received
9/10/02 CW

DOE/OR/07-2041&D1

RECORD COPY

Risk and Performance Evaluation of the C-746-U Landfill at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky

I-05306-0058

CLEARED FOR PUBLIC RELEASE

SCIENCE APPLICATIONS INTERNATIONAL CORPORATION

contributed to the preparation of this document and should not be considered an eligible contractor for its review.

CERTIFICATION

Document Identification: **Transmittal—*Risk and Performance Evaluation of the C-746-U Landfill at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky* (DOE/OR/07-2041&D1)**

I certify under penalty of law that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gather and evaluate the information submitted. Based on my inquiry of the person or persons directly responsible for gathering the information, the information submitted is to the best of my knowledge and belief, true, accurate, and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment for knowing violations.

U.S. Department of Energy (DOE)
Owner and Operator

W. Don Seaborg, Paducah Site Manager

8/15/02
Date Signed

I certify under penalty of law that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gather and evaluate the information submitted. Based on my inquiry of the person or persons directly responsible for gathering the information, the information submitted is to the best of my knowledge and belief, true, accurate, and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment for knowing violations.

Bechtel Jacobs Company LLC
Co-operator

Gordon L. Dover, Paducah Manager of Projects

8/15/02
Date Signed

DOE/OR/07-2041&D1

Risk and Performance Evaluation of the C-746-U Landfill at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky

Date Issued—August 2002

Prepared for the
U.S. DEPARTMENT OF ENERGY
Office of Environmental Management

Environmental Management Activities at the
Paducah Gaseous Diffusion Plant
Paducah, Kentucky 42001
managed by
Bechtel Jacobs Company LLC
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-98OR22700

01-248(doc)/080502

THIS PAGE INTENTIONALLY LEFT BLANK

PREFACE

This *Risk and Performance Evaluation of the C-746-U Landfill at the Paducah Gaseous Diffusion Plant* (DOE/OR/07-2041&D1, formerly BJC/PAD-204) was prepared to meet requirements of both the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the Resource Conservation and Recovery Act (RCRA). This document was developed for two purposes. The first purpose was to determine if the Paducah Gaseous Diffusion Plant (PGDP) could safely place projected nonhazardous CERCLA-derived solid waste in the C-746-U Landfill. The second was to determine if nonhazardous, nonradioactive wastes from the North–South Diversion Ditch and Scrap Yard response actions could be placed in the C-746-U Landfill and the potential effect of disposal of these wastes upon disposition in the landfill of wastes from other projects. The results and conclusions from this document, along with those from other activities, will be used in developing the operational limits for the C-746-U Landfill.

THIS PAGE INTENTIONALLY LEFT BLANK

CONTENTS

FIGURES ix
TABLES xiii
ACRONYMS xv
EXECUTIVE SUMMARY xvii

1. INTRODUCTION 1-1
   1.1 BACKGROUND AND REGULATORY SETTING 1-1
   1.2 METHODOLOGY 1-3
   1.3 REPORT ORGANIZATION 1-5

2. ENVIRONMENTAL SETTING 2-1
   2.1 GEOGRAPHY AND PHYSIOGRAPHY 2-1
   2.2 DEMOGRAPHY AND LAND USE 2-1
      2.2.1 Land Use 2-1
      2.2.2 Population 2-3
   2.3 CLIMATOLOGY AND METEOROLOGY 2-3
   2.4 GEOLOGY 2-5
      2.4.1 Bedrock and the Rubble Zone 2-5
      2.4.2 McNairy and Clayton Formations 2-5
      2.4.3 Porters Creek Clay 2-5
      2.4.4 Eocene Sands 2-8
      2.4.5 Continental Deposits 2-8
      2.4.6 Surficial Deposits/Soils 2-9
   2.5 HYDROLOGY 2-9
      2.5.1 Surface-Water Hydrology 2-9
      2.5.2 Groundwater Hydrology 2-11
   2.6 ECOLOGICAL RESOURCES 2-14
      2.6.1 Terrestrial Systems 2-16
      2.6.2 Aquatic Systems 2-16
      2.6.3 Wetlands 2-17
      2.6.4 Threatened and Endangered Species 2-17
   2.7 ENVIRONMENTAL SETTING OF THE C-746-U LANDFILL 2-20

3. CONCEPTUAL MODEL DEVELOPMENT 3-1
   3.1 WASTE VOLUME AND TYPES 3-1
      3.1.1 CERCLA-Derived Waste 3-1
      3.1.2 Non-CERCLA-Derived Waste 3-4
   3.2 C-746-U LANDFILL DESIGN 3-11
   3.3 SELECTION OF INDICATOR CHEMICALS 3-14
   3.4 RECEPTORS AND EXPOSURE PATHWAYS 3-14
      3.4.1 Human Health 3-15
      3.4.2 Ecological 3-16
   3.5 SELECTION OF TARGET DOSE AND RISK 3-16
   3.6 EXPOSURE PERIOD AND EXPOSURE POINT 3-23
      3.6.1 Period of Exposure 3-24
      3.6.2 Point of Exposure 3-24

4. FATE AND TRANSPORT MODELING 4-1
4.1 SELECTED MODELS AND THEIR APPLICATION 4-1
4.1.1 Hydrologic Evaluation of Landfill Performance (HELP) Model 4-3
4.1.2 Disposal Unit Source Term (DUST) Model 4-10
4.1.3 MODFLOW and MODPATH 4-11
4.1.4 Analytical Transient 1-, 2-, 3-Dimensional (AT123D) Model 4-20
4.1.5 RESRAD 4-20
4.2 DERIVATION OF DILUTION ATTENUATION FACTOR 4-22
4.3 MODEL RESULTS 4-24

5. RISK EVALUATION AND DERIVATION OF CERCLA-DERIVED WASTE DISPOSAL CRITERIA 5-1
5.1 HUMAN HEALTH 5-1
5.1.1 Risk Evaluation of the Most Sensitive Receptor 5-1
5.1.2 Risk Evaluation for Other Human Receptors 5-11
5.1.3 Preliminary CERCLA-derived Waste Disposal Criteria Protective of Human Health 5-19
5.2 ECOLOGICAL 5-19
5.2.1 Risk Evaluation 5-19
5.2.2 Preliminary CERCLA-derived Waste Disposal Criteria Protective of Ecological Receptors 5-46
5.3 DERIVATION OF FINAL CERCLA-DERIVED WASTE DISPOSAL CRITERIA AND INVENTORY LIMITS 5-46
5.4 ESTIMATED CUMULATIVE CANCER RISK, HAZARD, AND DOSE POSED TO HUMAN HEALTH ASSUMING DISPOSAL OF CERCLA-DERIVED WASTE WITH CONSTITUENT CONCENTRATIONS AT THE FINAL CERCLA-DERIVED WASTE DISPOSAL CRITERIA 5-51
5.4.1 Methods and Results 5-51
5.4.2 Discussion 5-66

6. UNCERTAINTIES 6-1
6.1 UNCERTAINTIES IN WASTE CHARACTERIZATION AND SOURCE TERM 6-1
6.2 UNCERTAINTIES ASSOCIATED WITH TRANSPORT MODELING 6-1
6.3 UNCERTAINTIES IN RISK CALCULATIONS 6-10
6.3.1 Human Health 6-10
6.3.2 Uncertainties in Ecological Risk 6-11
6.4 SUMMARY OF UNCERTAINTIES 6-13

7. CONCLUSIONS AND OBSERVATIONS 7-1
7.1 COMPARISON OF FINAL CERCLA-DERIVED WASTE DISPOSAL CRITERIA TO TCLP- AND TSCA-BASED VALUES AND EXPECTED WASTE CONCENTRATIONS 7-1
7.2 CONCLUSIONS AND OBSERVATIONS 7-4

8. REFERENCES 8-1

APPENDIX A – EVALUATION OF WASTE STREAMS FOR THE NORTH-SOUTH DIVERSION DITCH REMEDIAL ACTION A-1

APPENDIX B – EVALUATION OF WASTE STREAMS FOR THE SCRAP METAL REMOVAL ACTION B-1

APPENDIX C – SUPPORTING INFORMATION C-1
APPENDIX C.1 – HUMAN HEALTH RISK CALCULATIONS C1-1
APPENDIX C.2 – ECOLOGICAL RISK INFORMATION C2-1
APPENDIX C.3 – FATE AND TRANSPORT MODELING C3-1
APPENDIX C.4 – WASTE CHARACTERIZATION C4-1

THIS PAGE INTENTIONALLY LEFT BLANK

FIGURES

ES.1 Procedure used to develop CERCLA-derived waste disposal criteria (mg/kg or pCi/g) and waste inventory limits (kg or Ci). xviii
1.1 PGDP vicinity map. 1-2
1.2 Procedure used to develop CERCLA-derived waste disposal criteria (mg/kg or pCi/g) and waste inventory limits (kg or Ci). 1-4
2.1 Reasonable anticipated future land use. 2-2
2.2 Summary of Paducah climatological data. 2-4
2.3 Geologic columnar section in the vicinity of PGDP. 2-6
2.4 Geologic cross section of the PGDP area. 2-7
2.5 Surface water features in the vicinity of PGDP. 2-10
2.6 Hydrogeologic units beneath PGDP. 2-12
2.7 ^{99}Tc and TCE plume migration in the RGA. 2-15
2.8 Wetland and floodplains in the vicinity of the PGDP. 2-18
2.9 Wetlands and floodplains in the vicinity of the C-746-U Landfill. 2-19
2.10 Drainage areas for C-746-U Landfill (DOE 1995). 2-22
3.1 The total CERCLA-derived waste estimated to be generated at PGDP by year. 3-3
3.2 Cumulative volumes of wastes expected in the C-746-U Landfill if both CERCLA-derived and non-CERCLA-derived wastes were to be placed in the landfill. (Only CERCLA-derived waste assumed to meet C-746-U acceptance criteria, as defined earlier is included.) 3-10
3.3 C-746-U Landfill cross section (BJC 2002) 3-12
3.4 Conceptual Site Model for the human health risk and performance evaluation of the C-746-U Landfill. 3-21
3.5 Ecological exposure pathways diagram for the C-746-U Landfill risk and performance evaluation. 3-22
4.1 Conceptual diagram for the numerical modeling approach – C-746-U Landfill. 4-2
4.2(a) Water flux through the C-746-U Landfill waste as a function of time under the gradual failure scenario. 4-4
4.2(b) Percolation of C-746-U Landfill leachate to the RGA as a function of time under the gradual failure scenario. 4-4
4.3 Schematic diagram of DUST model layers and materials for the Operational Period under all scenarios. 4-16
4.4 Schematic diagram of DUST model layers and materials for Institutional Control Period under all scenarios and for the Post-Institutional Control Period under the no failure scenario. 4-17
4.5 Schematic diagram of DUST model layers and materials for the Post-Institutional Control Period under the gradual failure and immediate failure scenarios. 4-18
4.6 Preferential flowpath of particles released to the RGA. 4-19
4.7 Definitions of dilution attenuation factors at C-746-U Landfill. 4-23
4.8 Predicted groundwater concentration of vinyl chloride based on leaching from the C-746-U Landfill waste under the gradual failure scenario. 4-30
4.9 Predicted groundwater concentration of trichloroethene based on leaching from the C-746-U Landfill waste under the gradual failure scenario. 4-30
4.10 Predicted groundwater concentration of 2-butanone based on leaching from the C-746-U Landfill waste under the gradual failure scenario. 4-31
4.11 Predicted groundwater concentration of chlorobenzene based on leaching from the C-746-U Landfill waste under the gradual failure scenario. 4-31

4.12 Predicted groundwater concentration of benzene based on leaching from the C-746-U Landfill waste under the gradual failure scenario. 4-32
4.13 Predicted groundwater concentration of 2-methylphenol based on leaching from the C-746-U Landfill waste under the gradual failure scenario. 4-32
4.14 Predicted groundwater concentration of pentachlorophenol based on leaching from the C-746-U Landfill waste under the gradual failure scenario. 4-33
4.15 Predicted groundwater concentration of benzo(a)pyrene based on leaching from the C-746-U Landfill waste under the gradual failure scenario. 4-33
4.16 Predicted groundwater concentration of PCBs based on leaching from the C-746-U Landfill waste under the gradual failure scenario. 4-34
4.17 Predicted groundwater concentration of gamma-chlordane based on leaching from the C-746-U Landfill waste under the gradual failure scenario. 4-34
4.18 Predicted groundwater concentration of chromium based on leaching from the C-746-U Landfill waste under the gradual failure scenario. 4-35
4.19 Predicted groundwater concentration of uranium based on leaching from the C-746-U Landfill waste under the gradual failure scenario. 4-35
4.20 Predicted groundwater concentration of thallium based on leaching from the C-746-U Landfill waste under the gradual failure scenario. 4-36
4.21 Predicted groundwater concentration of ^{99}Tc based on leaching from the C-746-U Landfill waste under the gradual failure scenario. 4-36
4.22 Predicted groundwater concentration of ^{238}U based on leaching from the C-746-U Landfill waste under the gradual failure scenario. 4-37
4.23 Predicted groundwater concentration of selenium based on leaching from the C-746-U Landfill waste under the gradual failure scenario. 4-40
4.24 Predicted groundwater concentration of arsenic based on leaching from the C-746-U Landfill waste under the gradual failure scenario. 4-40
4.25 Predicted groundwater concentration of nickel based on leaching from the C-746-U Landfill waste under the gradual failure scenario. 4-41
4.26 Predicted groundwater concentration of iron based on leaching from the C-746-U Landfill waste under the gradual failure scenario. 4-41
4.27 Predicted groundwater concentration of uranium based on leaching from the C-746-U Landfill waste under the gradual failure scenario. 4-42
4.28 Predicted groundwater concentration of Np-237 based on leaching from the C-746-U Landfill waste for immediate failure scenario. 4-42
4.29 Predicted groundwater concentration of vinyl chloride based on leaching from the C-746-U Landfill waste for immediate failure scenario. 4-43
4.30 Predicted groundwater concentration of ^{99}Tc based on leaching from the C-746-U Landfill waste for immediate failure scenario. 4-43
4.31 Predicted groundwater concentration of vinyl chloride based on leaching from the C-746-U Landfill waste under the no failure scenario. 4-45
4.32 Predicted groundwater concentration of chromium based on leaching from the C-746-U Landfill waste under the no failure scenario. 4-45
4.33 Predicted groundwater concentration of ^{99}Tc based on leaching from the C-746-U Landfill waste under the no failure scenario. 4-46
5.1 Total cancer risk to residential groundwater user – gradual failure scenario. 5-3
5.2 Total hazard to residential groundwater user – gradual failure scenario. 5-3
5.3 Total dose to residential groundwater user – gradual failure scenario. 5-4
5.4 Chemical-specific cancer risk to residential groundwater user – exposure point at property boundary – gradual failure scenario. 5-4
5.5 Chemical-specific hazard to residential groundwater user – exposure point at property boundary – gradual failure scenario. 5-5

5.6 Radionuclide-specific dose to residential groundwater user – exposure point at property boundary – gradual failure scenario. 5-5
5.7 Comparison of gradual versus immediate failure scenarios – estimated cancer risk to residential groundwater user from vinyl chloride group at property boundary. 5-6
5.8 Comparison of gradual versus immediate failure scenarios – estimated cancer risk to residential groundwater user from ^{99}Tc at property boundary. 5-6
5.9 Comparison of gradual versus immediate failure scenarios – estimated dose to residential groundwater user from ^{99}Tc at the DOE property boundary. 5-7
5.10 Concentration of vinyl chloride in a well completed in the RGA at the DOE property boundary – comparison between expected waste-based and disposal criteria-based source terms. 5-60
5.11 Cancer risk posed by chemicals to a resident using groundwater withdrawn from the RGA at the DOE property boundary and Ohio River points of exposure – CERCLA-derived waste disposal criteria used as a source term for the C-746-U Landfill. 5-63
5.12 Cancer risk posed by radionuclides to a resident using groundwater withdrawn from the RGA at the DOE property boundary and Ohio River points of exposure – CERCLA-derived waste disposal criteria used as a source term for the C-746-U Landfill. 5-63
5.13 Hazard posed to a resident using groundwater withdrawn from the RGA at the DOE property boundary and Ohio River points of exposure – CERCLA-derived waste disposal criteria used as a source term for the C-746-U Landfill. 5-64
5.14 Dose posed to a resident using groundwater withdrawn from the RGA at the DOE property boundary and Ohio River points of exposure – CERCLA-derived waste disposal criteria used as a source term for the C-746-U Landfill. 5-64
5.15 Cancer risk posed by chemicals to a recreational user wading in groundwater discharged to springs at the Ohio River point of exposure – CERCLA-derived waste disposal criteria used as a source term for the C-746-U Landfill. 5-65
5.16 Hazard posed to a recreational user wading in groundwater discharged to springs at the Ohio River point of exposure – CERCLA-derived waste disposal criteria used as a source term for the C-746-U Landfill. 5-65
6.1 Graphical comparison of results of sensitivity analysis using ^{99}Tc as a test contaminant. 6-5
6.2 Predicted leachate concentration of ^{238}U to top of landfill liner system by DUST. 6-7
6.3 Model-predicted groundwater concentration at the DOE property boundary. 6-7

THIS PAGE INTENTIONALLY LEFT BLANK

TABLES

ES.1 CERCLA-derived waste disposal criteria[a] and contaminant inventory limits[a] for the C-746-U Landfill at PGDP xx
2.1 Federally listed, proposed, and candidate species potentially occurring within the PGDP area 2-20
2.2 Current inventory (yd^3) by waste form[a] in C-746-U Landfill 2-21
2.3 Summary of leachate generation from C-746-U Landfill through August 2001 2-23
3.1 Volumes (yd^3) of CERCLA waste generated by year 3-3
3.2 Generation of CERCLA-derived waste (yd^3) by year and form[a] 3-4
3.3 Toxicity Characteristic Leaching Procedure values for PGDP DOE waste disposal units 3-5
3.4 COPCs and analytical profiles used for CERCLA-derived waste used in C-746-U Landfill evaluation 3-6
3.5 Current inventory (yd^3) by waste form[a] in C-746-U Landfill 3-10
3.6 Represented groups and indicator chemicals 3-14
3.7 Exposure route summary 3-17
4.1 Climatic parameters used by the HELP model 4-6
4.2 PGDP C-746-U Landfill design profile and soil characteristics – Operational Period 4-7
4.3 PGDP C-746-U Landfill design profile and soil characteristics – Institutional Control Period 4-8
4.4 PGDP C-746-U Landfill design profile and soil characteristics – Post-Institutional Control Period 4-9
4.5 DUST model input parameters 4-12
4.6 Inventory of contaminant mass in different waste forms for the chemicals/radionuclides modeled 4-15
4.7 Parameters used by the AT123D model for saturated zone modeling 4-21
4.8 Site-to-exposure point distance 4-24
4.9 Wasteform-to exposure point DAF 4-25
4.10 Maximum predicted concentrations for all chemicals at receptor locations based on DAF for indicator chemical 4-27
4.11 Summary of surrogate ratios for C-746-U Landfill COPCs 4-38
4.12 Maximum predicted concentrations for all PGDP COPCs at receptor locations based on DAF for indicator chemical[a] immediate failure scenario 4-44
4.13 Maximum predicted concentrations for all PGDP COPCs at receptor locations based on DAF for indicator chemical for No Failure Scenario 4-44
5.1 Points of exposure, media, and receptors considered when selecting the most sensitive receptor 5-1
5.2 Back-calculation concentrations used in the derivation of preliminary CERCLA-derived waste disposal criteria and their source 5-9
5.3 Preliminary CERCLA risk-based disposal criteria and preliminary contaminant inventory limits not corrected for exceeding unity, exceeding volume of landfill, or solubility limit in water 5-12
5.4 Predicted concentrations of COPCs in water at all points of exposure derived from preliminary CERCLA risk-based disposal criteria corrected for unity, C-746-U Landfill volume, and solubility 5-14
5.5 Comparison of groundwater concentrations in RGA at all exposure points against PGDP risk-based values protective of a groundwater user 5-17
5.6 Comparison of water concentration in hypothetical springs located at the Ohio River against PGDP risk-based values protective of a surface water recreational user and industrial worker 5-20

5.7 Preliminary CERCLA-derived waste disposal criteria protective of human health 5-23
5.8 Ecological risk screening of predicted maximum concentrations for selected chemicals in groundwater from the C-746-U Landfill discharging to the Ohio River 5-27
5.9 Ecological risk screening of predicted maximum concentrations for selected radionuclides in groundwater from the C-746-U Landfill discharging to the Ohio River 5-31
5.10 Ecological risk screening of for mammals exposed to predicted maximum concentrations for selected chemicals in groundwater discharging from the C-746-U Landfill to springs at the Ohio River 5-32
5.11 Ecological risk screening for mammals exposed to predicted maximum concentrations for selected radionuclides in groundwater discharging from the C-746-U Landfill to springs at the Ohio River 5-35
5.12 Ecological risk screening for birds exposed to predicted maximum concentrations for selected chemicals in groundwater discharging from the C-746-U Landfill to springs at the Ohio River 5-36
5.13 Ecological risk screening for birds exposed to predicted maximum concentrations for selected radionuclides in groundwater discharging from C-746-U Landfill to springs at the Ohio River 5-39
5.14 Ecological risk screening of predicted maximum concentrations for selected chemicals in sediment at the Ohio River resulting from discharge of groundwater from the C-746-U Landfill 5-42
5.15 Ecological risk screening of predicted maximum concentrations for selected radionuclides in sediment at the Ohio River resulting from discharge of groundwater from the C-746-U Landfill 5-45
5.16 Summary of ecological COPCs and maximum concentrations in groundwater at springs at the Ohio River and at discharge to the Ohio River to meet PGDP NFA or alternative NFA concentrations 5-45
5.17 Modified preliminary CERCLA-derived waste disposal criteria 5-46
5.18 Selection of final CERCLA risk-based disposal criteria from preliminary criteria for all receptors 5-48
5.19 Contaminant inventory limits for the C-746-U Landfill 5-52
5.20 No Action screening values used to derive chemical-specific cancer risk, hazard, and dose estimates[a] 5-55
5.21 Concentrations in RGA groundwater at the DOE property boundary and Ohio River calculated from CERCLA-derived waste disposal criteria 5-58
5.22 Solubility limits, maximum constituent flux, and steady-state transport duration for inorganic chemicals and organic compounds 5-61
6.1 Comparison of results of sensitivity analysis using ^{99}Tc as a test contaminant 6-4
6.2 Summary of uncertainties that may affect derivation of final CERCLA-derived waste disposal criteria and contaminant inventory limits 6-13
7.1 Comparison between CERCLA-derived waste disposal criteria and TCLP values for PGDP DOE waste disposal units and concentrations reported for CERCLA-derived waste projected to be acceptable for placement in the C-746-U Landfill 7-2

ACRONYMS

amsl	above mean sea level
AT123D	Analytical Transient 1-, 2-, 3-Dimensional Model
bgs	below ground surface
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980
COC	contaminant of concern
COPC	contaminant of potential concern
CSM	conceptual site model
DAF	dilution attenuation factor
D&D	decontamination and decommissioning
DOE	U.S. Department of Energy
DUST	Disposal Unit Source Term
EPA	U.S. Environmental Protection Agency
ER-L	Effects Range–Low
FDEP	Florida Department of Environmental Protection
FML	flexible membrane lining
HELP	Hydrologic Evaluation of Landfill Performance
HQ	hazard quotient
HU	hydrogeologic unit
KDEP	Kentucky Department for Environmental Protection
KDFWR	Kentucky Department of Fish and Wildlife Resources
KOW	Kentucky Ordnance Works
MCL	maximum contaminant level
NFA	No Further Action
NOAEL	no observed adverse effect level
NRC	Nuclear Regulatory Commission
NSDD	North-South Diversion Ditch
PAH	polycyclic aromatic hydrocarbon
PCB	polychlorinated biphenyl
PGDP	Paducah Gaseous Diffusion Plant
PPE	personal protective equipment
RCRA	Resource Conservation and Recovery Act of 1976
RESRAD	Residual Radioactivity model
RFD	request for disposal
RGA	Regional Gravel Aquifer
SVOC	semivolatile organic compound
T&E	threatened and endangered species
TCE	trichloroethene
TCLP	Toxicity Characteristic Leaching Procedure
TEL	threshold effect level
TSCA	Toxic Substances Control Act of 1976
TVA	Tennessee Valley Authority
UCRS	Upper Continental Recharge System
USACE	U.S. Army Corps of Engineers
USEC	United States Enrichment Corporation
USGS	U.S. Geological Survey
VOC	volatile organic compound
WKWMA	West Kentucky Wildlife Management Area

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

The U.S. Department of Energy (DOE) is evaluating whether solid wastes from removal and remedial actions performed under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) that contain low concentrations of contaminants can be safely disposed of in the C-746-U Landfill at the Paducah Gaseous Diffusion Plant (PGDP) in Paducah, Kentucky. This report contributes to that evaluation by using fate and transport modeling, risk evaluation, and performance evaluation to derive a series of concentrations, termed CERCLA-derived waste disposal criteria. These criteria will be used to determine the maximum inventory of contaminants that can be placed in the C-746-U Landfill, while maintaining appropriate protectiveness to human health and the environment.

In this report, fate and transport modeling and risk and performance evaluation were performed iteratively. The process used to complete this iterative methodology began with three components. These were:

- an expected waste inventory for CERCLA-derived waste based upon the PGDP list of significant contaminants of potential concern (COPCs) taken from *Methods for Conducting Risk Assessments and Risk Evaluations at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky* (DOE/OR/07-1506&D2) and augmented with COPCs identified in previous waste characterization activities,

- a transport conceptual site model (CSM) based upon landfill design and site hydrology and geology, and

- an exposure CSM based upon the identification of potential receptors and complete exposure pathways.

Through this iterative process, which is discussed in detail in Sect. 1.2 of the report and shown graphically in Fig. ES.1, four items were generated. These were:

1) The potential cumulative and chemical-specific risk, hazard, and dose over a 10,000-year period to the most sensitive receptor exposed to contaminants that may migrate from CERCLA-derived waste projected to be placed in the C-746-U Landfill. In this report, the most sensitive receptor was determined to be the rural resident using groundwater drawn from a well located at the DOE property boundary.

2) The chemical concentrations that may be in waste disposed of in the C-746-U Landfill that will not adversely impact either the most sensitive receptor or any of a series of alternative receptors (i.e., the final CERCLA-derived waste disposal criteria). In this report, the alternative receptors quantitatively evaluated as part of the performance evaluation of the landfill were the recreational user and industrial worker exposed to contaminants in groundwater discharged to the surface at the Ohio River, terrestrial wildlife ingesting groundwater discharged to the surface at the Ohio River, and aquatic biota exposed to contaminants in groundwater discharged to the Ohio River. As noted above, the final criteria were subsequently used to develop inventory limits for each contaminant on the COPC list.

3) The potential cumulative and chemical-specific risk, hazard, and dose over a 10,000-year period to receptors exposed to contaminants that may migrate from CERCLA-derived waste if the contaminant concentrations in this waste attained the final CERCLA-derived waste disposal criteria.

4) A comparison between the CERCLA-derived waste disposal criteria and disposal criteria used by other programs [i.e., concentrations for waste derived from the Resource Conservation and Recovery Act of 1976 (RCRA) Toxicity Characteristic Leaching Procedure (TCLP) and in the Toxic Substances Control Act of 1976 (TSCA)] and between the criteria and the concentrations in the projected CERCLA-derived waste inventory.

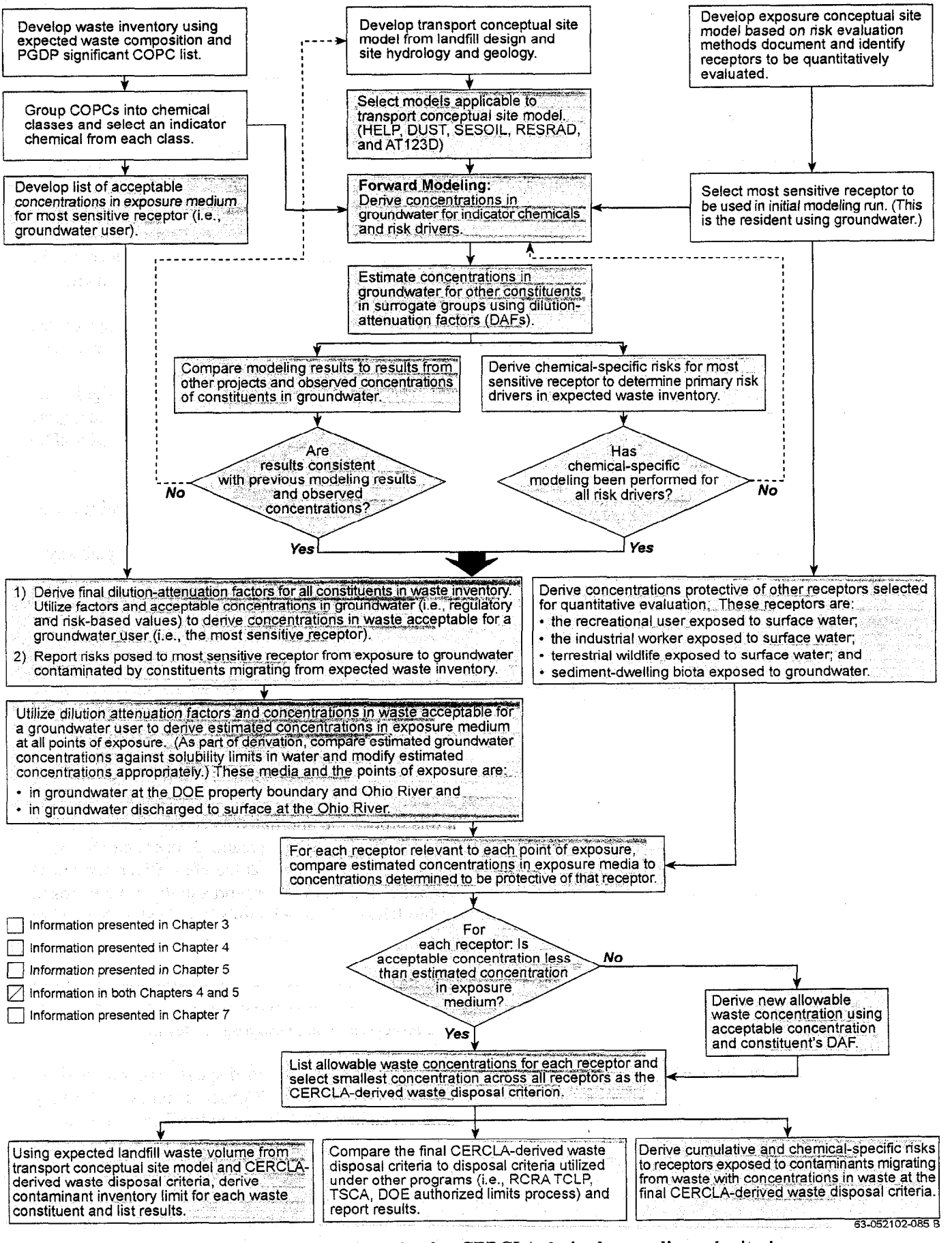


Fig. ES.1. Procedure used to develop CERCLA-derived waste disposal criteria (mg/kg or pCi/g) and waste inventory limits (kg or Ci).

The peak cumulative cancer risk, hazard, and dose for the rural resident using groundwater containing contaminants that may migrate from the expected waste inventory over the 10,000-year period modeled were 2×10^{-6}, 0.4, and 0.5 mrem/year, respectively. The driving contaminants for cancer risk were the radionuclides ^{237}Np, ^{99}Tc, ^{234}U, ^{238}U, and the inorganic chemical arsenic. Peak chemical-specific cancer risks were 3×10^{-7}, 4×10^{-8}, 5×10^{-8}, 4×10^{-7}, and 2×10^{-6}, respectively. The driving contaminant for hazard was uranium with a peak chemical-specific hazard of 0.2. No other contaminant has a peak chemical-specific hazard greater than 0.1. Finally, the driving contaminant for dose was ^{237}Np with a peak dose of 0.5 mrem/year. No other contaminants had a chemical-specific dose greater than 0.1 mrem/year.

The peak cumulative cancer risk, hazard, and dose for the rural resident using groundwater and the recreational user exposed to groundwater at springs containing contaminants migrating from the landfill containing a waste inventory with concentrations set at the CERCLA-derived waste disposal criteria derived in this report (see Table ES.1) over the 10,000-year period modeled are higher than those calculated using the expected waste inventory concentrations. This result is expected because the disposal criteria exceeded the expected waste inventory concentrations for most analytes (see below and Table ES.1). However, cumulative cancer risks, hazards, and doses for the recreational user are below all risk benchmarks and guidance levels at all times. [These benchmarks and guidance levels are EPA's site-related cancer risk, hazard, and dose values (i.e., 10^{-4}, 1, and 15 mrem/year, respectively) and the Nuclear Regulatory Commission's rule dose value (i.e., 25 mrem/year)]. Similarly, cumulative cancer risks posed by chemicals and radionuclides to groundwater users are below and at the upper end of the EPA risk-range for site-related exposures, cumulative hazard posed by chemicals will only attain levels that may be unacceptable (i.e., hazard index > 1) after 1,000 years of uncontrolled releases, and cumulative dose posed by radionuclide will only attain unacceptable levels (i.e., above the aforementioned dose values) after 1,000 years of uncontrolled releases. Because uncontrolled releases are unlikely due to the engineering of the C-746-U Landfill and continued maintenance by DOE for the foreseeable future, the potentially unacceptable cumulative hazard and dose are overestimates of the actual hazard and dose that may be posed to the groundwater user. Hence, even if waste placed in the C-746-U Landfill exceeded that projected for this waste stream and attained the CERCLA-derived waste disposal criteria, it is unlikely that unacceptable risk, hazard, or dose would be posed to human health or the environment.

