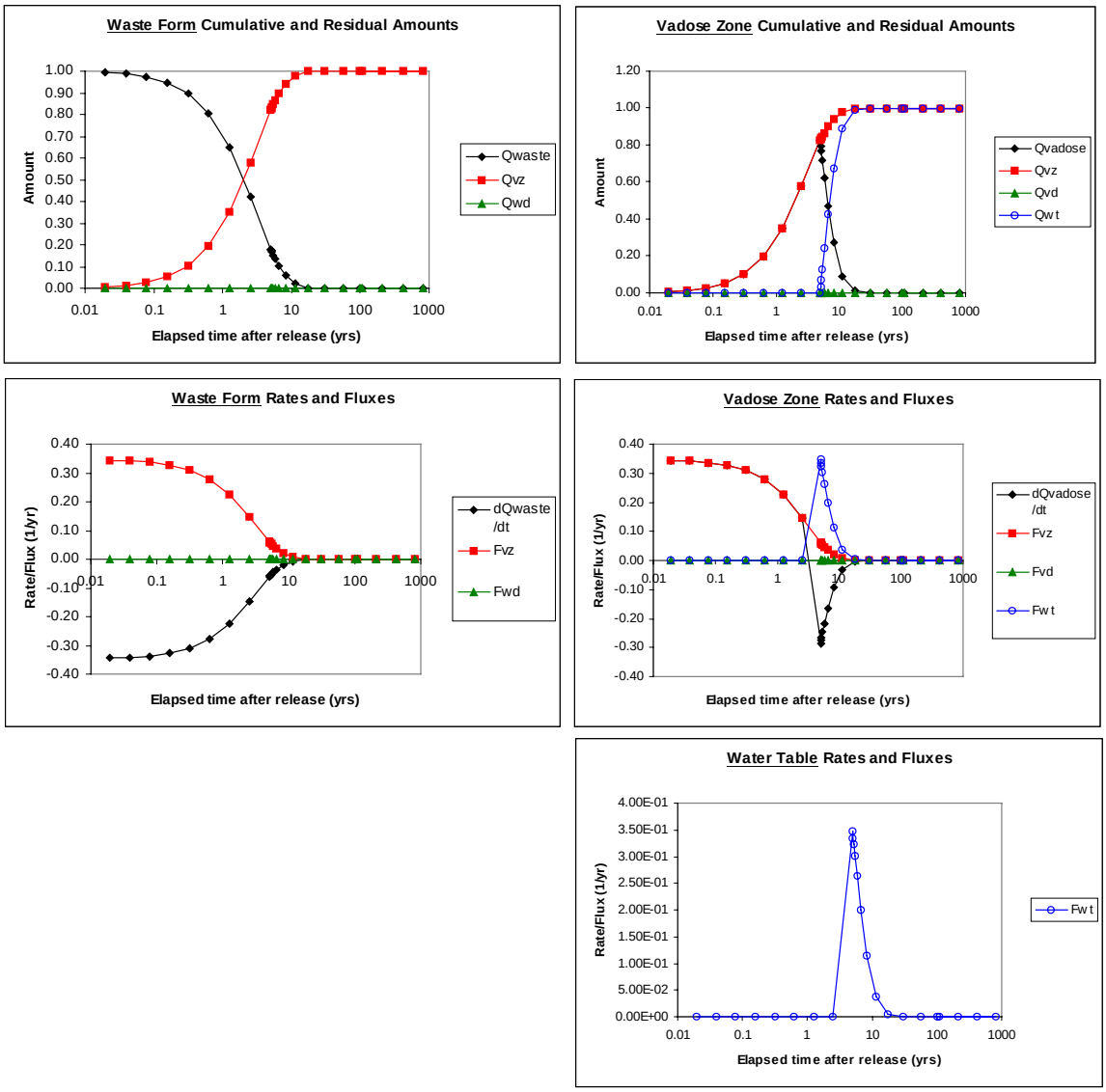

Figure 6 Unit release curves for VOCs (non-decaying contaminant).

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Appendix A Analytical solution for contaminant flux to the water table

Waste leaching/release rate to vadose zone

$$F_{vz} = kQ$$

Waste radioactive decay rate

$$F_{wd} = \lambda Q$$

Waste mass balance

$$\begin{aligned} dQ/dt &= -F_{vz} - F_{wd} \\ &= -kQ - \lambda Q \\ &= -(k+\lambda)Q \end{aligned}$$

Solution for residual waste

$$\begin{aligned} dQ/Q &= -(k+\lambda)dt \\ \ln\frac{Q}{Q_0} &= -(k+\lambda)t \\ Q(t) &= Q_0 e^{-(k+\lambda)t} \end{aligned}$$

Waste leaching/release rate to vadose zone becomes

$$F_{vz}(t) = Q_0 k e^{-(k+\lambda)t}$$

Waste radioactive decay rate becomes

$$F_{wd}(t) = Q_0 \lambda e^{-(k+\lambda)t}$$

Rate of change of waste residual

$$\begin{aligned} dQ/dt &= -(k+\lambda)Q \\ &= -(k+\lambda)Q_0 e^{-(k+\lambda)t} \\ &= -Q_0(k+\lambda)e^{-(k+\lambda)t} \end{aligned}$$

Check sum of fluxes

$$
\begin{aligned}
& dQ/dt + F_{vz} + F_{wd} \\
&= -Q_0(k+\lambda)e^{-(k+\lambda)t} + Q_0 k e^{-(k+\lambda)t} + Q_0 \lambda e^{-(k+\lambda)t} \\
&= -Q_0(k+\lambda)e^{-(k+\lambda)t} + Q_0(k+\lambda)e^{-(k+\lambda)t} \\
&= 0
\end{aligned}
$$

Cumulative release to vadose zone

$$
\begin{aligned}
Q_{vz}(t) &= \int_0^t F_{vz}(\eta)\,d\eta \\
&= \int_0^t Q_0 k e^{-(k+\lambda)\eta}\,d\eta \\
&= Q_0 k \int_0^t e^{-(k+\lambda)\eta}\,d\eta \\
&= Q_0 k \left[\frac{-e^{-(k+\lambda)\eta}}{k+\lambda}\right]_0^t \\
&= Q_0 \frac{k}{k+\lambda}\left[-e^{-(k+\lambda)t} + 1\right] \\
&= Q_0 \frac{k}{k+\lambda}\left[1 - e^{-(k+\lambda)t}\right]
\end{aligned}
$$

Cumulative radioactive decay in waste form

$$
\begin{aligned}
Q_{wd}(t) &= \int_0^t F_{wd}(\eta)\,d\eta \\
&= Q_0 \frac{\lambda}{k+\lambda}\left[1 - e^{-(k+\lambda)t}\right]
\end{aligned}
$$

Check sum of cumulative amounts

$$
\begin{aligned}
& Q(t) + Q_{vz}(t) + Q_{wd}(t) \\
&= Q_0 e^{-(k+\lambda)t} + Q_0 \frac{k}{k+\lambda}\left[1 - e^{-(k+\lambda)t}\right] + Q_0 \frac{\lambda}{k+\lambda}\left[1 - e^{-(k+\lambda)t}\right] \\
&= Q_0 e^{-(k+\lambda)t} + Q_0\left[1 - e^{-(k+\lambda)t}\right] \\
&= Q_0
\end{aligned}
$$

Again, waste leaching/release rate to vadose zone

$$F_{vz}(t) = Q_0 k e^{-(k+\lambda)t}$$

Vadose zone radioactive decay rate

$$F_{vd}(t) = \lambda Q$$

Vadose zone mass balance for t < Δt

$$\begin{aligned} dQ/dt &= F_{vz}(t) - F_{vd}(t) \\ &= Q_0 k e^{-(k+\lambda)t} - \lambda Q \end{aligned}$$

$$dQ/dt + \lambda Q = Q_0 k e^{-(k+\lambda)t}$$

For linear first-order ODE ...

$$\frac{dy}{dx} + P(x)y = Q(x)$$

... solution is

$$ye^{\int P dx} = \int Q e^{\int P dx} dx + C$$

Substitute $y = Q, x = t, P(x) = \lambda, Q(x) = Q_0 k e^{-(k+\lambda)t}$

$$\begin{aligned} Qe^{\int \lambda dt} &= \int Q_0 k e^{-(k+\lambda)t} e^{\int \lambda dt} dt + C \\ Qe^{\lambda t} &= \int Q_0 k e^{-(k+\lambda)t} e^{\lambda t} dt + C \\ Qe^{\lambda t} &= Q_0 k \int e^{-kt} dt + C \\ Qe^{\lambda t} &= Q_0 k \frac{-1}{k} e^{-kt} + C \\ Qe^{\lambda t} &= -Q_0 e^{-kt} + C \\ Q &= -Q_0 e^{-(k+\lambda)t} + Ce^{-\lambda t} \end{aligned}$$

Apply initial condition Q = 0 at t = 0

$$\begin{aligned} 0 &= -Q_0 + C \\ C &= Q_0 \end{aligned}$$

Vadose zone waste "residual" for t < Δt is

$$\begin{aligned} Q &= -Q_0 e^{-(k+\lambda)t} + Q_0 e^{-\lambda t} \\ &= Q_0 \left[e^{-\lambda t} - e^{-(k+\lambda)t} \right] \\ &= Q_0 e^{-\lambda t} \left[1 - e^{-kt} \right] \end{aligned}$$

Rate of change of vadose zone "residual" for t < Δt becomes

$$\begin{aligned} dQ/dt &= d\left\{ Q_0 \left[e^{-\lambda t} - e^{-(k+\lambda)t} \right] \right\} / dt \\ &= -\lambda Q_0 e^{-\lambda t} + (k+\lambda) Q_0 e^{-(k+\lambda)t} \\ &= Q_0 (k+\lambda) e^{-(k+\lambda)t} - Q_0 \lambda e^{-\lambda t} \end{aligned}$$

Vadose zone radioactive decay rate for t < Δt becomes

$$F_{vd}(t) = Q_0 \lambda \left[e^{-\lambda t} - e^{-(k+\lambda)t} \right]$$

Check solution for vadose zone waste "residual" for t < Δt

$$\begin{aligned} dQ/dt &= F_{vz}(t) - F_{vd}(t) \\ Q_0 (k+\lambda) e^{-(k+\lambda)t} - Q_0 \lambda e^{-\lambda t} &= Q_0 k e^{-(k+\lambda)t} - Q_0 \lambda \left[e^{-\lambda t} - e^{-(k+\lambda)t} \right] \\ (k+\lambda) e^{-(k+\lambda)t} - \lambda e^{-\lambda t} &= k e^{-(k+\lambda)t} - \lambda \left[e^{-\lambda t} - e^{-(k+\lambda)t} \right] \\ (k+\lambda) e^{-(k+\lambda)t} - \lambda e^{-\lambda t} &= k e^{-(k+\lambda)t} - \lambda e^{-\lambda t} + \lambda e^{-(k+\lambda)t} \\ (k+\lambda) e^{-(k+\lambda)t} - \lambda e^{-\lambda t} &= (k+\lambda) e^{-(k+\lambda)t} - \lambda e^{-\lambda t} \\ 0 &= 0 \end{aligned}$$

Waste flowrate to water table for t > Δt

$$\begin{aligned} F_{wt}(t) &= F_{vz}(t - \Delta t) \cdot e^{-\lambda \Delta t} \\ &= Q_0 k e^{-(k+\lambda)(t-\Delta t)} \cdot e^{-\lambda \Delta t} \\ &= Q_0 k e^{-(k+\lambda)t} \cdot e^{(k+\lambda)\Delta t} \cdot e^{-\lambda \Delta t} \\ &= Q_0 k e^{k \Delta t} e^{-(k+\lambda)t} \end{aligned}$$

Waste leaching/release rate to vadose zone for t > Δt

$$F_{vz}(t) = Q_0 k e^{-(k+\lambda)t}$$

Vadose zone radioactive decay rate (again)

$$F_{vd}(t) = \lambda Q$$

Vadose zone mass balance for t > Δt

$$\begin{aligned} dQ/dt &= -F_{wt}(t) + F_{vz}(t) - F_{vd}(t) \\ &= -Q_0 k e^{k\Delta t} e^{-(k+\lambda)t} + Q_0 k e^{-(k+\lambda)t} - \lambda Q \end{aligned}$$

$$\begin{aligned} dQ/dt + \lambda Q &= Q_0 k e^{-(k+\lambda)t} - Q_0 k e^{-(k+\lambda)t} e^{k\Delta t} \\ &= Q_0 k \left[1 - e^{k\Delta t}\right] \cdot e^{-(k+\lambda)t} \end{aligned}$$