As noted above, the CERCLA-derived waste disposal criteria and contaminant inventory limits developed in this report are in Table ES.1. Footnotes within this table identify chemicals having CERCLA-derived waste disposal criteria that do not exceed the disposal criteria from RCRA TCLP or TSCA. As shown in Table ES.1, only 2 inorganic chemicals and one organic compound have a final CERCLA-derived waste disposal criterion that is less than a waste concentration derived from the RCRA TCLP or limits in TSCA. The chemicals with a criterion less than the TCLP or TSCA concentrations are:

- arsenic with a criterion of 28.8 mg/kg versus a TCLP-derived value of 100 mg/kg,
- mercury with a criterion of 3.13 mg/kg versus a TCLP-derived value of 4 mg/kg, and
- chlorobenzene with a criterion of 179 mg/kg versus a TCLP-derived value of 2,000 mg/kg.

While these results are noteworthy because it appears that the CERCLA-derived waste disposal criteria may be more limiting for these chemicals when placing waste in the landfill than the RCRA TSCA-based values, a closer examination reveals that these results are probably of little significance. For mercury and chlorobenzene, the results have little significance because their disposal criteria are limited by their soil saturation limit (please see definition in footnote b of Table ES-1) and not by their migration potential. (That is, the disposal criteria calculated ignoring the soil saturation limit for these chemicals would be 61.8 mg/kg and unity, respectively.). Therefore, it appears that for mercury and chlorobenzene the disposal criteria are less than their TCLP-based values not because of restrictions due to migration but due to the lack of the consideration of soil saturation in the derivation of the TCLP-based values.

Table ES.1. CERCLA-derived waste disposal criteria[a] and contaminant inventory limits[a] for the C-746-U Landfill at PGDP

Chemical	Final CERCLA-derived waste disposal criteria (mg/kg or pCi/g)[a]	Final contaminant inventory limits (kg or Ci)[a]
	Inorganic Chemicals (mg/kg and kg)	
Antimony	6.79E+01	1.215E+05
Arsenic	2.88E+01[d]	5.153E+04
Barium	1.14E+04	2.040E+07
Beryllium	2.40E+04	4.294E+07
Cadmium	5.70E+02	1.020E+06
Chromium	4.37E+03	7.819E+06
Copper	5.22E+03	9.339E+06
Iron	1.00E+05[c,e]	1.789E+08
Lead	7.77E+04	1.390E+08
Manganese	4.68E+03	8.373E+06
Mercury	3.13E+00[b,d]	5.600E+03
Molybdenum	3.87E+01	6.924E+04
Nickel	1.00E+05[c]	1.789E+08
Selenium	7.77E+01	1.390E+05
Silver	7.77E+03	1.390E+07
Thallium	9.80E+01	1.753E+05
Uranium	7.79E+02	1.394E+06
Vanadium	1.00E+05[c]	1.789E+08
Zinc	7.47E+04	1.337E+08
	Organic Compounds (mg/kg and kg)	
Acenaphthene	1.00E+05[c]	1.789E+08
Acenaphthylene	1.00E+05[c]	1.789E+08
Acrylonitrile	1.47E+04[b]	2.630E+07
Anthracene	1.00E+05[c]	1.789E+08
Benzene	4.38E+02[b]	7.837E+05
Butanone, 2-	5.53E+04[b]	9.894E+07
Carbon Tetrachloride	2.57E+02[b]	4.598E+05
Chlordane, alpha-	1.00E+05[c]	1.789E+08
Chlordane, gamma-	1.00E+05[c]	1.789E+08
Chlorobenzene	1.79E+02[b,d]	3.203E+05
Chloroform	1.92E+03[b]	3.435E+06
Dichlorobenzene, 1,4-	1.00E+05[c]	1.789E+08
Dichloroethane, 1,2-	2.00E+03[b]	3.578E+06
Dichloroethene, 1,1-	5.72E+02[b]	1.023E+06
Dichloroethene, 1,2- (mixed isomers)	2.10E+02[b]	3.757E+05
Dichloroethene, cis-1,2-	8.01E+02[b]	1.433E+06
Dichloroethene, trans-1,2-	1.46E+03[b]	2.612E+06
Dinitrotoluene, 2,4-	1.00E+05[c]	1.789E+08
Dioxins/Furan (Total)	1.00E+05[c]	1.789E+08
Ethylbenzene	6.15E+01[b]	1.100E+05
Fluoranthene	1.00E+05[c]	1.789E+08
Fluorene	1.00E+05[c]	1.789E+08
Heptachlor Epoxide	1.00E+05[c]	1.789E+08
Hexachlorobenzene	1.00E+05[c]	1.789E+08
Hexachlorobutadine	1.39E+02[b]	2.487E+05
Hexachloroethane	1.00E+05[c]	1.789E+08
Methoxychlor	1.00E+05[c]	1.789E+08
Methylphenol, 2-	4.32E+03[b]	7.729E+06
Methylphenol, 3-	4.91E+03[b]	8.785E+06
Methylphenol, 4-	5.03E+03[b]	8.999E+06
Naphthalene	1.00E+05[c]	1.789E+08
Nitrobenzene	6.17E+02[b]	1.104E+06
Pentachlorophenol	1.00E+05[c]	1.789E+08
Phenanthrene	1.00E+05[c]	1.789E+08
Polychlorinated biphenyls (Total)	1.73E+02[b]	3.095E+05

For arsenic, the results probably have little significance for two reasons. First, the TCLP-based value, which is based on the current maximum contaminant level (MCL) of 50 μg/L, may be reduced by one-fifth once the revised MCL of 10 μg/L is used to regulate Subtitle D landfills. This will result in a TCLP-based value of 20 mg/kg, a value less than the disposal criteria. Second, as discussed next, the disposal criteria for arsenic is approximately seven times greater than the projected concentration in CERCLA-derived waste expected to be placed in the C-746-U Landfill (i.e., 4.22 mg/kg). Therefore, it is unlikely that arsenic will limit the placement of any waste package in the landfill.

Footnotes to Table ES.1 also show that 1 inorganic chemical and no organic compounds or radionuclides have a CERCLA-derived waste disposal criterion that is less than the concentration projected for CERCLA-derived waste that is projected to be placed in the C-746-U Landfill. The chemical with a criterion less than the projected concentrations is:

- iron with a criterion of 100,000 mg/kg versus a projected waste concentration of 191,777 mg/kg.

Like the previous discussion regarding of the comparison between the disposal criteria and TCLP-based values, while this result appears to be of importance at first glance, it is probably of little significance. The result for iron is of little significance because the disposal criteria is not based upon the migration potential of iron but upon instructions in a PGDP guidance document that limits concentrations back-calculated from risk-based values to 100,000 mg/kg. If this restriction is ignored then the disposal criteria for iron would equal unity (i.e., placement would not be restricted based upon concentration).

The results presented above and in Table ES.1 indicate that CERCLA-derived waste should be able to be safely placed in the C-746-U Landfill. Additionally, these results indicate that the RCRA TCLP and TSCA limits can serve as surrogates for the CERCLA-derived waste disposal criteria for all chemicals with these values available. However, the results also indicate that it may be appropriate to use a "sum-of-fraction" approach when placing waste in the C-746-U Landfill to ensure protectiveness.

The application of the CERCLA-derived waste disposal criteria and the contaminant inventory limits is demonstrated in Appendices A and B of the report. In those appendices, the impact upon the contaminant inventory limits of disposal in the C-746-U Landfill of waste from the Sects. 1 and 2 of the North-South Diversion Ditch action and the scrap yard action, respectively, is considered. As shown in those appendices, the forecast waste volumes from these projects may be placed in the landfill. However, this may require some sacrifice of a percentage of the total landfill contaminant inventory limits available for later response actions because, for some contaminants, the projected percentage of landfill contaminant inventory limit used exceeds the projected percentage of landfill volume used.

Table ES.1. CERCLA-derived waste disposal criteria[a] and contaminant inventory limits[a] for the C-746-U Landfill at PGDP (continued)

Chemical	Final CERCLA-derived waste disposal criteria (mg/kg or pCi/g)[a]	Final contaminant inventory limits (kg or Ci)[a]
Polynuclear Aromatic Hydrocarbons (Total)	1.00E+05 [c]	1.789E+08
Pyrene	1.00E+05 [c]	1.789E+08
Pyridine	1.00E+05 [b, c]	1.789E+08
Tetrachloroethene	8.27E+01 [b]	1.480E+05
Toxaphene	1.00E+05 [c]	1.789E+08
Trichloroethene	3.04E+02 [b]	5.439E+05
Trichlorophenol, 2,4,5-	1.00E+05 [c]	1.789E+08
Trichlorophenol, 2,4,6-	1.00E+05 [c]	1.789E+08
Vinyl Chloride	6.00E+02 [b]	1.073E+06
Xylene (mixture)	8.35E+01 [b]	1.494E+05
Xylene, m-	5.76E+01 [b]	1.031E+05
Xylene, o-	6.89E+01 [b]	1.233E+05
Xylene, p-	8.32E+01 [b]	1.489E+05
	Radionuclides (pCi/g and Ci)[f]	
Neptunium-237	2.26E+01	4.044E+01
Plutonium-238	5.66E+03	1.013E+04
Plutonium-239	5.49E+03	9.823E+03
Plutonium-240	5.49E+03	9.823E+03
Radium-226	4.06E+02	7.264E+02
Technetium-99	2.02E+01	3.614E+01
Thorium-230	2.47E+03	4.419E+03
Thorium-232	2.99E+03	5.350E+03
Uranium-234	1.27E+03	2.272E+03
Uranium-235	1.25E+03	2.236E+03
Uranium-238	1.03E+03	1.843E+03

Notes:

[a] The values presented in this table were taken from Chap. 5 of this report. The CERCLA (Comprehensive Environmental Response, Compensation, and Recovery Act of 1980)-derived waste disposal criteria are chemical-specific average waste concentration targets for CERCLA-derived waste placed in the landfill averaged over all waste forms (e.g., soil, construction debris, and concrete). During development of the C-746-U Landfill operational criteria, consideration of a sum-of-fractions approach would be appropriate to ensure protectiveness over all constituents placed in the landfill. The final contaminant inventory limits are the chemical-specific total leachable mass (for chemicals and compounds) or activity (for radionuclides) amounts that can be placed in the C-746-U Landfill and not adversely impact human health and the environment. Note that a concentration of 100,000 mg/kg was assigned to those chemicals and compounds with derived criteria exceeding 100,000 mg/kg. This value was assigned to chemicals and compounds to remain consistent with guidance in *Methods for Conduction Risk Assessments and Risk Evaluations at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky* (DOE/OR/07-1506&D2) regarding the back-calculation of chemical concentrations in soil from health-based standards.

[b] The final CERCLA-derived waste disposal criterion is the soil saturation limit in sand (0.08% organic content) for the chemical or compound. This value was chosen because liquids cannot be disposed of in the C-746-U Landfill. The value may be greater if the chemical or compound is found in a different soil matrix (i.e., with a higher clay or organic carbon content). [Note that the soil saturation limit is the contaminant concentration in soil at which the absorptive limits of the soil particles, the solubility limits of the soil pour water, and the saturation of soil pour air have been reached. Above this concentration, the soil contaminant may be present in free phase (i.e., nonaqueous phase liquids, NAPLs) for contaminants that are liquid at ambient soil temperatures and pure solid phases for compounds that are solid at ambient soil temperatures.]

[c] The final CERCLA-derived waste disposal criterion was reduced to 100,000 mg/kg in order to be consistent with guidance cited in footnote a. The actual back-calculated value is greater than that reported.

[d] The CERCLA-derived waste disposal criterion is less than a value derived from the Resource Conservation and Recovery Act of 1976 (RCRA) Toxicity Characteristic Leaching Procedure (TCLP). The TCLP-derived values of three chemicals indicated (i.e., arsenic, mercury, and chlorobenzene) are 100, 4, and 2,000 mg/kg, respectively.

[e] The CERCLA-derived waste disposal criterion is less than the concentration projected in the CERCLA-derived waste that may be placed in the C-746-U Landfill (see Chap. 3 of this report). The concentrations of the indicated chemicals in the CERCLA-derived waste characterization are 192,000 and 157 mg/kg for iron and uranium, respectively.

[f] Several radionuclides listed in the PGDP (Paducah Gaseous Diffusion Plant) significant contaminants of potential concern list are not included here. These are ^{241}Am, ^{137}Cs, ^{60}Co, ^{90}Sr, ^{222}Rn, and ^{228}Th. Cesium-137, ^{60}Co, ^{90}Sr, and ^{228}Th are not included because each of these can be expected to decay through more than 10 half-lives prior to transport to the groundwater user point of exposure (i.e., a well completed in the regional gravel aquifer at the DOE property boundary). Americium-241 is not included because this radionuclide can be expected to decay to ^{237}Np prior to transport to the groundwater user point of exposure. (If necessary, the ^{237}Np criterion can be used as a conservative screening value for ^{241}Am.) Radon-222 is not included because it is a gas.

plastic, and scrap metal]. The landfill is not permitted for disposal of RCRA- or TSCA-regulated hazardous wastes. However, waste containing incidental or low levels of residual radioactive material from natural sources, or from incidental contamination from site operations, is acceptable for disposal in the landfill. The disposal of materials containing residual radioactive materials is regulated under the authorized limits process contained in DOE Order 5400.5 (DOE 1993).

1.2 METHODOLOGY

In this report, fate and transport modeling and risk and performance evaluation are performed iteratively. This process, including the location where information is presented in the report, is depicted in Fig. 1.2. As shown there, the process begins with three components. These are:

- the development of an expected waste inventory based upon the PGDP list of significant contaminants of potential concern (COPCs) and augmented with COPCs identified in previous waste characterization activities,
- a transport conceptual site model (CSM) based upon landfill design and site hydrology and geology, and
- an exposure CSM based upon the identification of potential receptors and complete exposure pathways (DOE 2001b).

Subsequently, and in concert with other activities described below, the contaminants in the expected waste inventory are grouped by chemical class, and an indicator chemical is selected from each class for detailed modeling. Indicator chemicals are selected as part of this effort to streamline the modeling effort by reducing the number of chemicals requiring chemical-specific modeling. In addition to grouping chemicals by class and selecting indicator chemicals, a list of acceptable concentrations for the most sensitive receptor is developed for the COPCs. In this report, the most sensitive receptor is the resident using groundwater drawn from a well located at the PGDP property boundary, and the acceptable concentrations are risk-based values.

While COPCs are being grouped and a list of acceptable concentrations is being developed, a fate and transport modeling methodology based upon the transport CSM is developed, and transport modeling is performed. This methodology includes the selection of models applicable to the transport CSM and the collection of parameters needed to complete the modeling effort. In this report, the ultimate result of the transport modeling is a list of expected COPC concentrations in groundwater (mg/L and pCi/L) that are based upon the initial concentrations of COPCs in the expected CERCLA-derived waste inventory (mg/kg and pCi/g). As shown in Fig. 1.2, the development of this list of expected COPC concentrations in groundwater relies on an iterative process in which two criteria are considered. The first criterion is how the results of the modeling compare against those from other projects and against observed groundwater contaminant levels at the PGDP. Results determined to be inconsistent with other work and observed concentrations are critically examined, and the transport models are rerun after modifying modeling parameters to address inconsistencies. The second criterion is the estimated risk and dose posed to the most sensitive receptor described above. For this receptor, the risk and dose estimates are calculated by comparing the expected contaminant concentrations in groundwater against chemical-specific risk and dose targets calculated assuming household use of water and cancer risk, hazard, and dose targets of 1×10^{-6}, 1, and 1 mrem/year, respectively. As shown in Fig. 1.2, modeling is continued until chemical-specific modeling is available for all risk drivers. The final cumulative and chemical-specific risk and dose potentially posed to the most sensitive receptor by the expected waste inventory is subsequently calculated.

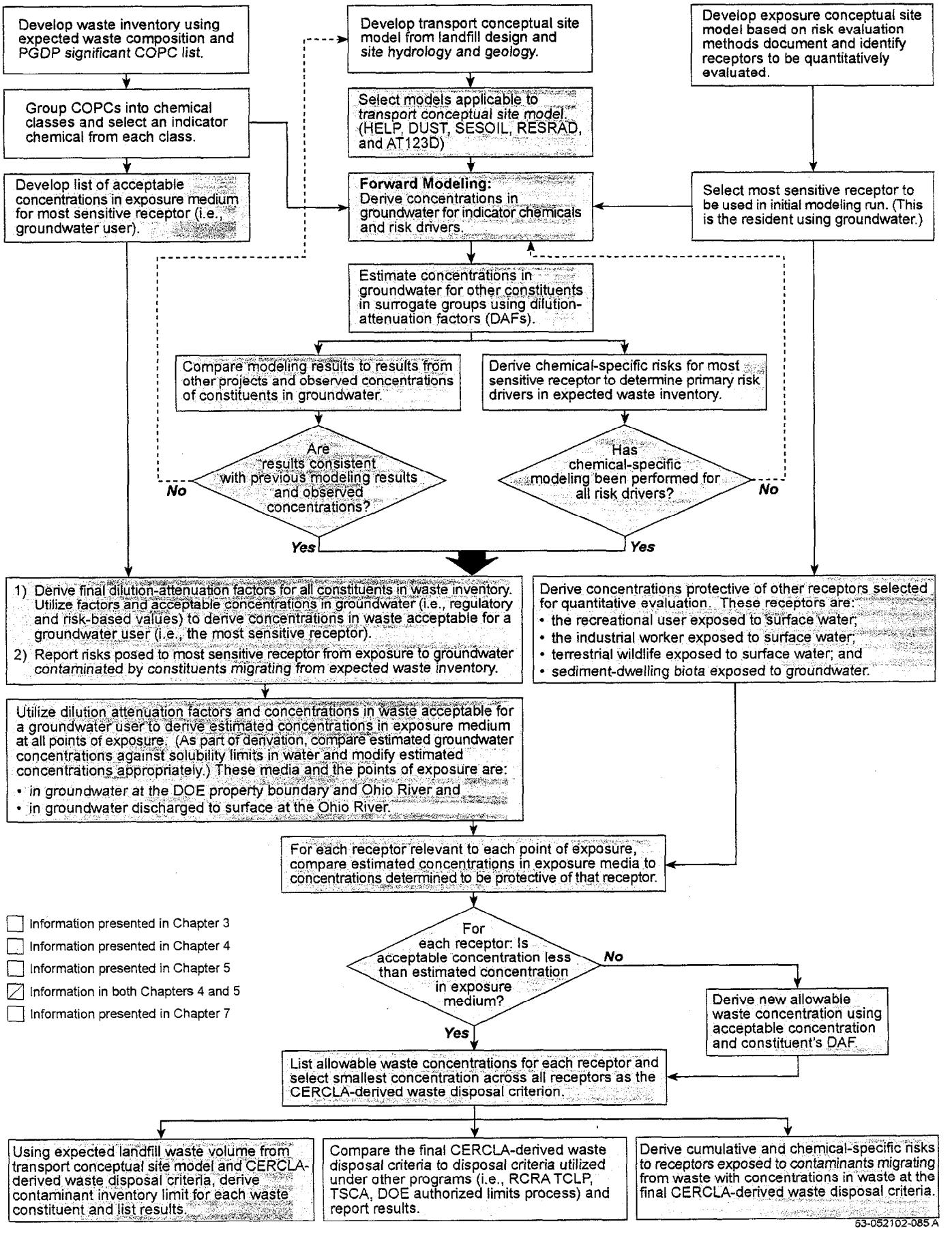


Fig. 1.2. Procedure used to develop CERCLA-derived waste disposal criteria (mg/kg or pCi/g) and waste inventory limits (kg or Ci).

1. INTRODUCTION

The U.S. Department of Energy (DOE) is evaluating whether solid wastes from removal and remedial actions performed under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) that contain low concentrations of contaminants can be safely disposed in the C-746-U Landfill at the Paducah Gaseous Diffusion Plant (PGDP) in Paducah, Kentucky. This report contributes to that evaluation by using fate and transport modeling, risk evaluation, and performance evaluation to derive a series of concentrations, termed CERCLA-derived waste disposal criteria. These criteria will be used to determine the maximum inventories of PGDP CERCLA-derived contaminants that can be placed in the C-746-U Landfill and not adversely impact the surrounding environment. In addition, the results in this report are meant to add to information used to evaluate the characteristics of CERCLA-derived waste against disposal limits established by the U.S. Environmental Protection Agency (EPA) under its Resource Conservation and Recovery Act of 1976 (RCRA) guidance or by the Commonwealth of Kentucky Department for Environmental Protection (KDEP) under its regulations.

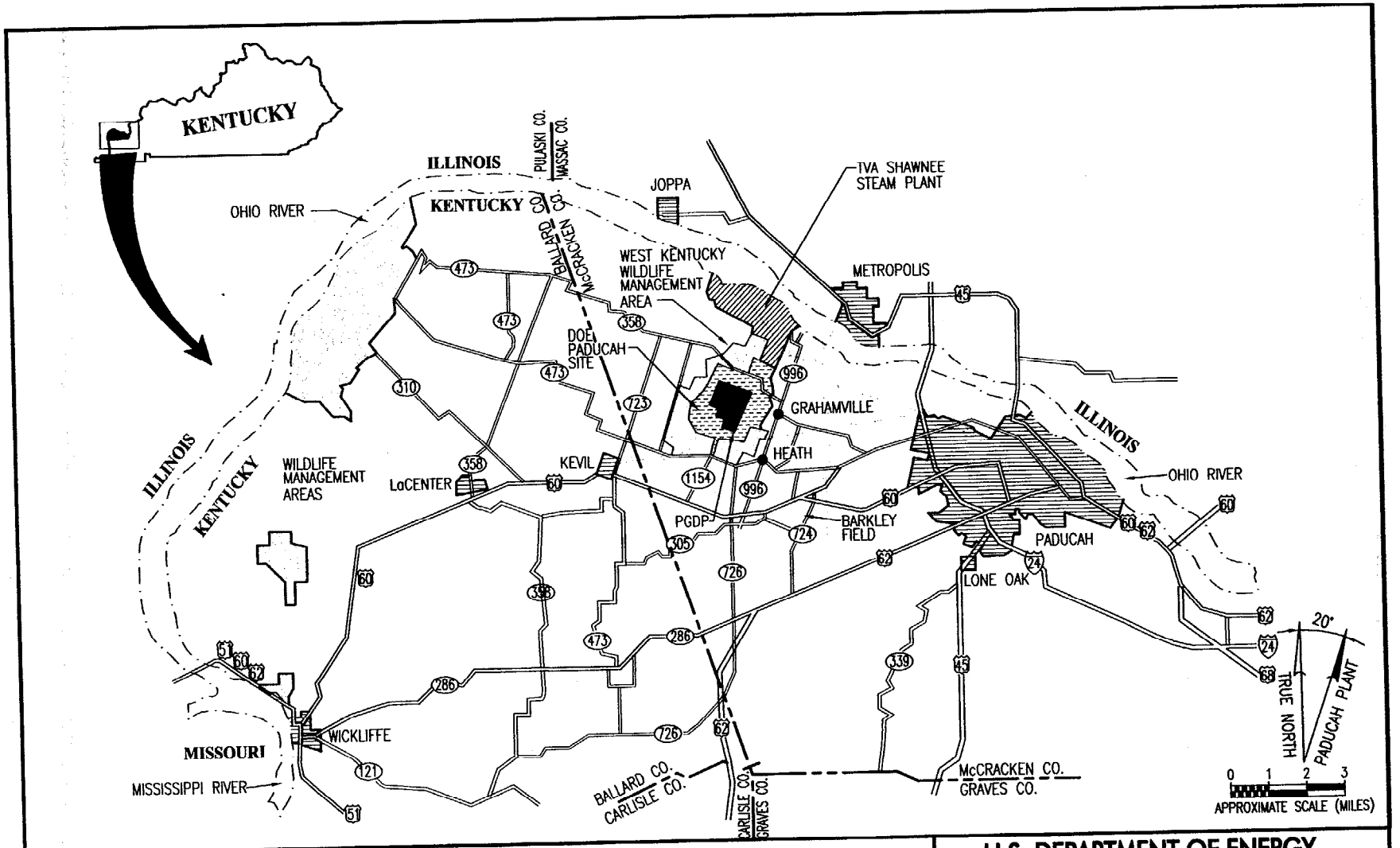
To derive the CERCLA-derived waste disposal criteria, the environmental setting, the expected waste inventory, and the design of the C-746-U Landfill are analyzed using fate and transport modeling and risk modeling. The result of this analysis is a set of contaminant inventories, or contaminant amounts, that can be safely placed in the C-746-U Landfill. In this analysis, it is assumed that a contaminant can be safely placed in the C-746-U Landfill if modeling predicts that disposal of a contaminant in the landfill at amounts at or below the inventory limit will not result in an unacceptable level of risk to receptors. To demonstrate the use of the inventory limits, the report also includes analyses of the waste inventories that may arise from Sects. 1 and 2 of the North-South Diversion Ditch (NSDD) and the scrap yard projects. In these analyses, the waste inventories arising from these actions are compared to the contaminant inventory limits derived for the landfill. A general overview of the methods used to complete the analysis is presented in Sect. 1.2.

1.1 BACKGROUND AND REGULATORY SETTING

PGDP is an operating uranium-enrichment plant located in northwestern Kentucky in McCracken County (Fig. 1.1). This plant consists of a diffusion cascade and extensive support facilities. The PGDP is owned by DOE but is operated under lease from DOE by the United States Enrichment Corporation (USEC). Environmental restoration activities at PGDP are managed and implemented by Bechtel Jacobs Company LLC (BJC) under a prime contract with DOE.

Construction of the PGDP began in 1951, and the PGDP began operations in 1952. From that time to the present, PGDP has generated a variety of commercial and industrial wastes. These wastes have been disposed in several landfills, of which the C-746-U Landfill is one. This landfill was constructed in 1995 for the disposal of solid wastes not regulated as hazardous materials under the RCRA or the Toxic Substances Control Act of 1976 (TSCA). The landfill is located north of the PGDP main plant area (see Chap. 2) and is permitted by the Commonwealth of Kentucky in accordance with the requirements of Kentucky solid waste regulations (401 Kentucky Administrative Regulation 48, *Standards for Solid Waste Facilities)* and Subtitle D of RCRA.

Wastes types listed in the permit for the C-746-U Landfill [Solid Waste Permit #073-00045 (Kentucky Division of Waste Management November 4, 1996), DOE 2001a] that may be disposed of in the landfill include construction and demolition wastes, commercial waste, and industrial waste. These waste types include soils, wood, concrete, roofing and similar construction debris, and other nonhazardous sanitary and industrial wastes [e.g., paper, fly ash, asbestos, cardboard, personal protective equipment (PPE),



LEGEND:

- WILDLIFE MANAGEMENT AREA
- PADUCAH GASEOUS DIFFUSION PLANT (PGDP)
- DEPARTMENT OF ENERGY (DOE) PADUCAH SITE
- MUNICIPALITY
- TENNESSEE VALLEY AUTHORITY (TVA)
- APPROXIMATE LOCATION OF RAILROADS IN AREA (REDRAWN FROM MICROSOFT STREETS AND TRIPS 2000)
- RIVER

U.S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS
BECHTEL JACOBS COMPANY, LLC
MANAGED FOR THE US DEPARTMENT OF ENERGY UNDER US GOVERNMENT CONTRACT DE-AC-05-98OR22700
Oak Ridge, Tennessee • Paducah, Kentucky • Portsmouth, Ohio

SAIC
Science Applications International Corporation
P.O. Box 2502
Oak Ridge, Tennessee 37831

Fig. 1.1. PGDP vicinity map.

Figure No. /99049/DWGS/P03VIC4
DATE 08-03-02

While the previous two efforts are underway, the development of the exposure CSM continues. During this activity, the most sensitive receptor is selected, and a list of other receptors to be evaluated quantitatively is developed. For each receptor selected for quantitative evaluation, medium-specific concentrations protective of the receptor at the point of exposure are derived. These receptors and the exposure media are the recreational user exposed to surface water, the industrial worker exposed to water, terrestrial wildlife exposed to surface water, and sediment-dwelling biota exposed to groundwater.

After transport modeling results are determined to be complete and sufficient for all COPCs, the list of acceptable concentrations and the modeling results are used to back-calculate concentrations in waste that would not result in unacceptable risk to the most sensitive receptor. These waste concentrations are subsequently used, along with the chemical-specific dilution-attenuation factors (DAFs), to derive estimated concentrations in exposure media for each of the receptors selected for quantitative evaluation (i.e., performance evaluation). In these calculations, the media and points of exposure considered are groundwater in wells located at the DOE property boundary and the Ohio River; groundwater discharged to the surface in springs at the Ohio River; and groundwater discharged directly to the Ohio River. These media-specific concentrations (mg/L and pCi/L) are then compared to protective concentrations derived for the other receptors. If a media-specific concentration is found to exceed a receptor's protective concentration, then the protective concentration and the modeling results are used to back-calculate concentrations in waste that would not result in unacceptable risk to the receptor.

After completing the evaluation discussed above, final acceptable concentrations in waste (mg/kg and pCi/g), termed CERCLA-derived waste disposal criteria in this report, are developed by listing the back-calculated values for each receptor and selecting the smallest concentration across all receptors. CERCLA-derived waste disposal criteria are subsequently used to derive chemical-specific contaminant inventory limits (kg and Ci) by combining the criteria with the expected landfill volume and average waste density derived as part of the transport CSM. In addition, the CERCLA-derived waste disposal criteria are compared to disposal criteria utilized under other programs (i.e., RCRA, TSCA, and DOE Orders) to provide information that can be used in subsequent work to develop the operating limits for the C-746-U Landfill. (Note that the operating limits are not derived in this report. However, a performance evaluation of the chemical-specific and cumulative risk and doses to the receptors is presented and discussed.)

1.3 REPORT ORGANIZATION

This report consists of eight sections and three appendices. In Chap. 1, the purpose and contents of the report are described, some background information about the C-746-U Landfill is provided, and the regulatory setting for the report is discussed. Chapter 2 provides a description of the environmental setting and includes discussions of the demography, land use, meteorology, climate, geology, hydrology, and ecology at PGDP, in general, and at the landfill, in particular. In Chap. 3, the CSM used for the risk evaluation and performance evaluation is derived using the material presented in Chap. 2 and the waste inventory and design information presented in Chap. 3. Chapter 3 also includes a description of the waste inventory that may be disposed of in the C-746-U Landfill, a discussion of the C-746-U Landfill design, a list of indicator chemicals used in fate and transport modeling, and a discussion of the receptors, target risks, and exposure points used in the risk evaluation. Chapter 4 describes the methods and models used to complete the fate and transport modeling and includes descriptions of each of the models used, a justification for the use of each model, and the results of the modeling effort. Chapter 5 presents the methods and models used to complete the human health and ecological risk evaluations and includes discussions of the sources and method of derivation of the screening values used to complete the risk evaluation and the results of this evaluation. Chapter 5 also includes the performance evaluation of the C-746-U Landfill for a set of human and ecological receptors and the derivation of contaminant inventory limits for the C-746-U Landfill from CERCLA-derived waste disposal criteria presented earlier. In Chapter 6, the various uncertainties that

may affect the results in Chaps. 4 and 5 are presented and evaluated. These uncertainties include those affecting the waste characterization, fate and transport modeling, and risk evaluation modeling. Chapter 7 summarizes the results of earlier chapters and includes a comparison against waste disposal criteria from other programs. In Chap. 8, the references cited in this report are presented.

In Appendices A and B of this report, the waste streams expected to originate from Sects. 1 and 2 of the NSDD and scrap yard projects, respectively, are analyzed, and the resulting waste inventories are compared to the contaminant inventory limits derived for the C-746-U Landfill. In Appendix C, supporting information that cannot be easily referenced is presented. Material in Appendix C includes human health risk calculations, ecological risk information, additional fate and transport modeling information, and waste characterization summaries.

2. ENVIRONMENTAL SETTING

This chapter presents descriptions of the environmental setting of the DOE-owned property that encompasses PGDP, including the C-746-U Landfill. This includes descriptions of the geography, physiography, demography, land use, climate, meteorology, geology, hydrology, and ecological resources at PGDP. In addition, a general description of the C-746-U Landfill and its history are provided. These materials are used later in Chap. 3 to develop the CSMs used to evaluate the C-746-U Landfill and in Chap. 5 to complete the human health and ecological exposure assessment for the landfill.

2.1 GEOGRAPHY AND PHYSIOGRAPHY

PGDP is located in western McCracken County, Kentucky, approximately 3 miles south of the Ohio River and approximately 10 miles west of the city of Paducah (Fig. 1.1). Approximately 90% of the area within a 5-mile radius of the plant is agricultural or forested land. Urban and industrial lands comprise less than 4% of the surrounding area, and surface-water bodies cover approximately 5% [Martin Marietta Energy Systems, Inc. (MMES) 1993].

PGDP is located in the Jackson Purchase Region of western Kentucky, at the northern tip of the Mississippi Embayment portion of the Atlantic Coastal Plain physiographic province. The area is bounded on the north and east by the Highland Rim portion of the Interior Low Plateau physiographic province, an area of low plateaus on stratified sedimentary rock. The Mississippi Embayment is a large sedimentary trough oriented north–south that received sediments from the middle of the North American continent.

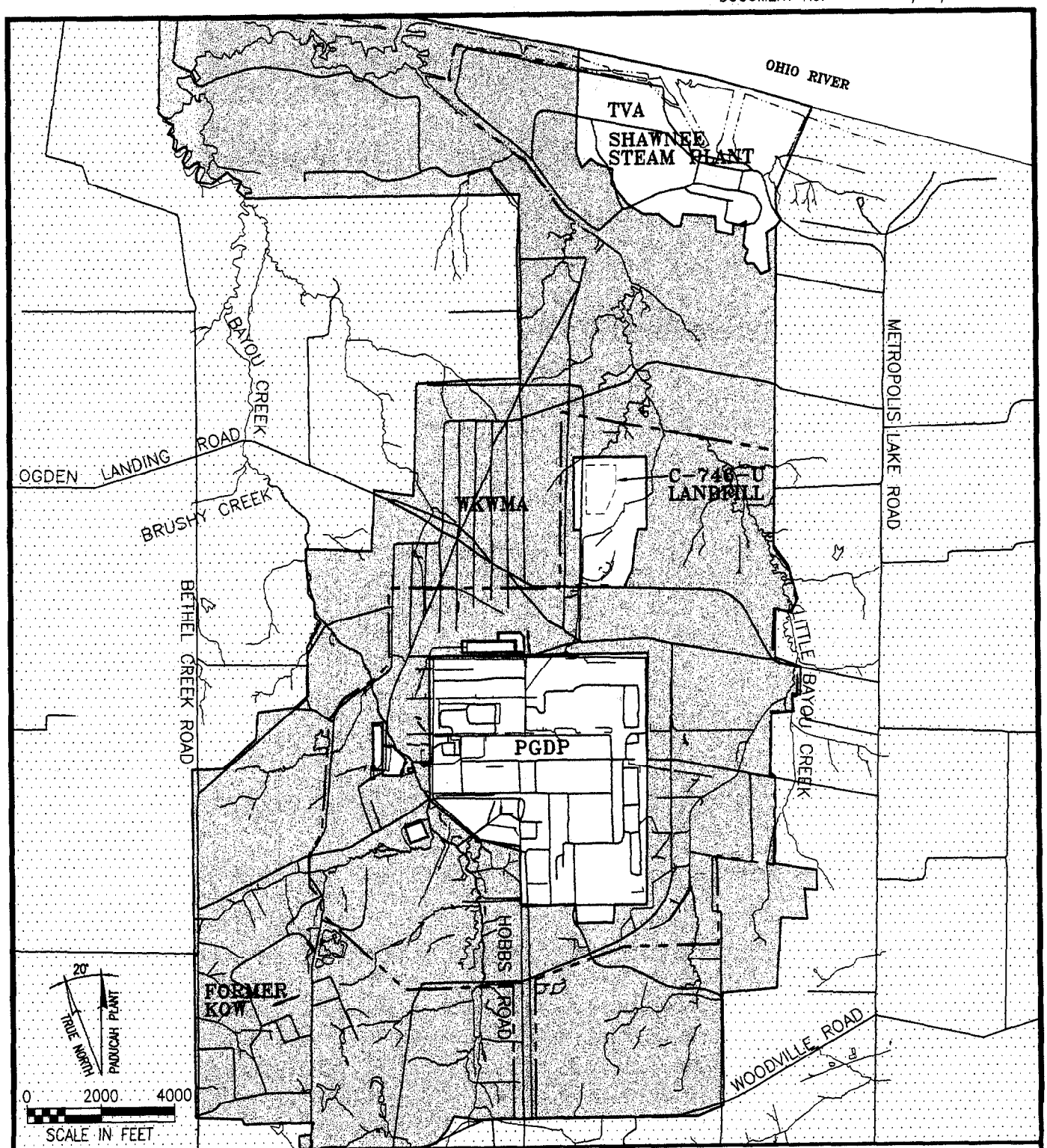
PGDP is situated in an area characterized by low relief. Elevations on the DOE-owned property vary from approximately 350 to 390 ft above mean sea level (amsl), with the ground surface sloping at a rate of approximately 27 ft/mile toward the Ohio River. Two main topographic features dominate the landscape in the surrounding area: the loess-covered plains, at an average elevation of 390 ft amsl; and the Ohio River floodplain zone, dominated by alluvial sediments, at an average elevation of 315 ft amsl [U.S. Department of Agriculture (USDA) 1976]. The terrain of the PGDP area is modified slightly by the dendritic (i.e., branching like a tree) drainage systems associated with the two principal streams in the area, Bayou Creek and Little Bayou Creek. These northerly flowing streams have eroded small valleys that are approximately 20 ft below the adjacent plain.

2.2 DEMOGRAPHY AND LAND USE

2.2.1 Land Use

DOE holds a total of 3,556 acres of land at the Paducah Site (Fig. 2.1). The industrial portion of PGDP is situated within a fenced security area consisting of approximately 748 acres. Within this area, designated as secured (i.e., fenced and patrolled) industrial land use, are the numerous buildings and offices, support facilities, equipment storage areas, and active and inactive waste management units that comprise the gaseous diffusion plant. Outside the fenced security area are approximately 822 acres that are not surrounded by the main security fence but are controlled for security purposes. This area is classified as on-site unsecured (i.e., patrolled but outside the main security fence) industrial land use. DOE currently holds lease agreements with USEC for the production facilities at PGDP and with Kentucky Department of Fish and Wildlife Resources (KDFWR) for certain portions of the West Kentucky Wildlife Management Area (WKWMA).

In total, DOE leases 1,986 acres of land to the Commonwealth of Kentucky as part of the WKWMA. The entire WKWMA covers approximately 6,823 acres. The WKWMA is managed intensively for outdoor



LEGEND:

- INDUSTRIAL
- RECREATIONAL
- RURAL RESIDENTIAL
- DOE BOUNDARY
- STREAMS
- ROADS
- WKWMA – WEST KENTUCKY WILDLIFE MANAGEMENT AREA
- KOW – KENTUCKY ORDNANCE WORK

SOURCE: (DOE 2001c)

U.S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS
BECHTEL JACOBS COMPANY, LLC
MANAGED FOR THE US DEPARTMENT OF ENERGY UNDER US GOVERNMENT CONTRACT DE-AC-05-980R22700
Oak Ridge, Tennessee • Paducah, Kentucky • Portsmouth, Ohio

SAIC
Science Applications International Corporation
P.O. Box 2502
Oak Ridge, Tennessee 37831

Fig. 2.1. Land use in the PGDP area.

Figure No. /99049/DWGS/P03LU1
DATE 08-05-02

recreation such as hunting and fishing. The WKWMA is designated as recreational land use. Portions of both the DOE-owned property and WKWMA occupy land that once was part of the Kentucky Ordnance Works (KOW), a trinitrotoluene production facility in operation between 1942 and 1946. North of the DOE-owned property, the Tennessee Valley Authority (TVA) operates the Shawnee Steam Plant. This TVA property is designated as industrial.

Property surrounding the DOE-owned property, WKWMA, and TVA is private property. This property is primarily rural and agricultural. Near PGDP, the main crops include soybeans, corn, and various grain crops. Other foods grown in the area include persimmons and apples. A variety of small gardens also are present where tomatoes, squash, beans, peppers, okra, potatoes, and other vegetables are grown (CH2M HILL 1991). Twenty-six percent of the total land area of Ballard County and 24% of McCracken County are designated as commercial forestland. Figure 2.1 details the current land use surrounding PGDP, as described in the PGDP *Site Management Plan* (DOE 2001c).

The C-746-U Landfill site is located in the far north–central portion of PGDP and encompasses 59.7 acres (Fig. 2.1). As shown in Fig. 2.1, the permitted landfill site is within a zone surrounding the security area of PGDP that is not leased to the Commonwealth of Kentucky. Although the land near the C-746-U Landfill is not managed by the KDFWR, it is surrounded by lands designated for recreational use. The C-746-U Landfill area is designated for industrial use.

2.2.2 Population

The largest cities within a 50-mile radius of the PGDP are Paducah, Kentucky, located approximately 10 miles east of the plant, and Cape Girardeau, Missouri, located about 40 miles northwest of PGDP. The population of the city of Paducah in 2000 was 26,307 [U.S. Department of Commerce (DOC) 2002)]. The population of the city of Cape Girardeau was 35,349 in 2000 (DOC 2002).

The total population within a 50-mile radius of the PGDP is estimated at 500,000 with approximately 66,000 people residing within a 10-mile radius (DOC 1994). The population of McCracken County in 2000 was 65,514. Counties adjacent to McCracken have the following populations: Ballard County (KY) to the west, 8,286; Carlisle County (KY) to the southwest, 5,351; Graves County (KY) to the south, 37,028; Marshall County (KY) to the east, 30,125; Livington County (IL) to the northeast, 39,678; and Massac County (IL) to the north, 15,161.

Several small communities are within 5 miles of PGDP. The closest communities, both unincorporated, are Grahamville and Heath, located 1 to 2 miles east. Kevil, Kentucky, and Metropolis, Illinois, are the closest communities that have public water supplies.

2.3 CLIMATOLOGY AND METEOROLOGY

The climate of the PGDP area can be described as humid–continental. It is characterized by warm and humid summers and moderately cold and humid winters. Temperatures for the summer months average 85°F, while winter temperatures average 36°F. During the winter months, temperatures drop below freezing an average of 60 nights and 10 days. The summers average 40 days per year of 90°F or higher temperatures.

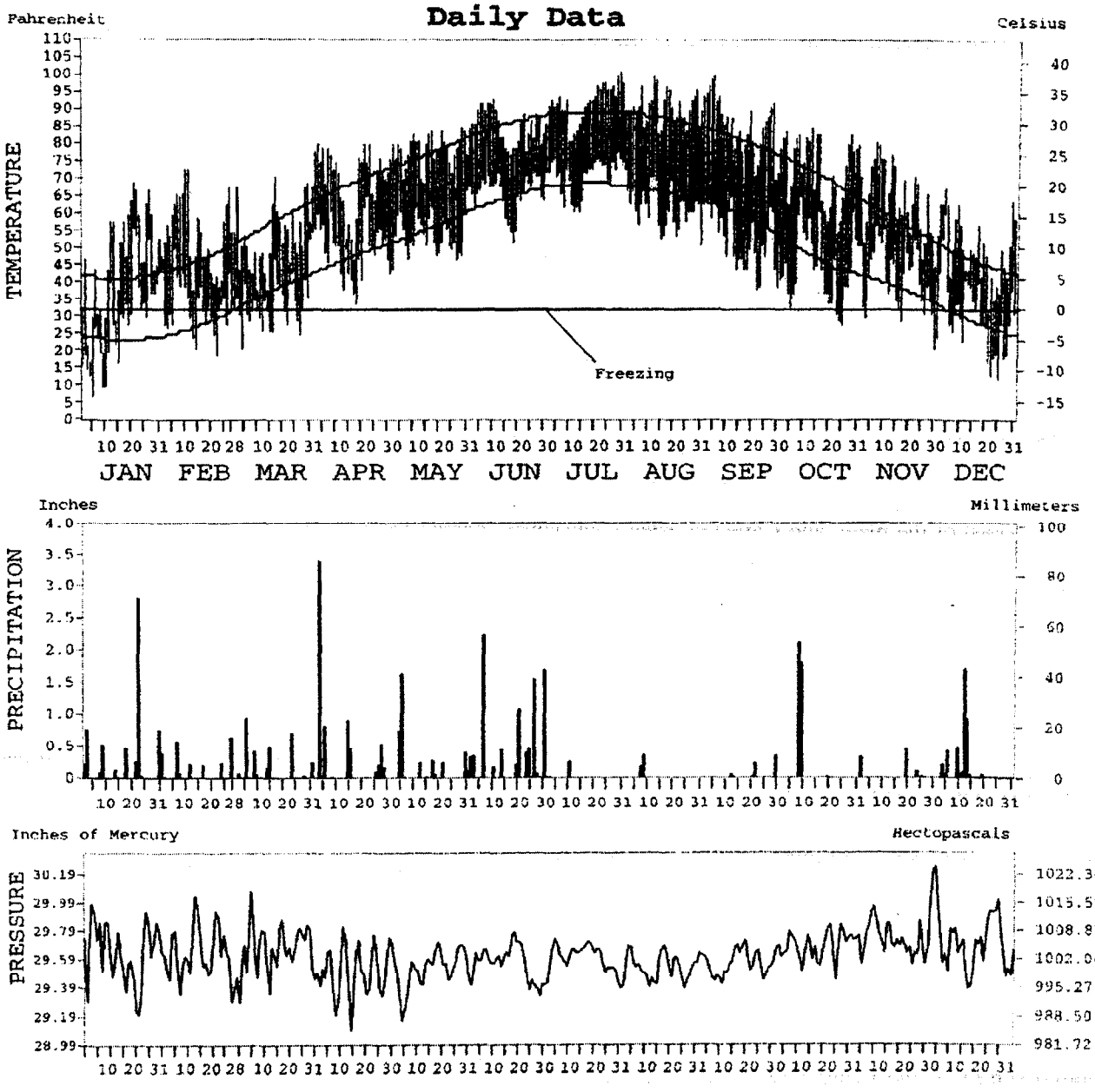
Precipitation is distributed relatively evenly throughout the year and averaged 50 inches per year from 1969 to 1989 (CH2M HILL 1992). The average annual precipitation for the region from 1984 to 1999 was 47.84 inches per year [National Climatic Data Center (NCDC) 2000]. Most groundwater recharge and stream flooding occur between November and May, when evapotranspiration normally is less than the remainder of the year. Figure 2.2 shows the 1999 annual summary of Paducah climatological data.

1999 LOCAL CLIMATOLOGICAL DATA
ANNUAL SUMMARY WITH COMPARATIVE DATA

PADUCAH,
KENTUCKY (PAH)

ISSN 0888-9988

Daily Data



SOURCE: NCDC 2000

U.S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS
BECHTEL JACOBS COMPANY, LLC
MANAGED FOR THE US DEPARTMENT OF ENERGY UNDER
US GOVERNMENT CONTRACT DE-AC-05-98OR22700
Oak Ridge, Tennessee • Paducah, Kentucky • Portsmouth, Ohio

SAIC
Science Applications International Corporation
P.O. Box 2502
Oak Ridge, Tennessee 37831

Fig. 2.2. Summary of Paducah climatological data.

The average prevailing wind in the area is from the south to southwest at approximately 9.8 mph. Generally, stronger winds are observed when the winds are from the southwest or northwest.

2.4 GEOLOGY

The subsurface in the PGDP vicinity consists of approximately 350 ft of Cretaceous, Tertiary, and Quaternary sediments unconformably overlying Paleozoic bedrock. In the PGDP vicinity, these sediments dip gently to the south–southwest toward the axis of the Mississippi Embayment and overlie northward-dipping Paleozoic bedrock. In ascending stratigraphic order, bedrock is overlaid by a rubble zone, the McNairy Formation, the Paleocene Porters Creek Clay, undifferentiated Eocene sediments, and Pliocene and Pleistocene continental deposits (Fig. 2.3).

The erosion and subsequent fill of the ancestral Tennessee River Valley during the Pleistocene is a primary factor controlling the geologic units beneath PGDP. During the Pleistocene, the ancestral Tennessee River occupied a position close to the present-day course of the Ohio River. The southern edge of the former Tennessee River Valley underlies PGDP. Figure 2.4 presents a general north–south cross section of the geologic units extending from PGDP to the Ohio River.

Several engineering and environmental investigations have defined the geology of DOE's PGDP reservation. A 1993 siting investigation for the C-746-U Landfill (DOE 1994a) provides the site-specific information presented in the following discussions.

2.4.1 Bedrock and the Rubble Zone

Deep borings at PGDP have encountered Mississippian limestone bedrock approximately 335 to 350 ft below ground surface (bgs). Immediately overlying bedrock at PGDP is a rubble zone, which consists of a 5- to 20-ft-thick layer of subangular chert and silicified limestone fragments.

2.4.2 McNairy and Clayton Formations

Overlying the rubble zone are the unconsolidated deposits of the Upper Cretaceous McNairy Formation. This formation is composed of interbedded and interlensing sand, silt accessory, and clay. The sands are well-sorted, fine-grained, micaceous (i.e., composed of mica, a group of aluminum silicate minerals), and often glauconitic (i.e., containing glauconite, a greenish mineral of the mica group composed of hydrous silicate of potassium, iron, aluminum, or manganese). Near PGDP, the McNairy Formation can be subdivided into three lithologic members: (1) a 60-ft-thick sand-dominant lower member; (2) a 100- to 130-ft-thick middle member composed predominantly of silty and clayey fine sand; and (3) a 30- to 50-ft-thick upper member consisting of interbedded sands, silts, clays, and occasional gravels. Deposits of the Clayton Formation overlie the McNairy Formation. Because of difficulties in distinguishing between the Clayton and McNairy Formations at PGDP, these lithologies have been grouped together and termed the McNairy Formation. Total thickness of the McNairy Formation is approximately 225 ft. The McNairy Formation underlies the C-746-U Landfill site.

2.4.3 Porters Creek Clay

Stratigraphically overlying the McNairy Formation, the Paleocene Porters Creek Clay occurs in southern portions of the site as a massive, glauconitic clay with lesser interbeds of sand. A terrace slope of the ancestral Tennessee River completely cuts through the thickness of the Porters Creek Clay under the south end of PGDP. The Porters Creek Clay is approximately 100-ft thick immediately southwest of PGDP but is absent, or present only as thin isolated remnants, to the north of the terrace slope.

SYSTEM	SERIES	FORMATION	THICKNESS (IN FEET)	DESCRIPTION
QUATERNARY	PLEISTOCENE AND RECENT	ALLUVIUM	0-40	Brown or gray sand and silty clay or clayey silt with streaks of sand.
	PLEISTOCENE	LOESS	0-43	Brown or yellowish-brown to tan unstratified silty clay.
	PLEISTOCENE	CONTINENTAL DEPOSITS	3-121	Clay Facies - mottled gray and yellowish brown to brown clayey silt and silty clay, some very fine sand, trace of gravel. Often micaceous.
TERTIARY	PLIOCENE-MIOCENE (?)			Gravel Facies - reddish-brown clayey, silty and sandy chert gravel and beds of gray sand.
	EOCENE	JACKSON, CLAIBORNE, AND WILCOX FORMATIONS	0-200+	Red, brown or white fine to coarse grained sand. Beds of white to dark gray clay are distributed at random.
			0-100+	White to gray sandy clay, clay conglomerates and boulders, scattered clay lenses and lenses of coarse red sand. Black to dark gray lignitic clay, silt or fine grained sand.
	PALEOCENE	PORTERS CREEK CLAY	0-200	Dark gray, slightly to very micaceous clay. Fine grained clayey sand, commonly glauconitic in the upper part. Glauconitic sand and clay at the base.
		CLAYTON FORMATION	Undetermined	Lithologically similar to underlying McNairy Formation.
UPPER CRETACEOUS		McNAIRY FORMATION	200-300	Grayish-white to dark gray micaceous clay, often silty, interbedded with light gray to yellowish-brown very fine to medium grained sand with lignite and pyrite. The upper part is interbedded clay and sand, and the lower part is sand.
		RUBBLE ZONE	Undetermined	White, semi-rounded and broken chert gravel with clay.
MISSISSIPPIAN		MISSISSIPPIAN CARBONATES	500+	Dark gray limestone and interbedded chert, some shale.

SOURCE:
MODIFIED FROM LMES 1992a

NOT TO SCALE

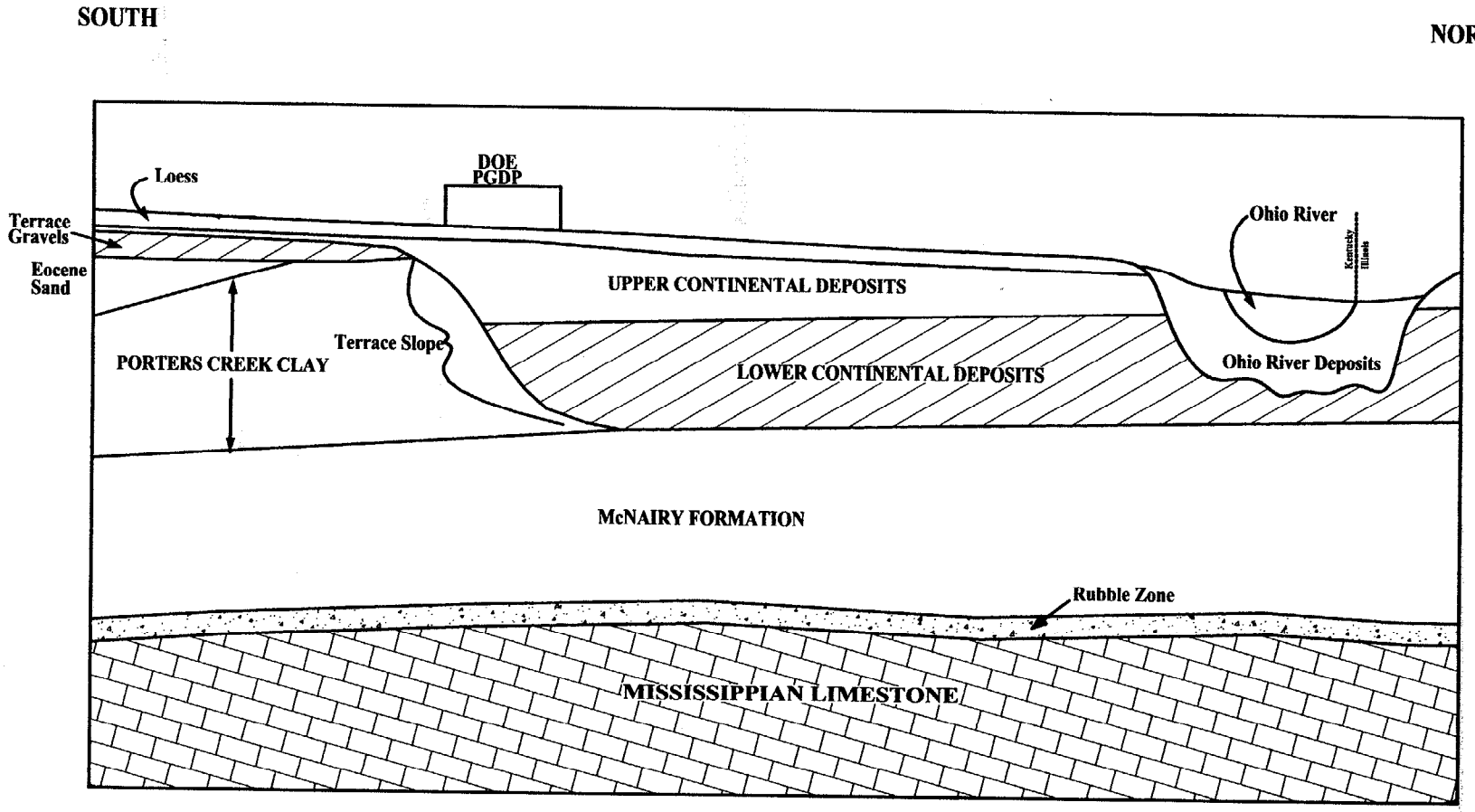
U.S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS
BECHTEL JACOBS COMPANY, LLC
MANAGED FOR THE US DEPARTMENT OF ENERGY UNDER US GOVERNMENT CONTRACT DE-AC-05-98OR22700
Oak Ridge, Tennessee • Paducah, Kentucky • Portsmouth, Ohio

SAIC
Science Applications International Corporation
P.O. Box 2502
Oak Ridge, Tennessee 37831

Fig. 2.3. Geologic columnar section in the vicinity of PGDP.

Figure No. /99049/DWGS/P037JPSC
DATE 08-03-02



SOURCE:
MODIFIED FROM ERC 1989

U.S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS
BECHTEL JACOBS COMPANY, LLC
MANAGED FOR THE US DEPARTMENT OF ENERGY UNDER US GOVERNMENT CONTRACT DE-AC-05-98OR22700
Oak Ridge, Tennessee • Paducah, Kentucky • Portsmouth, Ohio

SAIC
Science Applications International Corporation
P.O. Box 2502
Oak Ridge, Tennessee 37831

Fig. 2.4. Geologic cross section of the PGDP area.

Figure No. /99049/DWGS/P03XSEC
DATE 08-03-02

The top of the Porters Creek Clay south of PGDP has significant topographic relief. A greater depth to the top of the Porters Creek Clay to the east of PGDP permitted deposition of a thick, relatively permeable Pliocene gravel deposit near the surface. Because the C-746-U Landfill lies to the north of the terrace slope, Porters Creek Clay is not present at the C-746-U Landfill site.

2.4.4 Eocene Sands

Eocene sands, silts, and clays overlie the Porters Creek Clay south of PGDP. Researchers have not attributed these sediments to a specific formation. The thickness of the Eocene sands approaches zero near the terrace slope and increases southward to greater than 100 ft. As with the Porters Creek Clay, Eocene deposits do not underlie the C-746-U Landfill.

2.4.5 Continental Deposits

Pliocene and Pleistocene continental deposits unconformably overlie the Cretaceous through Eocene strata in the vicinity of PGDP. The Pliocene deposits consist of lobes of poorly sorted, silty sand and gravel that occur south of PGDP (i.e., terrace gravels). These sediments represent an alluvial fan deposit that covered all of western Kentucky and parts of Tennessee and Illinois during the Pliocene Epoch.

Beginning near the southern boundary of PGDP and extending north of the C-746-U Landfill, and subsequently beyond the Ohio River, a thick sequence of Pleistocene continental deposits fills the buried valley of the ancestral Tennessee River. This sediment package consists of a basal sand and gravel member, the lower continental deposits, an overlying finer-textured lithofacies, and the upper continental deposits. Where fully developed, the upper continental deposits include a bottom sand unit overlain by a thick silt and clay interval containing at least two horizons of sand and gravel.

Lower Continental Deposits – Pleistocene sand and gravel units, collectively averaging 30-ft thick, underlie most of PGDP and the northern portion of the DOE-owned property. Depth to top of this lower member in the main plant area is approximately 60 ft. The matrix is characteristically medium to coarse sand and chert gravel of variable sorting. Thickness of the individual depositional units varies widely. The lateral continuity of the individual depositional units typically is limited. In the area of the C-746-U Landfill, these deposits are 45 to 50 ft deep and average 35 ft thick.

Upper Continental Deposits – The upper member sediments (Pleistocene) include a wide variety of textures within three depositional series.

A basal sand unit is generally present, representing the transition from gravel and coarser sand of the lower member continental deposits to the overlying silty clay unit. The sand generally has a fining upward texture, becoming siltier toward the top of the unit.

An overlying interval of fine-textured sediments defines a middle unit. This unit occurs in most locations and is generally comprised of silty clay or clayey silt. However, a silty, fine sand facies is common. The thickness of the unit varies widely from <10 ft to 40 ft and is approximately 20 ft thick at the C-746-U Landfill.

Sand and gravel deposits define an upper unit. Texture and sorting are widely variable among the sand and gravel deposits. Where the unit is fully developed, three horizons are present: (1) a basal sand and gravel horizon; (2) a middle, finer-textured horizon, typically consisting of a silty, fine sand or silt; and (3) an upper sand and gravel horizon. At the C-746-U Landfill, the uppermost unit is present as a thin, sandy horizon.

Other than the broad lens-character of some sand and gravel units, the upper member continental deposits do not contain recognizable bedding features. Gradational textural changes are common. Silt and clay facies typically are mottled with frequent vertical traces filled with lighter colored silt or clay.

2.4.6 Surficial Deposits/Soils

Silt of the Pleistocene Peorian Loess and an older unit tentatively identified as the Roxanna Loess covers sediments both north and south of the buried terrace slope (DOE 1997a). The loess deposit is virtually indistinguishable from silt facies of the upper member of the continental deposits. Loess typically is 10- to 15-ft thick beneath most of PGDP; however, construction activities have excavated the loess or replaced the loess with fill material in many areas. Soils of the area are predominantly silt loams that are poorly drained, acidic, and have little organic content.

Six soil types are associated with PGDP as mapped by the Natural Resources Conservation Service, formerly the Soil Conservation Service (USDA 1976). These are Calloway silt loam, Grenada silt loam, Loring silt loam, Falaya-Collins silt loam, Vicksburg silt loam, and Henry silt loam. The dominant soil types, the Calloway and Henry silt loams, consist of nearly level, somewhat poorly drained to poorly drained soils that formed in deposits of loess and alluvium. These soils tend to have low organic content, low buffering capacity, and acidic pH ranging from 4.5 to 5.5. The Henry and Calloway series have a fragipan horizon, a compact and brittle silty clay loam layer that extends from 26 inches bgs to a depth of 50 inches or more. The fragipan reduces the vertical movement of water and causes a seasonally perched water table in some areas at PGDP. In areas within PGDP where past construction activities have disturbed the fragipan layer, the soils are best classified as "urban."

In the area of the C-746-U Landfill, the surficial deposits are approximately 6.5-ft thick, and the Calloway-Henry and Grenada-Calloway associations dominate (USDA 1976). Construction of the C-746-U Landfill and associated structures has eliminated any fragipan.

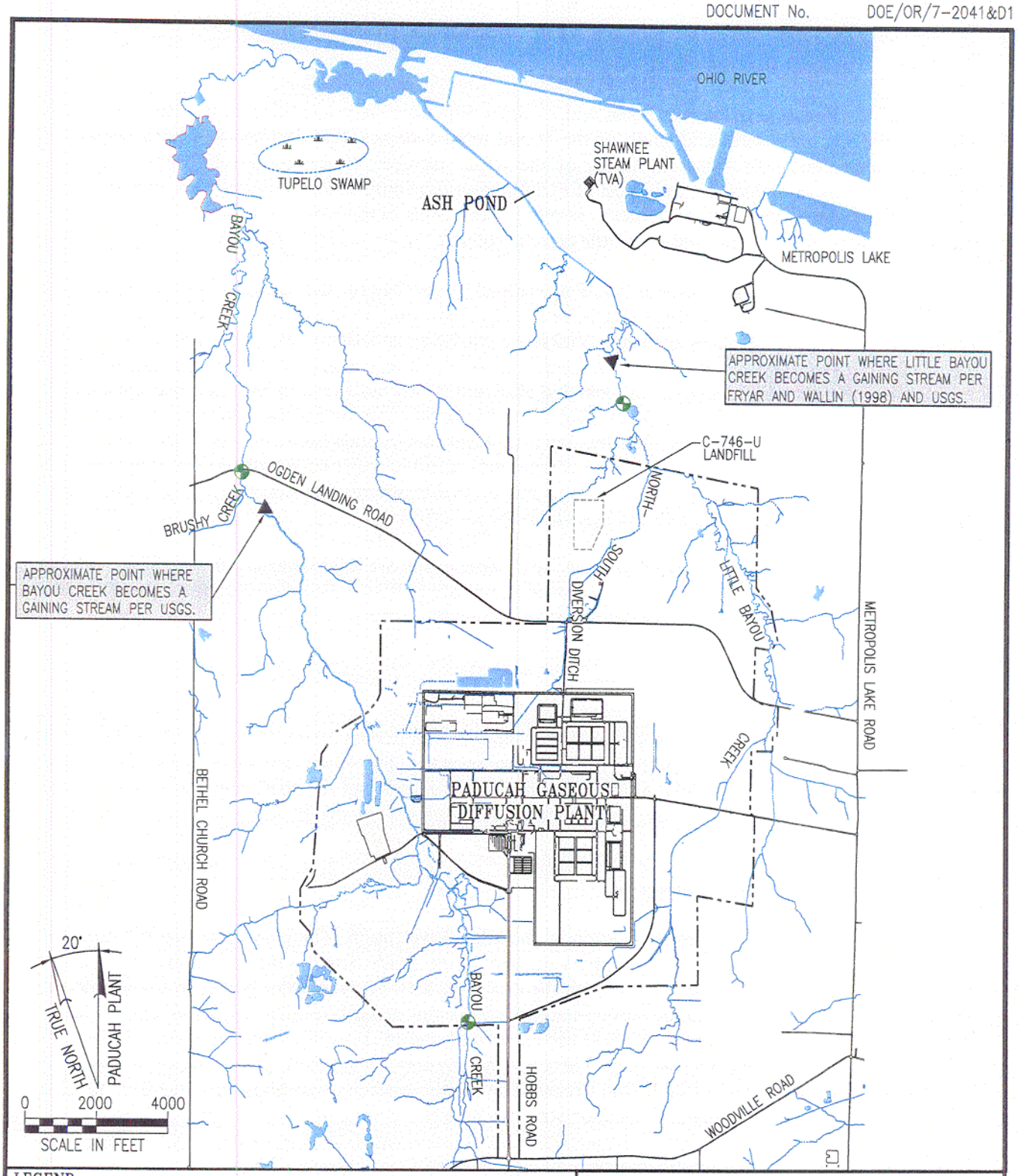
2.5 HYDROLOGY

PGDP is in an area of abundant surface water and groundwater resources. Creeks that bound the east and west sides of PGDP flow north from PGDP to join with the Ohio River. The sands and gravels of the continental deposit form a shallow aquifer beneath most of PGDP and the contiguous area to the north, beginning at the Porters Creek Clay Terrace under the south end of PGDP and extending to the north beyond the Ohio River.