For linear first-order ODE ...

$$\frac{dy}{dx} + P(x)y = Q(x)$$

... solution is

$$ye^{\int P dx} = \int Q e^{\int P dx} dx + C$$

Substitute $y = Q, x = t, P(x) = \lambda, Q(x) = Q_0 k \left[1 - e^{k\Delta t}\right] \cdot e^{-(k+\lambda)t}$

$$\begin{aligned} Qe^{\int \lambda dt} &= \int Q_0 k \left[1 - e^{k\Delta t}\right] e^{-(k+\lambda)t} e^{\int \lambda dt} dt + C \\ Qe^{\lambda t} &= \int Q_0 k \left[1 - e^{k\Delta t}\right] e^{-(k+\lambda)t} e^{\lambda t} dt + C \\ Qe^{\lambda t} &= Q_0 k \left[1 - e^{k\Delta t}\right] \int e^{-kt} dt + C \\ Qe^{\lambda t} &= Q_0 k \left[1 - e^{k\Delta t}\right] \frac{-1}{k} e^{-kt} + C \\ Qe^{\lambda t} &= -Q_0 \left[1 - e^{k\Delta t}\right] e^{-kt} + C \\ Q &= -Q_0 \left[1 - e^{k\Delta t}\right] e^{-(k+\lambda)t} + Ce^{-\lambda t} \end{aligned}$$

Apply initial condition $Q = Q_0 e^{-\lambda\Delta t}\left[1 - e^{-k\Delta t}\right]$ at $t = \Delta t$

$$
\begin{aligned}
Q_0 e^{-\lambda\Delta t}\left[1 - e^{-k\Delta t}\right] &= -Q_0\left[1 - e^{k\Delta t}\right]e^{-(k+\lambda)\Delta t} + Ce^{-\lambda\Delta t} \\
Q_0 e^{-\lambda\Delta t}\left[1 - e^{-k\Delta t}\right] + Q_0\left[1 - e^{k\Delta t}\right]e^{-(k+\lambda)\Delta t} &= Ce^{-\lambda\Delta t} \\
Q_0 e^{-\lambda\Delta t}\left[1 - e^{-k\Delta t}\right] + Q_0\left[1 - e^{k\Delta t}\right]e^{-k\Delta t}e^{-\lambda\Delta t} &= Ce^{-\lambda\Delta t} \\
Q_0\left[1 - e^{-k\Delta t}\right] + Q_0\left[1 - e^{k\Delta t}\right]e^{-k\Delta t} &= C \\
Q_0\left[1 - e^{-k\Delta t}\right] + Q_0\left[e^{-k\Delta t} - 1\right] &= C \\
Q_0\left[1 - e^{-k\Delta t}\right] - Q_0\left[1 - e^{-k\Delta t}\right] &= C \\
C &= 0
\end{aligned}
$$

Vadose zone waste "residual" for t > Δt is

$$
\begin{aligned}
Q &= -Q_0\left[1 - e^{k\Delta t}\right]e^{-(k+\lambda)t} \\
Q &= Q_0\left[e^{k\Delta t} - 1\right]e^{-(k+\lambda)t}
\end{aligned}
$$

alternatively...

$$
\begin{aligned}
Q &= Q_0\left[e^{k\Delta t} - 1\right]e^{-(k+\lambda)t} \\
&= Q_0\left[e^{k\Delta t} - 1\right]e^{-kt}e^{-\lambda t} \\
&= Q_0\left[e^{-kt}e^{k\Delta t} - e^{-kt}\right]e^{-\lambda t} \\
&= Q_0 e^{-\lambda t}\left[e^{-k(t-\Delta t)} - e^{-kt}\right]
\end{aligned}
$$

Rate of change of vadose zone "residual" for t > Δt becomes

$$
\begin{aligned}
dQ/dt &= d\left\{Q_0\left[e^{k\Delta t} - 1\right]e^{-(k+\lambda)t}\right\}/dt \\
&= -Q_0(k+\lambda)\left[e^{k\Delta t} - 1\right]e^{-(k+\lambda)t}
\end{aligned}
$$

Vadose zone radioactive decay rate for t > Δt becomes

$$
\begin{aligned}
F_{vd}(t) &= \lambda Q_0\left[e^{k\Delta t} - 1\right]e^{-(k+\lambda)t} \\
&= Q_0\lambda\left[e^{k\Delta t} - 1\right]e^{-(k+\lambda)t}
\end{aligned}
$$

Check solution for vadose zone waste "residual" for t > Δt

$$
\begin{aligned}
dQ/dt &= -F_{wt}(t) + F_{vz}(t) - F_{vd}(t) \\
-Q_0(k+\lambda)\left[e^{k\Delta t} - 1\right]e^{-(k+\lambda)t} &= -Q_0 k e^{k\Delta t} e^{-(k+\lambda)t} + Q_0 k e^{-(k+\lambda)t} \\
&\quad - Q_0 \lambda \left[e^{k\Delta t} - 1\right]e^{-(k+\lambda)t} \\
-(k+\lambda)\left[e^{k\Delta t} - 1\right]e^{-(k+\lambda)t} &= -k\left[e^{k\Delta t} - 1\right]e^{-(k+\lambda)t} - \lambda\left[e^{k\Delta t} - 1\right]e^{-(k+\lambda)t} \\
-(k+\lambda)\left[e^{k\Delta t} - 1\right]e^{-(k+\lambda)t} &= -(k+\lambda)\left[e^{k\Delta t} - 1\right]e^{-(k+\lambda)t} \\
0 &= 0
\end{aligned}
$$

Cumulative waste flowrate to water table (t > Δt)

$$
\begin{aligned}
F_{wt}(t) &= Q_0 k e^{k\Delta t} \cdot e^{-(k+\lambda)t} \\
Q_{wt}(t) &= \int_{\Delta t}^{t} F_{wt}(\eta)\, d\eta \\
&= \int_{\Delta t}^{t} Q_0 k e^{k\Delta t} \cdot e^{-(k+\lambda)\eta}\, d\eta \\
&= Q_0 k e^{k\Delta t} \left[\frac{e^{-(k+\lambda)\eta}}{-(k+\lambda)}\right]_{\Delta t}^{t} \\
&= -Q_0 \frac{k}{k+\lambda} e^{k\Delta t}\left[e^{-(k+\lambda)t} - e^{-(k+\lambda)\Delta t}\right] \\
&= Q_0 \frac{k}{k+\lambda} e^{k\Delta t}\left[e^{-(k+\lambda)\Delta t} - e^{-(k+\lambda)t}\right]
\end{aligned}
$$

Cumulative decay in vadose zone water table (t < Δt)

$$
\begin{aligned}
Q_{vd}(t) &= \int_0^t \lambda Q d\eta \\
&= \lambda Q_0 \int_0^t e^{-\lambda\eta}\left[1-e^{-k\eta}\right] d\eta \\
&= \lambda Q_0 \int_0^t e^{-\lambda\eta} d\eta - \lambda Q_0 \int_0^t e^{-(k+\lambda)\eta} d\eta \\
&= \lambda Q_0 \left[\frac{e^{-\lambda\eta}}{-\lambda}\right]_0^t - \lambda Q_0 \left[\frac{e^{-(k+\lambda)\eta}}{-(k+\lambda)}\right]_0^t \\
&= Q_0\left[-e^{-\lambda\eta}\right]_0^t - Q_0 \frac{\lambda}{(k+\lambda)}\left[-e^{-(k+\lambda)\eta}\right]_0^t \\
&= Q_0\left[1-e^{-\lambda t}\right] - Q_0 \frac{\lambda}{(k+\lambda)}\left[1-e^{-(k+\lambda)t}\right]
\end{aligned}
$$

Check sum of cumulative amounts for t < Δt

$$
Q_{vd}(t) = Q_0\left[1-e^{-\lambda t}\right] - Q_0 \frac{\lambda}{(k+\lambda)}\left[1-e^{-(k+\lambda)t}\right]
$$

$$
Q_{vz}(t) = Q_0 \frac{k}{k+\lambda}\left[1-e^{-(k+\lambda)t}\right]
$$

$$
Q = Q_0 e^{-\lambda t}\left[1-e^{-kt}\right]
$$

$$
\begin{aligned}
&Q_{vz}(t) - Q_{vd}(t) - Q(t) \\
&= Q_0 \frac{k}{k+\lambda}\left[1-e^{-(k+\lambda)t}\right] - Q_0\left[1-e^{-\lambda t}\right] + Q_0 \frac{\lambda}{(k+\lambda)}\left[1-e^{-(k+\lambda)t}\right] - Q_0 e^{-\lambda t}\left[1-e^{-kt}\right] \\
&= Q_0 \frac{k+\lambda}{k+\lambda}\left[1-e^{-(k+\lambda)t}\right] - Q_0\left[1-e^{-\lambda t}\right] - Q_0\left[e^{-\lambda t} - e^{-(k+\lambda)t}\right] \\
&= Q_0\left[1-e^{-(k+\lambda)t}\right] - Q_0[1] - Q_0\left[-e^{-(k+\lambda)t}\right] \\
&= Q_0\left[1-e^{-(k+\lambda)t}\right] - Q_0\left[1-e^{-(k+\lambda)t}\right] \\
&= 0
\end{aligned}
$$

Cumulative decay in vadose zone water table for t > Δt

$$Q_{vd}(t) = Q_{vd}(\Delta t) + \int_{\Delta t}^{t} \lambda Q d\eta$$

$$\begin{aligned}
Q_{vd}(t) - Q_{vd}(\Delta t) &= \int_{\Delta t}^{t} \lambda Q d\eta \\
&= \int_{\Delta t}^{t} \lambda Q_0 \left[e^{k\Delta t} - 1\right] e^{-(k+\lambda)\eta} d\eta \\
&= \lambda Q_0 \left[e^{k\Delta t} - 1\right] \int_{\Delta t}^{t} e^{-(k+\lambda)\eta} d\eta \\
&= \lambda Q_0 \left[e^{k\Delta t} - 1\right] \left[-\frac{e^{-(k+\lambda)\eta}}{k+\lambda}\right]_{\Delta t}^{t} \\
&= Q_0 \frac{\lambda}{k+\lambda} \left[1 - e^{k\Delta t}\right] \left[e^{-(k+\lambda)t} - e^{-(k+\lambda)\Delta t}\right]
\end{aligned}$$

$$
\begin{aligned}
Q_{vd}(t) &= Q_0\left[1-e^{-\lambda\Delta t}\right] - Q_0\frac{\lambda}{(k+\lambda)}\left[1-e^{-(k+\lambda)\Delta t}\right] \\
&\quad + Q_0\frac{\lambda}{k+\lambda}\left[1-e^{k\Delta t}\right]\left[e^{-(k+\lambda)t} - e^{-(k+\lambda)\Delta t}\right] \\
&= Q_0\left[1-e^{-\lambda\Delta t}\right] - Q_0\frac{\lambda}{(k+\lambda)}\left[1-e^{-(k+\lambda)\Delta t}\right] \\
&\quad + Q_0\frac{\lambda}{k+\lambda}\left[e^{-(k+\lambda)t} - e^{-(k+\lambda)\Delta t} - e^{-(k+\lambda)t}e^{k\Delta t} + e^{-(k+\lambda)\Delta t}e^{k\Delta t}\right] \\
&= Q_0\left[1-e^{-\lambda\Delta t}\right] - Q_0\frac{\lambda}{(k+\lambda)} + Q_0\frac{\lambda}{k+\lambda}\left[e^{-(k+\lambda)t} - e^{-(k+\lambda)t}e^{k\Delta t} + e^{-\lambda\Delta t}\right] \\
&= Q_0\left[1-e^{-\lambda\Delta t}\right] - Q_0\frac{\lambda}{(k+\lambda)} + Q_0\frac{\lambda}{k+\lambda}\left[e^{-(k+\lambda)t} - e^{-(k+\lambda)t}e^{k\Delta t}\right] + Q_0\frac{\lambda}{k+\lambda}\left[e^{-\lambda\Delta t}\right] \\
&= Q_0\left[1-e^{-\lambda\Delta t}\right] - Q_0\frac{\lambda}{(k+\lambda)}\left[1-e^{-\lambda\Delta t}\right] + Q_0\frac{\lambda}{k+\lambda}e^{-(k+\lambda)t}\left[1-e^{k\Delta t}\right] \\
&= Q_0\left[1-e^{-\lambda\Delta t}\left[1-\frac{\lambda}{(k+\lambda)}\right]\right] + Q_0\frac{\lambda}{k+\lambda}e^{-(k+\lambda)t}\left[1-e^{k\Delta t}\right] \\
&= Q_0\frac{k}{k+\lambda}\left[1-e^{-\lambda\Delta t}\right] + Q_0\frac{\lambda}{k+\lambda}\left[1-e^{k\Delta t}\right]e^{-(k+\lambda)t}
\end{aligned}
$$

Check sum of cumulative amounts for t > Δt

$$Q_{vz}(t) = Q_0\frac{k}{k+\lambda}\left[1-e^{-(k+\lambda)t}\right]$$

$$Q_{vd}(t) = Q_0\frac{k}{k+\lambda}\left[1-e^{-\lambda\Delta t}\right] + Q_0\frac{\lambda}{k+\lambda}\left[1-e^{k\Delta t}\right]e^{-(k+\lambda)t}$$

$$Q_{wt}(t) = Q_0\frac{k}{k+\lambda}e^{k\Delta t}\left[e^{-(k+\lambda)\Delta t} - e^{-(k+\lambda)t}\right]$$

$$Q = Q_0\left[e^{k\Delta t} - 1\right]e^{-(k+\lambda)t}$$

$$Q_{vz}(t) - Q_{vd}(t) - Q_{wt}(t) - Q(t)$$

$$
\begin{aligned}
&= Q_0 \frac{k}{k+\lambda}\left[1-e^{-(k+\lambda)t}\right] \\
&- Q_0 \frac{k}{k+\lambda}\left[1-e^{-\lambda\Delta t}\right] - Q_0 \frac{\lambda}{k+\lambda}\left[1-e^{k\Delta t}\right]e^{-(k+\lambda)t} \\
&- Q_0 \frac{k}{k+\lambda} e^{k\Delta t}\left[e^{-(k+\lambda)\Delta t} - e^{-(k+\lambda)t}\right] \\
&- Q_0 \left[e^{k\Delta t} - 1\right]e^{-(k+\lambda)t}
\end{aligned}
$$

$$
\begin{aligned}
&= Q_0 \frac{k}{k+\lambda}\left[1-e^{-(k+\lambda)t}\right] \\
&- Q_0 \frac{k}{k+\lambda}\left[1-e^{-\lambda\Delta t}\right] \\
&- Q_0 \frac{\lambda}{k+\lambda}\left[1-e^{k\Delta t}\right]e^{-(k+\lambda)t} \\
&- Q_0 \frac{k}{k+\lambda} e^{k\Delta t} e^{-(k+\lambda)\Delta t} \\
&+ Q_0 \frac{k}{k+\lambda} e^{k\Delta t} e^{-(k+\lambda)t} \\
&- Q_0 \frac{k}{k+\lambda}\left[e^{k\Delta t} - 1\right]e^{-(k+\lambda)t} \\
&- Q_0 \frac{\lambda}{k+\lambda}\left[e^{k\Delta t} - 1\right]e^{-(k+\lambda)t}
\end{aligned}
$$

$$
\begin{aligned}
&= Q_0 \frac{k}{k+\lambda}\left[1-e^{-(k+\lambda)t}\right] \\
&- Q_0 \frac{k}{k+\lambda}\left[1-e^{-\lambda\Delta t}\right] \\
&- Q_0 \frac{\lambda}{k+\lambda}\left[1-e^{k\Delta t}\right]e^{-(k+\lambda)t} \\
&- Q_0 \frac{k}{k+\lambda} e^{-\lambda\Delta t} \\
&+ Q_0 \frac{k}{k+\lambda} e^{k\Delta t} e^{-(k+\lambda)t} \\
&+ Q_0 \frac{k}{k+\lambda}\left[1-e^{k\Delta t}\right]e^{-(k+\lambda)t} \\
&+ Q_0 \frac{\lambda}{k+\lambda}\left[1-e^{k\Delta t}\right]e^{-(k+\lambda)t}
\end{aligned}
$$

$$
\begin{aligned}
&= Q_0 \frac{k}{k+\lambda}\left[1-e^{-(k+\lambda)t}\right] \\
&- Q_0 \frac{k}{k+\lambda} \\
&- Q_0 \frac{\lambda}{k+\lambda}\left[1-e^{k\Delta t}\right]e^{-(k+\lambda)t} \\
&+ Q_0 \frac{k}{k+\lambda} e^{-(k+\lambda)t} \\
&+ Q_0 \frac{\lambda}{k+\lambda}\left[1-e^{k\Delta t}\right]e^{-(k+\lambda)t}
\end{aligned}
$$

$$
\begin{aligned}
&= Q_0 \frac{k}{k+\lambda}\left[1-e^{-(k+\lambda)t}\right] \\
&- Q_0 \frac{k}{k+\lambda} \\
&+ Q_0 \frac{k}{k+\lambda} e^{-(k+\lambda)t}
\end{aligned}
$$

$$
\begin{aligned}
&= Q_0 \frac{k}{k+\lambda}\left[1-e^{-(k+\lambda)t}\right] \\
&- Q_0 \frac{k}{k+\lambda}\left[1-e^{-(k+\lambda)t}\right] \\
&= 0
\end{aligned}
$$

Check vadose decay match at t = Δt

$$
Q_0\left[1-e^{-\lambda\Delta t}\right] - Q_0 \frac{\lambda}{(k+\lambda)}\left[1-e^{-(k+\lambda)\Delta t}\right] = Q_0 \frac{k}{k+\lambda}\left[1-e^{-\lambda\Delta t}\right] + Q_0 \frac{\lambda}{k+\lambda}\left[1-e^{k\Delta t}\right]e^{-(k+\lambda)\Delta t}
$$

$$
\left[1-e^{-\lambda\Delta t}\right] - \frac{\lambda}{k+\lambda}\left[1-e^{-(k+\lambda)\Delta t}\right] = \frac{k}{k+\lambda}\left[1-e^{-\lambda\Delta t}\right] + \frac{\lambda}{k+\lambda}e^{-(k+\lambda)\Delta t} - \frac{\lambda}{k+\lambda}e^{-\lambda\Delta t}
$$

$$
1-e^{-\lambda\Delta t} - \frac{\lambda}{k+\lambda} + \frac{\lambda}{k+\lambda}e^{-(k+\lambda)\Delta t} = \frac{k}{k+\lambda} - \frac{k}{k+\lambda}e^{-\lambda\Delta t} + \frac{\lambda}{k+\lambda}e^{-(k+\lambda)\Delta t} - \frac{\lambda}{k+\lambda}e^{-\lambda\Delta t}
$$

$$
1-e^{-\lambda\Delta t} - \frac{\lambda}{k+\lambda} = \frac{k}{k+\lambda} - \frac{k}{k+\lambda}e^{-\lambda\Delta t} - \frac{\lambda}{k+\lambda}e^{-\lambda\Delta t}
$$

$$
1-e^{-\lambda\Delta t} = 1-e^{-\lambda\Delta t}
$$

$$
0 = 0
$$

Summary of waste rates/fluxes

$$dQ_{waste} / dt = -F_{vz}(t) - F_{wd}(t)$$

$$dQ_{waste} / dt = -Q_0 (k + \lambda) e^{-(k+\lambda)t}$$

$$F_{vz}(t) = Q_0 k e^{-(k+\lambda)t}$$

$$F_{wd}(t) = Q_0 \lambda e^{-(k+\lambda)t}$$

Summary of waste cumulatives/residuals

$$Q_0 = Q_{waste}(t) + Q_{vz}(t) + Q_{wd}(t)$$

$$Q_{waste}(t) = Q_0 e^{-(k+\lambda)t}$$

$$Q_{vz}(t) = Q_0 \frac{k}{k+\lambda}\left[1 - e^{-(k+\lambda)t}\right]$$

$$Q_{wd}(t) = Q_0 \frac{\lambda}{k+\lambda}\left[1 - e^{-(k+\lambda)t}\right]$$

Summary of vadose zone rates/fluxes for t < Δt

$$dQ_{vadose} / dt = F_{vz}(t) - F_{vd}(t)$$

$$dQ_{vadose} / dt = Q_0 (k + \lambda) e^{-(k+\lambda)t} - Q_0 \lambda e^{-\lambda t}$$

$$F_{vz}(t) = Q_0 k e^{-(k+\lambda)t}$$

$$F_{vd}(t) = Q_0 \lambda \left[e^{-\lambda t} - e^{-(k+\lambda)t}\right]$$

Summary of vadose zone rates/fluxes for t > Δt

$$dQ_{vadose} / dt = F_{vz}(t) - F_{vd}(t) - F_{wt}(t)$$

$$dQ_{vadose} / dt = -Q_0 (k+\lambda)\left[e^{k\Delta t} - 1\right]e^{-(k+\lambda)t}$$

$$F_{vz}(t) = Q_0 k e^{-(k+\lambda)t}$$

$$F_{vd}(t) = Q_0 \lambda \left[e^{k\Delta t} - 1\right]e^{-(k+\lambda)t}$$

$$\boxed{F_{wt}(t) = Q_0 k e^{k\Delta t} e^{-(k+\lambda)t} = Q_0 k e^{-\lambda\Delta t} e^{-(k+\lambda)(t-\Delta t)} \text{ (for t > Δt)}}$$

Summary of vadose zone cumulatives/residuals for t < Δt

$$Q_{vz}(t) = Q_{vadose}(t) + Q_{vd}(t)$$

$$Q_{vz}(t) = Q_0 \frac{k}{k+\lambda}\left[1 - e^{-(k+\lambda)t}\right]$$

$$Q_{vadose}(t) = Q_0 \left[e^{-\lambda t} - e^{-(k+\lambda)t}\right] = Q_0 e^{-\lambda t}\left[1 - e^{-kt}\right]$$

(no water table flux yet)

$$Q_{vd}(t) = Q_0 \left[1 - e^{-\lambda t}\right] - Q_0 \frac{\lambda}{(k+\lambda)}\left[1 - e^{-(k+\lambda)t}\right]$$

Summary of vadose zone cumulatives/residuals for t > Δt

$$Q_{vz}(t) = Q_{vadose}(t) + Q_{wt}(t) + Q_{vd}(t)$$

$$Q_{vz}(t) = Q_0 \frac{k}{k+\lambda}\left[1 - e^{-(k+\lambda)t}\right]$$

$$Q_{vadose}(t) = Q_0 \left[e^{k\Delta t} - 1\right]e^{-(k+\lambda)t} = Q_0 e^{-\lambda t}\left[e^{-k(t-\Delta t)} - e^{-kt}\right]$$

$$\boxed{Q_{wt}(t) = Q_0 \frac{k}{k+\lambda} e^{k\Delta t}\left[e^{-(k+\lambda)\Delta t} - e^{-(k+\lambda)t}\right] \text{ (for t > Δt)}}$$

$$Q_{vd}(t) = Q_0 \frac{k}{k+\lambda}\left[1 - e^{-\lambda\Delta t}\right] + Q_0 \frac{\lambda}{k+\lambda}\left[1 - e^{k\Delta t}\right]e^{-(k+\lambda)t}$$

Appendix B Computer software and verification cases for tritium

All computer runs were made on an SGI R10000 UNIX workstation running IRIX 6.4.