2.5.1 Surface-Water Hydrology

PGDP is located in the western portion of the Ohio River basin. The plant is within the drainage areas of Bayou and Little Bayou Creeks and is situated on the divide between the two creeks, with Bayou Creek on the west and Little Bayou Creek on the east (Fig. 2.5). Surface-water bodies in the vicinity of PGDP include the Ohio River to the north, Metropolis Lake (located east of Shawnee Steam Plant), Bayou Creek, Little Bayou Creek, numerous small tributaries and creeks, as well as surface-water ditches and lagoons located within the plant boundary. There is a marshy area, called the Tupelo Swamp, just south of the confluence of Bayou and Little Bayou Creeks. The smaller surface-water bodies are expected to have only localized effects on the regional groundwater flow pattern.

Bayou Creek is a perennial stream with a drainage area of approximately 18.6 mi^2 that flows generally northward to the Ohio River from approximately 2.5 miles south of the plant. Little Bayou Creek, which becomes a perennial stream north of the plant due to PGDP discharges, originates within the WKWMA and flows northward to the Ohio River. The approximate drainage area of Little Bayou Creek is 8.5 mi^2 (CH2M HILL 1992). The confluence of the two creeks is approximately 3 miles north of the plant site (as measured over land), just upstream of the location at which the creeks discharge into the Ohio River. The drainage areas for both creeks generally are rural and located mostly within the properties of the WKWMA,



LEGEND:

- ASPHALT ROAD
- DOE BOUNDARY
- FENCE LINE
- SURFACE WATER
- SWAMP OR MARSH
- APPROXIMATE POINT AT WHICH LITTLE BAYOU CREEK BECOME GAINING
- USGS GAUGING STATIONS
- APPROXIMATE POINT AT WHICH BAYOU CREEK BECOME GAINING

U.S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS
BECHTEL JACOBS COMPANY, LLC
MANAGED FOR THE US DEPARTMENT OF ENERGY UNDER US GOVERNMENT CONTRACT DE-AC-05-98OR22700
Oak Ridge, Tennessee • Paducah, Kentucky • Portsmouth, Ohio

SAIC
Science Applications International Corporation
P.O. Box 2502
Oak Ridge, Tennessee 37831

Fig. 2.5. Surface water features in the vicinity of PGDP.

Figure No. /99049/DWGS/P03SWF
DATE 08-05-02

PGDP, and the TVA Shawnee Steam Plant. However, they receive surface drainage from numerous swales that drain residential and commercial properties. A major portion of the flow in both creeks north of PGDP is effluent water from the plant, discharged through Kentucky Pollutant Discharge Elimination System-permitted outfalls. The C-746-U Landfill is contained within the Little Bayou Creek drainage area.

The U.S. Geological Survey (USGS) maintains gauging stations on Bayou Creek, 4.1 and 7.3 river-miles from the Ohio River, and a station on Little Bayou Creek, 2.2 river-miles upstream from its confluence with Bayou Creek. The mean monthly discharge at Bayou Creek, including plant discharge, varies from 6.5 to 60.7 ft^3/s. The mean monthly discharge on Little Bayou Creek, including plant discharge, ranges from 0.89 to 33.5 ft^3/s. Two studies have investigated the dynamics of interaction between surface water and groundwater in Bayou and Little Bayou Creeks. The USGS performed a seepage survey in Bayou and Little Bayou Creeks on August 15 and 16, 1989 (Evaldi and McClain 1989). Mr. Eric Wallin monitored indicators of seepage between the creeks and groundwater during the period from July 22, 1996, through October 12, 1997, as the subject for a Master of Science thesis at the University of Kentucky (Fryar and Wallin 1998).

The 1989 USGS study determined a point on both Bayou and Little Bayou Creeks where the creeks changed from losing streams (Bayou Creek), or streams of no groundwater interaction (Little Bayou Creek), to gaining streams. On Bayou Creek, the gaining reach began approximately 3.5 river-miles upstream from the Ohio River. On Little Bayou Creek, the point where the creek became a gaining stream was located approximately 2.6 river-miles upstream from the Ohio River. The USGS researchers noted channel-bank seeps along the lower reaches of both creeks.

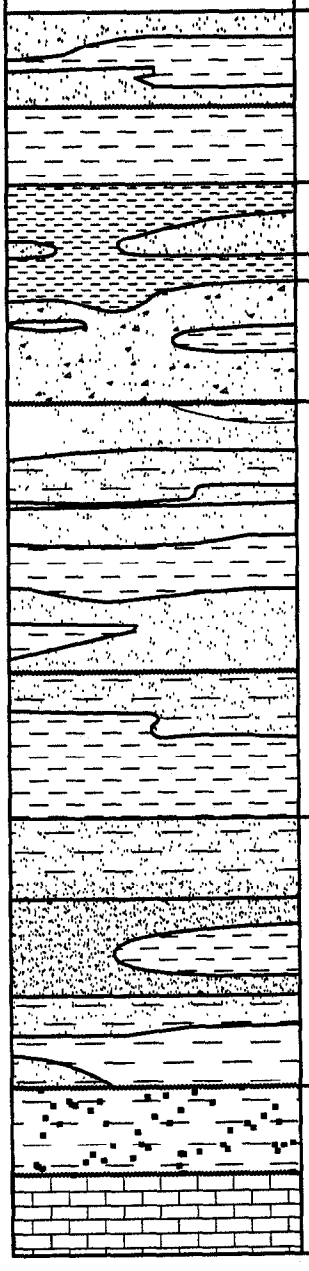
The 1996–1997 study by Wallin assessed both spatial and temporal trends in stream-to-groundwater interaction along the creeks. This study assessed Bayou Creek from south of PGDP to the Ohio River and Little Bayou Creek from the plant outfalls to the river. The investigation found that the magnitude of seepage varied with season, but it concurred with the 1989 survey location of the inflection point on Little Bayou Creek where the stream begins to gain. The Wallin study also found that gaining reaches on Bayou Creek are limited to the area south of PGDP and the area near the Ohio River. The C-746-U Landfill is located in an area where Little Bayou Creek and surrounding minor creeks and ditches are expected to be losing; therefore, discharge of C-746-U area groundwater to these creeks cannot reasonably be expected (see Chap. 3).

Man-made drainages receive stormwater and effluent from PGDP. The plant monitors 17 outfalls, which have a combined average daily flow of approximately 4.9 million gallons per day (MMES 1992b). Water flow in some of these ditches is intermittent based on seasonal rainfall. A significant man-made drainage located on the southern and eastern sides of the C-746-U Landfill is the NSDD. The NSDD served as a major effluent channel from the industrialized PGDP until the mid-1990s when process water was diverted to treatment systems. Currently, the part of the NSDD located outside the secure area of PGDP carries surface runoff to Little Bayou Creek.

2.5.2 Groundwater Hydrology

The Jackson Purchase Region is characterized by a thick sequence of unconsolidated Cretaceous through Holocene period sediments deposited on an erosionally truncated Paleozoic surface. The flow system in the vicinity of PGDP exists primarily within unconsolidated sediments.

The regional groundwater flow systems occur within the Mississippian bedrock, Cretaceous McNairy Formation, Eocene sands, Pliocene terrace gravel, Pleistocene lower continental deposits, and upper continental deposits. Terms used to describe the hydrogeologic flow system are the Bedrock Aquifer, McNairy Flow System, Eocene Sands and Terrace Gravel, the Regional Gravel Aquifer (RGA), and the Upper Continental Recharge System (UCRS). Specific components for the regional groundwater flow system, shown in Fig. 2.6, have been identified and are defined in the following subsections.



LITHOLOGY	HYDROLOGIC UNITS	HYDROGEOLOGIC UNITS	FORMATION
	HU 1	UPPER CONTINENTAL RECHARGE SYSTEM	ALLUVIUM
			LOESS
	HU 2		CONTINENTAL DEPOSITS
	HU 3		
	HU 4 HU 5	REGIONAL GRAVEL AQUIFER	
	EOCENE SANDS AND TERRACE GRAVEL		EOCENE FORMATIONS PLIOCENE CONTINENTAL DEPOSITS
	McNAIRY FLOW SYSTEM		McNAIRY FORMATION
	BEDROCK AQUIFER		RUBBLE ZONE
			MISSISSIPPIAN CARBONATES

HU = HYDROLOGIC UNIT

SOURCE:
MODIFIED FROM ORNL 1990

Not To Scale

U.S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS
BECHTEL JACOBS COMPANY, LLC
MANAGED FOR THE US DEPARTMENT OF ENERGY UNDER US GOVERNMENT CONTRACT DE-AC-05-98OR22700
Oak Ridge, Tennessee • Paducah, Kentucky • Portsmouth, Ohio

SAIC
Science Applications International Corporation
P.O. Box 2502
Oak Ridge, Tennessee 37831

Fig. 2.6. Hydrogeologic units beneath PGDP.

Figure No. /99049/DWGS/P03HYDGEO
DATE 08-05-02

2.5.2.1 Bedrock aquifer

Limestone, which is believed to be Mississippian-age Warsaw Limestone, subcrops beneath PGDP. Groundwater production from the bedrock aquifers comes from fissures and fractures and from the weathered rubble zone near the top of the bedrock. The bottom of the rubble zone generally marks the base of the active groundwater flow system beneath PGDP.

2.5.2.2 McNairy flow system

This component, formerly termed the "deep groundwater system," consists of the interbedded and interlensing sand, silt, and clay of the Cretaceous McNairy Formation. The sand in the McNairy Formation is an excellent aquifer in the southeastern part of the Jackson Purchase Region; however, near PGDP, the McNairy Formation contains significant amounts of silt and clay (MMES 1992a). Reported hydraulic conductivities for the McNairy Flow System range from 1.4E-8 to 4.7E-2 cm/s (DOE 1996). Regionally, the McNairy Formation recharges along areas of outcrop in the eastern part of the region, near Kentucky Lake and Lake Barkley (USGS 1973). Water movement is north and northwest toward discharge areas in Missouri and along the Ohio River.

The McNairy Formation subcrops beneath the plant at depths ranging from approximately 100 to 350 ft. Overall, sand facies account for 40 to 50% of the total formation thickness of approximately 225 ft. The upper and middle McNairy members in the area of PGDP are predominately silty and clayey fine sands. However, where the RGA is in direct hydraulic connection with coarser-grained sediments of the McNairy Formation, the McNairy flow is coincident with that of the RGA.

2.5.2.3 Terrace gravel and eocene sands

Pliocene-age gravel deposits and Eocene sands overlie the Paleocene Porters Creek Clay in the southern portion of the DOE-owned property. A water table flow system developed in these units provides some throughflow to the north, across the Porters Creek Clay Terrace. Most of this throughflow is realized east of PGDP, where the Pliocene Terrace Gravel is thickest adjacent to the Porters Creek Clay Terrace. The water table flow systems, immediately south and west of PGDP, generally discharge to Bayou Creek because of the shallow depth of the Porters Creek Clay in those areas. However, closer to the northern limit of the terrace, throughflow provides recharge to the RGA. Reported hydraulic conductivities for these flow systems range from 1E-6 to 1.4E-3 cm/s (DOE 1996). As noted earlier, these features are not present in the area of the C-746-U Landfill.

2.5.2.4 Regional gravel aquifer

The RGA consists primarily of the coarse sand and gravel facies of the lower continental deposits. Permeable sands of the upper continental deposits and the McNairy Formation, where they occur in contact with the lower continental deposits, are included in the RGA. The RGA is found throughout the plant area and to the north, but pinches out to the south, southeast, and southwest along the slope of the Porters Creek Clay terrace. Regionally, the RGA includes the Holocene-aged alluvium found adjacent to the Ohio River.

The RGA is the uppermost aquifer beneath PGDP and is the dominant groundwater flow system in the area extending from PGDP to the Ohio River, including the area of the C-746-U Landfill. Regional groundwater flow within the RGA trends north–northeast toward a base level represented by the Ohio River. East–west heterogeneities within the lower continental deposits and leaks from PGDP utilities cause groundwater flow to be directed locally to the northeast and northwest of the plant. Differences in permeability and aquifer thickness also affect the hydraulic gradient. Low gradients in the north–central portion of the plant site are the result of a thick section of the RGA containing higher fractions of coarse

sand and gravel. Northward, near the Ohio River, the hydraulic gradient increases as a result either of a thinner section of RGA or of low-permeability bottom sediments in the Ohio River. The hydraulic gradient varies spatially but is on the order of 1.0E-4 to 1.0E-3 m/m. Hydraulic conductivities from the RGA have been reported as ranging from 1.0E-4 to 1.0E+0 cm/s (DOE 1997b).

The RGA is the dominant pathway by which groundwater contamination migrates off-site. Figure 2.7 displays the most recent mapping (BJC 2001) of trichloroethene (TCE) and technetium-99 (^{99}Tc) plumes in the RGA. The C-746-U Landfill overlies the ^{99}Tc plume but not a TCE plume. However, an area of TCE contamination is located to the south of the C-746-U Landfill. The sources of the TCE and ^{99}Tc plumes found near the landfill are located primarily within the secure area of the PGDP. However, landfills located to the south of the C-746-U Landfill (i.e., the C-746-S and C-746-T Landfills) are potential sources of these contaminants.

2.5.2.5 Upper Continental recharge system

The UCRS consists of a thick, surface loess unit and the upper continental deposits. Hydrogeologists at PGDP have differentiated the UCRS into three general horizons, or hydrogeologic units (HUs), which are as follows:

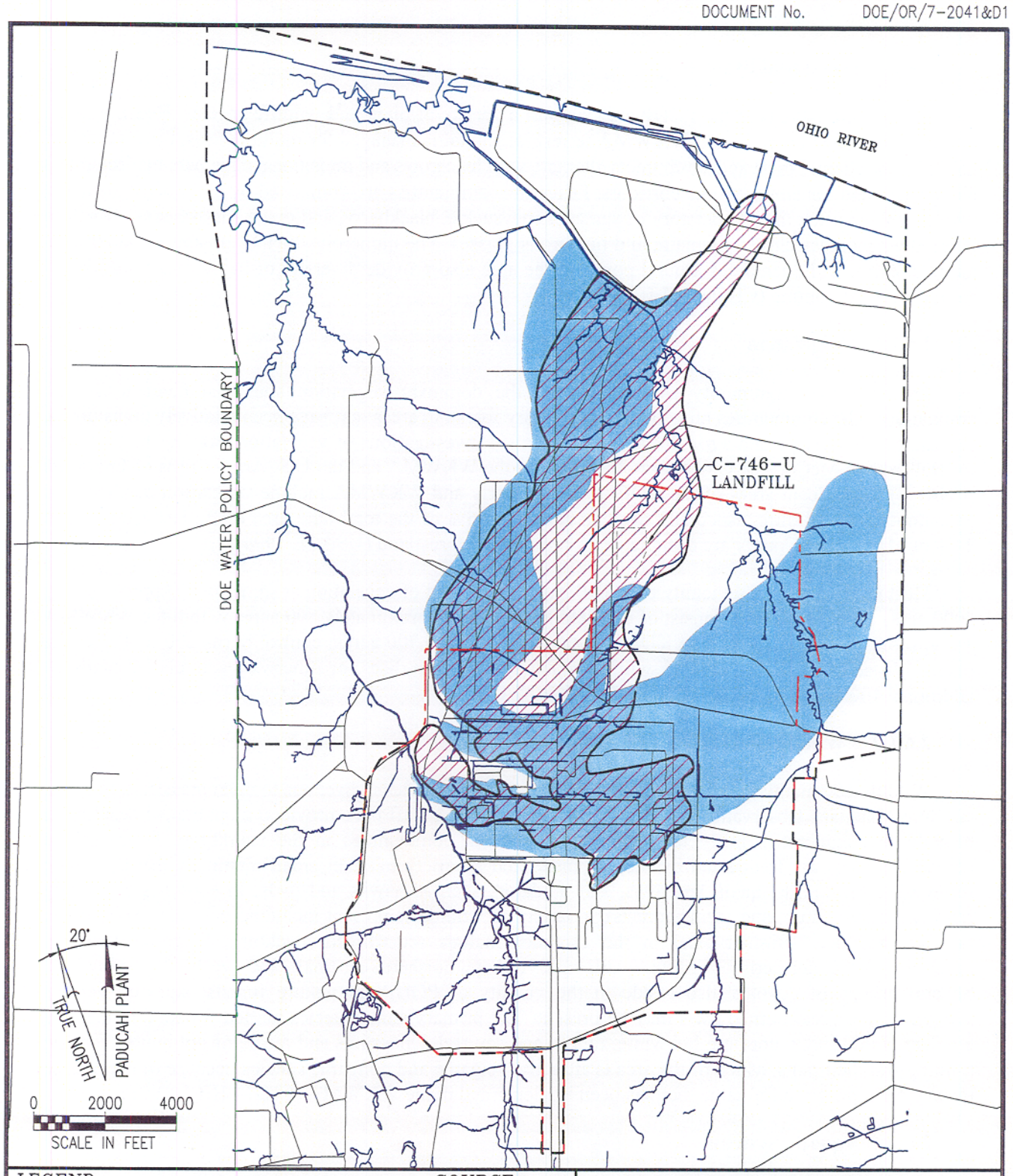
- HU 1—an upper silt and clay interval (the surface loess unit),
- HU 2—an intervening interval of common sand and gravel lenses, and
- HU 3—a lower silt and clay interval.

Each of these is present in the area of the C-746-U Landfill.

Groundwater flow in the UCRS is predominantly downward into the RGA, hence the term "recharge system." Vertical hydraulic gradients generally range from 0.5 to 1 m/m where measured by wells completed at different depths in the UCRS. The presence of steep, but undetermined, vertical gradients for most areas of PGDP has limited the ability to map a water table at PGDP. However, the available UCRS well network is sufficient to determine the main features of the water table. Regionally, the thickness of the saturated UCRS ranges from 0 to 50 ft. At the C-746-U Landfill, the expected thickness of the UCRS is approximately 30 ft. Measurements of UCRS hydraulic conductivity range from 1.7E-08 to 3.2E+00 cm/s (DOE 1999a). The range of eight orders of magnitude reflects the varied textures of the UCRS matrix.

2.6 ECOLOGICAL RESOURCES

PGDP and surrounding DOE-owned property are located in the Interior Low Plateau, Shawnee Hills Section of the Eastern Broadleaf Forest (Continental) Province of the Hot Continental Division of the Humid Temperate Domain (Bailey 1994). The vegetation types typical of this ecoregion are oak-hickory forests in the uplands and oak-gum-cypress forests in the bottomlands. The floodplain of the Ohio River in this area is dominated by sycamore, Kentucky coffeetree, sugar berry, and honey locust with local tupelo and cypress swamp communities. Due to anthropogenic disturbances, the landscape now is a mosaic of primarily forest and agricultural lands. The ecological resources [i.e., terrestrial and aquatic flora and fauna, wetlands, and threatened and endangered (T&E) species] in the PGDP vicinity are briefly summarized below. Each of these resources can be assumed to exist near the C-746-U Landfill because this site is surrounded by land managed by the WKWMA.



LEGEND:

- DOE WATER POLICY BOUNDARY
- DOE BOUNDARY
- EXTENT OF TRICHLOROETHENE CONTAMINATION ABOVE 5 ug/L
- EXTENT OF TECHNETIUM-99 CONTAMINATION ABOVE 900 pCi/L

SOURCE:
BJC 2001

U.S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS COMPANY, LLC
MANAGED FOR THE US DEPARTMENT OF ENERGY UNDER US GOVERNMENT CONTRACT DE-AC-05-98OR22700
Oak Ridge, Tennessee • Paducah, Kentucky • Portsmouth, Ohio

Science Applications International Corporation
P.O. Box 2502
Oak Ridge, Tennessee 37831

Fig. 2.7. Technetium-99 and trichloroethene plume migration in the RGA.

Figure No. /99049/DWGS/P03-PLUME
DATE 08-05-02

2.6.1 Terrestrial Systems

The upland habitats in the PGDP area support a variety of plant and wildlife species. Because much of the DOE-owned property and WKWMA terrestrial habitat is managed for multiple uses, the diversity of habitat is excellent. Forest and shrub tracts alternate with fencerows and transitional edge habitats (ecotones) along roads and transmission-line corridors. Fencerow communities are dominated by elm, locust, oak, and maple, with an often thick understory of sumac, honeysuckle, blackberry, and grape. Herbaceous growth in these areas includes clover, plantain, and numerous grasses. The numerous ditches, upland embankments along streams, and open areas around ponds in the area also provide diversity of habitat for wildlife and for recreational hunting (CH2M HILL 1991).

2.6.1.1 Vegetation

The terrestrial community is described by the dominant vegetation sites that characterize the community. The communities range from oak-hickory forest, in areas that have been relatively undisturbed, to managed fencerows and agricultural lands. Detailed investigations of vegetation have been conducted for Ballard and McCracken Counties in Kentucky by the WKWMA and the U.S. Army Corps of Engineers (USACE). Significant areas of the DOE-owned property and WKWMA include vegetation managed for consumption by wildlife, especially deer. In addition, 26% of the total land area of Ballard County and 24% of McCracken County are designated as commercial forestland (USACE 1994).

Most of the area in the vicinity of PGDP has been cleared of vegetation at some time. Approximately 2000 acres in the WKWMA consist of old field grasslands. Approximately 800 acres within the WKWMA are in scrub or shrub habitat. The KDFWR staff mows 600 to 700 acres; control burns 200 to 400 acres; plants 150 acres of food plots (for wildlife); and sprays, strip-discs, or otherwise actively manages an additional 100 to 500 acres annually on the WKWMA.

2.6.1.2 Wildlife

Wildlife commonly found in the PGDP area consists of species indigenous to open grassland, thickets, and forest habitats. Observations by ecologists and WKWMA staff have provided a qualitative description of wildlife communities likely to inhabit the vegetation communities in the vicinity of PGDP. Open herbaceous areas are frequented by rabbits, mice, and a variety of other small mammals. Birds include red-winged blackbirds, quail, sparrows, and predators such as hawks and owls. In ecotones (including fencerows, low shrub, and young forests), a variety of wildlife is present including opossum, vole, mole, raccoon, and deer. Birds typical in the ecotones include red-winged blackbird, loggerhead shrike, mourning dove, northern bobwhite quail, wild turkey, northern cardinal, and western meadowlark. Several groups of coyotes also reside in the vicinity of PGDP. In mature forests, squirrel, various songbirds, and great horned owls may be present. The primary game species hunted for food in the area are deer, wild turkey, northern bobwhite, rabbit, and squirrel. Opossums and raccoons are hunted for dog training and their pelts. Much of the area is attractive to game and nongame species because of the intense management program for game that has been implemented in the WKWMA (CH2M HILL 1991).

2.6.2 Aquatic Systems

Both Bayou and Little Bayou Creeks and tributaries support a variety of aquatic life including several species of sunfish, as well as spotted and largemouth bass, bullheads, and creek chub. Inhabitants of shallow streams, characteristic of the two main area creeks, are dominantly bluegill, green and longear sunfish, and central stonerollers.

In addition to stream habitats, approximately 13 fishing ponds are located primarily in the WKWMA. Most of the ponds north of PGDP are used for public fishing. Ponds in the former KOW area have been posted with consumption warnings, due to contamination from the former KOW operations. Pond areas generally are dominated by largemouth bass, bluegill, and to a lesser extent, green sunfish. Prior to 1990, Little Bayou Creek also was fished; however, due to the detection of elevated concentrations of polychlorinated biphenyls (PCBs) in fish taken from Little Bayou Creek, consumption warnings have been posted.

Aquatic habitats are used by muskrat and beaver. Many species of water birds, including wood duck, geese, heron, and species of migratory birds, also use these areas. Numerous other smaller ponds and abandoned gravel pits usually contain water and may have functioning ecosystems.

2.6.3 Wetlands

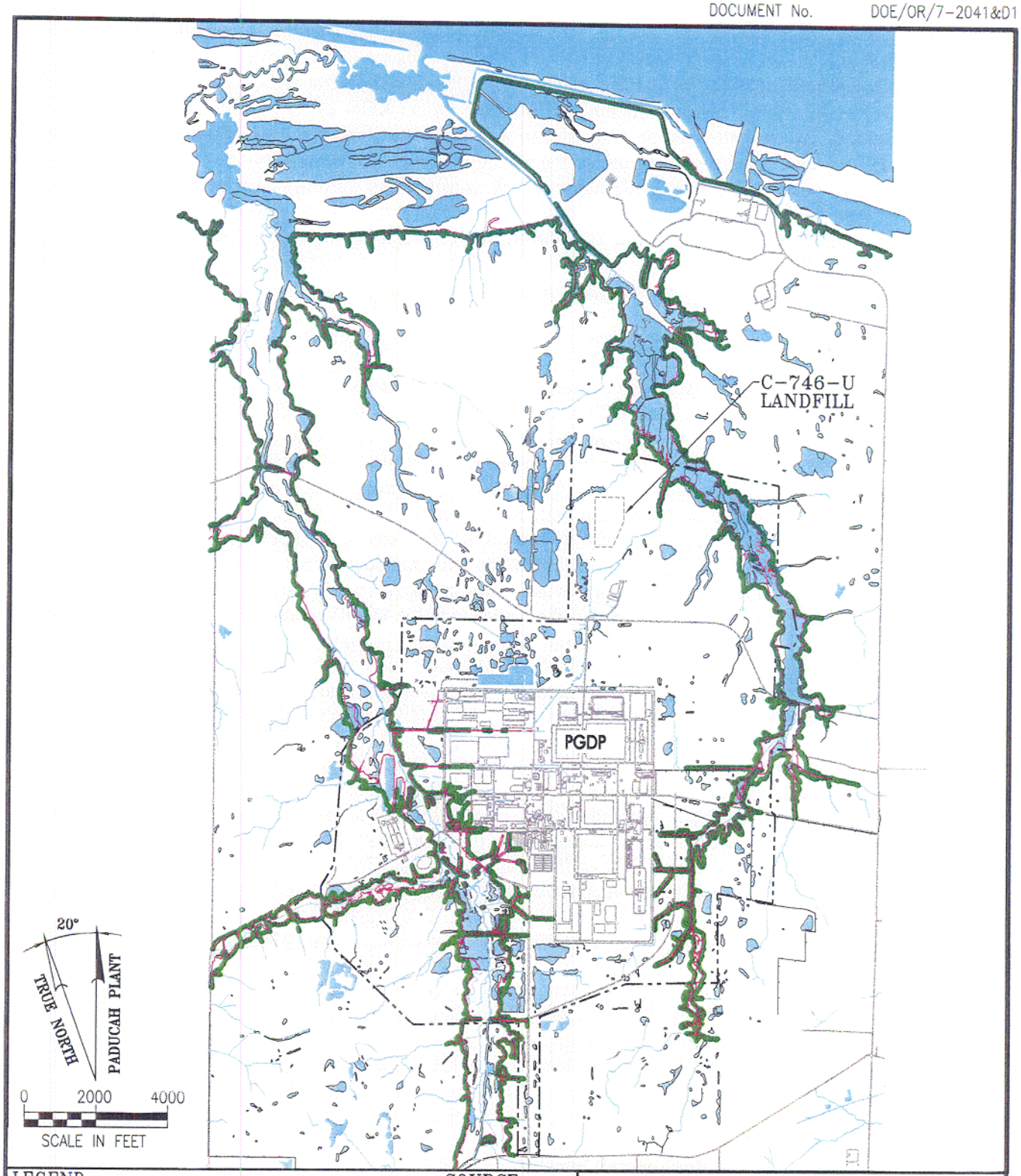
Habitats that have soil and hydrology capable of supporting vegetation adapted for hydric environments are considered wetlands. These habitats include marshes (wetlands dominated by herbaceous species) and swamps (wetlands dominated by woody species), as well as many other ecotones between terrestrial and aquatic habitats. Near PGDP, there are numerous areas where these conditions prevail, particularly in the region adjacent to the Ohio River. Within the WKWMA, approximately 4000 acres have been identified as having hydric soil capable of supporting wetlands. Some of these systems include a special-status species, the water hickory. Approximately 400 acres of this area are Tupelo Swamp, and another 600 acres are bottomland hardwood. The Tupelo Swamp, which is located near the PGDP, is considered very unusual by state and federal land managers and is thought to be only one of three similar systems left in the United States. Most of the remainder of the wetlands in the PGDP vicinity is in agricultural use or is in some stage of succession to wetland scrub. Other wetland habitats are found associated with the shorelines of ditches and creeks (riparian vegetation), although many of these are incised and have only marginal areas of wetlands. Most ponds also include shallow wetland systems along their shorelines and along contiguities with bottomland hardwood systems (CH2M HILL 1991).

The 1994 USACE environmental investigations identified 11,728 acres of wetlands surrounding PGDP (Fig. 2.8). This investigation identified and grouped wetlands into vegetation cover types encompassing forested, scrub/shrub, and emergent wetlands (USACE 1994). Wetlands inside the plant security fence are confined to portions of drainage ditches traversing the site (CDM Federal 1994). Functions and values of these areas inside the plant as wetlands are low to moderate with regard to groundwater recharge, floodwater retention, and sediment/toxicant retention (Jacobs 1995). Other functions and values such as wildlife habitat/benefits are low. The wetlands closest to the C-746-U Landfill are located to the west (Fig. 2.9). A small wetland, approximately 1 acre in area, is present near the northwest corner of the landfill.

Flooding is associated with the Ohio River, Bayou Creek, and Little Bayou Creek. The majority of overland flooding is associated with the Ohio River floodplain. Bayou and Little Bayou Creek flooding is generally confined to the areas within, and immediately adjacent to, the channels of these streams. A floodplain analysis performed by USACE in 1994 found that much of the built-up portions of the plant, including the C-746-U Landfill, lie outside the 100- and 500-year floodplains of these streams, as shown on Figs. 2.8 and 2.9 (USACE 1994).

2.6.4 Threatened and Endangered Species

Potential habitat for federally listed T&E species was evaluated for the area surrounding PGDP during the 1994 USACE environmental investigation of PGDP and inside the fence of PGDP during the 1994 investigation of sensitive resources at PGDP (USACE 1994; CDM Federal 1994). No T&E species or potential habitat for any T&E species were observed during the inside-the-fence investigation. In 1999, five Indiana bats were captured near the lower downstream reaches of Bayou Creek (KDFWR 2000).



LEGEND:

- DOE BOUNDARY
- 100-YEAR FLOODPLAIN
- 500-YEAR FLOODPLAIN
- DELINEATED WETLANDS

SOURCE:
USACE 1994

U.S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS COMPANY, LLC
MANAGED FOR THE US DEPARTMENT OF ENERGY UNDER US GOVERNMENT CONTRACT DE-AC-05-98OR22700
Oak Ridge, Tennessee • Paducah, Kentucky • Portsmouth, Ohio

Science Applications International Corporation
P.O. Box 2502
Oak Ridge, Tennessee 37831

Fig. 2.8. Wetlands and floodplains in the vicinity of the PGDP.

Figure No. /99049/DWGS/P03WETLAND
DATE 08-03-02

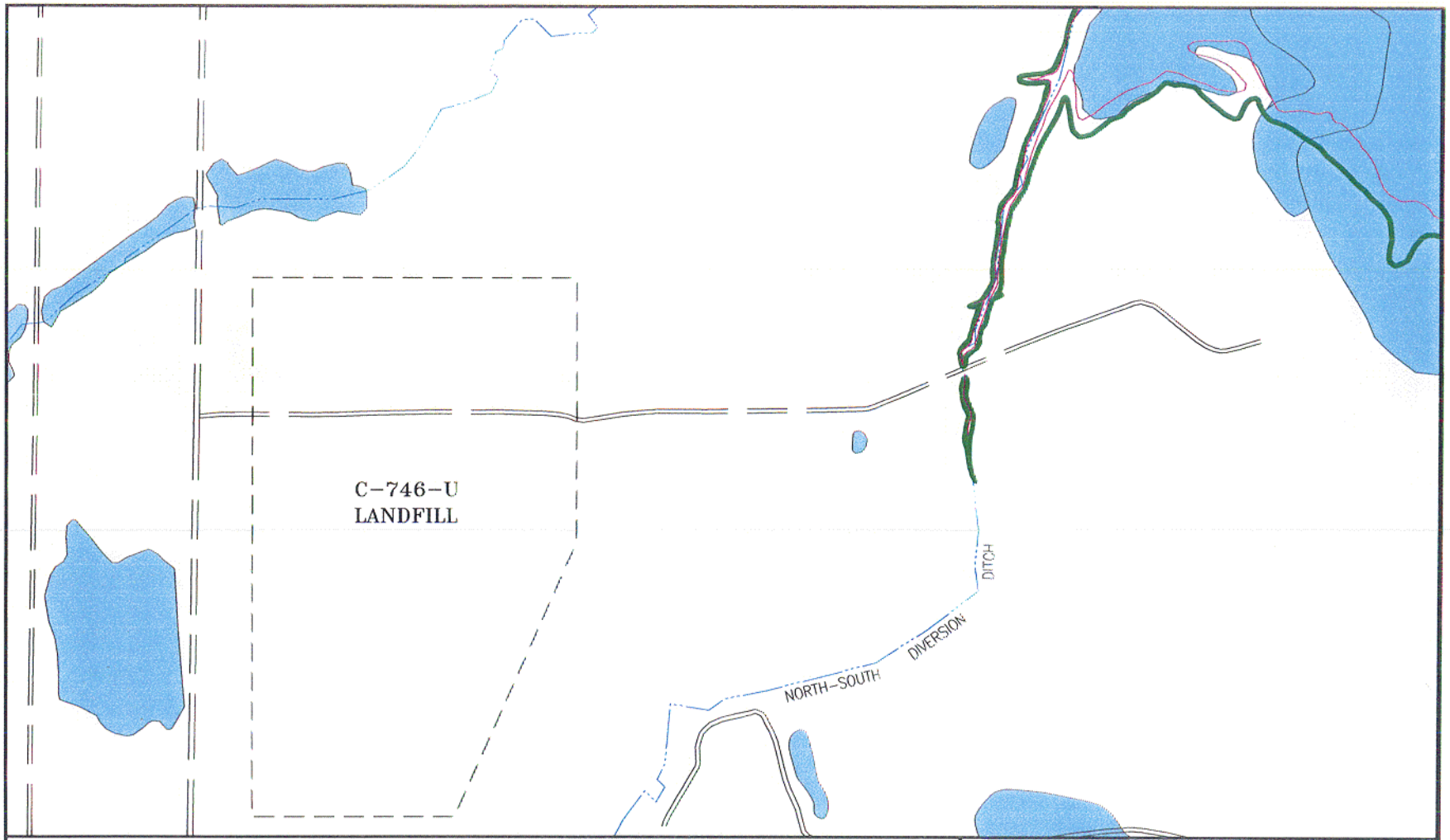


Fig. 2.9. Wetlands and floodplains in the vicinity of the C-746-U Landfill.