Makefile

```
IncludePath = ./Include
include ${IncludePath}/FFLAGS.inc
include ${IncludePath}/LDFLAGS.inc

Fields     = 17
TauDecay   = 12.3
TauLeach   = 2


VerificationRuns:
        - rm VerificationNotMound.out
        cp VerificationNotMound.tim Times.tim
        make    Case=VerificationNotMound \
                BreachTime=0 \
                TravelTime=5 \
                Q0Default=100 \
                Q0factor=1 \
                Template
        - rm VerificationMound.out
        cp VerificationMound.tim Times.tim
        make    Case=VerificationMound \
                BreachTime=50 \
                TravelTime=50 \
                Q0Default=100 \
                Q0factor=1 \
                Template

Test:
        - rm TestCase.out
        make    Case=TestCase \
                BreachTime=10 \
                TravelTime=5 \
                Q0Default=100 \
                Q0factor=1 \
                Template

All:
        cp TimesCOBRA.tim Times.tim
        make Case=offsite_SpecialMound \
                BreachTime=50 \
                TravelTime=50 \
                Q0Default=0 \
                Q0factor=1 \
                Template
        make Case=offsite_NotSpecialMound \
                BreachTime=0 \
                TravelTime=5 \
                Q0Default=0 \
                Q0factor=1 \
                Template
        make Case=known_beds_for_greg \
                BreachTime=0 \
                TravelTime=5 \
                Q0Default=500 \
                Q0factor=1 \
                Template
        make Case=SuspectBeds \
                BreachTime=0 \
                TravelTime=5 \
                Q0Default=500 \
                Q0factor=1 \
                Template
        make Case=knwn_spent_melts_and_crucibles_for_greg \
                BreachTime=0 \
                TravelTime=5 \
                Q0Default=400 \
```

```
                Q0factor=0.67 \
                Template
        make Case=SuspectMelts \
                BreachTime=0 \
                TravelTime=5 \
                Q0Default=400 \
                Q0factor=0.67 \
                Template
        make Case=other_tritium_for_greg \
                BreachTime=0 \
                TravelTime=5 \
                Q0Default=0 \
                Q0factor=1 \
                Template


### Process COBRA data
Template:
        make    Case=${Case} \
                BreachTime=${BreachTime} \
                TravelTime=${TravelTime} \
                Q0Default=${Q0Default} \
                Q0factor=${Q0factor} \
                ${Case}.out

${Case}.out:   WTfluxCOBRA    ${Case}.txt    Times.tim
        @ echo "===== ${Case} ====="
        echo "${Case}.txt"      >tmp
        echo "Times.tim"       >>tmp
        echo "${Case}.out"     >>tmp
        echo "${Case}.flx"     >>tmp
        echo "${Case}.log"     >>tmp
        echo "${Fields}"       >>tmp
        echo "${TauDecay}"     >>tmp
        echo "${TauLeach}"     >>tmp
        echo "${TravelTime}"   >>tmp
        echo "${BreachTime}"   >>tmp
        echo "${Q0Default}"    >>tmp
        echo "${Q0factor}"     >>tmp
        cat tmp| WTfluxCOBRA

### Segregate mound and non-mound off-site burials
offsite_Mound.txt:    offsite_tritium_burials_for_greg.txt
        cat offsite_tritium_burials_for_greg.txt \
        |sed /999-MND/!d \
        |sort \
        >offsite_Mound.txt

offsite_NotMound.txt:  offsite_tritium_burials_for_greg.txt
        cat offsite_tritium_burials_for_greg.txt \
        |sed /999-MND/d \
        |sort \
        >offsite_NotMound.txt


### Compile/link codes ###
WTfluxCOBRA:   WTfluxCOBRA.o IostatCheck.o FindTabs.o ReadError.o
        ${F90} -mips4 -o WTfluxCOBRA WTfluxCOBRA.o \
        IostatCheck.o FindTabs.o ReadError.o


### Define suffix rules ###
.SUFFIXES: .o .f90
.f90.o:
        ${F90} ${F90FLAGS} $<
```

INCLUDE files

```
### FORTRAN FLAGS ###
FFLAGS = -c -mips4 -DEBUG:subscript_check=ON -DEBUG:trap_uninitialized=ON -
DEBUG:verbose_runtime=ON -g
F90FLAGS = -c -mips4 -check_bounds -trapuv -g

LDFLAGS = -mips4
```

Fortran90 source code

```
program WTfluxCOBRA

implicit none

integer, parameter :: RecordLength=250, MaxTimes=1000
integer, parameter :: itxt=11, &
                      itim=12, &
                      iout=21, &
                      iflx=22, &
                      ilog=23
integer, dimension(20) :: TabPos
integer i, n, iostat_flag, NumTabs, NumFields
integer :: Sequence=SELECTED_INT_KIND(6)
integer :: BurialCode
integer :: Month, Day, Year, Delimiter1, Delimiter2, nTimes, &
           iVar, CountNoQuantity, CountComments

real :: srsN, srsE
real, dimension(2) :: Quantity
real, dimension(MaxTimes) :: Times
real :: TempReal, BurialTime
real :: TauDecay, TauLeach, TravelTime, BreachTime, DecayBeforeBreech
real :: k, l, Fwt, Qwt, ReleaseTime, FiniteDiff, Time, ElapsedTime
real :: FwtFunc, QwtFunc
real :: UnitsConversion, Q0, Q0Default, Q0factor, CumulativeQ0, CumulativeQwt
real, parameter :: CiPerG=9780.

character(len=6) :: NC, EC
character(len=9) :: Date
character(len=6) :: Bldg
character(len=2), dimension(2) :: Variety
character(len=1), dimension(2) :: Units
character(len=80) :: Desc1, Desc2, Desc3
character(len=80) :: TempChar
character(len=3) :: MonthChar

character(len=RecordLength) Record
character(len=80) FileName
character(len=1), parameter :: tab='  ', bar='|', space=' '

logical exit_flag, OK


!INITIALIZE VARIABLES
CountNoQuantity = 0
CountComments = 0
CumulativeQ0 = 0
CumulativeQwt = 0


!OPEN FILES AND READ INPUT DATA
read(5,'(a)') FileName
open (unit=itxt, file=FileName, status='old', action='read')

read(5,'(a)') FileName
open (unit=itim, file=FileName, status='old', action='read')

read(5,'(a)') FileName
open (unit=iout, file=FileName, status='unknown', action='write')

read(5,'(a)') FileName
open (unit=iflx, file=FileName, status='unknown', action='write')

read(5,'(a)') FileName
open (unit=ilog, file=FileName, status='unknown', action='write')

read(5,*) NumFields
read(5,*) TauDecay
read(5,*) TauLeach
read(5,*) TravelTime
```

```
read(5,*) BreachTime
read(5,*) Q0Default
read(5,*) Q0factor


!READ TIMES AT WHICH TO COMPUTE WATER TABLE FLUX
nTimes = 1
do
  read (itim,*,iostat=iostat_flag) Times(nTimes)
  call IostatCheck (iostat_flag, "Times", exit_flag)
  if (exit_flag) then
    nTimes = nTimes - 1
    exit
  end if
  nTimes = nTimes + 1
end do


!READ COBRA RECORDS
n = 1
do
  !READ DATA RECORD
  read (itxt,'(a)',iostat=iostat_flag) Record
  call IostatCheck (iostat_flag, "Record", exit_flag)
  if (exit_flag) then
    n = n - 1
    exit
  end if

  !READ DATA FIELDS
  if (Record(1:1) .eq. '!')  then
    write (iout, '(a)') TRIM(Record)
    CountComments = CountComments + 1
  else
    !FIND TAB POSITIONS
    call FindTabs (Record,RecordLength,NumFields, NumTabs,TabPos,OK)
    if (.not.OK) then
      if (NumTabs+1 .lt. 14) then
        write (6,*) "*** ERROR *** not enough fields", n, NumTabs+1
        write (ilog,*) Record
        write (ilog,'(20i4)') (TabPos(i), i=1,NumTabs)
        stop
      end if
    end if
    !write (iout,'(20i4)') (TabPos(i), i=1,NumTabs)

    !READ FIELDS
    read (Record(           1: TabPos( 1)-1),'(a)',iostat=iostat_flag) TempChar
    call                                      ReadError(iostat_flag,n,"NC")
    NC = ADJUSTL(TempChar)

    read (Record(TabPos( 1)+1: TabPos( 2)-1),'(a)',iostat=iostat_flag) TempChar
    call                                      ReadError(iostat_flag,n,"EC")
    EC = ADJUSTL(TempChar)

    read (Record(TabPos( 2)+1: TabPos( 3)-1),    *,iostat=iostat_flag) srsN
    call                                      ReadError(iostat_flag,n,"srsN")

    read (Record(TabPos( 3)+1: TabPos( 4)-1),    *,iostat=iostat_flag) srsE
    call                                      ReadError(iostat_flag,n,"srsE")

    read (Record(TabPos( 4)+1: TabPos( 5)-1),'(a)',iostat=iostat_flag) TempChar
    call                                      ReadError(iostat_flag,n,"Date")
    Date = ADJUSTL(TempChar)

    read (Record(TabPos( 5)+1: TabPos( 6)-1),    *,iostat=iostat_flag) TempReal
    call                                      ReadError(iostat_flag,n,"Sequence")
    Sequence = TempReal

    read (Record(TabPos( 6)+1: TabPos( 7)-1),'(a)',iostat=iostat_flag) TempChar
    call                                      ReadError(iostat_flag,n,"Bldg")
    Bldg = ADJUSTL(TempChar)

    read (Record(TabPos( 7)+1: TabPos( 8)-1),    *,iostat=iostat_flag) TempReal
    call                                      ReadError(iostat_flag,n,"BurialCode")
    BurialCode = TempReal
```

```
read (Record(TabPos( 8)+1: TabPos( 9)-1),'(a)',iostat=iostat_flag) TempChar
call                                      ReadError(iostat_flag,n,"Variety(1)")
Variety(1) = ADJUSTL(TempChar)

read (Record(TabPos( 9)+1: TabPos(10)-1),    *,iostat=iostat_flag) Quantity(1)
call                                      ReadError(iostat_flag,n,"Quantity(1)")

read (Record(TabPos(10)+1: TabPos(11)-1),'(a)',iostat=iostat_flag) TempChar
call                                      ReadError(iostat_flag,n,"Units(1)")
Units(1) = ADJUSTL(TempChar)

read (Record(TabPos(11)+1: TabPos(12)-1),'(a)',iostat=iostat_flag) TempChar
call                                      ReadError(iostat_flag,n,"Variety(2)")
Variety(2) = ADJUSTL(TempChar)

read (Record(TabPos(12)+1: TabPos(13)-1),    *,iostat=iostat_flag) Quantity(2)
call                                      ReadError(iostat_flag,n,"Quantity(2)")

read (Record(TabPos(13)+1: TabPos(14)-1),'(a)',iostat=iostat_flag) TempChar
call                                      ReadError(iostat_flag,n,"Units(2)")
Units(2) = ADJUSTL(TempChar)

Desc1 = ''
read (Record(min(TabPos(14)+1,RecordLength):TabPos(15)-1), &
      '(a)',iostat=iostat_flag) Desc1
call   ReadError(iostat_flag,n,"Desc1")

Desc2 = ''
read (Record(min(TabPos(15)+1,RecordLength):TabPos(16)-1), &
      '(a)',iostat=iostat_flag) Desc2
call   ReadError(iostat_flag,n,"Desc2")

Desc3 = ''
read (Record(min(TabPos(16)+1,RecordLength):            ), &
      '(a)',iostat=iostat_flag) Desc3
call   ReadError(iostat_flag,n,"Desc3")

!ECHO INPUT
write (iout, '(   a,a, &
         &        a,a, &
         &     f9.2,a, &
         &     f9.2,a, &
         &        a,a, &
         &       i8,a, &
         &        a,a, &
         &       i4,a, &
         &        a,a, &
         &  1pe10.3,a, &
         &        a,a, &
         &        a,a, &
         &  1pe10.3,a, &
         &        a,a, &
         &        a,a, &
         &        a,a, &
         &        a,a    )') &
  TRIM(NC)        , tab, &
  TRIM(EC)        , tab, &
  srsN            , tab, &
  srsE            , tab, &
  TRIM(Date)      , tab, &
  Sequence        , tab, &
  TRIM(Bldg)      , tab, &
  BurialCode      , tab, &
  TRIM(Variety(1)), tab, &
  Quantity(1)     , tab, &
  TRIM(Units(1))  , tab, &
  TRIM(Variety(2)), tab, &
  Quantity(2)     , tab, &
  TRIM(Units(2))  , tab, &
  TRIM(Desc1)     , space, &
  TRIM(Desc2)     , space, &
  TRIM(Desc3)

!COMPUTE BURIAL TIME IN YEARS
do i=1,9
```

```
    if (Date(i:i).eq.'/' .or. Date(i:i).eq.'-') then
      Delimiter1=i
      exit
    end if
  end do
  do i=Delimiter1+1,9
    if (Date(i:i).eq.'/' .or. Date(i:i).eq.'-') then
      Delimiter2=i
      exit
    end if
  end do

  if (Date(Delimiter1:Delimiter1) .eq. '/') then
    read (Date(            :Delimiter1-1),*,iostat=iostat_flag) Month
    call                              ReadError(iostat_flag,n,"Month")

    read (Date(Delimiter1+1:Delimiter2-1),*,iostat=iostat_flag) Day
    call                              ReadError(iostat_flag,n,"Day")

    read (Date(Delimiter2+1:            ),*,iostat=iostat_flag) Year
    call                              ReadError(iostat_flag,n,"Year")
  else
    read (Date(            :Delimiter1-1),*,iostat=iostat_flag) Day
    call                              ReadError(iostat_flag,n,"Day")

    MonthChar = Date(Delimiter1+1:Delimiter2-1)
    if (MonthChar.eq.'Jan' .or. MonthChar.eq.'JAN') Month =  1
    if (MonthChar.eq.'Feb' .or. MonthChar.eq.'FEB') Month =  2
    if (MonthChar.eq.'Mar' .or. MonthChar.eq.'MAR') Month =  3
    if (MonthChar.eq.'Apr' .or. MonthChar.eq.'APR') Month =  4
    if (MonthChar.eq.'May' .or. MonthChar.eq.'MAY') Month =  5
    if (MonthChar.eq.'Jun' .or. MonthChar.eq.'JUN') Month =  6
    if (MonthChar.eq.'Jul' .or. MonthChar.eq.'JUL') Month =  7
    if (MonthChar.eq.'Aug' .or. MonthChar.eq.'AUG') Month =  8
    if (MonthChar.eq.'Sep' .or. MonthChar.eq.'SEP') Month =  9
    if (MonthChar.eq.'Oct' .or. MonthChar.eq.'OCT') Month = 10
    if (MonthChar.eq.'Nov' .or. MonthChar.eq.'NOV') Month = 11
    if (MonthChar.eq.'Dec' .or. MonthChar.eq.'DEC') Month = 12

    read (Date(Delimiter2+1:            ),*,iostat=iostat_flag) Year
    call                              ReadError(iostat_flag,n,"Year")
  end if

  BurialTime = (Day-1)/365. + (Month-1)/12. + Year + 1900

  !DETERMINE QUANTITY IN CURIES
  if      (Variety(1) .eq. '87') then
    iVar = 1
  else if (Variety(2) .eq. '87') then
    iVar = 2
  else
    write (   *,*) '*** WARNING (Variety not 87) ***', n,Variety(1),Variety(2)
    write (ilog,*) '*** WARNING (Variety not 87) ***', n,Variety(1),Variety(2)
    iVar = 0
  end if

  if (iVar .ne. 0) then
    if (Quantity(iVar) .gt. 0) then
      if      (Units(iVar) .eq. 'G') then
        UnitsConversion = CiPerG
      else if (Units(iVar) .eq. 'C') then
        UnitsConversion = 1
      else
        write (   *,*) '*** ERROR (Units not G or C) ***', n,'|'//Units(iVar)//'|'
        write (ilog,*) '*** ERROR (Units not G or C) ***', n,'|'//Units(iVar)//'|'
        stop
      end if
      Q0 = Quantity(iVar) * UnitsConversion
    else
      Q0 = Q0Default; CountNoQuantity = CountNoQuantity + 1
    end if
  else
      Q0 = Q0Default; CountNoQuantity = CountNoQuantity + 1
  end if

  CumulativeQ0 = CumulativeQ0 + Q0
```

```
    !COMPUTE FLUX TO VADOSE ZONE AND WATER TABLE AS FUNCTION OF TIME
    l = log(2.)/TauDecay
    k = log(2.)/TauLeach

    DecayBeforeBreech = exp(-l*BreachTime)

    ReleaseTime = BurialTime + BreachTime

    if (Q0 .gt. 0) then
      write (iflx, '("===== Record No. ",i6,2x,40("="))') n
      write (iflx, '(i8,2x,a,2x,a,2x,a))') Sequence, Date, Bldg, &
        TRIM(Desc1)//space//TRIM(Desc2)//space//TRIM(Desc3)
      write (iflx, '(2(f9.0),2x,a,2x,a))') srsE, srsN, NC, EC
      write (iflx, '(g12.5,2x,a,g15.7,2x,a))')  Q0*Q0factor, &
                                        Variety(max(iVar,1)), &
                                       Quantity(max(iVar,1)), &
                                          Units(max(iVar,1))
      write (iflx, '(2(g15.7,2x),i4)') BurialTime, ReleaseTime, nTimes

      do i=1, nTimes
        Time = Times(i)
        ElapsedTime  = Time - ReleaseTime

        Fwt = FwtFunc(k,l,TravelTime,ElapsedTime)*DecayBeforeBreech
        Qwt = QwtFunc(k,l,TravelTime,ElapsedTime)*DecayBeforeBreech

        write (iflx, '(4(g15.7,2x))') Time, ElapsedTime, Fwt, Qwt
      end do

      CumulativeQwt = CumulativeQwt + Q0*Q0factor*DecayBeforeBreech* &
                                      QwtFunc(k,l,TravelTime,1000.)
    end if

  end if
  n = n + 1
end do

write (   *,*) 'Total records', n
write (ilog,*) 'Total records', n

write (   *,*) 'Comment records', CountComments
write (ilog,*) 'Comment records', CountComments

write (   *,*) 'Data records', n-CountComments
write (ilog,*) 'Data records', n-CountComments

write (   *,*) 'Records with quantity not specified/unknown', CountNoQuantity
write (ilog,*) 'Records with quantity not specified/unknown', CountNoQuantity

write (   *,*) 'Cumulative buried activity', CumulativeQ0
write (ilog,*) 'Cumulative buried activity', CumulativeQ0

write (   *,*) 'Cumulative activity entering water table', CumulativeQwt
write (ilog,*) 'Cumulative activity entering water table', CumulativeQwt

write (   *,*) 'Ratio', CumulativeQwt/CumulativeQ0
write (ilog,*) 'Ratio', CumulativeQwt/CumulativeQ0

stop

end program WTfluxCOBRA


function FwtFunc(k,l,Dt,t)
real, intent(in) :: k, l, Dt, t
if (t .gt. Dt) then
  FwtFunc = k*exp(-l*Dt)*exp(-(k+l)*(t-Dt))
else
  FwtFunc = 0
end if
end function FwtFunc


function QwtFunc(k,l,Dt,t)
real, intent(in) :: k, l, Dt, t
```

```
if (t .gt. Dt) then
  QwtFunc = k/(k+l)*exp(k*Dt)*(exp(-(k+l)*Dt) - exp(-(k+l)*t))
else
  QwtFunc = 0
end if
end function QwtFunc

subroutine ReadError (iostat_flag,n,WhichOne)

implicit none

integer         , intent(in) :: iostat_flag,n
character(len=*), intent(in) :: WhichOne

if (iostat_flag .ne. 0) then
  write (*,*) '*** ReadError *** WhichOne, n: ', WhichOne, n
  stop
end if

end subroutine ReadError

subroutine IostatCheck (iostat_flag, string, exit_flag)

integer  , intent(in) :: iostat_flag
character, intent(in) :: string

logical, intent(out) ::  exit_flag

if      (iostat_flag .eq. 0) then !OK
  exit_flag = .false.

else if (iostat_flag .lt. 0) then !END-OF-FILE
  exit_flag = .true.

else if (iostat_flag .gt. 0) then !ERROR
  write (*,'(2a)') '*** READ ERROR *** ', string
  stop

end if

end subroutine IostatCheck

subroutine FindTabs(Record,RecordLength,NumFields, NumTabs,TabPos,OK)

integer,                     intent(in) :: RecordLength
integer,                     intent(in) :: NumFields
character(len=RecordLength), intent(in) :: Record

integer,                         intent(out) :: NumTabs
integer, dimension(NumFields-1), intent(out) :: TabPos
logical,                         intent(out) :: OK

real, parameter :: zero=0.0
integer i, n

n = 0
TabPos = RecordLength

do i=1,RecordLength
  if (Record(i:i) .eq. '      ') then
    n = n + 1
    if (n .lt. NumFields) then
      TabPos(n) = i
    else
      !write (6,*) "*** WARNING *** n .ge. NumFields", n, NumFields
    end if
  end if
end do
NumTabs = n

if (NumTabs .ge. NumFields-1) then
  OK = .true.
else
  OK = .false.
end if
```

```
end subroutine FindTabs
```

Verification run 1 (default tritium parameters)

```
Input file:
!NC     EC      SRS_N   SRS_E   DATE_SAIC       SEQ     BLDG_SAIC       BC      V1      Q1
        U1      V2      Q2      U2      DESC    DESC2   DESC3

N??.??  E??.??  99999.  99999.  1/1/00  999999  999-Z   1.      IA      400.    C       87
        1.      G       Default burial (not special   Mound)

N??.??  E??.??  99999.  99999.  1-Jan-00       999999  999-Z   1.      87      1.      C
        87      0.      G       Default burial (not special   Mound)

N??.??  E??.??  99999.  99999.  1/1/00  999999  999-Z   1.      87      0.      C       87
        0.      G       Default burial (not special   Mound)

Output flux file:
===== Record No.      2  ========================================
  999999  1/1/00     999-Z   Default burial (not special Mound)
   99999.   99999.  N??.??  E??.??
  9780.0      87   1.000000      G
   1900.000         1900.000        22
   1899.000        -1.000000         0.000000         0.000000
   1900.000         0.000000         0.000000         0.000000
   1900.020        0.1953125E-01     0.000000         0.000000
   1900.039        0.3906250E-01     0.000000         0.000000
   1900.078        0.7812500E-01     0.000000         0.000000
   1900.156        0.1562500         0.000000         0.000000
   1900.313        0.3125000         0.000000         0.000000
   1900.625        0.6250000         0.000000         0.000000
   1901.250         1.250000         0.000000         0.000000
   1902.500         2.500000         0.000000         0.000000
   1905.000         5.000000         0.000000         0.000000
   1905.100         5.099976        0.2511487        0.2562123E-01
   1905.200         5.199951        0.2412328        0.5023103E-01
   1905.400         5.400024        0.2225490        0.9660102E-01
   1905.800         5.800049        0.1894200        0.1788220
   1906.600         6.599976        0.1372295        0.3083504
   1908.200         8.199951        0.7202269E-01    0.4701832
   1911.400         11.40002        0.1983772E-01    0.5996979
   1917.800         17.80005        0.1505075E-02    0.6451966
   1930.600         30.59998        0.8663874E-05    0.6489104
   1956.200         56.19995        0.2870772E-09    0.6489320
   2107.400         207.3999        0.9992454E-36    0.6489320
===== Record No.      3  ========================================
  999999  1-Jan-00   999-Z   Default burial (not special Mound)
   99999.   99999.  N??.??  E??.??
  1.0000      87   1.000000      C
   1900.000         1900.000        22
   1899.000        -1.000000         0.000000         0.000000
   1900.000         0.000000         0.000000         0.000000
   1900.020        0.1953125E-01     0.000000         0.000000
   1900.039        0.3906250E-01     0.000000         0.000000
   1900.078        0.7812500E-01     0.000000         0.000000
   1900.156        0.1562500         0.000000         0.000000
   1900.313        0.3125000         0.000000         0.000000
   1900.625        0.6250000         0.000000         0.000000
   1901.250         1.250000         0.000000         0.000000
   1902.500         2.500000         0.000000         0.000000
   1905.000         5.000000         0.000000         0.000000
   1905.100         5.099976        0.2511487        0.2562123E-01
   1905.200         5.199951        0.2412328        0.5023103E-01
   1905.400         5.400024        0.2225490        0.9660102E-01
   1905.800         5.800049        0.1894200        0.1788220
   1906.600         6.599976        0.1372295        0.3083504
   1908.200         8.199951        0.7202269E-01    0.4701832
   1911.400         11.40002        0.1983772E-01    0.5996979
   1917.800         17.80005        0.1505075E-02    0.6451966
   1930.600         30.59998        0.8663874E-05    0.6489104
   1956.200         56.19995        0.2870772E-09    0.6489320
   2107.400         207.3999        0.9992454E-36    0.6489320
===== Record No.      4  ========================================
```

```
  999999  1/1/00     999-Z   Default burial (not special Mound)
   99999.   99999.  N??.??  E??.??
  100.00      87   0.000000      C
   1900.000         1900.000        22
   1899.000        -1.000000         0.000000         0.000000
   1900.000         0.000000         0.000000         0.000000
   1900.020        0.1953125E-01     0.000000         0.000000
   1900.039        0.3906250E-01     0.000000         0.000000
   1900.078        0.7812500E-01     0.000000         0.000000
   1900.156        0.1562500         0.000000         0.000000
   1900.313        0.3125000         0.000000         0.000000
   1900.625        0.6250000         0.000000         0.000000
   1901.250         1.250000         0.000000         0.000000
   1902.500         2.500000         0.000000         0.000000
   1905.000         5.000000         0.000000         0.000000
   1905.100         5.099976        0.2511487        0.2562123E-01
   1905.200         5.199951        0.2412328        0.5023103E-01
   1905.400         5.400024        0.2225490        0.9660102E-01
   1905.800         5.800049        0.1894200        0.1788220
   1906.600         6.599976        0.1372295        0.3083504
   1908.200         8.199951        0.7202269E-01    0.4701832
   1911.400         11.40002        0.1983772E-01    0.5996979
   1917.800         17.80005        0.1505075E-02    0.6451966
   1930.600         30.59998        0.8663874E-05    0.6489104
   1956.200         56.19995        0.2870772E-09    0.6489320
   2107.400         207.3999        0.9992454E-36    0.6489320
```