U.S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS COMPANY, LLC
MANAGED FOR THE US DEPARTMENT OF ENERGY UNDER US GOVERNMENT CONTRACT DE-AC-05-98OR22700
Oak Ridge, Tennessee • Paducah, Kentucky • Portsmouth, Ohio

Science Applications International Corporation
P.O. Box 2502
Oak Ridge, Tennessee 37831

Figure No. /99049/DWGS/P03ULFIL
DATE 08-03-02

Eleven federally listed, proposed, or candidate species have been identified as potentially occurring at or near PGDP (Table 2.1). None of the species has been reported as sighted on the DOE-owned property. Potential summer habitat exists on DOE-owned property for the Indiana bat based on roosting studies (USACE 1994), and Indiana bats have been captured in the vicinity (KDFWR 2000). Suitable forage habitat for the Indiana bat is present throughout the DOE-owned property. A sub-adult copperbelly water snake was caught in the Tupelo Swamp on the WKWMA in the summer of 2000. No critical habitat for any of these species has been designated anywhere in the area of the C-746-U Landfill (BJC 2000).

Table 2.1. Federally listed, proposed, and candidate species potentially occurring within the PGDP area

Common Name	Scientific Name	Endangered Species Act Status
Indiana bat	*Myotis sodalis*	Listed Endangered
Interior least tern	*Sterna antillarum athalassos*	Listed Endangered
Pink mucket	*Lampsilis abrupta*	Listed Endangered
Ring pink	*Obovaria retusa*	Listed Endangered
Orange-footed pearly mussel	*Plethobasus cooperianus*	Listed Endangered
Fat pocketbook	*Potamilus capax*	Listed Endangered
Tubercled-blossom pearly mussel	*Epioblasma torulosa torulosa*	Listed Endangered
Bald eagle	*Haliaeetus leucocephalus*	Listed Threatened
Sturgeon chub	*Macrhybopsis gelida*	Candidate
Sicklefin chub	*Macrhybopsis meeki*	Candidate
Copperbelly water snake	*Nerodia erythrogaster neglecta*	Candidate

PGDP = Paducah Gaseous Diffusion Plant.

2.7 ENVIRONMENTAL SETTING OF THE C-746-U LANDFILL

The C-746-U Landfill began operating in 1997 under Solid Waste Permit #073-00045 (Kentucky Division of Waste Management, November 4, 1996). The landfill site encompasses 59.7 acres and is located in the buffer zone surrounding the industrialized portion of PGDP (Fig. 2.1). Although surrounded by recreational use areas, the landfill is in an area designated unsecured, industrial (i.e., patrolled but outside the main security fence).

To date, five landfill cells have been constructed covering approximately 5 of the 22.1 acres permitted for waste disposal. (Please see Sect. 3.2 for a complete description of the C-746-U Landfill design, including figures). These cells have a composite liner and leachate management system designed to prevent and control the migration of contaminants from the unit by collecting leachate. The composite liner consists of a low-permeability, flexible membrane liner and a layer of compacted clay.

No landfill cells have been closed to date. However, the planned closure cap will consist of a gas vent system and a multilayer cap composed of soil, clay, geomembrane, filter fabric, and revegetative soil.

Only nonhazardous solid waste generated at PGDP can be accepted for disposal at the C-746-U Landfill. Acceptable solid waste forms include construction and demolition wastes, commercial wastes, and industrial wastes (DOE 2001a).

The disposals, to date, in the C-746-U Landfill are presented in Table 2.2. As shown there, 28,438 yd^3 of solid wastes have been placed. Of these, the majority have come from maintenance activities, with concrete and general construction debris (i.e., timbers and roofing material) forming the greatest portion of the waste. Please see Chap. 3 for additional discussion of current and projected waste inventories for the C-746-U Landfill.

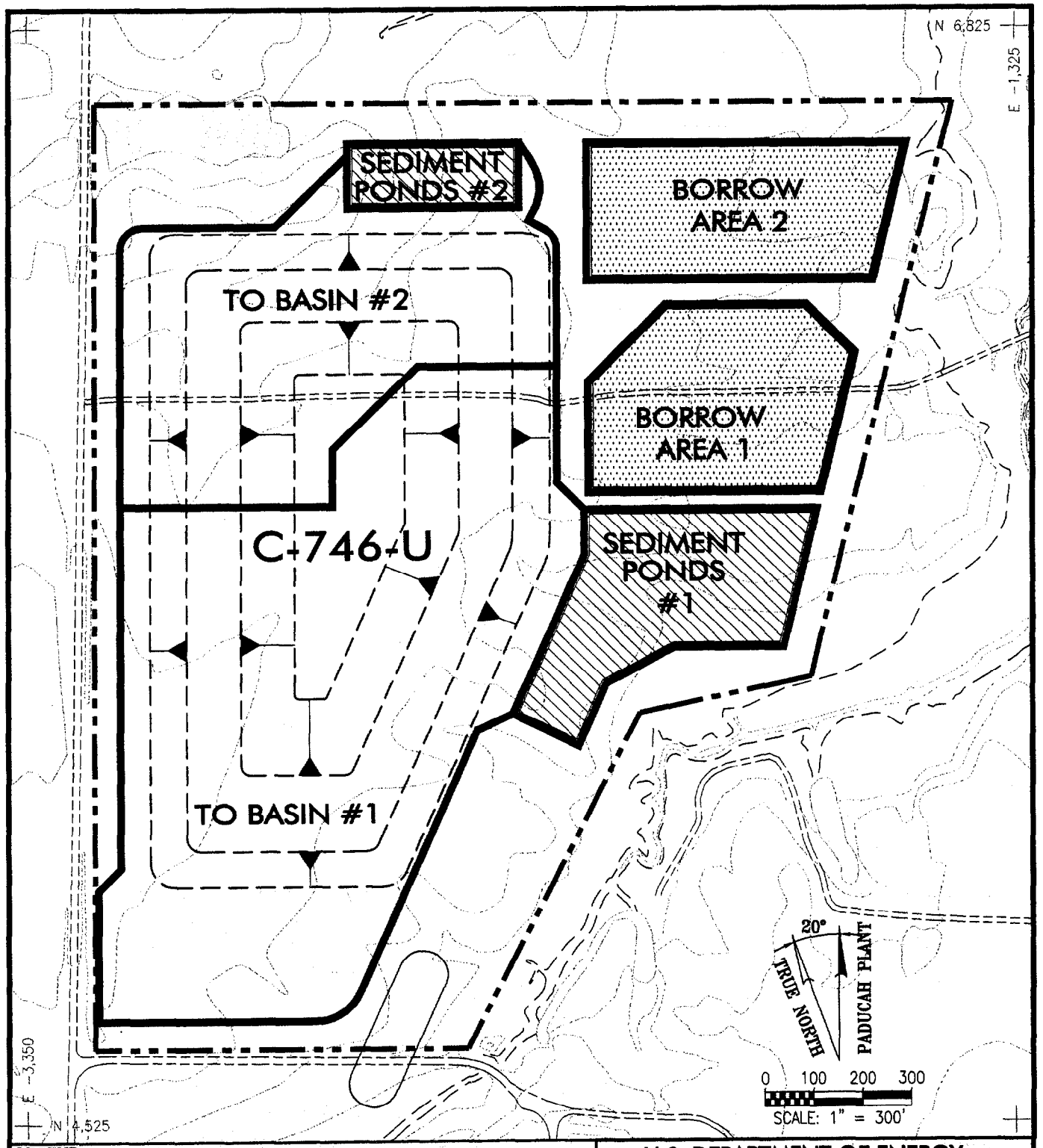
Table 2.2. Current inventory (yd^3) by waste form[a] in C-746-U Landfill

Source	Year	Asbestos	Concrete	General	Other Dry	Scrap Metal	Soil	Other SW	Total
All Sources	Total	629	8,680	14,994	149	60	3,845	80	28,438
	1997	300	200	11,534	30	0	1,149	0	13,213
	1998	101	2,370	2,610	100	50	1,100	80	6,411
	1999	228	3,860	850	20	10	846	0	5,814
	2001	0	2,250	0	0	0	750	0	3,000
Non-maintenance[b]	Total	0	2,250	40	23	0	1,878	0	4,191
	1997	0	0	20	0	0	320	0	340
	1998	0	0	20	3	0	267	0	290
	1999	0	0	0	20	0	541	0	561
	2001	0	2,250	0	0	0	750	0	3,000
Maintenance[c]	Total	629	6,430	14,954	126	60	1,968	80	24,247
	1997	300	200	11,514	29.575	0	828.925	0	12,873
	1998	101	2,370	2,590	97	50	833	80	6,121
	1999	228	3,860	850	0	10	306	0	5,253
	2001	0	0	0	0	0	0	0	0

[a]Definitions of waste forms are as follows:
Asbestos = solid waste containing asbestos.
Concrete = solid waste composed of large pieces of concrete.
General = solid waste composed of general construction debris such as lumber, wall board, etc.
Other dry = solid waste composed of personal protective equipment, plastic, and packing material.
Scrap metal = solid pieces of metal.
Other solid waste = materials not falling within the earlier categories, including putrescent waste and paper products.
[b]Includes materials not derived from Paducah Diffusion Plant (PGDP) operations and plant maintenance. This category includes concrete and soil that came from environmental restoration projects.
[c]Solid waste derived from PGDP operations and plant maintenance.
Note:
No requests for disposal numbers were issued in 2000.
Data taken from the C-746-U Landfill Waste Stream List maintained by PGDP (see Appendix C.4).
SW = solid waste.

Surface runoff at the C-746-U Landfill is controlled using several sediment ponds (Fig. 2.10). These ponds prevent runoff of contaminated soils and sediments to surrounding creeks, and are involved in leachate collection. Discharge from these ponds, when necessary, is through KPDES Outfall 019. Contamination in leachate to date has been minimal. Table 2.3 provides a summary of leachate analyses, including a summary of some physical parameters. When compared to risk-based screening values for groundwater ingestion values by a child resident taken from PGDP human health methods document (Table A.5 in DOE 2001b), only aluminum, iron, manganese, nickel, and zinc are found to have been detected at a maximum concentration exceeding their no action screening value (1.49, 0.449, 0.0671, 0.0301, and 0.450 mg/L, respectively).No volatile organic compounds (VOCs) have been detected in leachate, and no radionuclides have been detected at a concentration greater than the respective PGDP no-action, groundwater ingestion screening value.

The NSDD lies near the southern and eastern boundary of the C-746-U Landfill site. An unnamed creek borders the northern edge of the landfill (Fig. 2.5). Both the unnamed creek and the NSDD empty into Little Bayou Creek. In the area of the landfill, the NSDD and Little Bayou Creek are perennial streams that are assumed to provide aquatic habitat, but the unnamed creek is intermittent and is not assumed to provide aquatic habitat. The areas surrounding the creeks form habitat for a variety of terrestrial wildlife, including the T&E species discussed earlier.



LEGEND:

- ASPHALT ROADS
- GRAVEL ROADS
- C-746-U LANDFILL BOUNDARY
- STREAM OR TRIBUTARY
- LAKE, POND OR WETLAND
- GROUND CONTOUR (10 FT INTERVAL)
- GROUND CONTOUR (2 FT INTERVAL)
- SEDIMENT BASIN
- BORROW AREA

U.S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS
BECHTEL JACOBS COMPANY, LLC
MANAGED FOR THE US DEPARTMENT OF ENERGY UNDER US GOVERNMENT CONTRACT DE-AC-05-98OR22700
Oak Ridge, Tennessee • Paducah, Kentucky • Portsmouth, Ohio

SAIC
Science Applications International Corporation
P.O. Box 2502
Oak Ridge, Tennessee 37831

Fig. 2.10 Drainage areas for C-746-U Landfill (DOE 1994)

Figure No. /99049/DWGS/P03C746U
DATE 08-03-02

Table 2.3. Summary of leachate generation from C-746-U Landfill through August 2001

Analyte	Units	Proportion Detected[a]	Minimum[b]	Maximum[b]	Arithmetic Mean[c]
		Analytes Detected			
Alkalinity	mg/L	5/5	57.0	149	104
Aluminum	mg/L	6/6	1.32	13.6	5.84
Bicarbonate as $CaCO_3$	mg/L	6/6	57.0	149	108
Calcium	mg/L	6/6	26.6	116	76.0
Chemical Oxygen Demand	mg/L	1/6	31.0	31.0	15.6
Chloride	mg/L	6/6	22.3	55.1	41.1
Iron	mg/L	6/6	0.921	11.8	4.98
Magnesium	mg/L	6/6	7.74	37.7	23.9
Manganese	mg/L	6/6	0.110	5.28	2.00
Nickel	mg/L	2/6	0.116	0.116	0.0720
Orthophosphate	mg/L	2/2	0.270	0.330	0.300
Phosphate as Phosphorous	mg/L	1/1	0.130	0.130	0.130
Phosphorous	mg/L	1/1	1.30	1.30	1.30
Potassium	mg/L	6/6	2.79	13.1	6.09
Sodium	mg/L	6/6	14.2	65.7	42.3
Sulfate	mg/L	6/6	37.7	329	184
Suspended Solids	mg/L	4/6	19.0	151	67.8
Total Organic Carbon	mg/L	6/6	4.00	9.00	6.15
Total Phosphate as Phosphorus	mg/L	2/2	2.10	2.10	2.10
Uranium	mg/L	3/6	0.002	0.002	0.00125
Zinc	mg/L	3/6	0.220	0.533	0.262
Conductivity	µmho/cm	7/7	307	1140	793
Dissolved Oxygen	mg/L	1/1	4.60	4.60	4.60
Dissolved Solids	mg/L	6/6	214	813	533
pH	Std Unit	5/5	6.04	7.06	6.70
Temperature	deg F	1/1	73.2	73.2	73.2
Beta activity	pCi/L	7/9	9.70	109	24.6
Technetium-99	pCi/L	1/9	23.0	23.0	3.20
		Analytes not Detected			
Cadmium	mg/L	0/6	0.020	0.100	0.0475
Chromium	mg/L	0/6	0.020	0.050	0.0350
Copper	mg/L	0/6	0.020	0.100	0.0600
Lead	mg/L	0/6	0.200	0.250	0.213
Benzene	mg/L	0/6	0.005	0.005	0.005
Ethylbenzene	mg/L	0/6	0.005	0.005	0.005
Polychlorinated biphenyl (total)	mg/L	0/5	0.00017	0.00017	0.00017
Trichloroethene	mg/L	0/6	0.001	0.001	0.001
Americium-241	pCi/L	0/3	30.6	64.8	42.2
Cesium-137	pCi/L	0/3	14.2	15.7	15.2
Neptunium-237	pCi/L	0/2	0.950	0.950	0.950
Plutonium-239/240	pCi/L	0/3	0.110	0.130	0.117
Thorium-230	pCi/L	0/3	0.340	0.480	0.430

[a]Number of samples in which analyte was detected over number of samples collected.

[b]The minimum and maximum detected values for analytes detected and the minimum and maximum sample quantitation limits for samples never detected.

[c]For detected analytes, the average value was calculated including nondetected values at their sample quantitation limit; therefore, the mean for some analytes is less than the analyte's minimum detected value.

Note: Information taken from the Paducah Gaseous Diffusion Plant Oak Ridge Environmental Information System Database in October 2001.

Groundwater flow at the C-746-U Landfill is similar to other locations at PGDP located above the RGA. Groundwater flow in the UCRS is primarily vertical, and flow in the RGA is primarily lateral. Once groundwater reaches the RGA, flow is towards the north-northeast. Based upon water level measurements, groundwater reaching the RGA is assumed to pass under Little Bayou Creek, as it flows to the Ohio River, and not discharge to this creek. The ultimate discharge point of RGA groundwater originating at the C-746-U Landfill is the Ohio River. Please see Chap. 4 for additional discussion of groundwater movement based on particle tracking using the MODPATH model.

3. CONCEPTUAL MODEL DEVELOPMENT

In this section, the conceptual site models used for the transport modeling and for the risk and performance evaluation are derived using the material presented in Chap. 2 and waste inventory and landfill design information. This section includes a description of the waste inventory that is projected for disposal in the C-746-U Landfill, a discussion of the C-746-U Landfill design, a list of indicator chemicals used in fate and transport modeling, and a discussion of the receptors, target risks, target doses, and exposure points used in the risk evaluation and performance evaluation.

3.1 WASTE VOLUME AND TYPES

This section presents estimates of the volumes, generation rates, and characterization of CERCLA and non-CERCLA waste at PGDP that are being evaluated for placement in the C-746-U Landfill. The methodology and assumptions used in the development of this information are discussed. (Additional information appears in Appendix C.4.) The waste characterization presented here is used to focus the fate and transport modeling on the significant waste forms and contaminants that might be present in the CERCLA- and non-CERCLA-derived waste streams.

3.1.1 CERCLA-Derived Waste

CERCLA-derived waste is material that is expected to be generated at PGDP as a result of environmental restoration (ER) and decontamination and decommissioning (D&D) activities. This waste inventory was developed using information contained in the Fiscal Year (FY) 2001 *Oak Ridge Operations Environmental Program Life Cycle Baseline* (DOE 2001d). This baseline contains information on planned activities, including waste volumes, waste categories, and activity schedules and is subject to change over time as additional information regarding remedial activities at the PGDP is developed. When pertinent information was not available in the baseline, the information used to develop the inventory was taken from historical documents, produced following site visits, or derived from interviews with subject matter experts.

3.1.1.1 Inventory of CERCLA-derived waste

At the PGDP, CERCLA-derived waste includes materials containing a wide range of contaminant concentrations. However, only materials that are solid wastes (i.e., not RCRA- or TSCA- regulated hazardous wastes or radioactive waste) may be placed in the landfill under the current permit (i.e., Solid Waste Permit #073-00045; DOE 2001a). Therefore, for this evaluation of the C-746-U Landfill, the chemical concentrations of the expected waste inventory (i.e., the waste characteristics of the inventory) were developed considering only a subset of the total CERCLA-derived waste that may be generated by the PGDP. Note that waste containing an incidental or residual level of radioactive material (i.e., a total uranium concentration less than 30 pCi/g) was included in the waste inventory to allow for the evaluation of the placement of these types of materials in the C-746-U Landfill. Other important assumptions and restrictions used in deriving the inventory for the CERCLA-derived waste to be placed in the C-746-U Landfill including its rate of generation, are as follows:

- soil will swell by a factor of 30% upon excavation;
- no classified waste is included;
- contents of burial grounds are not included; and

- D&D of buildings and facilities currently in use at PGDP, including building foundations, underground utilities, and associated soils will begin in 2010.

When compiling the waste inventory, wastes were categorized by waste form (i.e., media type). Wastes were categorized by form to support waste characterization and the modeling effort. Waste forms and their definitions are provided below.

- **Asbestos.** Material containing asbestos (friable and non-friable). This material is to be generated largely as a result of D&D tasks. Transite, an asbestos-containing material, was commonly used for exterior siding and piping during the construction of the plant. It also is expected that older flooring and insulation material in the plant contain asbestos.

- **Concrete.** An aggregate generally composed of sand and/or gravel bound together with Portland cement. This media type is to be generated largely as a result of D&D tasks. Expected major sources of concrete include building slabs and foundations, storage pads, roadways, and sidewalks.

- **Construction Debris.** Material (exclusive of asbestos, concrete, scrap metal, and other dry solids) generated as a result of the demolition of existing structures or construction of new structures. This media type is to be generated largely as a result of D&D tasks and includes wood, plastics, composites, glass, porcelain, gypsum board, cellulose, and organic-based roofing material.

- **Other Dry Solids.** Materials used to prevent the spread of contamination. This media type is expected to be generated during a variety of tasks at PGDP. This media type includes PPE composed of Tyvek, latex, cotton, leather, etc.; isolation plastic (plastic sheeting); duct tape; and high-efficiency particulate air (HEPA) filters.

- **Scrap Metal.** Waste metal, whether currently in storage or generated in the future, at PGDP. This media type would include process equipment (i.e., cascade components, structural steel, tanks, and piping).

- **Soil.** Unconsolidated solids excavated during cleanups that are not man-made.

The total CERCLA-derived waste estimated to be generated at PGDP is presented in Fig. 3.1. The data used to derive this figure are in Table 3.1. Rate of generation of waste that may be placed in the C-746-U Landfill by waste form and year of generation, is in Table 3.2.

3.1.1.2 Characterization of CERCLA-derived waste

This section characterizes the CERCLA-derived waste volumes for those wastes that may be placed in the C-746-U Landfill. Characterization includes developing a list of contaminants of potential concern (COPCs) for the specific waste forms defined above and developing an analytical profile for the COPCs. The COPCs and their analytical profile established in this section form the basis for development of the initial fate and transport modeling run and the selection of COPCs that drive risk, hazard, or dose (i.e., are "risk drivers").

Analytical data are not available for many of the waste sources and waste forms. Therefore, characterization of projected waste streams uses available analytical data and process knowledge from similar areas at PGDP to establish COPCs and analytical profiles. Because of the uncertainties associated with this characterization, the results presented here are estimates of the nature of projected waste volumes. Only analytical profiles for the subset of waste described earlier are included in this analysis.

As discussed in Appendix C.4, the Paducah Oak Ridge Environmental Information Management database was utilized to compile the waste characterization profile for soil. The soil waste characterization

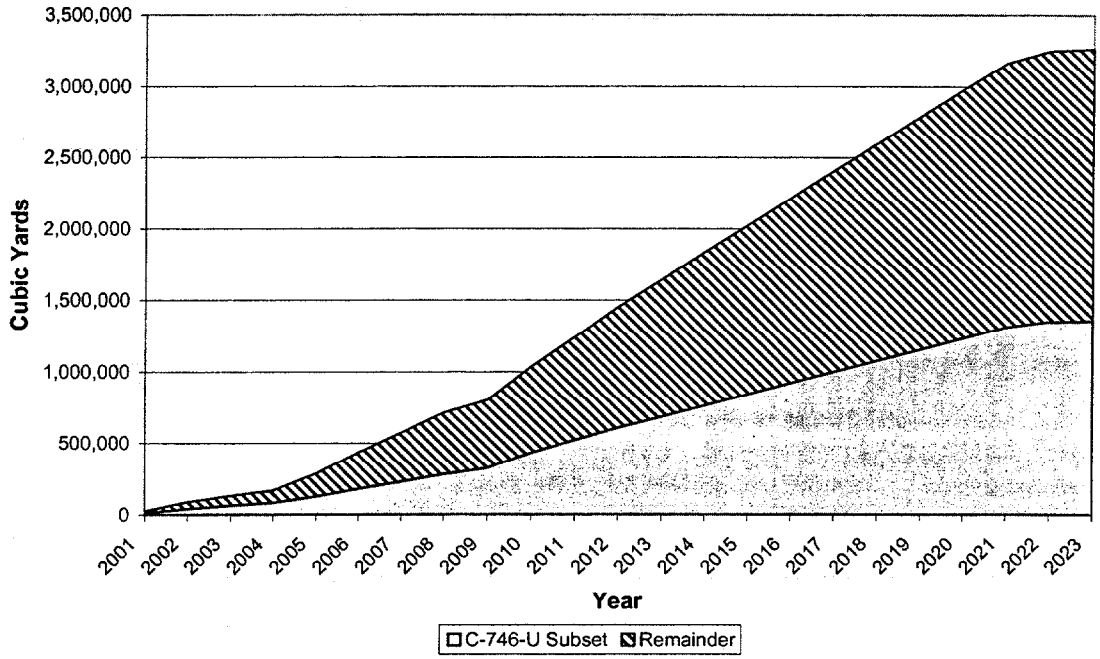


Fig. 3.1. The total CERCLA-derived waste estimated to be generated at PGDP by year.

Table 3.1. Volumes (yd^3) of CERCLA waste generated by year

Year	All CERCLA	C-746-U Subset	Remainder	Cumulative C-746-U Subset	Cumulative Remainder
2001	28,527	14,369	14,158	14,369	14,158
2002	59,914	29,100	30,814	43,469	44,972
2003	44,174	23,126	21,048	66,595	66,020
2004	38,557	19,283	19,274	85,878	85,294
2005	115,765	42,502	73,263	128,380	158,557
2006	147,467	52,902	94,565	181,282	253,122
2007	139,540	51,026	88,514	232,308	341,636
2008	139,938	51,387	88,551	283,695	430,187
2009	90,366	42,166	48,200	325,861	478,387
2010	233,171	106,635	126,536	432,496	604,923
2011	208,187	89,173	119,014	521,669	723,937
2012	206,785	88,291	118,494	609,960	842,431
2013	191,364	78,589	112,775	688,549	955,206
2014	191,364	78,589	112,775	767,138	1,067,981
2015	191,364	78,589	112,775	845,727	1,180,756
2016	191,364	78,589	112,775	924,316	1,293,531
2017	191,364	78,589	112,775	1,002,905	1,406,306
2018	191,364	78,589	112,775	1,081,494	1,519,081
2019	191,364	78,589	112,775	1,160,083	1,631,856
2020	191,364	78,589	112,775	1,238,672	1,744,631
2021	182,497	75,219	107,278	1,313,891	1,851,909
2022	84,963	38,162	46,801	1,352,053	1,898,710
2023	14,161	6,361	7,800	1,358,414	1,906,510
Total	3,264,924	1,358,414	1,906,510		

CERCLA = Comprehensive Environmental Response, Compensation, and Liability Act of 1980.
Remainder = Wastes with characteristics that will not allow placement into the C-746-U Landfill.

Table 3.2. Generation of CERCLA-derived waste (yd^3) by year and form[a]

Year	Asbestos	Concrete	General Construction Debris	Other Dry Solid	Scrap Metal	Soil	Total
2001	—	680	985	929	8,171	3,604	14,369
2002	—	659	1,034	939	8,299	18,169	29,100
2003	—	659	1,101	992	8,498	11,876	23,126
2004	—	659	1,101	959	8,498	8,066	19,283
2005	—	659	15,636	1,003	8,498	16,706	42,502
2006	—	659	16,860	5,184	7,998	22,201	52,902
2007	—	659	16,841	5,214	5,575	22,737	51,026
2008	—	659	16,881	5,236	5,681	22,930	51,387
2009	—	904	4,949	5,049	5,579	25,685	42,166
2010	58	23,453	18,007	1,205	29,224	34,688	106,635
2011	99	24,607	18,400	843	29,219	16,005	89,173
2012	96	24,430	18,285	773	28,754	15,953	88,291
2013	58	22,488	17,022	—	23,644	15,377	78,589
2014	58	22,488	17,022	—	23,644	15,377	78,589
2015	58	22,488	17,022	—	23,644	15,377	78,589
2016	58	22,488	17,022	—	23,644	15,377	78,589
2017	58	22,488	17,022	—	23,644	15,377	78,589
2018	58	22,488	17,022	—	23,644	15,377	78,589
2019	58	22,488	17,022	—	23,644	15,377	78,589
2020	58	22,488	17,022	—	23,644	15,377	78,589
2021	58	22,488	15,603	—	21,693	15,377	75,219
2022	58	22,488	—	—	239	15,377	38,162
2023	10	3,748	—	—	40	2,563	6,361
Total	843	307,315	281,859	28,326	365,118	374,953	1,358,414
% of Total	0.06%	22.62%	20.75%	2.09%	26.88%	27.60%	100.00%

CERCLA = Comprehensive Environmental Response, Compensation, and Liability Act of 1980.
[a]Only waste meeting restrictions discussed in Sect. 3.1.1.2 is included.

profile was developed by retaining soil samples whose analytical data showed total uranium activity less than 30 pCi/g, total PCBs less than 50 mg/kg, and no hazardous waste characteristic (see Table 3.3). Soil data were compiled for samples taken at depths up to a maximum of 16 ft bgs. The COPCs and analytical profiles for the projected soil waste stream are shown in Table 3.4.

3.1.2 Non-CERCLA-Derived Waste

The non-CERCLA-derived waste is material that is expected to be generated at PGDP as a result of activities other than those encompassed by ER and D&D. Examples of these activities are manufacturing activities and facility maintenance. The waste inventory presented below is based largely on information from requests for disposal (RFDs) through October 2001. However, projected use estimates for the C-746-U Landfill also were used to determine if past, non-CERCLA-derived waste disposal matched estimates.

3.1.2.1 Inventory of non-CERCLA-derived waste

The current inventory of wastes disposed in the C-746-U Landfill was derived from a listing of completed RFDs maintained by PGDP Waste Operations. This listing is presented in Appendix C.4. A summary taken from this listing is presented in Table 3.5.

Table 3.3. Toxicity Characteristic Leaching Procedure values for PGDP DOE waste disposal units

Chemical	TCLP	Units	Assumed Hazardous Waste Characteristic	Units
Arsenic	5	mg/L	100	mg/kg
Barium	100	mg/L	2000	mg/kg
Cadmium	1	mg/L	20	mg/kg
Chromium	5	mg/L	100	mg/kg
Lead	5	mg/L	100	mg/kg
Mercury	0.2	mg/L	4	mg/kg
Selenium	1	mg/L	20	mg/kg
Silver	5	mg/L	100	mg/kg
2,4-D	10	mg/L	200	mg/kg
Benzene	0.5	mg/L	10	mg/kg
Butanone, 2-	200	mg/L	4000	mg/kg
Carbon tetrachloride	0.5	mg/L	10	mg/kg
Chlordane	0.03	mg/L	0.6	mg/kg
Chlorobenzene	100	mg/L	2000	mg/kg
Chloroform	6	mg/L	120	mg/kg
Dichlorobenzene, 1,4-	7.5	mg/L	150	mg/kg
Dichloroethane, 1,2-	0.5	mg/L	10	mg/kg
Dichloroethene, 1,1-	0.7	mg/L	14	mg/kg
Dinitrotoluene, 2,4-	0.13	mg/L	2.6	mg/kg
Endrin	0.02	mg/L	0.4	mg/kg
Heptachlor	0.008	mg/L	0.16	mg/kg
Heptachlor epoxide	0.008	mg/L	0.16	mg/kg
Hexachlorobenzene	0.13	mg/L	2.6	mg/kg
Hexachlorobutadiene	0.5	mg/L	10	mg/kg
Hexachloroethane	3	mg/L	60	mg/kg
Lindane	0.4	mg/L	8	mg/kg
Methoxychlor	10	mg/L	200	mg/kg
Methylphenol, 2-	200	mg/L	4000	mg/kg
Methylphenol, 3-	200	mg/L	4000	mg/kg
Methylphenol, 4-	200	mg/L	4000	mg/kg
Nitrobenzene	2	mg/L	40	mg/kg
Pentachlorophenol	100	mg/L	200	mg/kg
Pyridine	5	mg/L	100	mg/kg
Silvex	1	mg/L	20	mg/kg
Tetrachloroethene	0.7	mg/L	14	mg/kg
Total Cresols	200	mg/L	4000	mg/kg
Toxaphene	0.5	mg/L	10	mg/kg
Trichloroethene	0.5	mg/L	10	mg/kg
Trichlorophenol, 2,4,5-	400	mg/L	8000	mg/kg
Trichlorophenol, 2,4,6-	2	mg/L	40	mg/kg
Vinyl chloride	0.2	mg/L	4	mg/kg

Notes:

Values taken from *Waste Acceptance Criteria for Department of Energy Treatment, Storage, and Disposal Units at the PGDP* (BJC/PAD-11, Rev 2) (DOE 1999b).

DOE = U.S. Department of Energy.

PGDP = Paducah Gaseous Diffusion Plant.

TCLP = Toxicity Characteristic Leaching Procedure.