Verification run 2 (Mound Special Burial parameters)

```
Input file:
!NC     EC      SRS_N   SRS_E   DATE_SAIC       SEQ     BLDG_SAIC       BC      V1      Q1
        U1      V2      Q2      U2      DESC    DESC2   DESC3
N??.??  E??.??  99999.  99999.  1/1/00  999999  999-Z   1.      IA      400.    C       87
        1.      G       Special Mound
N??.??  E??.??  99999.  99999.  1-Jan-00        999999  999-Z   1.      87      1.      C
        87      0.      G       Special Mound
N??.??  E??.??  99999.  99999.  1/1/00  999999  999-Z   1.      87      0.      C       87
        0.      G       Special Mound

Output flux file:
===== Record No.      2  ========================================
  999999  1/1/00     999-Z   Special Mound
   99999.   99999.  N??.??  E??.??
  9780.0      87   1.000000      G
   1900.000         1950.000        22
   1900.000        -50.00000         0.000000         0.000000
   1949.000        -1.000000         0.000000         0.000000
   1950.195        0.1953125         0.000000         0.000000
   1950.391        0.3906250         0.000000         0.000000
   1950.781        0.7812500         0.000000         0.000000
   1951.563         1.562500         0.000000         0.000000
   1953.125         3.125000         0.000000         0.000000
   1956.250         6.250000         0.000000         0.000000
   1962.500         12.50000         0.000000         0.000000
   1975.000         25.00000         0.000000         0.000000
   2000.000         50.00000         0.000000         0.000000
   2000.100         50.09998        0.1188236E-02    0.1212207E-03
   2000.200         50.19995        0.1141322E-02    0.2376500E-03
   2000.400         50.40002        0.1052925E-02    0.4570395E-03
   2000.800         50.80005        0.8961847E-03    0.8460433E-03
   2001.600         51.59998        0.6492608E-03    0.1458868E-02
   2003.200         53.19995        0.3407541E-03    0.2224534E-02
   2006.400         56.40002        0.9385632E-04    0.2837295E-02
   2012.800         62.80005        0.7120816E-05    0.3052559E-02
   2025.600         75.59998        0.4099056E-07    0.3070130E-02
   2051.200         101.2000        0.1358221E-11    0.3070231E-02
   2102.400         152.3999        0.1491226E-20    0.3070231E-02
===== Record No.      3  ========================================
  999999  1-Jan-00   999-Z   Special Mound
   99999.   99999.  N??.??  E??.??
  1.0000      87   1.000000      C
   1900.000         1950.000        22
   1900.000        -50.00000         0.000000         0.000000
   1949.000        -1.000000         0.000000         0.000000
```

```
   1950.195        0.1953125         0.000000         0.000000
   1950.391        0.3906250         0.000000         0.000000
   1950.781        0.7812500         0.000000         0.000000
   1951.563         1.562500         0.000000         0.000000
   1953.125         3.125000         0.000000         0.000000
   1956.250         6.250000         0.000000         0.000000
   1962.500         12.50000         0.000000         0.000000
   1975.000         25.00000         0.000000         0.000000
   2000.000         50.00000         0.000000         0.000000
   2000.100         50.09998        0.1188236E-02    0.1212207E-03
   2000.200         50.19995        0.1141322E-02    0.2376500E-03
   2000.400         50.40002        0.1052925E-02    0.4570395E-03
   2000.800         50.80005        0.8961847E-03    0.8460433E-03
   2001.600         51.59998        0.6492608E-03    0.1458868E-02
   2003.200         53.19995        0.3407541E-03    0.2224534E-02
   2006.400         56.40002        0.9385632E-04    0.2837295E-02
   2012.800         62.80005        0.7120816E-05    0.3052559E-02
   2025.600         75.59998        0.4099056E-07    0.3070130E-02
   2051.200         101.2000        0.1358221E-11    0.3070231E-02
   2102.400         152.3999        0.1491226E-20    0.3070231E-02
===== Record No.      4  ======================================
  999999  1/1/00     999-Z   Special Mound
   99999.   99999.  N??.??  E??.??
  100.00      87   0.000000      C
   1900.000         1950.000        22
   1900.000        -50.00000         0.000000         0.000000
   1949.000        -1.000000         0.000000         0.000000
   1950.195        0.1953125         0.000000         0.000000
   1950.391        0.3906250         0.000000         0.000000
   1950.781        0.7812500         0.000000         0.000000
   1951.563         1.562500         0.000000         0.000000
   1953.125         3.125000         0.000000         0.000000
   1956.250         6.250000         0.000000         0.000000
   1962.500         12.50000         0.000000         0.000000
   1975.000         25.00000         0.000000         0.000000
   2000.000         50.00000         0.000000         0.000000
   2000.100         50.09998        0.1188236E-02    0.1212207E-03
   2000.200         50.19995        0.1141322E-02    0.2376500E-03
   2000.400         50.40002        0.1052925E-02    0.4570395E-03
   2000.800         50.80005        0.8961847E-03    0.8460433E-03
   2001.600         51.59998        0.6492608E-03    0.1458868E-02
   2003.200         53.19995        0.3407541E-03    0.2224534E-02
   2006.400         56.40002        0.9385632E-04    0.2837295E-02
   2012.800         62.80005        0.7120816E-05    0.3052559E-02
   2025.600         75.59998        0.4099056E-07    0.3070130E-02
   2051.200         101.2000        0.1358221E-11    0.3070231E-02
   2102.400         152.3999        0.1491226E-20    0.3070231E-02
```

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Appendix C Computer software and verification cases for job control waste

All computer runs were made on an SGI R10000 UNIX workstation running IRIX 6.4.

Makefile

```
IncludePath = ./Include
include ${IncludePath}/FFLAGS.inc
include ${IncludePath}/LDFLAGS.inc

Fields     = 14
TauDecay   = 1.e+6
TauLeach   = 2

#OutputDir = /work4/JobCntrlWTsrc
OutputDir = .


VerificationRuns:
        - rm VerificationNotMound.out
        cp VerificationNotMound.tim Times.tim
        make    Case=VerificationNotMound \
                BreachTime=0 \
                TravelTime=5 \
                Q0Default=100 \
                Q0factor=1 \
                Template

TestCase:
        - rm TestCase.out
        make    Case=TestCase \
                BreachTime=0 \
                TravelTime=5 \
                Q0Default=-999 \
                Q0factor=1 \
                Template

job_control_waste:
        cp TimesCOBRA.tim Times.tim
        make Case=job_control_waste \
                BreachTime=0 \
                TravelTime=5 \
                Q0Default=0 \
                Q0factor=1 \
                Template


### Process COBRA data
Template:
        make    Case=${Case} \
                BreachTime=${BreachTime} \
                TravelTime=${TravelTime} \
                Q0Default=${Q0Default} \
                Q0factor=${Q0factor} \
                ${Case}.out

${Case}.out:   WTfluxCOBRA    ${Case}.txt    Times.tim
        @ echo "===== ${Case} ====="
        echo "${Case}.txt"      >tmp
        echo "Times.tim"       >>tmp
        echo "${OutputDir}/${Case}.out"       >>tmp
        echo "${OutputDir}/${Case}.flx"       >>tmp
        echo "${OutputDir}/${Case}.log"       >>tmp
        echo "${Fields}"       >>tmp
        echo "${TauDecay}"     >>tmp
        echo "${TauLeach}"     >>tmp
        echo "${TravelTime}"   >>tmp
        echo "${BreachTime}"   >>tmp
        echo "${Q0Default}"    >>tmp
        echo "${Q0factor}"     >>tmp
        cat tmp| WTfluxCOBRA
```

```
### Compile/link codes ###
WTfluxCOBRA:   WTfluxCOBRA.o IostatCheck.o FindTabs.o ReadError.o
        ${F90} -mips4 -o WTfluxCOBRA WTfluxCOBRA.o \
        IostatCheck.o FindTabs.o ReadError.o


### Define suffix rules ###
.SUFFIXES: .o .f90
.f90.o:
        ${F90} ${F90FLAGS} $<
```

INCLUDE files

```
### FORTRAN FLAGS ###
FFLAGS = -c -mips4 -DEBUG:subscript_check=ON -DEBUG:trap_uninitialized=ON -
DEBUG:verbose_runtime=ON -g
F90FLAGS = -c -mips4 -check_bounds -trapuv -g

LDFLAGS = -mips4
```