Table 3.4. COPCs and analytical profiles used for CERCLA-derived waste used in C-746-U Landfill evaluation

Chemical	Soil / Sediment[1]	Concrete	Debris	Other Dry	Rationale Code 1[2]	Scrap Metal	Rationale Code 2[3]	Volume Weighted Average[4]	Why on List?[5]
Volume (yd^3)	374,953	307,315	282,702	28,326		365,118		1,358,414	
				Inorganic Chemicals (mg/kg)					
Antimony	3.4	0.66	0.66	0.66	a	0.0034	f	1.24	COPC
Arsenic	3.42	7.2	7.2	7.2	a	0.00342	f	4.22	COPC
Barium	63.3	580	580	580	a	0.0633	f	281	CERCLA
Beryllium	0.507	0.92	0.92	0.92	a	0.000507	f	0.56	COPC
Cadmium	0.85	0.85	0.85	0.85	b	0.00681	l*	0.62	COPC
Chromium	13.1	54	54	54	a	158	g	70.7	COPC
Copper	8.78	25	25	25	a	1,137	g	319	COPC
Fluoride	99.2	99.2	99.2	99.2	b	0.0992	f	72.6	CERCLA
Iron	13,100	26,000	26,000	26,000	a	656,020	g	191,777	COPC
Lead	10.4	19	19	19	a	19	h	16.6	COPC
Manganese	227	550	550	550	a	0.227	f	313	COPC, CERCLA
Mercury	0.094	0.09	0.09	0.09	a	0.000094	f	0.07	COPC
Molybdenum	4.31	4.31	4.31	4.31	b	0.00431	f	3.15	COPC
Nickel	10.9	19	19	19	b	256,621	g	68,987	COPC
Nitrate/Nitrite	4.05	4.05	4.05	4.05	b	0.00405	f	2.96	CERCLA
Selenium	0.308	0.39	0.39	0.39	a	0.000308	f	0.26	COPC
Silver	1.21	1.21	1.21	1.21	b	0.00121	f	0.89	COPC
Sulfate	357	357	357	357	b	0.000357	f	261	CERCLA
Thallium	0.603	0.603	0.603	0.603	b	0.000603	f	0.44	COPC, CERCLA
Uranium	29.7	206	206	206	k	206	k	157	COPC, CERCLA
Vanadium	19.6	80	80	80	a	0.0196	f	41.8	COPC, CERCLA
Zinc	29.6	60	60	60	a	60	h	51.6	COPC
				Organic Compounds (mg/kg)					
Acenaphthene	0.0737	0.0737	0.0737	0.0737	c	0.007	i	0.059	COPC
Acenaphthylene	0.076	0.076	0.076	0.076	c	0.008	i	0.058	COPC
Acrylonitrile	0.00882	0	0	0	l	0	j	0.0024	COPC
Anthracene	0.114	0.114	0.114	0.114	c	0.011	i	0.086	COPC
Benzene	0.00646	0.005	0.005	0.005	d	0	j	0.0041	COPC, CERCLA
Butanone, 2-	0.0138	2	2	2	d	0	j	0.91	CERCLA
Carbon tetrachloride	0.00409	0.005	0.005	0.005	d	0	j	0.0034	COPC, CERCLA
Chlordane, alpha-	0.00355	0.002	0.002	0.002	c*	0	j*	0.0019	CERCLA
Chlordane, gamma-	0.00355	0.002	0.002	0.002	c*	0	j*	0.0019	CERCLA
Chlorobenzene	0.00409	1	1	1	d	0	j	0.46	CERCLA

Table 3.4. COPCs and analytical profiles used for CERCLA-derived waste used in C-746-U Landfill evaluation (continued)

Chemical	Soil / Sediment[1]	Concrete	Debris	Other Dry	Rationale Code 1[2]	Scrap Metal	Rationale Code 2[3]	Volume Weighted Average[4]	Why on List?[5]
Chloroform	0.00409	0.06	0.06	0.06	d	0	j	0.028	COPC, CERCLA
Dichlorobenzene, 1,4-	0.0758	0.075	0.075	0.075	d	0.0075	i	0.057	CERCLA
1,2-Dichloroethane	0.00409	0.005	0.005	0.005	d	0	j	0.0034	CERCLA
Dichloroethene, 1,1-	0.0391	0.007	0.007	0.007	d	0	j	0.014	COPC, CERCLA
Dichloroethene, 1,2- (Mixed)	1.20E-04	1.20E-04	1.20E-04	1.20E-04	c	0	j	0.0001	COPC
Dichloroethene, cis-1,2-	0.304	0.304	0.304	0.304	c	0	j	0.22	COPC
Dichloroethene, trans-1,2-	0.115	0.115	0.115	0.115	c	0	j	0.084	COPC
Dinitrotoluene, 2,4-	0.076	0.0013	0.0013	0.0013	d	0	j	0.022	CERCLA
Ethylbenzene	0.00586	0.00586	0.00586	0.00586	c	0	j	0.0043	COPC
Fluoranthene	0.2	0.2	0.2	0.2	c	0.02	i	0.15	COPC
Fluorene	0.0725	0.0725	0.0725	0.0725	c	0.00725	i	0.055	COPC
Heptachlor epoxide	4.64E-04	0.00008	0.00008	0.00008	d	0	j*	0.0002	CERCLA
Hexachlorobenzene	0.076	0.0013	0.0013	0.0013	d	0.00013	i	0.022	CERCLA
Hexachlorobutadiene	0.076	0.005	0.005	0.005	d	0.0005	i	0.023	CERCLA
Hexachloroethane	0.076	0.03	0.03	0.03	d	0.003	i	0.035	CERCLA
Methoxychlor	0.00375	0.1	0.1	0.1	d	0	j*	0.047	CERCLA
Methylphenol, 2-	0.0755	0.2	2	0.2	d*	0.02	i	0.49	CERCLA
Methylphenol, 3-	0	0.2	2	0.2	d*	0.02	i	0.47	CERCLA
Methylphenol, 4-	0.0681	0.2	2	0.2	d*	0.02	i	0.49	CERCLA
Naphthalene	0.0738	0.0738	0.0738	0.0738	c	0.007	i	0.056	COPC
Nitrobenzene	0.076	0.02	0.02	0.02	d	0.002	i	0.031	CERCLA
Pentachlorophenol	0.229	0.229	0.489	0.25	l*	0.0229	i	0.23	Future COPC
Phenanthrene	0.16	0.16	0.16	0.16	c	0.02	i	0.12	COPC
Pyrene	0.188	0.188	0.188	0.188	c	0.02	i	0.14	COPC
Pyridine	0.0267	0.05	0.05	0.05	d	0.005	i	0.032	CERCLA
Tetrachloroethene	0.00748	0.007	0.007	0.007	d	0	j	0.0053	COPC, CERCLA
Total Dioxin/Furans	6.38E-06	6.38E-06	6.38E-06	6.38E-06	c	6.38E-07	i	4.8E-06	COPC
Total PCBs	1.09	1.09	1.09	1.09	c	0.109	i	0.83	COPC
Total PAH (benzo(a)pyrene)	0.129	0.129	0.129	0.129	c	0.013	i	0.10	COPC
Toxaphene	0.00854	0.005	0.005	0.005	d	0	j*	0.0046	CERCLA
Trichloroethene	0.118	0.068	0.0612	0.0264	l*	0	j	0.061	COPC, CERCLA
Trichlorophenol, 2,4,5-	0.0964	0.4	4	0.4	d**	0.04	i	0.97	CERCLA
Trichlorophenol, 2,4,6-	0.076	0.02	0.2	0.02	d**	0.002	i	0.068	CERCLA
Vinyl chloride	0.25	0.002	0.002	0.002	d	0	j	0.070	COPC, CERCLA
Xylene, m	0.00634	0.00634	0.00634	0.00634	c	0	j	0.0046	COPC, CERCLA

Table 3.4. COPCs and analytical profiles used for CERCLA-derived waste used in C-746-U Landfill evaluation (continued)

Chemical	Soil / Sediment[1]	Concrete	Debris	Other Dry	Rationale Code 1[2]	Scrap Metal	Rationale Code 2[3]	Volume Weighted Average[4]	Why on List?[5]
Xylene, Mixture	0.00634	0.00634	0.00634	0.00634	c	0	j	0.0046	COPC, CERCLA
Xylene, o	0.00634	0.00634	0.00634	0.00634	c	0	j	0.0046	COPC
Xylene, p	0.00634	0.00634	0.00634	0.00634	c	0	j	0.0046	COPC, CERCLA
				Radionuclides (pCi/g)					
Americium-241	1.73	0.053	0.053	0.053	e	0.053	k	0.52	COPC
Cesium-137	0.145	0.03	0.03	0.03	e	0.03	k	0.06	COPC, CERCLA
Cobalt-60	0.966	0.966	0.966	0.966	e	0.966	c	0.97	COPC, CERCLA
Neptunium-237	0.0328	0.902	0.902	0.902	e	0.902	k	0.66	COPC
Plutonium-238	9.59E-04	0.053	0.053	0.053	e	0.053	k	0.039	COPC
Plutonium-239	0.023	0.118	0.118	0.118	e	0.118	k	0.092	COPC
Plutonium-240	0.115	0.115	0.115	0.115	e	0.115	c	0.12	COPC
Radium-226	0.899	0.899	0.899	0.899	e	0.899	c	0.90	COPC
Radon-222	0.737	0	0	0	e	0	k	0.20	COPC
Strontium-90	0	0	0	0	e	0	k	0.00	COPC
Technetium-99	2.51	0.015	0.015	0.015	e	0.015	k	0.70	COPC
Thorium-228	1.16	1.16	1.16	1.16	e	1.16	c	1.16	COPC, CERCLA
Thorium-230	1.63	0.005	0.005	0.005	e	0.005	k	0.45	COPC
Thorium-232	1	1	1	1	e	1	c	1.00	COPC
Uranium-234	0.948	7.35	7.35	7.35	e	7.35	k	5.58	COPC, CERCLA
Uranium-235	0.212	0.301	0.301	0.301	e	0.301	k	0.28	COPC, CERCLA
Uranium-238	1.06	7.35	7.35	7.35	e	7.35	k	5.61	COPC, CERCLA

Notes:

[1] Soil/sediment concentrations derived as described in text.

[2] Rationale Code 1 used to explain concentration used for concrete, debris, and other dry waste forms. These codes are defined as follows:

a = background soil value from Shacklette and Boerngen 1984

b = same as average soil medium; no Shacklette and Boerngen 1984 values available

c = same as average soil medium

c* = 1/2 average soil medium; pesticides are applied to soil not other media.

d = equals one-two-thousandth of the TCLP-based values presented in Table 3.3. This surface contamination conversion factor was derived by taking one-half of the TCLP-based value presented in Table 3.3 and dividing the result by 1,000 to account for the presence of surface contamination only.

d* = same as d except conversion factor is 1/1000 for the debris medium only; concrete and other dry media are 1/10th of debris medium to account for the presence of preservatives, such as the cresols, present in wood products included in the debris category.

d** = same as d* except conversion factor is 1/100 for the debris medium as opposed to 1/1000 to account for presence of these preservatives in the wood products included in the debris category.

e = same as scrap metal medium. Please see Rationale Code 2 for explanation of the derivation of the concentration for scrap metal.

[3] Rational Code 2 used to explain concentration used for scrap metal waste forms. These codes are defined as follows:

f = 1/1000 of average soil medium to account for presence of surface contamination.

Table 3.4. COPCs and analytical profiles used for CERCLA-derived waste used in C-746-U Landfill evaluation (continued)

g = prorated mass of metal derived from the *Engineering Analysis/Cost Analysis for Scrap Yard Disposition at the Paducah Gaseous Diffusion Plant, Paducah Kentucky*, DOE/OR/07-1880&D2/R1.

h = same as concrete medium to account for galvanization or lead fittings.

i = 1/10 of concrete medium to account for removal of semivolatile organic compound through weathering.

j = no VOCs in scrap due to volatilization.

j* = no pesticides in scrap based due to weathering.

k = Isotopic distribution based on Rucker 1994. Uranium isotopes prorated to 30 pCi/g maximum, 15 pCi/g average; other isotopes prorated by same ratio. Uranium metal concentration prorated based on ratio of uranium isotope in metal and uranium isotope in soil. Radon-222 is a gas and is assumed to not be present in scrap metal.

l = Assumed 0 based on extremely low frequency of detection in soil analyses.

l* = Concentration based upon qualitative analyses of waste analyses from other projects.

[4] Volume weighted average concentration calculated by multiplying the concentration of each contaminant by the waste form volume, summing these results over all waste forms, and dividing this sum by the total volume of waste.

[5] Code for reason that the analyte was included in the waste profile. These are defined as follows:

COPC = analyte appears on the list of significant PGDP COPCs in DOE 2000d.

CERCLA = analyte was retained in the CERCLA waste stream per results of "binning" logic discussed in text.

Future COPC = the wood preservative pentachlorophenol (PCP) was included in the analytical profile assuming its presence in lumber included in the debris waste form.

Table 3.5. Current inventory (yd^3) by waste form[a] in C-746-U Landfill

Year	Asbestos	Concrete	General construction debris	Other dry	Scrap metal	Soil	Other solid waste	Total
Total	629	6,430	14,954	126	60	1,968	80	24,247
1997	300	200	11,514	30	0	829	0	12,873
1998	101	2,370	2,590	97	50	833	80	6,121
1999	228	3,860	850	0	10	306	0	5,254

Note: Data taken from the C-746-U Landfill Waste Stream List maintained by Paducah Gaseous Diffusion Plant (see Appendix C.4).
[a] Definitions of waste forms are presented in Sect. 3.1.1.1.

In Table 3.5, all waste forms are as defined earlier, except for "Other solid waste." This waste form, which was not discussed earlier, is used for materials not falling within the other categories and includes materials such as putrescent waste and office-derived paper products.

Assuming three full years of operation, about 8000 yd^3 of waste have been generated per year, on average. This value exceeds, but is similar to, estimates of landfill use for non-CERCLA waste contained in the *Technical Application for Contained Solid Waste Landfill* (DOE 1994b). In that document, the estimated usage rate is 6000 yd^3 per year.

Generally, these results show that non-CERCLA-derived waste would make up only a small percentage of total waste volume if CERCLA-derived wastes were also to be placed in the C-746-U Landfill. Figure 3.2 depicts the cumulative volumes expected in the C-746-U Landfill if both CERCLA-derived and non-CERCLA-derived wastes are placed in the landfill.

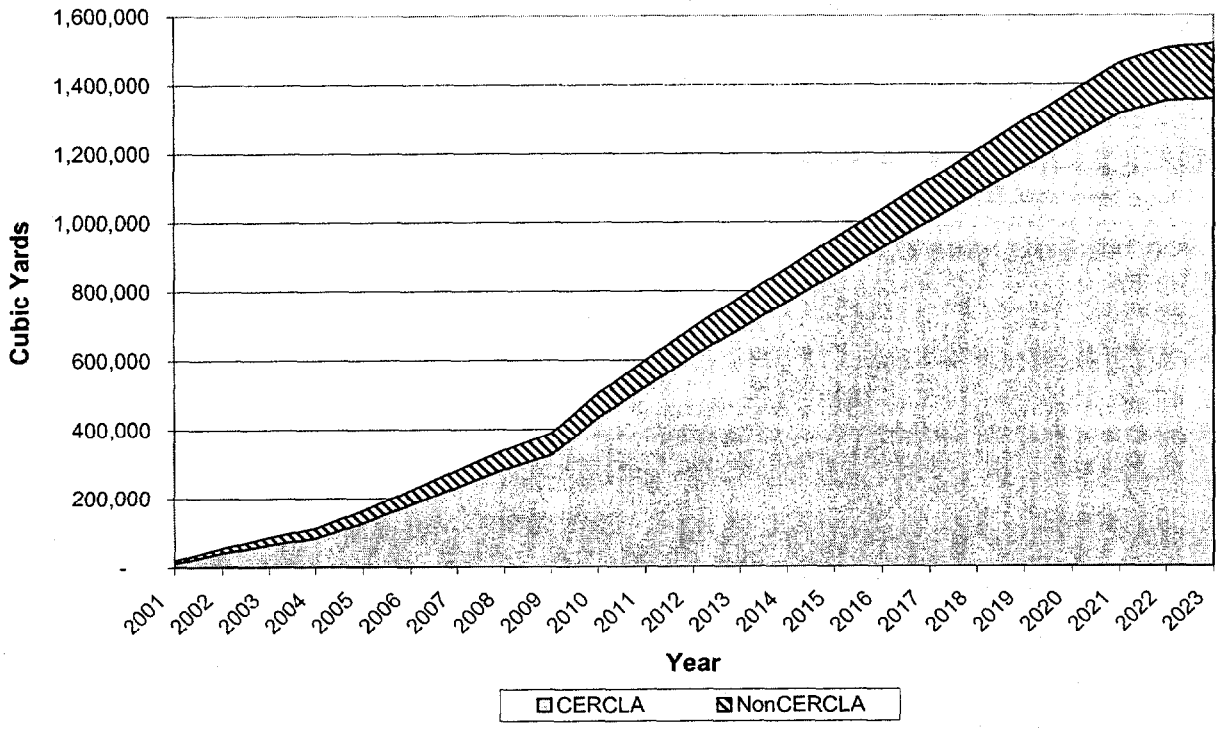


Fig. 3.2. Cumulative volumes of wastes expected in the C-746-U Landfill if both CERCLA-derived and non-CERCLA-derived wastes were to be placed in the landfill. (Only CERCLA-derived waste assumed to meet C-746-U acceptance criteria, as defined earlier is included.)

A unique waste form in non-CERCLA-derived waste is that described as putrescible or likely to become putrid (i.e., food waste). The volume of these types of waste is included in the other solid waste category. PGDP Waste Operations estimates that the volume of these types of waste is approximately 2 yd^3 per year.

3.1.2.2 Characterization of non-CERCLA-derived waste

Based on the information presented in Sect. 3.1.2.1, the characteristics for non-CERCLA-derived waste are expected to be similar to CERCLA-derived waste, except for waste identified as putrescible. However, the volume of putrescible waste expected to be placed in the landfill is very small. Therefore, including the characteristics (i.e., analyte concentrations) of this waste into the overall average contaminant concentrations of all solid waste that may be placed in the landfill would result in insignificant changes in overall contaminant concentrations. Therefore, the analyte concentrations derived in Sect. 3.1.2.1 also were used for non-CERCLA-derived waste in the fate and transport modeling runs.

3.2 C-746-U LANDFILL DESIGN

This section describes the aspects of the C-746-U Landfill design (Fig. 3.3) that were used to develop the conceptual model for fate and transport modeling. Changes in physical characteristics over time are considered to account for degradation of the landfill cap and liner. The conceptual design of the landfill developed here was taken from the detailed information presented in the *Technical Application for Contained Solid Waste Landfill* (DOE 1994b).

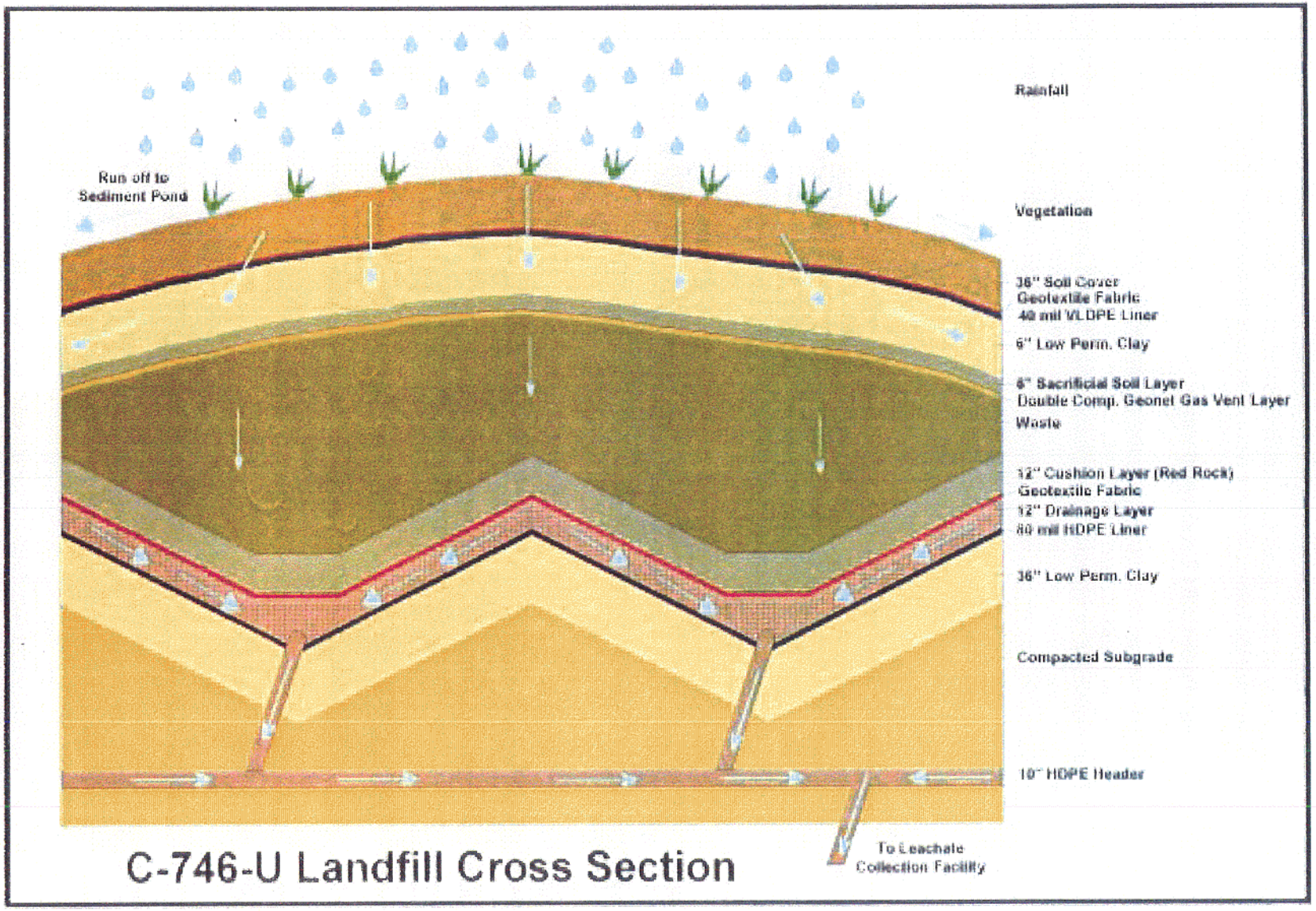
When filled, the landfill will encompass 22.1 acres; however, the total permitted landfill site, including perimeter roads and support facilities, will encompass 59.7 acres. The placement of approximately 1.56 million yd^3 of waste is projected for the facility (DOE 1994b). This conceptual design includes the following key elements.

- **Permanent Cover.** The final cover planned for the C-746-U Landfill is designed to minimize infiltration. The final cover will have six layers with a total thickness of 5 ft. The cover will include, from top to bottom, a 3-ft vegetative soil erosion prevention layer, a geotextile filter fabric above a 40-mil low-density polyethylene membrane, a 0.5-ft clay barrier, a 0.5-ft sacrificial soil layer, and a 1-ft sand gas-venting system. The average side slope of the top erosion prevention layer is planned to be approximately 18.25% (including stormwater diversion benches). The final cover will be installed at the end of the active landfill operating period.

- **Waste.** When full, the landfill is projected to contain soil, concrete, scrap metal and lumber, roofing and construction debris, and other nonhazardous sanitary and industrial waste. Because the landfill will have sloping sides, the waste thickness will vary. The maximum waste height in the landfill is projected to be 76.4 ft with an average thickness of 38 ft.

  Wastes disposed of in the landfill will be compacted and covered with clean cover soil, as permitted by the Commonwealth of Kentucky in accordance with the requirements of Kentucky solid waste regulations and Subtitle D of RCRA. The overall mixing of wastes and cover material is assumed to result in an 8:1 ratio of waste to soil within the landfill, based on the placement of 0.5 ft of daily cover for every 4 ft lift of compacted waste. This ratio may be decreased (i.e., less waste placed per amount of soil) if waste is placed in the landfill at a rate slower than projected in Sect. 3.1.

- **Multi-Layer Base Liner System.** The purpose of the base liner is to prevent contaminants from migrating from the waste facility to groundwater. The liner for the landfill has five layers with a total thickness of approximately 5 ft. The liner includes, from top to bottom, a 1-ft protective soil layer, a



Source: BJC 2002

Fig. 3.3. C-746-U Landfill cross section

geotextile filter fabric, a 1-ft gravel drainage layer for primary leachate collection, a layer of geotextile fabric and an 80-mil high-density polyethylene membrane (HDPE textured geomembrane), and a 3-ft clay liner. In order to facilitate leachate collection and transfer, the drainage layer also contains perforated pipes placed on a 1.6% slope. Leachate is accumulated in a collection sump. During the Operational and Institutional Control Periods, the leachate is assumed to be sent to a wastewater treatment facility.

- **Geologic Buffer.** A 34-ft geologic buffer layer composed of native soils (i.e., HU 3, see Sect. 2.5.2.5) is assumed to lie between the base liner and the uppermost aquifer at PGDP (i.e., the RGA, see Sect. 2.5.2.4). The buffer includes 6.5 ft of alluvium soil and 27.5 ft of clay to clayey silt.

- **Clean Fill Perimeter Dike.** A clean-fill dike will be constructed around the landfill to provide stable lateral containment of wastes. The dike will tie together the cover and base liner components and provide for drainage ditches and a perimeter access road.

Three periods of landfill performance are expected under the current landfill design and rate of waste placement depicted in Sect. 3.1. Each of these periods is described below.

- The **Operational Period** occurs during the first 20 years of landfill operation. During this period, waste is placed in the landfill until it is full, and 0.5 ft of uncompacted soil is assumed to be used as interim daily cover for disposed waste. The multi-layer base liner, including the leachate collection system, is assumed operational.

- The **Institutional Control Period** occurs between the years 20 and 50. During this period, all components of the solid waste landfill [i.e., liners, flexible membrane linings (FMLs), drainage layer, and clay layers] are assumed to be in place. The final cover is assumed to operate successfully for 30 years after emplacement. Similarly, the multi-layer base liner system, including the leachate collection system, is assumed to operate during this period.

- The **Post-Institutional Control Period** occurs between the years 50 and 10,000. During this period, it is assumed that infiltration of water through the cap and liner system increases due to degradation of some layers. However, it is also assumed DOE continues to control the landfill as an industrial site, which includes preventing cap erosion. Therefore, access by the public will continue to be limited, and access for industrial purposes will be controlled with workers being protected.

While all components of the waste disposal cell are assumed to be in place, some layers are assumed to degrade. The FMLs are assumed to degrade completely, and the hydraulic conductivity of the top and bottom clay barriers is assumed to increase by one order of magnitude. Additionally, the gravel layer in the base liner is assumed to no longer function as a drainage layer, and its hydraulic conductivity is assumed to decrease by one order of magnitude due to clogging with fine materials.

Although the cap and the liner system can reasonably be expected to degrade slowly, it is uncertain at what rate degradation will occur. Therefore, both a gradual failure rate and an immediate failure are considered in the modeling presented in Chap. 4. [Note that the assumption that DOE ceases maintenance of the landfill liner system would be inconsistent with the requirements of DOE Order 5400.5 (DOE 1993). Under Order 5400.5, if the landfill contains any materials containing residual radioactivity above guideline values, then DOE is required to maintain the landfill until radiation levels from residual radioactive materials disposed in it no longer exceed guideline values calculated presuming a worst-case, plausible-use scenario for the property. Therefore, the conservative failure scenario developed here is used for modeling purposes only. For comparison, a no failure scenario that assumes perpetual maintenance of the cap and

liner system is also examined in Chap. 4. Under this scenario, the modeling parameters used for the institutional control period were also used for the post-institutional control period.]

3.3 SELECTION OF INDICATOR CHEMICALS

In order to streamline the modeling process, each chemical and radionuclide of potential concern was placed into one of 14 contaminant groups. As a first approximation, the transport of all chemicals within each of these groups was estimated utilizing the transport of an indicator chemical. These indicator chemicals and a description of the chemical or radionuclide surrogate group that they represent are presented in Table 3.6. A complete listing of all chemicals and radionuclides by surrogate group is presented in Table C.3.1. (Appendix C.3) of this report.

Table 3.6. Represented groups and indicator chemicals

Chemical/Radionuclide Group	Description	Indicator Chemical
Halogenated Hydrocarbons	Non-Aromatic, Straight-Chain Halogenated Hydrocarbons – More Mobile[a]	Vinyl Chloride
Halogenated Hydrocarbons	Non-Aromatic, Straight-Chain Halogenated Hydrocarbons – Less Mobile[a]	TCE
Halogenated Hydrocarbons	Aromatic, Ring-Structured Halogenated Hydrocarbons	Chlorobenzene
Nonhalogenated Hydrocarbons	Straight-Chain Hydrocarbons	2-Butanone
Nonhalogenated Hydrocarbons	Aromatic, Ring-Structured Nonhalogenated Hydrocarbons	Benzene
Semivolatile Organic Compounds	Light (molecular weight < 200 g/mole)	2-Methylphenol
Semivolatile Organic Compounds	Heavy (molecular weight > 200 g/mole) – More Mobile[b]	Pentachlorophenol
Semivolatile Organic Compounds	Heavy (molecular weight > 200 g/mole) – Less Mobile[b]	Benzo(a)pyrene
PCB		PCB
Pesticides		gamma-Chlordane
Inorganic Chemicals/Metals	Highly Mobile[c]	Chromium
Inorganic Chemicals/Metals	Moderately Mobile[c]	Copper
Inorganic Chemicals/Metals	Less Mobile[c]	Thallium
Radionuclides	Highly Mobile[d]	Technetium-99
Radionuclides	Less Mobile[d]	Uranium-238

[a]Non-aromatic, straight-chain halogenated hydrocarbons were assigned to the more mobile group if their K_d was less than 0.075 L/kg, and they were assigned to the less mobile group if their K_d was greater than 0.075 L/kg.

[b]Heavy semivolatile organic compounds were assigned to the more mobile group if their K_d was less than 100 L/kg, and they were assigned to the less mobile group if their K_d was greater than 100 L/kg.

[c]Inorganic chemicals and metals with a K_d less than 35 L/kg were assigned to the highly mobile group. Those with a K_d between 35 L/kg and 70 L/kg were assigned to the moderately mobile group. Finally, those with a K_d greater than 70 L/kg were assigned to the less mobile group.

[d]Radionuclides with a K_d less than 50 L/kg were assigned to the highly mobile group. Radionuclides with a K_d greater than 50 L/kg were assigned to the mobile group.

PCB = polychlorinated biphenyl.

As shown in Table 3.6, each surrogate group represents chemicals and radionuclides of concern with similar chemical properties, including solubility, volatility, and mobility; therefore, each surrogate group contains chemicals or radionuclides that behave similarly in the environment.

3.4 RECEPTORS AND EXPOSURE PATHWAYS

This section describes the receptors and exposure pathways that were considered as part of the development of the CERCLA-derived waste disposal criteria. This material was developed to be consistent

with guidance contained in PGDP's *Methods for Conducting Risk Assessments and Risk Evaluations at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky, Volume 1, Human Health,* and *Volume 2, Ecological* (DOE 2001b).

3.4.1 Human Health

This section performs the exposure assessment for human receptors that may be exposed to contamination in, or migrating from, wastes placed in the C-746-U Landfill. The exposure assessment for ecological receptors is presented in Sect. 3.4.2.

3.4.1.1 Receptors

Several human receptors were considered in support of the development of the CERCLA-derived waste disposal criteria. However, the preliminary criteria were developed by considering the risk posed to the most sensitive receptor. These preliminary criteria are subsequently modified considering the potential effect on other potential receptors (see Chap. 5). The descriptions of all potential receptors are provided below.

Residential Groundwater User. This receptor is a resident drawing drinking water from a well completed in the uppermost aquifer during the Post-Institutional Control Period. (See Sect. 3.2 for definitions of the periods of landfill performance.) This receptor is exposed to contaminants migrating to groundwater only. The points of exposure considered are at the DOE property boundary and at the Ohio River.

Rural Resident. This receptor is assumed to be a subsistence farmer who lives in a home near the property boundary during the Post-Institutional Control Period. This receptor may be exposed to contaminants remaining in source material and to contaminants that may have migrated from the source material. Because erosion of the landfill cap is not being considered in this evaluation, direct exposure to source material is unlikely. Therefore, exposure by this receptor is functionally equivalent to that of the residential groundwater user drawing water from a well located at the property boundary.

Excavation Worker. This receptor is a worker who inadvertently digs into source material at the disposal facility during the Post-Institutional Control Period. This scenario provides the only mechanism through which exposure to disposed waste can be assumed to occur and would require loss of institutional control of the landfill. The exposure point for this scenario is at the landfill.

Industrial Worker. This receptor is a worker who is employed at a location that is on, or near, the site of the disposal facility during the Post-Institutional Control Period. This receptor is not exposed to waste material or to groundwater (as drinking water). The point of exposure considered is at the first location where groundwater discharges to surface water downgradient of the landfill (i.e., the Ohio River). Note that the industrial worker employed at the landfill during the Operational and Institutional Control Periods is not included in the evaluation because that worker is assumed to be protected by regulation.

Recreational User. This receptor is assumed to be a local resident who hunts, fishes, or just visits the area near the landfill during all three periods of performance. This receptor is assumed to be exposed only to contaminants migrating from the source material because erosion of the cap is not being evaluated, as discussed in Sect. 3.2. The point of exposure is at the first location where groundwater discharges to surface water downgradient of the landfill (i.e., the Ohio River).

3.4.1.2 Exposure pathways

This section provides information delineating the exposure pathways through which each of the receptors listed in Sect. 3.4.1.1 may be exposed to contamination at, or migrating from, the waste disposal

facility. In addition, the rationale for the selection or exclusion of pathways of exposure for each of the receptors is provided. Consistent with guidelines in DOE (2001b), this material is presented (Table 3.7) utilizing the format recommended in EPA's *Risk Assessment Guidance for Superfund, Volume 1, Part D* (EPA 1998). This material is also depicted in Fig. 3.4.

3.4.2 Ecological

This section describes the ecological receptors (Sect. 3.4.2.1) and exposure pathways (Sect. 3.4.2.2) evaluated to develop the CERCLA-derived waste disposal criteria. A CSM summarizing this information is in Fig. 3.5.

3.4.2.1 Receptors

The ecological receptors considered in the development of the CERCLA-derived waste disposal criteria are plants and animals living or foraging at those locations potentially impacted by release of contaminants from the C-746-U Landfill. The ecological receptors considered are those judged to be most at risk, should release of contaminants occur.

The ecological receptors selected are terrestrial mammals and birds, sediment-dwelling invertebrate animals, and aquatic biota. These receptors were chosen in light of the exposure pathways considered in the following section.

3.4.2.2 Exposure pathways

The exposure pathways considered in the development of the CERCLA-derived waste disposal criteria are those judged most likely to occur and most likely to produce the highest potential exposures to plants or animals residing or foraging at those locations potentially impacted by release of contaminants from the C-746-U Landfill. The exposure pathways (and the receptors) evaluated are as follows:

- ingestion of water at seeps or springs contaminated by groundwater discharging to surface (terrestrial mammal and birds);
- direct contact with sediment contaminated by groundwater discharging into nearby creeks and rivers (sediment-dwelling biota); and
- direct contact with surface water contaminated by leachate or groundwater discharging into nearby creeks and rivers (aquatic biota).

3.5 SELECTION OF TARGET DOSE AND RISK

The receptor selected for preliminary CERCLA-derived waste disposal criteria development is the residential groundwater user drawing water from a well located at the DOE property boundary during the Post-Operational Period. This receptor was selected because this individual can reasonably be expected to receive the largest chemical and/or radionuclide dose from most contaminants migrating from the landfill over both the near- and long-term as indicated by the material in Table 3.7, and an evaluation of the risk-based screening values contained in DOE 2001b. Additionally, the use of this receptor meets the requirements in DOE Order 5400.5, *Radiation Protection of the Public and the Environment* (DOE 1993); DOE Order 5400.1, *General Environmental Protection Program* (DOE 1990); and EPA's preference for preventing contamination of groundwater. Finally, the use of this receptor allows for the consistent analysis of contaminant concentrations and potential risks posed by migration to multiple points of exposure.

Table 3.7. Exposure route summary

Scenario Timeframe	Medium	Exposure Medium	Exposure Point	Receptor Population	Receptor Age	Exposure Route	On-Site/ Off-Site	Type of Analysis	Rationale for Selection or Exclusion of Exposure Pathway
Operational Period	*Groundwater*	*Groundwater*	*DOE Property Boundary – RGA Well*	*Resident*	*Adult*	*Ingestion*	*Off-Site*	*Quantitative*	*Groundwater use would occur if no policy box.*[a]
						Dermal (Shower)	*Off-Site*	*Quantitative*	
					Child	*Ingestion*	*Off-Site*	*Quantitative*	
						Dermal (Shower)	*Off-Site*	*Quantitative*	
		Air	*DOE Property Boundary – RGA Well*	*Resident*	*Adult*	*Inhalation (Shower)*	*Off-Site*	*Quantitative*	
						Inhalation (Home)	*Off-Site*	*Quantitative*	
					Child	*Inhalation (Shower)*	*Off-Site*	*Quantitative*	
						Inhalation (Home)	*Off-Site*	*Quantitative*	
		Surface Water	*Discharge point at Ohio River*	*Recreational User*	*Adult*	Ingestion	Off-Site	Qualitative	Depth of springs is insufficient for swimming. Dilution of leachate would result in very low contaminant concentrations.
						Dermal (Swimming)	Off-Site	Qualitative	
						Dermal (Wading)	*Off-Site*	*Quantitative*	*Area is a recreational area.*
					Teen	Ingestion	Off-Site	Qualitative	Depth of springs is insufficient for swimming. Dilution of leachate would result in very low contaminant concentrations.
						Dermal (Swimming)	Off-Site	Qualitative	
						Dermal (Wading)	*Off-Site*	*Quantitative*	*Area is a recreational area.*
					Child	Ingestion	Off-Site	Qualitative	Depth of springs is insufficient for swimming. Dilution of leachate would result in very low contaminant concentrations.
						Dermal (Swimming)	Off-Site	Qualitative	
						Dermal (Wading)	*Off-Site*	*Quantitative*	*Area is a recreational area.*
		Fish	Discharge point at Ohio River	Recreational User	Adult	Ingestion	Off-Site	Qualitative	Dilution of leachate would result in very low contaminant concentrations. Modeling indicates discharge to streams is unlikely.
					Teen	Ingestion	Off-Site	Qualitative	
					Child	Ingestion	Off-Site	Qualitative	
		Game	Discharge point at Ohio River	Recreational User	Adult	Ingestion	Off-Site	Qualitative	Springs are unlikely to be a water source for significant numbers of game animals.
					Teen	Ingestion	Off-Site	Qualitative	
					Child	Ingestion	Off-Site	Qualitative	
	Source Material and Soil	Air	DOE Property Boundary	Resident	Adult	Inhalation	Off-Site	Qualitative	Homes are located near DOE boundary. However, releases to air at the landfill are regulated under RCRA. Therefore, dose from this pathway can be expected to be below any level of concern.
					Child	Inhalation	Off-Site	Qualitative	
		Vegetables (Deposition)	DOE Property Boundary	Resident	Adult	Inhalation	Off-Site	Qualitative	
					Child	Inhalation	Off-Site	Qualitative	
Institutional Control Period	*Groundwater*	*Groundwater*	*DOE Property Boundary – RGA Well*	*Resident*	*Adult*	*Ingestion*	*Off-Site*	*Quantitative*	*Groundwater use would occur if no policy box.*[a]
						Dermal (Shower)	*Off-Site*	*Quantitative*	
					Child	*Ingestion*	*Off-Site*	*Quantitative*	
						Dermal (Shower)	*Off-Site*	*Quantitative*	
		Air	*DOE Property Boundary – RGA Well*	*Resident*	*Adult*	*Inhalation (Shower)*	*Off-Site*	*Quantitative*	
						Inhalation (Home)	*Off-Site*	*Quantitative*	
					Child	*Ingestion*	*Off-Site*	*Quantitative*	
						Dermal (Shower)	*Off-Site*	*Quantitative*	
		Surface Water	*Discharge point at Ohio River*	*Recreational User*	*Adult*	Ingestion	Off-Site	Qualitative	Depth of springs is insufficient for swimming. Dilution of leachate would result in very low contaminant concentrations
						Dermal (Swimming)	Off-Site	Qualitative	
						Dermal (Wading)	*Off-Site*	*Quantitative*	*Area is a recreational area.*
					Teen	Ingestion	Off-Site	Qualitative	Depth of springs is insufficient for swimming. Dilution of leachate would result in very low contaminant concentrations.
						Dermal (Swimming)	Off-Site	Qualitative	
						Dermal (Wading)	*Off-Site*	*Quantitative*	*Area is a recreational area.*

Table 3.7. Exposure route summary (continued)

Scenario Timeframe	Medium	Exposure Medium	Exposure Point	Receptor Population	Receptor Age	Exposure Route	On-Site/ Off-Site	Type of Analysis	Rationale for Selection or Exclusion of Exposure Pathway
					Child	Ingestion	Off-Site	Qualitative	Volume insufficient to act as drinking source. Also, depth of springs is insufficient for swimming.
						Dermal (Swimming)	Off-Site	Qualitative	
						Dermal (Wading)	*Off-Site*	*Quantitative*	*Area is a recreational area.*
		Fish	Discharge point at Ohio River	Recreational User	Adult	Ingestion	Off-Site	Qualitative	Dilution of leachate would result in very low contaminant concentrations. Modeling indicates discharge to streams is unlikely.
					Teen	Ingestion	Off-Site	Qualitative	
					Child	Ingestion	Off-Site	Qualitative	
		Game	Discharge point at Ohio River	Recreational User	Adult	Ingestion	Off-Site	Qualitative	Springs are unlikely to be a water source for significant numbers of game animals.
					Teen	Ingestion	Off-Site	Qualitative	
					Child	Ingestion	Off-Site	Qualitative	
Post-Institutional Control Period	*Groundwater*	*Groundwater*	*At DOE Property Boundary - RGA Well*	*Resident*	*Adult*	*Ingestion*	*Off-Site*	*Quantitative*	*Groundwater use would occur if no policy box.*[a]
						Dermal (Shower)	*Off-Site*	*Quantitative*	
					Child	*Ingestion*	*Off-Site*	*Quantitative*	
						Dermal (Shower)	*Off-Site*	*Quantitative*	
		Air	*At DOE Property Boundary - RGA Well*	*Resident*	*Adult*	*Inhalation (Shower)*	*Off-Site*	*Quantitative*	
						Inhalation (Home)	*Off-Site*	*Quantitative*	
					Child	*Ingestion*	*Off-Site*	*Quantitative*	
						Dermal (Shower)	*Off-Site*	*Quantitative*	
		Surface Water	*Discharge point at Ohio River*	*Recreational User*	*Adult*	Ingestion	Off-Site	Qualitative	Volume insufficient to act as drinking source. Also, depth of springs is insufficient for swimming.
						Dermal (Swimming)	Off-Site	Qualitative	
						Dermal (Wading)	*Off-Site*	*Quantitative*	*Area is a recreational area.*
					Teen	Ingestion	Off-Site	Qualitative	Volume insufficient to act as drinking source. Also, depth of springs is insufficient for swimming.
						Dermal (Swimming)	Off-Site	Qualitative	
						Dermal (Wading)	*Off-Site*	*Quantitative*	*Area is a recreational area.*
					Child	Ingestion	Off-Site	Qualitative	Volume insufficient to act as drinking source. Also, depth of springs is insufficient for swimming.
						Dermal (Swimming)	Off-Site	Qualitative	
						Dermal (Wading)	*Off-Site*	*Quantitative*	*Area is a recreational area.*
		Fish	Discharge point at Ohio River	Recreational Use	Adult	Ingestion	Off-Site	Qualitative	Dilution in Ohio River would result in very low contaminant concentrations. Modeling indicates discharge to streams is unlikely.
					Teen	Ingestion	Off-Site	Qualitative	
					Child	Ingestion	Off-Site	Qualitative	
		Game	Discharge point at Ohio River	Recreational User	Adult	Adult	Ingestion	Off-Site	Springs are unlikely to be a water source for significant numbers of game animals.
					Teen	Teen	Ingestion	Off-Site	
					Child	Child	Ingestion	Off-Site	
	Soil	Soil	At facility	Resident	Adult	Ingestion	On-Site	Qualitative	The cap will prevent direct exposure to contaminated soil.[b]
						Dermal	On-Site	Qualitative	
						External Exposure	On-Site	Qualitative	
					Child	Ingestion	On-Site	Qualitative	The cap will prevent direct exposure to contaminated soil.[b]
						Dermal	On-Site	Qualitative	
						External Exposure	On-Site	Qualitative	
				Recreational User	Adult	Ingestion	On-Site	Qualitative	The cap will prevent direct exposure to contaminated soil.[b]
						Dermal	On-Site	Qualitative	
						External Exposure	On-Site	Qualitative	
					Teen	Ingestion	On-Site	Qualitative	The cap will prevent direct exposure to contaminated soil.[b]
						Dermal	On-Site	Qualitative	
						External Exposure	On-Site	Qualitative	

Table 3.7. Exposure route summary (continued)

Scenario Timeframe	Medium	Exposure Medium	Exposure Point	Receptor Population	Receptor Age	Exposure Route	On-Site/ Off-Site	Type of Analysis	Rationale for Selection or Exclusion of Exposure Pathway
					Child	Ingestion	On-Site	Qualitative	The cap will prevent direct exposure to contaminated soil.[b]
						Dermal	On-Site	Qualitative	
						External Exposure	On-Site	Qualitative	
				Excavation Worker	Adult	Ingestion	On-Site	Qualitative	Unrestricted excavation is unreasonable given projected future use of landfill site.
						Dermal	On-Site	Qualitative	
						External Exposure	On-Site	Qualitative	
				Industrial Worker	Adult	Ingestion	On-Site	Qualitative	The cap will prevent direct exposure to contaminated soil.[b]
						Dermal	On-Site	Qualitative	
						External Exposure	On-Site	Qualitative	
		Air (Vapors and Particulates)	At facility	Resident	Adult	Inhalation	On-Site	Qualitative	The cap will prevent direct exposure to contaminated soil.[b]
					Child	Inhalation	On-Site	Qualitative	
				Recreational User	Adult	Inhalation	On-Site	Qualitative	
					Teen	Inhalation	On-Site	Qualitative	
					Child	Inhalation	On-Site	Qualitative	
				Excavation Worker	Adult	Inhalation	On-Site	Qualitative	Unrestricted excavation is unreasonable given projected future use of landfill site.
				Industrial Worker	Adult	Inhalation	On-Site	Qualitative	The cap will prevent direct exposure to contaminated soil.[b]
		Vegetables	At facility	Resident	Adult	Ingestion	On-Site	Qualitative	The cap will prevent direct exposure to contaminated soil.[b] Also, contamination through use of groundwater for irrigation is unlikely because surface water would be used for large-scale irrigation (DOE 2001b).
					Child	Ingestion	On-Site	Qualitative	
		Beef	At facility	Resident	Adult	Ingestion	On-Site	Qualitative	
					Child	Ingestion	On-Site	Qualitative	
		Milk	At facility	Resident	Adult	Ingestion	On-Site	Qualitative	
					Child	Ingestion	On-Site	Qualitative	
		Pork	At facility	Resident	Adult	Ingestion	On-Site	Qualitative	
					Child	Ingestion	On-Site	Qualitative	
		Poultry	At facility	Resident	Adult	Ingestion	On-Site	Qualitative	
					Child	Ingestion	On-Site	Qualitative	
		Game	At facility	Recreational User	Adult	Ingestion	Off-Site	Qualitative	
					Teen	Ingestion	Off-Site	Qualitative	
					Child	Ingestion	Off-Site	Qualitative	

Table 3.7. Exposure route summary (continued)

Scenario Timeframe	Medium	Exposure Medium	Exposure Point	Receptor Population	Receptor Age	Exposure Route	On-Site/ Off-Site	Type of Analysis	Rationale for Selection or Exclusion of Exposure Pathway
	Source Material	Source Material	At facility	Resident	Adult	Ingestion	On-Site	Qualitative	The cap will prevent direct exposure to contaminated soil.[h]
						Dermal	On-Site	Qualitative	
						External Exposure	On-Site	Qualitative	
					Child	Ingestion	On-Site	Qualitative	
						Dermal	On-Site	Qualitative	
						External Exposure	On-Site	Qualitative	
				Excavation Worker	Adult	Ingestion	On-Site	Qualitative	Unrestricted excavation is unreasonable given projected future use of landfill site.
						Dermal	On-Site	Qualitative	
						External Exposure	On-Site	Qualitative	
		Air (Vapors and Particulates)	At facility	Resident	Adult	Inhalation	On-Site	Qualitative	The cap will prevent direct exposure to contaminated soil.[h]
					Child	Inhalation	On-Site	Qualitative	
				Excavation Worker	Adult	Inhalation	On-Site	Qualitative	Unrestricted excavation is unreasonable given projected future use of landfill site.

Note: Cells with italic font are quantitatively evaluated in Chap. 5.

[g]"Policy box" refers to a current DOE institutional control at the PGDP under which drinking water from municipal sources is supplied to residence affected or potentially affected by contaminants in groundwater originating at the PGDP.

[h]As discussed in Sect. 3.2, during the post-institutional control period, site maintenance by DOE is assumed to prevent cap erosion (and direct contact with waste) but not degradation of the position of the landfill cap and liner containment system that may result in increased water percolation and contaminant migration.

DOE = U.S. Department of Energy.

RCRA = Resource Conservation and Recovery Act of 1976.

RGA = Regional Gravel Aquifer.

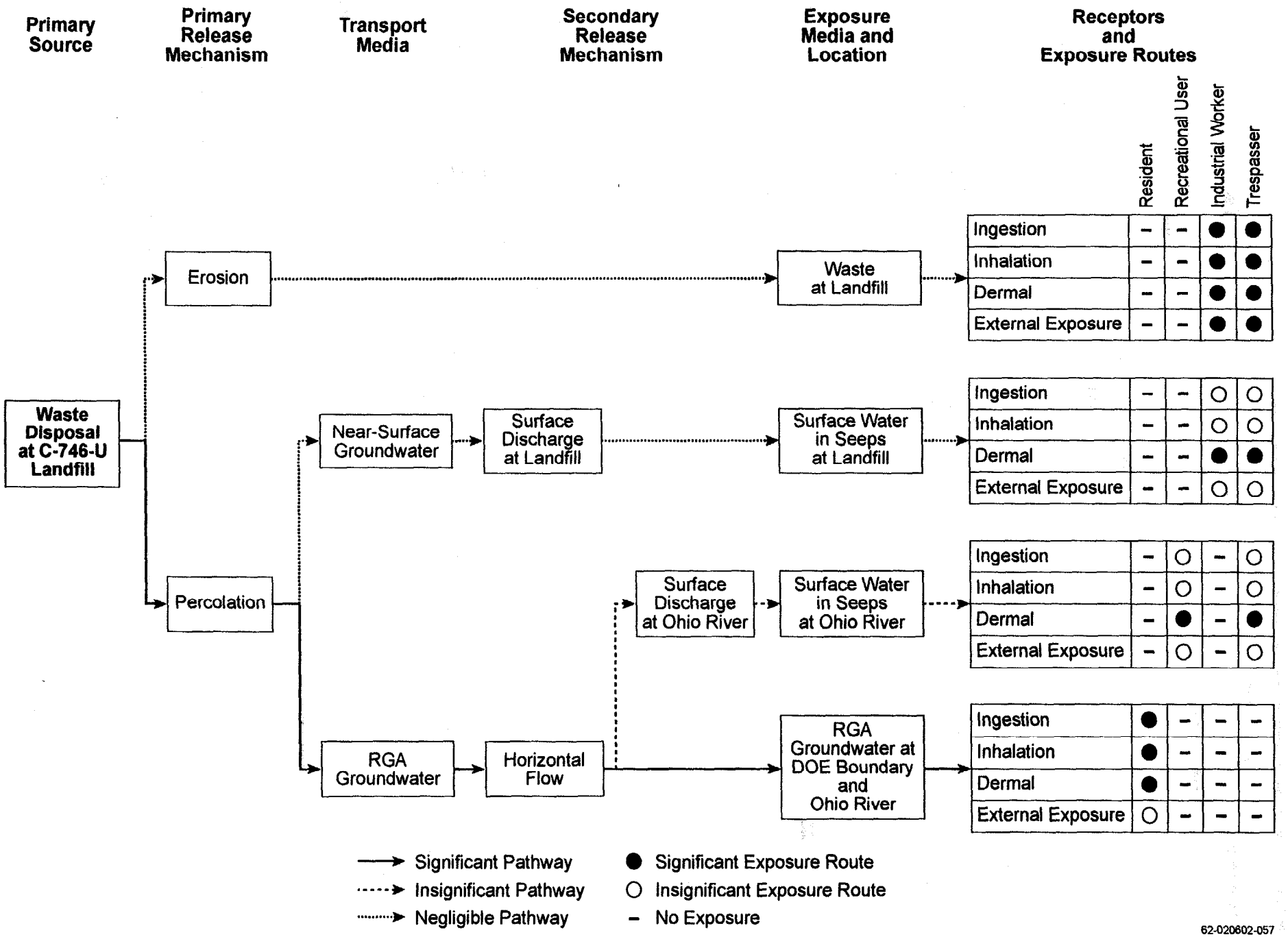


Fig. 3.4. Conceptual Site Model for the human health risk and performance evaluation of the C-746-U Landfill.

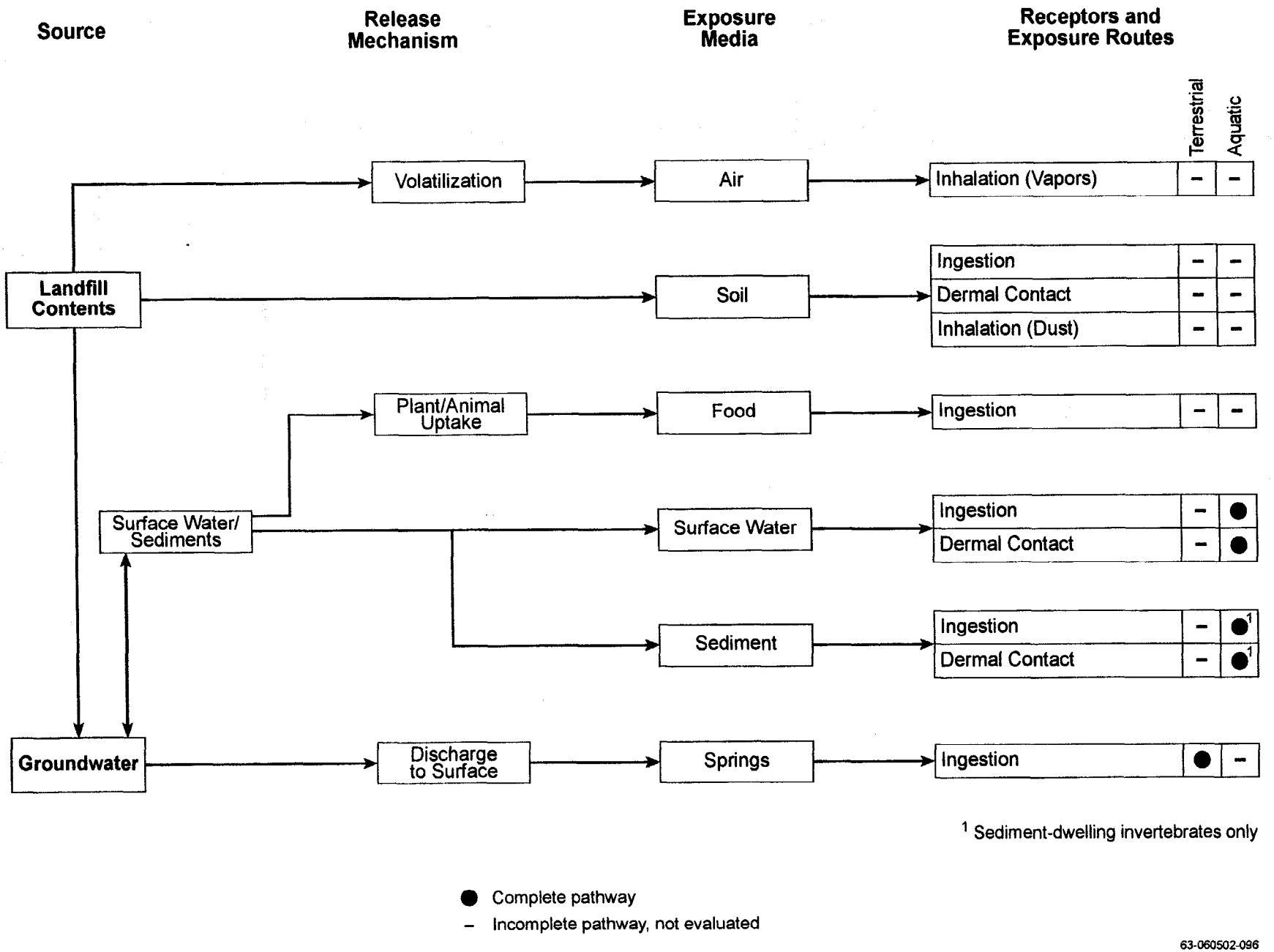


Fig. 3.5. Ecological exposure pathways diagram for the C-746-U Landfill risk and performance evaluation.

The exposure routes selected in the analysis for the residential groundwater user are ingestion of groundwater, inhalation of vapors emitted by groundwater during household use and bathing (i.e., showering), and dermal absorption during bathing (i.e., showering). An exposure route not retained is consumption of farm produce contaminated by groundwater through irrigation. The farm produce pathways are not included because this pathway relies on modeling containing a significant level of uncertainty and because water used for irrigation would most likely be surface and not groundwater (DOE 2001b). Additionally, direct exposure to waste is not expected due to the distance between the farmstead and the landfill, expected future use of the site, and landfill maintenance.

Although only the risk posed to the groundwater user is considered in the development of the preliminary CERCLA-derived waste disposal criteria, the risks posed to the other human and ecological receptors selected for quantitative analysis are considered further when developing the final criteria. These analyses are presented in Chap. 5.

Reasons for not utilizing a receptor when deriving the preliminary CERCLA-derived waste disposal criteria are presented below.

Rural Resident. This receptor was not selected because the design for the model included the landfill cover, which is designed to prevent intrusion into the waste. Because direct exposure to waste materials is not considered, the analysis of this individual essentially becomes equivalent to the near off-site residential groundwater user.

Excavation Worker. This receptor was not selected because experience at PGDP has shown that the risk levels calculated for a groundwater user normally exceed those posed under a direct contact scenario, and continued control of the area around the landfill can be expected. Additionally, any worker involved in waste excavation would be protected per DOE work rules.

Industrial Worker. This receptor was not selected because experience at PGDP has shown that the risk levels calculated for a groundwater user normally exceed those posed under a direct contact scenario. Additionally, continued control of the area around the landfill can be expected and any worker involved in waste excavation would be protected per DOE work rules.

Recreational User. This receptor was not selected because experience at PGDP has shown that the risk levels calculated for a groundwater user normally exceed those posed under a direct contact scenario, such as exposure to groundwater discharged to the surface. Additionally, the point of exposure for the recreational user is much further from the landfill than that for the groundwater user, thus making the exposure concentrations lower.

Ecological User Receptors. Ecological receptors were not selected because exposures to contaminants in groundwater discharged to the surface are likely to be smaller than the off-site residential groundwater user due to lower exposure rates and increased attenuation and dilution of contaminant concentrations in the media to which ecological receptors are exposed.

3.6 EXPOSURE PERIOD AND EXPOSURE POINT

This section discusses the basis for selecting the period over which contaminants are assumed to be released, and the locations at which exposure to contaminants migrating from the disposal facility is assumed to occur. Both the period (i.e., exposure period) and locations (exposure points) were selected to meet guidance in the PGDP risk methods document (DOE 2001b) and to provide information useful in meeting the substantive requirements of regulatory programs. These regulatory programs include RCRA, TSCA,

and radioactive waste requirements (DOE Orders). [Note that any requirements of RCRA and TSCA are addressed together because the disposal requirements as stated in the Mega-Amendments for TSCA (effective August 1998) are equivalent to RCRA.]

3.6.1 Period of Exposure

The exposure period selected for the modeling effort was 10,000 years after considering guidance in the PGDP risk methods document (DOE 2001b) and requirements of regulatory programs (e.g., RCRA). The use of 10,000 years is consistent with guidance in DOE 2001b. Although that document does not specify a minimum time period to be considered in transport modeling, the document notes that the intent of the modeling is to determine if concentrations at downgradient points of exposure may be greater in the future. The evaluation presented here uses 10,000 years because several of the analytes that may be placed in the landfill (i.e., metals) will be released only after several hundreds to thousands of years.

The use of 10,000 years exceeds the RCRA requirements deemed applicable to an on-site land disposal unit. These standards specify a minimum period of compliance of 30 years (40 *Code of Federal Regulations* 264.117) with the option to increase the period if deemed necessary.

3.6.2 Point of Exposure

The exposure points selected for the modeling effort were at the point on the DOE-reservation property boundary closest to the facility along the groundwater flow path and at the point at which discharge of groundwater to surface water can reasonably be expected.

The selection of these two points was based upon guidance in DOE 2001b and consideration of requirements of regulatory programs (e.g., RCRA). In DOE 2001b, the points of exposure required to be considered for source units above the RGA are at the source unit, at the point along the PGDP security fence closest to the source unit, at the point along the DOE-reservation property boundary closest to the source unit, and where discharge to surface water may occur. Of these, only the DOE property boundary and surface discharge points were relevant to the analysis because the landfill is outside the PGDP security fence and is located near the DOE property boundary. (Note that the DOE property boundary was selected as opposed to the landfill boundary because the DOE property boundary point of exposure was determined to be most consistent with the requirements of CERCLA per the land use map shown in Fig. 2.1 and discussed in Sect. 2.2.1.)

The use of the two points of exposure is also consistent with RCRA. Under RCRA, the point of compliance (not exposure) for a Subtitle D landfill is a vertical surface located at the hydraulically downgradient limit of the waste management area that extends into the uppermost aquifer underlying the unit. Because the landfill is near the DOE property boundary, the point on the DOE property boundary meets the need to evaluate this compliance point within the uncertainty bounds of the transport model.

4. FATE AND TRANSPORT MODELING

This section discusses models and parameters used to complete the fate and transport modeling performed to develop the CERCLA-derived waste disposal criteria and contaminant inventory limits. This section concludes with a presentation of the results of this modeling.

4.1 SELECTED MODELS AND THEIR APPLICATION

CERCLA-derived waste disposal criteria were determined by utilizing the following models to represent conditions at the C-746-U Landfill and areas to which contaminants may migrate: Hydrologic Evaluation of Landfill Performance (HELP); Disposal Unit Source Term (DUST); MODFLOW; MODPATH; and Analytical Transient 1-, 2-, 3-Dimensional (AT123D) model. Also, in order to examine transport of radiological decay products, the RESRAD model was used in an uncertainty analysis. Note that each of these models are industry standards, that have received regulatory and stakeholder acceptance for use at the PGDP in other projects.

Use of these models is consistent with Tier 3 of the groundwater-modeling matrix presented in DOE 2001b. As explained there, Tier 3 is used when enhanced modeling is needed to support decision documents such as Proposed Remedial Action Plans and Records of Decision.

The fate and transport modeling for this site was performed in eight steps. These steps and the use of the models in performing each are discussed in following sections. A conceptual diagram of the transport modeling is also presented in Fig. 4.1.

- **First**, HELP model simulations were performed under three failure scenarios to estimate the water flux percolating through the wastes and into the water table under each of these scenarios.

- **Second,** a list of contaminants expected to be in the disposed wastes in the landfill was developed. The contaminants in the list were categorized into surrogate groups, as discussed in Sect. 3.1, and one or two indicator chemical(s) or radionuclide(s) predicted to have the fastest transit time to the points of exposure were selected to represent each group.

- **Third**, DUST modeling was performed for each indicator chemical and radionuclide under the gradual failure scenario to predict the contaminant flux entering the aquifer over time. (DUST modeling was performed for selected chemicals as part of an uncertainty analysis under the immediate and no failure scenarios.)

- **Fourth**, MODFLOW/MODPATH modeling was performed to predict the groundwater migration rate from the location where leachate enters the RGA to the exposure point locations and the shortest transit times to each exposure point.

- **Fifth,** the AT123D model was used to predict concentrations of each indicator chemical and radionuclide at each exposure point over time due to lateral transport. The contaminant flux from the DUST model was used as input for the AT123D modeling.

- **Sixth**, the maximum concentrations and the time to attain the maximum concentrations at the exposure points were predicted, and dilution attenuation factors (DAFs) associated with source-to-exposure point transport of the indicator chemicals and radionuclides were calculated.