Fortran90 source code

```
program WTfluxCOBRA

implicit none

integer, parameter :: RecordLength=250, MaxTimes=1000
integer, parameter :: itxt=11, &
                      itim=12, &
                      iout=21, &
                      iflx=22, &
                      ilog=23
integer, dimension(20) :: TabPos
integer i, n, iostat_flag, NumTabs, NumFields
integer :: Sequence=SELECTED_INT_KIND(6)
integer :: BurialCode
integer :: Month, Day, Year, Delimiter1, Delimiter2, nTimes, &
           CountNoQuantity, CountComments

real :: srsN, srsE
real :: Volume
real, dimension(MaxTimes) :: Times
real :: TempReal, BurialTime
real :: TauDecay, TauLeach, TravelTime, BreachTime, DecayBeforeBreech
real :: k, l, Fwt, Qwt, ReleaseTime, FiniteDiff, Time, ElapsedTime
real :: FwtFunc, QwtFunc
real :: UnitsConversion, Q0, Q0Default, Q0factor, CumulativeQ0, CumulativeQwt
real, parameter :: CiPerG=9780.

character(len=6) :: NC, EC
character(len=9) :: Date
character(len=6) :: Bldg
character(len=2), dimension(2) :: Variety
character(len=80) :: Desc1, Desc2, Desc3
character(len=80) :: TempChar
character(len=3) :: MonthChar

character(len=RecordLength) Record
character(len=80) FileName
character(len=1), parameter :: tab='  ', bar='|', space=' '

logical exit_flag, OK


!INITIALIZE VARIABLES
CountNoQuantity = 0
CountComments = 0
CumulativeQ0 = 0
CumulativeQwt = 0
```

```
!OPEN FILES AND READ INPUT DATA
read(5,'(a)') FileName
open (unit=itxt, file=FileName, status='old', action='read')

read(5,'(a)') FileName
open (unit=itim, file=FileName, status='old', action='read')

read(5,'(a)') FileName
open (unit=iout, file=FileName, status='unknown', action='write')

read(5,'(a)') FileName
open (unit=iflx, file=FileName, status='unknown', action='write')

read(5,'(a)') FileName
open (unit=ilog, file=FileName, status='unknown', action='write')

read(5,*) NumFields
read(5,*) TauDecay
read(5,*) TauLeach
read(5,*) TravelTime
read(5,*) BreachTime
read(5,*) Q0Default
read(5,*) Q0factor


!READ TIMES AT WHICH TO COMPUTE WATER TABLE FLUX
nTimes = 1
do
  read (itim,*,iostat=iostat_flag) Times(nTimes)
  call IostatCheck (iostat_flag, "Times", exit_flag)
  if (exit_flag) then
    nTimes = nTimes - 1
    exit
  end if
  nTimes = nTimes + 1
end do


!READ COBRA RECORDS
n = 1
do
  !READ DATA RECORD
  read (itxt,'(a)',iostat=iostat_flag) Record
  call IostatCheck (iostat_flag, "Record", exit_flag)
  if (exit_flag) then
    n = n - 1
    exit
  end if

  !READ DATA FIELDS
  if (Record(1:1) .eq. '!')  then
    write (iout, '(a)') TRIM(Record)
    CountComments = CountComments + 1
  else
    !FIND TAB POSITIONS
    call FindTabs (Record,RecordLength,NumFields, NumTabs,TabPos,OK)
    if (.not.OK) then
      if (NumTabs+1 .lt. 14) then
        write (6,*) "*** ERROR *** not enough fields", n, NumTabs+1
        write (ilog,*) Record
        write (ilog,'(20i4)') (TabPos(i), i=1,NumTabs)
        stop
      end if
    end if
    !write (iout,'(20i4)') (TabPos(i), i=1,NumTabs)

    !READ FIELDS
    read (Record(           1: TabPos( 1)-1),'(a)',iostat=iostat_flag) TempChar
    call                                     ReadError(iostat_flag,n,"NC")
    NC = ADJUSTL(TempChar)

    read (Record(TabPos( 1)+1: TabPos( 2)-1),'(a)',iostat=iostat_flag) TempChar
    call                                     ReadError(iostat_flag,n,"EC")
    EC = ADJUSTL(TempChar)
```

```
read (Record(TabPos( 2)+1: TabPos( 3)-1),    *,iostat=iostat_flag) srsN
call                                       ReadError(iostat_flag,n,"srsN")

read (Record(TabPos( 3)+1: TabPos( 4)-1),    *,iostat=iostat_flag) srsE
call                                       ReadError(iostat_flag,n,"srsE")

read (Record(TabPos( 4)+1: TabPos( 5)-1),'(a)',iostat=iostat_flag) TempChar
call                                       ReadError(iostat_flag,n,"Date")
Date = ADJUSTL(TempChar)

read (Record(TabPos( 5)+1: TabPos( 6)-1),    *,iostat=iostat_flag) TempReal
call                                       ReadError(iostat_flag,n,"Sequence")
Sequence = TempReal

read (Record(TabPos( 6)+1: TabPos( 7)-1),'(a)',iostat=iostat_flag) TempChar
call                                       ReadError(iostat_flag,n,"Bldg")
Bldg = ADJUSTL(TempChar)

read (Record(TabPos( 7)+1: TabPos( 8)-1),    *,iostat=iostat_flag) TempReal
call                                       ReadError(iostat_flag,n,"BurialCode")
BurialCode = TempReal

read (Record(TabPos( 8)+1: TabPos( 9)-1),    *,iostat=iostat_flag) Volume
call                                       ReadError(iostat_flag,n,"Volume")

read (Record(TabPos( 9)+1: TabPos(10)-1),'(a)',iostat=iostat_flag) TempChar
call                                       ReadError(iostat_flag,n,"Variety(1)")
Variety(1) = ADJUSTL(TempChar)

read (Record(TabPos(10)+1: TabPos(11)-1),'(a)',iostat=iostat_flag) TempChar
call                                       ReadError(iostat_flag,n,"Variety(2)")
Variety(2) = ADJUSTL(TempChar)

Desc1 = ''
read (Record(min(TabPos(11)+1,RecordLength):TabPos(12)-1), &
      '(a)',iostat=iostat_flag) Desc1
call   ReadError(iostat_flag,n,"Desc1")

Desc2 = ''
read (Record(min(TabPos(12)+1,RecordLength):TabPos(13)-1), &
      '(a)',iostat=iostat_flag) Desc2
call   ReadError(iostat_flag,n,"Desc2")

Desc3 = ''
read (Record(min(TabPos(13)+1,RecordLength):            ), &
      '(a)',iostat=iostat_flag) Desc3
call   ReadError(iostat_flag,n,"Desc3")

!ECHO INPUT
write (iout, '(   a,a, &
         &        a,a, &
         &     f9.2,a, &
         &     f9.2,a, &
         &        a,a, &
         &       i8,a, &
         &        a,a, &
         &       i4,a, &
         &  1pe10.3,a, &
         &        a,a, &
         &        a,a, &
         &        a,a, &
         &        a,a, &
         &        a,a    )') &
  TRIM(NC)        , tab, &
  TRIM(EC)        , tab, &
  srsN            , tab, &
  srsE            , tab, &
  TRIM(Date(:8))  , tab, &
  Sequence        , tab, &
  TRIM(Bldg)      , tab, &
  BurialCode      , tab, &
  Volume          , tab, &
  TRIM(Variety(1)), tab, &
  TRIM(Variety(2)), tab, &
  TRIM(Desc1)     , space, &
  TRIM(Desc2)     , space, &
```

```
  TRIM(Desc3)

!COMPUTE BURIAL TIME IN YEARS
do i=1,9
  if (Date(i:i).eq.'/' .or. Date(i:i).eq.'-') then
    Delimiter1=i
    exit
  end if
end do
do i=Delimiter1+1,9
  if (Date(i:i).eq.'/' .or. Date(i:i).eq.'-') then
    Delimiter2=i
    exit
  end if
end do

if (Date(Delimiter1:Delimiter1) .eq. '/') then
  read (Date(            :Delimiter1-1),*,iostat=iostat_flag) Month
  call                              ReadError(iostat_flag,n,"Month")

  read (Date(Delimiter1+1:Delimiter2-1),*,iostat=iostat_flag) Day
  call                              ReadError(iostat_flag,n,"Day")

  read (Date(Delimiter2+1:Delimiter2+3),*,iostat=iostat_flag) Year
  call                              ReadError(iostat_flag,n,"Year")
else
  read (Date(            :Delimiter1-1),*,iostat=iostat_flag) Day
  call                              ReadError(iostat_flag,n,"Day")

  MonthChar = Date(Delimiter1+1:Delimiter2-1)
  if (MonthChar.eq.'Jan' .or. MonthChar.eq.'JAN') Month =  1
  if (MonthChar.eq.'Feb' .or. MonthChar.eq.'FEB') Month =  2
  if (MonthChar.eq.'Mar' .or. MonthChar.eq.'MAR') Month =  3
  if (MonthChar.eq.'Apr' .or. MonthChar.eq.'APR') Month =  4
  if (MonthChar.eq.'May' .or. MonthChar.eq.'MAY') Month =  5
  if (MonthChar.eq.'Jun' .or. MonthChar.eq.'JUN') Month =  6
  if (MonthChar.eq.'Jul' .or. MonthChar.eq.'JUL') Month =  7
  if (MonthChar.eq.'Aug' .or. MonthChar.eq.'AUG') Month =  8
  if (MonthChar.eq.'Sep' .or. MonthChar.eq.'SEP') Month =  9
  if (MonthChar.eq.'Oct' .or. MonthChar.eq.'OCT') Month = 10
  if (MonthChar.eq.'Nov' .or. MonthChar.eq.'NOV') Month = 11
  if (MonthChar.eq.'Dec' .or. MonthChar.eq.'DEC') Month = 12

  read (Date(Delimiter2+1:            ),*,iostat=iostat_flag) Year
  call                              ReadError(iostat_flag,n,"Year")
end if

BurialTime = (Day-1)/365. + (Month-1)/12. + Year + 1900

!DETERMINE VOLUME
Q0 = Volume
if (Volume .eq. 0) then
  Q0 = Q0Default; CountNoQuantity = CountNoQuantity + 1
end if

CumulativeQ0 = CumulativeQ0 + Q0

!COMPUTE FLUX TO VADOSE ZONE AND WATER TABLE AS FUNCTION OF TIME
l = log(2.)/TauDecay
k = log(2.)/TauLeach

DecayBeforeBreech = exp(-l*BreachTime)

ReleaseTime = BurialTime + BreachTime

if (Q0 .gt. 0) then
  write (iflx, '("===== Record No. ",i6,2x,40("="))') n
  write (iflx, '(i8,2x,a,2x,a,2x,a))') Sequence, Date(:8), Bldg, &
    TRIM(Desc1)//space//TRIM(Desc2)//space//TRIM(Desc3)
  write (iflx, '(2(f9.0),2x,a,2x,a))') srsE, srsN, NC, EC
  write (iflx, '(g12.5))')  Q0*Q0factor
  write (iflx, '(2(g15.7,2x),i4)') BurialTime, ReleaseTime, nTimes

  do i=1, nTimes
    Time = Times(i)
    ElapsedTime  = Time - ReleaseTime
```

```
        Fwt = FwtFunc(k,l,TravelTime,ElapsedTime)*DecayBeforeBreech
        Qwt = QwtFunc(k,l,TravelTime,ElapsedTime)*DecayBeforeBreech

        write (iflx, '(4(g15.7,2x))') Time, ElapsedTime, Fwt, Qwt
      end do

      CumulativeQwt = CumulativeQwt + Q0*Q0factor*DecayBeforeBreech* &
                                      QwtFunc(k,l,TravelTime,1000.)
    end if

  end if
  n = n + 1
end do

write (   *,*) 'Total records', n
write (ilog,*) 'Total records', n

write (   *,*) 'Comment records', CountComments
write (ilog,*) 'Comment records', CountComments

write (   *,*) 'Data records', n-CountComments
write (ilog,*) 'Data records', n-CountComments

write (   *,*) 'Records with quantity not specified/unknown', CountNoQuantity
write (ilog,*) 'Records with quantity not specified/unknown', CountNoQuantity

write (   *,*) 'Cumulative buried activity', CumulativeQ0
write (ilog,*) 'Cumulative buried activity', CumulativeQ0

write (   *,*) 'Cumulative activity entering water table', CumulativeQwt
write (ilog,*) 'Cumulative activity entering water table', CumulativeQwt

write (   *,*) 'Ratio', CumulativeQwt/CumulativeQ0
write (ilog,*) 'Ratio', CumulativeQwt/CumulativeQ0

stop

end program WTfluxCOBRA


function FwtFunc(k,l,Dt,t)
real, intent(in) :: k, l, Dt, t
if (t .gt. Dt) then
  FwtFunc = k*exp(-l*Dt)*exp(-(k+l)*(t-Dt))
else
  FwtFunc = 0
end if
end function FwtFunc


function QwtFunc(k,l,Dt,t)
real, intent(in) :: k, l, Dt, t
if (t .gt. Dt) then
  QwtFunc = k/(k+l)*exp(k*Dt)*(exp(-(k+l)*Dt) - exp(-(k+l)*t))
else
  QwtFunc = 0
end if
end function QwtFunc

subroutine ReadError (iostat_flag,n,WhichOne)

implicit none

integer         , intent(in) :: iostat_flag,n
character(len=*), intent(in) :: WhichOne

if (iostat_flag .ne. 0) then
  write (*,*) '*** ReadError *** WhichOne, n: ', WhichOne, n
  stop
end if

end subroutine ReadError

subroutine IostatCheck (iostat_flag, string, exit_flag)
```

```
integer  , intent(in) :: iostat_flag
character, intent(in) :: string

logical, intent(out) ::  exit_flag

if      (iostat_flag .eq. 0) then !OK
  exit_flag = .false.

else if (iostat_flag .lt. 0) then !END-OF-FILE
  exit_flag = .true.

else if (iostat_flag .gt. 0) then !ERROR
  write (*,'(2a)') '*** READ ERROR *** ', string
  stop

end if

end subroutine IostatCheck

subroutine FindTabs(Record,RecordLength,NumFields, NumTabs,TabPos,OK)

integer,                     intent(in) :: RecordLength
integer,                     intent(in) :: NumFields
character(len=RecordLength), intent(in) :: Record

integer,                         intent(out) :: NumTabs
integer, dimension(NumFields-1), intent(out) :: TabPos
logical,                         intent(out) :: OK

real, parameter :: zero=0.0
integer i, n

n = 0
TabPos = RecordLength

do i=1,RecordLength
  if (Record(i:i) .eq. '      ') then
    n = n + 1
    if (n .lt. NumFields) then
      TabPos(n) = i
    else
      !write (6,*) "*** WARNING *** n .ge. NumFields", n, NumFields
    end if
  end if
end do
NumTabs = n

if (NumTabs .ge. NumFields-1) then
  OK = .true.
else
  OK = .false.
end if

end subroutine FindTabs
```

Verification run

```
Input file:
!nc     ec      srs_n   srs_e   date_saic       seq     bldg_saic       bc      vo      v1
        v2      desc    desc2   desc3
N13.70  E18.20  74970.00        57620.00        5/31/96 0:00:00         1346.00 677-G   3.00
        150.00  81              CARTON
N15.20  E26.20  75120.00        58420.00        3/16/70 0:00:00         4787.00 773-A   4.00
        9.00    46
N15.20  E26.20  75120.00        58420.00        3/18/70 0:00:00         4795.00 773-A   4.00
        9.00    46      FP
N15.20  E26.20  75120.00        58420.00        3/19/70 0:00:00         4796.00 105-K   2.00
        34.00   FP
N15.20  E26.20  75120.00        58420.00        3/19/70 0:00:00         4799.00 221-F   2.00
        300.00  FP              EP 831.1
N15.20  E27.10  75120.00        58510.00        3/16/70 0:00:00         4806.00 221-F   1.00
        250.00  FP
N15.20  E26.20  75120.00        58420.00        3/16/70 0:00:00         4810.00 773-A   4.00
```

```
        12.00   46      FP
N15.20  E26.20  75120.00       58420.00       3/16/70 0:00:00       4811.00 773-A   4.00
        12.00   46      FP
N15.20  E26.20  75120.00       58420.00       3/16/70 0:00:00       4812.00 773-A   3.00
        10.00   46


Output flux file:
===== Record No.      2  ========================================
    1346  5/31/96   677-G   CARTON
   57620.   74970.  N13.70  E18.20
  150.00
   1996.416         1996.416        17
   1970.000        -26.41553         0.000000         0.000000
   1975.000        -21.41553         0.000000         0.000000
   1980.000        -16.41553         0.000000         0.000000
   1985.000        -11.41553         0.000000         0.000000
   1990.000        -6.415527         0.000000         0.000000
   1995.000        -1.415527         0.000000         0.000000
   2000.000         3.584473         0.000000         0.000000
   2005.000         8.584473        0.1000636        0.7112727
   2010.000         13.58447        0.1768884E-01    0.9489554
   2015.000         18.58447        0.3126965E-02    0.9909720
   2020.000         23.58447        0.5527726E-03    0.9983996
   2025.000         28.58447        0.9771696E-04    0.9997126
   2030.000         33.58447        0.1727403E-04    0.9999447
   2050.000         53.58447        0.1686893E-07    0.9999945
   2100.000         103.5845        0.5027156E-15    0.9999946
   2150.000         153.5845        0.1498160E-22    0.9999946
   2200.000         203.5845        0.4464701E-30    0.9999946
===== Record No.      3  ========================================
    4787  3/16/70   773-A
   58420.   75120.  N15.20  E26.20
  9.0000
   1970.208         1970.208        17
   1970.000       -0.2077637         0.000000         0.000000
   1975.000         4.792236         0.000000         0.000000
   1980.000         9.792236        0.6583989E-01    0.8100212
   1985.000         14.79224        0.1163892E-01    0.9664118
   1990.000         19.79224        0.2057483E-02    0.9940580
   1995.000         24.79224        0.3637137E-03    0.9989451
   2000.000         29.79224        0.6429591E-04    0.9998090
   2005.000         34.79224        0.1136597E-04    0.9999618
   2010.000         39.79224        0.2009233E-05    0.9999887
   2015.000         44.79224        0.3551845E-06    0.9999936
   2020.000         49.79224        0.6278808E-07    0.9999944
   2025.000         54.79224        0.1109943E-07    0.9999946
   2030.000         59.79224        0.1962113E-08    0.9999946
   2050.000         79.79224        0.1916103E-11    0.9999946
   2100.000         129.7922        0.5710231E-19    0.9999946
   2150.000         179.7922        0.1701726E-26    0.9999946
   2200.000         229.7922        0.5071370E-34    0.9999946
===== Record No.      4  ========================================
    4795  3/18/70   773-A
   58420.   75120.  N15.20  E26.20
  9.0000
   1970.213         1970.213        17
   1970.000       -0.2132568         0.000000         0.000000
   1975.000         4.786743         0.000000         0.000000
   1980.000         9.786743        0.6596536E-01    0.8096592
   1985.000         14.78674        0.1166110E-01    0.9663478
   1990.000         19.78674        0.2061403E-02    0.9940466
   1995.000         24.78674        0.3644068E-03    0.9989431
   2000.000         29.78674        0.6441842E-04    0.9998087
   2005.000         34.78674        0.1138763E-04    0.9999617
   2010.000         39.78674        0.2013061E-05    0.9999887
   2015.000         44.78674        0.3558612E-06    0.9999936
   2020.000         49.78674        0.6290771E-07    0.9999944
   2025.000         54.78674        0.1112058E-07    0.9999946
   2030.000         59.78674        0.1965852E-08    0.9999946
   2050.000         79.78674        0.1919753E-11    0.9999946
   2100.000         129.7867        0.5721112E-19    0.9999946
   2150.000         179.7867        0.1704968E-26    0.9999946
   2200.000         229.7867        0.5081013E-34    0.9999946
===== Record No.      5  ========================================
    4796  3/19/70   105-K
```

```
   58420.   75120.  N15.20  E26.20
  34.000
   1970.216         1970.216        17
   1970.000       -0.2159424         0.000000         0.000000
   1975.000         4.784058         0.000000         0.000000
   1980.000         9.784058        0.6602678E-01    0.8094819
   1985.000         14.78406        0.1167196E-01    0.9663165
   1990.000         19.78406        0.2063323E-02    0.9940411
   1995.000         24.78406        0.3647461E-03    0.9989421
   2000.000         29.78406        0.6447840E-04    0.9998085
   2005.000         34.78406        0.1139823E-04    0.9999617
   2010.000         39.78406        0.2014936E-05    0.9999887
   2015.000         44.78406        0.3561926E-06    0.9999936
   2020.000         49.78406        0.6296629E-07    0.9999944
   2025.000         54.78406        0.1113094E-07    0.9999946
   2030.000         59.78406        0.1967683E-08    0.9999946
   2050.000         79.78406        0.1921541E-11    0.9999946
   2100.000         129.7841        0.5726439E-19    0.9999946
   2150.000         179.7841        0.1706556E-26    0.9999946
   2200.000         229.7841        0.5085745E-34    0.9999946
===== Record No.      6  ========================================
    4799  3/19/70   221-F   EP 831.1
   58420.   75120.  N15.20  E26.20
  300.00
   1970.216         1970.216        17
   1970.000       -0.2159424         0.000000         0.000000
   1975.000         4.784058         0.000000         0.000000
   1980.000         9.784058        0.6602678E-01    0.8094819
   1985.000         14.78406        0.1167196E-01    0.9663165
   1990.000         19.78406        0.2063323E-02    0.9940411
   1995.000         24.78406        0.3647461E-03    0.9989421
   2000.000         29.78406        0.6447840E-04    0.9998085
   2005.000         34.78406        0.1139823E-04    0.9999617
   2010.000         39.78406        0.2014936E-05    0.9999887
   2015.000         44.78406        0.3561926E-06    0.9999936
   2020.000         49.78406        0.6296629E-07    0.9999944
   2025.000         54.78406        0.1113094E-07    0.9999946
   2030.000         59.78406        0.1967683E-08    0.9999946
   2050.000         79.78406        0.1921541E-11    0.9999946
   2100.000         129.7841        0.5726439E-19    0.9999946
   2150.000         179.7841        0.1706556E-26    0.9999946
   2200.000         229.7841        0.5085745E-34    0.9999946
===== Record No.      7  ========================================
    4806  3/16/70   221-F
   58510.   75120.  N15.20  E27.10
  250.00
   1970.208         1970.208        17
   1970.000       -0.2077637         0.000000         0.000000
   1975.000         4.792236         0.000000         0.000000
   1980.000         9.792236        0.6583989E-01    0.8100212
   1985.000         14.79224        0.1163892E-01    0.9664118
   1990.000         19.79224        0.2057483E-02    0.9940580
   1995.000         24.79224        0.3637137E-03    0.9989451
   2000.000         29.79224        0.6429591E-04    0.9998090
   2005.000         34.79224        0.1136597E-04    0.9999618
   2010.000         39.79224        0.2009233E-05    0.9999887
   2015.000         44.79224        0.3551845E-06    0.9999936
   2020.000         49.79224        0.6278808E-07    0.9999944
   2025.000         54.79224        0.1109943E-07    0.9999946
   2030.000         59.79224        0.1962113E-08    0.9999946
   2050.000         79.79224        0.1916103E-11    0.9999946
   2100.000         129.7922        0.5710231E-19    0.9999946
   2150.000         179.7922        0.1701726E-26    0.9999946
   2200.000         229.7922        0.5071370E-34    0.9999946
===== Record No.      8  ========================================
    4810  3/16/70   773-A
   58420.   75120.  N15.20  E26.20
  12.000
   1970.208         1970.208        17
   1970.000       -0.2077637         0.000000         0.000000
   1975.000         4.792236         0.000000         0.000000
   1980.000         9.792236        0.6583989E-01    0.8100212
   1985.000         14.79224        0.1163892E-01    0.9664118
   1990.000         19.79224        0.2057483E-02    0.9940580
   1995.000         24.79224        0.3637137E-03    0.9989451
   2000.000         29.79224        0.6429591E-04    0.9998090
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   2005.000         34.79224        0.1136597E-04    0.9999618
   2010.000         39.79224        0.2009233E-05    0.9999887
   2015.000         44.79224        0.3551845E-06    0.9999936
   2020.000         49.79224        0.6278808E-07    0.9999944
   2025.000         54.79224        0.1109943E-07    0.9999946
   2030.000         59.79224        0.1962113E-08    0.9999946
   2050.000         79.79224        0.1916103E-11    0.9999946
   2100.000         129.7922        0.5710231E-19    0.9999946
   2150.000         179.7922        0.1701726E-26    0.9999946
   2200.000         229.7922        0.5071370E-34    0.9999946
===== Record No.      9  ========================================
    4811  3/16/70   773-A
   58420.   75120.  N15.20  E26.20
  12.000
   1970.208         1970.208        17
   1970.000       -0.2077637         0.000000         0.000000
   1975.000         4.792236         0.000000         0.000000
   1980.000         9.792236        0.6583989E-01    0.8100212
   1985.000         14.79224        0.1163892E-01    0.9664118
   1990.000         19.79224        0.2057483E-02    0.9940580
   1995.000         24.79224        0.3637137E-03    0.9989451
   2000.000         29.79224        0.6429591E-04    0.9998090
   2005.000         34.79224        0.1136597E-04    0.9999618
   2010.000         39.79224        0.2009233E-05    0.9999887
   2015.000         44.79224        0.3551845E-06    0.9999936
   2020.000         49.79224        0.6278808E-07    0.9999944
   2025.000         54.79224        0.1109943E-07    0.9999946
   2030.000         59.79224        0.1962113E-08    0.9999946
   2050.000         79.79224        0.1916103E-11    0.9999946
   2100.000         129.7922        0.5710231E-19    0.9999946
   2150.000         179.7922        0.1701726E-26    0.9999946
   2200.000         229.7922        0.5071370E-34    0.9999946
===== Record No.     10  ========================================
    4812  3/16/70   773-A
   58420.   75120.  N15.20  E26.20
  10.000
   1970.208         1970.208        17
   1970.000       -0.2077637         0.000000         0.000000
   1975.000         4.792236         0.000000         0.000000
   1980.000         9.792236        0.6583989E-01    0.8100212
   1985.000         14.79224        0.1163892E-01    0.9664118
   1990.000         19.79224        0.2057483E-02    0.9940580
   1995.000         24.79224        0.3637137E-03    0.9989451
   2000.000         29.79224        0.6429591E-04    0.9998090
   2005.000         34.79224        0.1136597E-04    0.9999618
   2010.000         39.79224        0.2009233E-05    0.9999887
   2015.000         44.79224        0.3551845E-06    0.9999936
   2020.000         49.79224        0.6278808E-07    0.9999944
   2025.000         54.79224        0.1109943E-07    0.9999946
   2030.000         59.79224        0.1962113E-08    0.9999946
   2050.000         79.79224        0.1916103E-11    0.9999946
   2100.000         129.7922        0.5710231E-19    0.9999946
   2150.000         179.7922        0.1701726E-26    0.9999946
   2200.000         229.7922        0.5071370E-34    0.9999946
```

Appendix D CDROM software archive

(CDROM pocket)

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