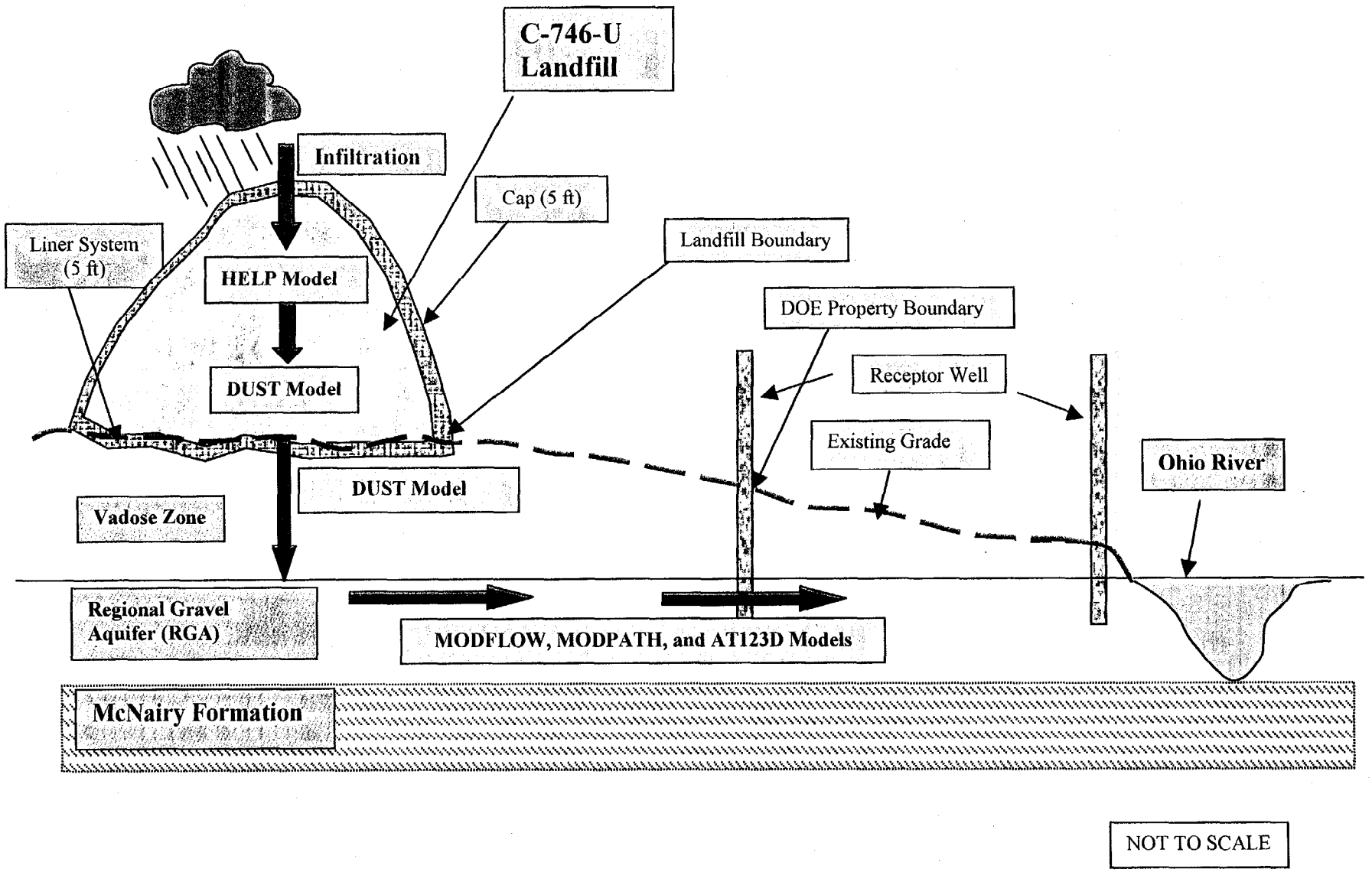


Figure 4.1. Conceptual diagram for the numerical modeling approach – C-746-U Landfill.

- **Seventh**, the concentration versus time plot at each exposure point for each chemical or radionuclide in each group was predicted by applying the calculated DAFs. (As noted above, results for all chemicals were available for the gradual failure scenario only.)

- **Eighth**, for results from the gradual failure scenario, the concentration versus time curve for each contaminant was converted to a risk curve, and the risk curves for each exposure point were summed to estimate the cumulative risk at the exposure point over time that would result from the expected waste inventory. (Results in Chap. 5.) The percentage contribution of each contaminant to the cumulative risk was then determined, and contaminants contributing greatest to the cumulative risk were identified. The list of major COPCs was examined, and if a constituent was determined to be a major COPC but was not an indicator chemical or radionuclide, then modeling to predict the fate and transport of that constituent was performed. The results of this additional modeling were subsequently used in development of the preliminary CERCLA-derived waste disposal criteria. The calculations used to derive the preliminary CERCLA-derived waste disposal criteria are presented in Sect. 5.1.

4.1.1 Hydrologic Evaluation of Landfill Performance (HELP) Model

The HELP model was used to determine the rate of water infiltration into the waste facility (Schroeder et al. 1994). HELP is a quasi-two-dimensional, deterministic, water-routing model for developing water balances. The model accepts weather, soil, and design data. The solution accounts for the effects of surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, and leakage through soil, geomembrane, or composite liners. This program is the most widely used model to conduct water balance analyses of landfills, cover systems, and solid waste disposal and containment facilities and is accepted by the regulators. The model facilitates rapid estimation of the amounts of runoff, evapotranspiration, drainage, leachate collection, and liner leakage that may be expected to result from the operation of a wide variety of landfill designs. The HELP model was applied to determine the water balance during each of three periods modeled. These periods are described below and in Sect. 3.2. Figure 4.2(a) illustrates the functional behavior of water flux through the solid waste landfill as a function of time, which includes the three periods. Note that leachate collection is expected only during the first two periods (i.e., Operation Period and Institutional Control Period) under the gradual failure and immediate failure scenarios but during all periods under the no failure scenario.

- **Operational Period** (Years 0 to 20)—Landfill components that would be in place include the leachate collection system with a barrier liner beneath the waste. During this period, the waste was assumed to be covered daily with a 6-inch soil cover only. The average water flux through the landfill was predicted to be 24.97 cm/year based on HELP model simulation results. The average flux to the water table is 0.08 cm/year [Fig. 4.2(b)]. (Results for this period do not vary by scenario.)

- **Institutional Control Period** (Years 21 to 50)—All the components of the waste disposal cell would be in place [i.e., both cover and liner components including FMLs, drainage layers, and low-permeability clay layers and the geologic buffer]. The average annual water flux through the landfill for this period was predicted to be 0.09 cm/year based on HELP model simulation results. The average flux to the water table is 0.08 cm/year [Fig. 4.2(b)]. (Results for this period do not vary by scenario.)

- **Post-Institutional Control Period** (Years 51 to 10,000)—The flow during this period varied by scenario. Under all scenarios, all components of the waste disposal cell were assumed to be in place. However, under the gradual and immediate failure scenarios, the lateral gravel drainage layer beneath the waste was assumed to degrade. To account for degradation, the gravel drainage layer was changed to a vertical percolation layer with lesser hydraulic conductivity. Additionally, the barrier clay cover and

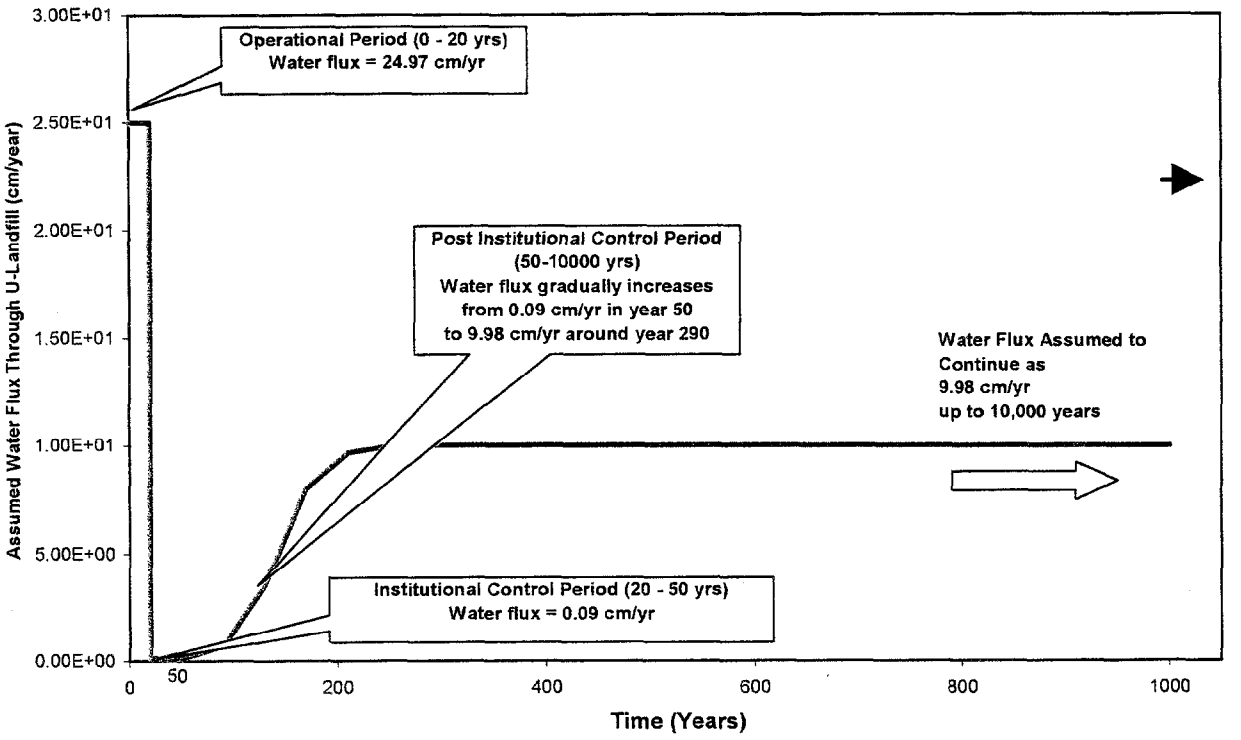


Fig. 4.2(a). Water flux through the C-746-U Landfill waste as a function of time under the gradual failure scenario.

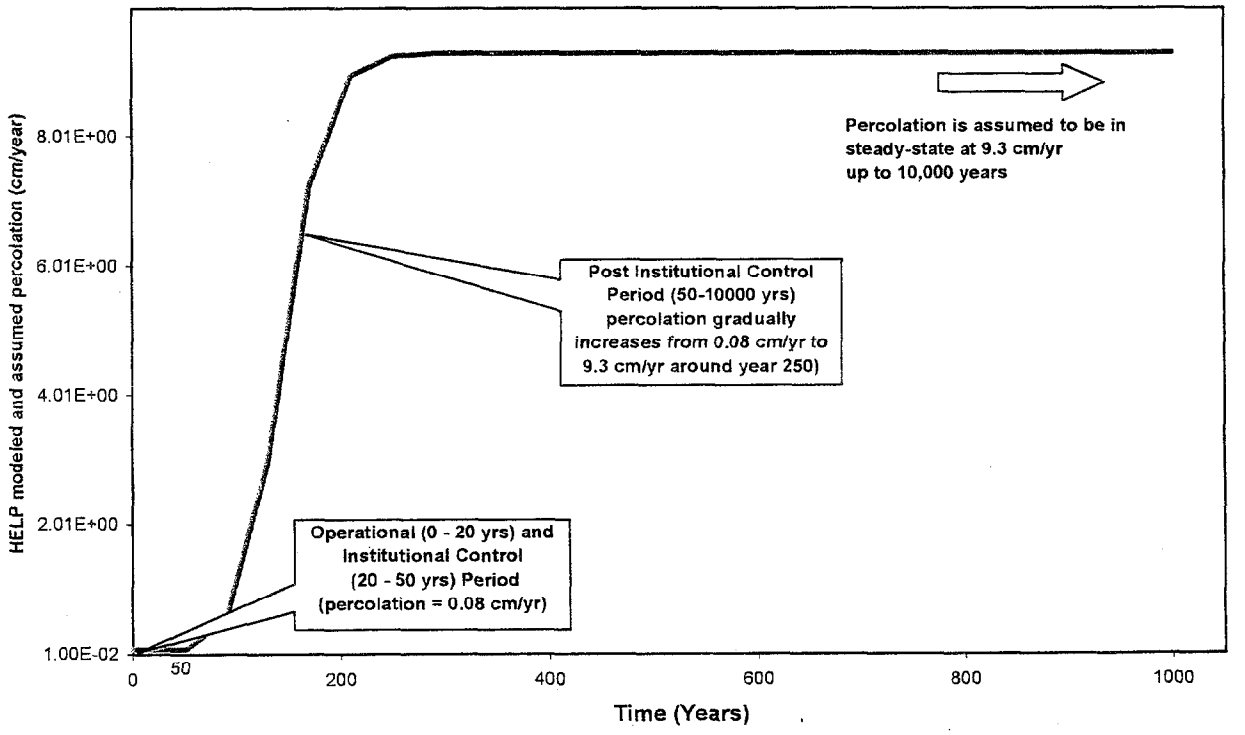


Fig. 4.2(b). Percolation of C-746-U Landfill leachate to the RGA as a function of time under the gradual failure scenario.

liner layers were assumed to degrade, and the hydraulic conductivity of that layer was increased by a factor of 10. Finally, the FML layers were assumed to degrade to the point at which they provided no significant barrier to flow and were removed from the model.

Due to the aforementioned degradation, the average water flux through the landfill under both the gradual and immediate failure scenarios was estimated to increase to 9.98 cm/year after failure was complete, and the average flux to the water table was estimated to increase to 9.3 cm/year [Fig. 4.2(b)] after failure was complete. However, as noted in the scenario's name, under the gradual failure scenario, the degradation and concurrent increase in average water flux due to degradation were assumed to increase gradually from that during the Institutional Control Period (f_2) to that during the Post-Institutional Control Period (f_3). Similarly, under the immediate failure scenario, the increase to the higher water fluxes was assumed to be instantaneous.

To model the gradual failure due to degradation of the FML, cover, and liner, the following equation was used (Lee et al. 1995).

$$F(t) = \frac{f_2 \times f_3}{f_2 + (f_3 - f_2) \times e^{-\alpha(t-t_1)}}$$

where

f_1 = average groundwater recharge in the Operational Period based on HELP run, cm/year,
f_2 = average groundwater recharge in the Institutional Control Period based on HELP run, cm/year,
f_3 = the final groundwater recharge based on HELP run for the Post-Institutional Control Period after cover and liner failure, cm/year,
t = the time (years) at which F(t) is measured,
t_1 = the time (years) at the end of the Institutional Control Period (i.e., 50 years for C-746-U Landfill),
α = the decay constant (0.05 $year^{-1}$).

The value of α was assumed to be 0.05 $year^{-1}$, which caused the water flux to be equal to f_3 approximately 200 years after the close of the landfill. However, because the model can only handle linear interpolation, the recharge calculated by the above method was entered into the model in 40-year time intervals (e.g., at 50, 90, 130, 170, 210, and 250 years). From 250 to 10,000 years, the final steady-state recharge value (i.e., f_3) was used.

In the no failure scenario, all components of the disposal cell were assumed to continue to operate as designed. Therefore, under this scenario, the average water flux during the Post-Institutional Control Period was assumed to match that during the Institutional Control Period (f_2; 0.09 and 0.08 cm/year for flux through the landfill and to the water table, respectively).

Key parameters used in the HELP model simulations were as follows:

- climatic parameters—growing season, average quarterly relative humidity, normal mean monthly temperature and precipitation, maximum leaf area index, and evaporative zone depth;

- C-746-U Landfill design parameters—surface slope, maximum drainage distance for lateral drainage layers, layer thickness, layer description, area, leachate recirculation procedure, subsurface inflows, surface characteristics, and geonet and geomembrane (i.e., FML) characteristics; and

- soil characteristics—porosity, field capacity, wilting point, saturated hydraulic conductivity, initial moisture storage, and Soil Conservation Service runoff curve number.

Values for the climatic parameters are presented in Table 4.1. The landfill layers and underlying native soil characteristics for the Operational Period, Institutional Control Period, and the Post-Institutional Control Period are listed in Tables 4.2 through 4.4, respectively.

Table 4.1. Climatic parameters used by the HELP model

Parameter	Values
Fraction of area allowing runoff [a]	100%
Evaporative zone depth [b]	21 inches for Operational Period, and 26 inches for Institutional and Post-Institutional Control Periods
Start of growing season [b]	105th Julian day
End of growing season [b]	300th Julian day
Average annual wind speed [b]	8.2 mph
Average 1st quarter relative humidity [b]	70%
Average 2nd quarter relative humidity [b]	67%
Average 3rd quarter relative humidity [b]	72%
Average 4th quarter relative humidity [b]	54%
Normal mean monthly precipitation (Jan) [c]	3.27 inches
Normal mean monthly precipitation (Feb)	3.90 inches
Normal mean monthly precipitation (Mar)	4.92 inches
Normal mean monthly precipitation (April)	5.01 inches
Normal mean monthly precipitation (May)	4.94 inches
Normal mean monthly precipitation (Jun)	4.05 inches
Normal mean monthly precipitation (Jul)	4.19 inches
Normal mean monthly precipitation (Aug)	3.34 inches
Normal mean monthly precipitation (Sept)	3.69 inches
Normal mean monthly precipitation (Oct)	3.00 inches
Normal mean monthly precipitation (Nov)	4.32 inches
Normal mean monthly precipitation (Dec)	4.65 inches
Normal mean monthly temperature (Jan) [c]	32.6 °F
Normal mean monthly temperature (Feb)	36.9 °F
Normal mean monthly temperature (Mar)	47.5 °F
Normal mean monthly temperature (Apr)	57.9 °F
Normal mean monthly temperature (May)	66.7 °F
Normal mean monthly temperature (Jun)	75.2 °F
Normal mean monthly temperature (Jul)	78.8 °F
Normal mean monthly temperature (Aug)	76.8 °F
Normal mean monthly temperature (Sept)	70.2 °F
Normal mean monthly temperature (Oct)	58.7 °F
Normal mean monthly temperature (Nov)	47.9 °F
Normal mean monthly temperature (Dec)	37.3 °F

[a]The actual amount of runoff is calculated by the model depending on the slope of topsoil.

[b]Evapotranspiration data are default values for Evansville, Indiana (approximately same latitude as Paducah, Kentucky), depending on the growth and type of the vegetation on the topsoil.

[c]Obtained from 30 years of historical National Oceanic and Atmospheric Administration precipitation and temperature data for Paducah, Kentucky (Owenby and Ezell 1992).

Table 4.2. PGDP C-746-U Landfill design profile and soil characteristics – Operational Period

Layer Number	Material Type	Layer Type	Layer Thickness (inches)	Soil Texture Type	Soil Texture Symbol (USDA)	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Recircu-lation?	FML Pinhole Density (#holes/acre)	FML Installation Defects (#holes/acre)	FML Placement Quality
1	Uncompacted daily cover (native)	1	6		SiC	0.300[a]	0.140[a]	0.130[a]	2.50E-05						
2	Waste	1	528[b]	19	Municipal waste with channeling	0.168	0.073	0.019	1.00E-03						
3	Protective layer (native soil)	1	12		SiC	0.300[a]	0.140[a]	0.130[a]	5.00E-05						
4	Geotextile filter	2	0.24	20		0.850	0.010	0.005	1.00E+01						
5	Drainage layer (gravel)	2	12	21	Gravel	0.397	0.032	0.013	3.00E-01	800	1.5	50%			
6	HDPE	4	0.08	35	HDPE				2.00E-13				1	1	3(Good)
7	Clay barrier	3	36	16	Barrier soil	0.427	0.418	0.367	1.00E-07						
8	Alluvium soils (native)	1	78[c]		SiC	0.451	0.419	0.332	9.26E-6[a]						
9	Clay confining unit (native)	1	330		C	0.475	0.378	0.265	3.80E-7[a]						

[a] User-defined values based on field conditions (usually site-specific values).
[b] "Normalized" waste thickness = Total waste volume/Landfill area.
[c] Thickness of alluvium soil layer at south end of landfill (worst case).
FML = flexible membrane lining.
HDPE = high-density polyethylene lining.
USDA = U.S. Department of Agriculture.

Table 4.3. PGDP C-746-U Landfill design profile and soil characteristics – Institutional Control Period

Layer Number	Material Type	Layer Type	Layer Thickness (inches)	Soil Texture Type	Soil Texture Symbol (USDA)	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Recircu-lation?	FML Pinhole Density (#holes/acre)	FML Installation Defects (#holes/acre)	FML Placement Quality
1	Vegetative soil (root zone)	1	13	28	SiC	0.300[a]	0.140[a]	0.130[a]	5.38E-06[b]						
2	Vegetative soil	1	23	28	SiC	0.300[a]	0.140[a]	0.130[a]	1.20E-06						
3	Geonet	1	1	20	Drainage mat	0.850	0.010	0.005	1.00E+01						
4	FML	4	0.04	36	LDPE				4.00E-13				1	1	3 (Good)
5	Clay barrier	3	6	16	C	0.427	0.418	0.367	1.00E-07						
6	Native soil (compacted)	1	6		SiC	0.300[a]	0.140[a]	0.130[a]	1.20E-06						
7	Sand layer representing gas vent	1	12	2	S	0.437	0.062	0.024	5.80E-03						
8	Waste	1	528[c]	19	Municipal waste with channeling	0.168	0.073	0.019	1.00E-03						
9	Protective layer (native soil)	1	12		SiC	0.300[a]	0.140[a]	0.130[a]	5.00E-05						
10	Geotextile filter	2	0.24	20	Geotextile	0.850	0.010	0.005	1.00E+01						
11	Drainage layer (gravel)	2	12	21	Gravel	0.397	0.032	0.013	3.00E-01	800	1.5	75%			
12	HDPE	4	0.08	35	HDPE				2.00E-13				1	1	3(Good)
13	Clay barrier	3	36	16	Barrier soil	0.427	0.418	0.367	1.00E-07						
14	Alluvium soils (native)	1	78[d]		SiC	0.451	0.419	0.265	9.26E-6[a]						
15	Clay confining unit (native)	1	330		C	0.475	0.378	0.265	3.80E-7[a]						

Note that parameters used in this table were also used for the Post-Institutional Control Period under the no failure scenario.
[a] User-defined values based on field conditions (usually site-specific values).
[b] K in root zone is 4.48 times greater than default K for SiC (guidance from *Hydrologic Evaluation of Landfill Performance* manual).
[c] "Normalized" waste thickness = Total waste volume/Landfill area.
[d] Thickness of alluvium soil layer at south end of landfill (worst case).
FML = flexible membrane lining.
HDPE = high-density polyethylene lining.
LDPE = low-density polyethylene lining.
USDA = U.S. Department of Agriculture.

Table 4.4. PGDP C-746-U Landfill design profile and soil characteristics – Post-Institutional Control Period

Layer Number	Material Type	Layer Type	Layer Thickness (inches)	Soil Texture Type	Soil Texture Symbol (USDA)	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Recircu-lation?	FML Pinhole Density (#holes/acre)	FML Installation Defects (#holes/acre)	FML Placement Quality
1	Vegetative soil (root zone)	1	13		SiC	0.300[a]	0.140[a]	0.130[a]	5.38E-06[b]						
2	Vegetative soil	1	23		SiC	0.300[a]	0.140[a]	0.130[a]	1.20E-06						
3	Clay barrier	3	7		C	0.427	0.418	0.367	1.00E-06[c]						
4	Native soil (compacted)	1	6		SiC	0.300[a]	0.140[a]	0.130[a]	1.20E-06						
5	Sand layer representing gas vent	1	12	2	S	0.437	0.062	0.024	5.80E-03						
6	Waste	1	582[d]	19	Municipal waste with channeling	0.168	0.073	0.019	1.00E-03						
7	Protective layer (native soil)	1	12		SiC	0.300[a]	0.140[a]	0.130[a]	5.00E-05						
8	Drainage layer (gravel)[e]	1	12.24		Gravel	0.397	0.032	0.013	3.00E-02			No			
9	Clay barrier	3	36.07		Barrier soil	0.427	0.418	0.367	1.00E-06[f]						
10	Alluvium soils (native)	1	78[g]		SiC	0.451	0.419	0.265	9.26E-6[a]						
11	Clay confining unit (native)	1	330		C	0.475	0.378	0.265	3.80E-7[a]						

Note that parameters used in this table were not used under the no failure scenario.
[a] User-defined values based on field conditions (usually site-specific values).
[b] K in root zone is 4.48 times greater than default K for SiC (guidance from *Hydrologic Evaluation of Landfill Performance* manual).
[c] K of upper clay barrier assumed to increase by one order of magnitude, no drainage is considered.
[d] "Normalized" waste thickness = Total waste volume/Landfill area.
[e] Gravel layer no longer functions as drainage layer and becomes vertical percolation layer. K assumed to decrease by one order of magnitude.
[f] K of bottom clay barrier assumed to increase by one order of magnitude.
[g] Thickness of alluvium soil layer at south end of landfill (worst case).
FML = flexible membrane lining.
USDA = U.S. Department of Agriculture.

4.1.2 Disposal Unit Source Term (DUST) Model

The DUST model (Sullivan 1993) was used to estimate the rate at which a contaminant will migrate out of the disposal facility. This model allows for the consideration of the characteristics affecting migration rate. These include contaminant inventory, the waste forms and the containers used to dispose of the inventory, and the physical processes that lead to release from the facility (i.e., fluid flow, container degradation, waste form leaching, and contaminant transport). The DUST model is designed to achieve a balance between (1) the use of extremely simple but conservative assumptions that may lead to predicted releases greater than that which may be reasonably expected, and (2) the use of complicated models that include all known physical and chemical processes that may influence a release but require long lists of input variables, the value of which are generally unknown. Therefore, the DUST model was used to determine contaminant release rates from the disposal unit to surrounding soil, using water infiltration rates determined from the HELP model. DUST is a one-dimensional model that simulates contaminant transport through, and leaching from up to, 10 different materials (soil, debris, etc.). Disposal units typically are complex systems of waste forms, engineered structures, liners, and soils; however, the DUST code allows for simplification of the unit while still accounting for the most important physical processes and parameters influencing release (Sullivan 1993). In the past, the DUST model has been used in similar types of analysis (DOE 1998).

For the gradual failure scenario, DUST modeling was performed for three separate time periods for the 13 indicator chemicals. For both the immediate failure and no failure scenarios, modeling was limited to selected chemicals as part of the uncertainty analysis. Chemicals modeled for the immediate failure scenario were those in the vinyl chloride group and ^{99}Tc. Chemicals modeled for the no failure scenario were those in the vinyl chloride, chromium, and ^{99}Tc groups. Four general disposal waste forms were identified in the waste inventory assessment (soil-like material, concrete, metal, and lumber/debris). The total volume of waste was divided into four volume-weighted layers in order to simulate proportional distribution of contaminants throughout the facility.

Two transport models are included in the DUST code: the Finite Difference Model and the Multiple-Cell Mixing Model. The Finite Difference Model was used for the C-746-U Landfill transport modeling because it can incorporate diffusive/dispersive transport and offers the flexibility to model a wider range of conditions, which is more appropriate for the solid waste landfill facility. Four mechanisms of waste from leaching can be considered in DUST: solubility-limited release, surface rinse, diffusion, and uniform (or dissolution) release. Based on guidelines provided in Sullivan (1993) for contaminated soils, metals, and debris, only the surface rinse release mechanism was used for the C-746-U Landfill transport modeling. For concrete waste a combination of both surface rinse and diffusion release mechanisms was used.

General and localized deterioration of waste forms can also be modeled in DUST. General deterioration represents a situation where the waste forms or containers no longer provide a barrier to infiltration or contaminant release. Localized deterioration represents the release of contaminants prior to general deterioration and is usually characterized by corrosion or pitting of steel containers. For the solid waste landfill, only general failure was modeled because the landfill design indicates that wastes would not be containerized prior to disposal into the facility. The time of general failure chosen for this analysis is 0 years. This means that contaminants in the waste are immediately available for leaching as soon as water contact occurs.

Key parameters used for DUST modeling include the following:

- landfill design parameters—height, horizontal surface area, thickness of layers, and placement sequence of waste types;
- percolation rate as determined by the HELP model;

- waste inventory—initial chemical/radionuclide mass, initial concentration of chemicals in different layers, contaminant half-life, and approximate size and thickness of waste types (i.e., thickness of waste forms placed in the landfill);

- waste form characteristics—waste form types and volumes, site-specific and generic K_d factors, diffusion coefficient, and release mechanisms for each waste form; and

- backfill soil characteristics—site-specific and generic K_d factors, diffusion coefficient, dispersivity, porosity, density, and moisture content.

Values for the above parameters are listed in Tables 4.5 and 4.6. Schematic diagrams showing the different layers and material aggregations modeled in DUST for the Operational Period, Institutional Control Period, and Post-Institutional Control Period are shown in Figs. 4.3 through 4.5, respectively.

4.1.3 MODFLOW and MODPATH

The MODFLOW/MODPATH models were used to estimate hydraulic gradients, flow distances, and hydraulic conductivities along site-to-receptor flowpaths. This information was subsequently used to support the AT123D modeling effort (discussed below). MODFLOW is a three-dimensional, finite-difference model capable of simulating both steady-state and transient head distribution for a saturated groundwater flow field. In contrast, MODPATH is a three-dimensional, particle-tracking model capable of using the steady-state, head distribution generated by MODFLOW to track flowpaths of particles released in the groundwater flow field modeled by MODFLOW.

The MODFLOW model used in the development of the CERCLA-derived waste disposal criteria was the site-wide groundwater flow model developed earlier by DOE (1998b). This model covers most of the DOE reservation except that portion above the Porters Creek Clay terrace. It has been approved by both the PGDP Modeling Steering Committee and the Risk Assessment Working Group. Therefore, this model was used without any modification. The parameters used in this model are summarized in the ***PGDP Quarterly Modeling Report*** **(BJC 2001)** and are not discussed further here. Please see the aforementioned reference for additional information.

As noted above, the MODPATH model was used to track flowpaths of particles released from a location by using the steady-state, head distribution generated by MODFLOW. The key parameter of MODPATH is the particle depth at release. For the development of the CERCLA-derived waste disposal criteria, the mid-depth of a layer was assumed to represent average flow condition, and the particles were released from this depth of an aquifer.

First, MODFLOW was run. Figure 4.6 shows the steady-state, head distribution in the RGA depicted by the run. Second, MODPATH was run. The figure also shows flowpaths of several particles released from the site. The flowpaths are marked with arrows drawn at equal-day intervals; thus, the fastest flowpath to any particular point has the fewest arrows. Also, the figure shows locations selected to represent two exposure points. These are as follows:

- R1—The DOE property boundary exposure point located at the intersection of the property boundary line and the fastest flowpath to the DOE property boundary. The distance to this exposure point is estimated to be 407 m from the source.

- R2—The Ohio River exposure point, located at the intersection of the river and the fastest flowpath from the landfill to the river. The distance to this exposure point is estimated to be 3275 m from the source.

Table 4.5. DUST model input parameters

Chemical-Specific Parameters

Parameter	Units	Vinyl Chloride	TCE	2-Butanone	Chloro-benzene	Benzene	2-Methyl-phenol	Pentachloro-phenol	Benzo(a)-pyrene	PCB[a]	gamma-Chlordane
Half - life [a]	years	7.90E+00	4.50E+00	1.97E+00	1.64E+00	1.97E+00	1.97E+00	4.20E+00	5.80E+00	1.00E+02	7.60E+00
Atomic weight [b]	g/mol	62.5	131.4	72.1	112.6	78.1	108.0	266.3	252.3	375.7	409.8
Solubility limit [c]	gm/cc	2.76E-03	1.10E-03	2.75E-01	4.72E-04	1.75E-03	2.00E-02	1.95E-03	1.62E-03	8.00E-08	5.60E-08
Distribution coefficient (K_d) [d]	cc/gm	1.49E-02	7.52E-02	9.20E-04	1.79E-01	4.96E-02	1.60E-02	4.74E-01	7.75E+02	2.47E+02	4.71E+01
Diffusion coefficient [e]	cm^2/sec	1.23E-06	9.10E-06	1.02E-05	8.70E-06	9.80E-06	8.30E-06	6.10E-06	9.00E-06	1.00E-06	4.37E-06
Simulation period [f]	years	1,000	1,000	1,000	1,000	1,000	1,000	1,000	10,000	10,000	1,000
Initial mass of contaminant in soil [g]	Ci or g	1.08E+05 (g)	5.07E+04 (g)	5.93E+03	1.76E+03 (g)	2.78E+03 (g)	3.25E+04 (g)	9.85E+04 (g)	5.55E+04 (g)	4.69E+05 (g)	1.53E+03 (g)
Initial mass of contaminant in concrete [g]	Ci or g	9.40E+02 (g)	3.20E+04 (g)	9.40E+05	4.70E+05 (g)	2.35E+03 (g)	9.40E+04 (g)	1.08E+05 (g)	6.06E+05 (g)	5.12E+05 (g)	9.40E+02 (g)
Initial mass of contaminant in metal [g]	Ci or g	0.00E+00 (g)	0.00E+00 (g)	0.00E+00	0.00E+00 (g)	0.00E+00 (g)	1.40E+04 (g)	1.60E+04 (g)	9.07E+33 (g)	7.61E+04 (g)	0 (g)
Initial mass of contaminant in lumber and debris [g]	Ci or g	7.13E+02 (g)	2.07E+04 (g)	7.13E+05	3.57E+05 (g)	1.78E+03 (g)	6.55E+05 (g)	1.67E+05 (g)	4.22E+05 (g)	3.89E+05 (g)	7.13E+02 (g)

Parameter	Units	Selenium	Arsenic	Iron	Nickel	Chromium	Uranium	Thallium	Tc-99	Neptunium-237	Uranium-238
Half - life [a]	years	1.00E+05	1.00E+05	1.00E+05	1.00E+05	1.00E+05	1.00E+05	1.00E+05	2.13E+05	2.14E+06	4.47E+09
Atomic weight [b]	g/mol	78.9	75	55.7	58.7	52	238	204.4	99	2.37E+02	238.0
Solubility limit [c]	gm/cc	1.00E+01	1.00E+01	1.00E+01	1.00E+01	1.00E+01	1.00E+01	1.00E+01	1.00E+00	1.00E+01	1.00E+01
Distribution coefficient (K_d) [d]	cc/gm	5 (clay) 150 (sand)	200 (sand) 200 (clay)	220 (sand) 165 (clay)	400 (sand) 650 (clay)	19 (sand) 30 (clay)	66.8 (sand) 410 (organic) 3640 (clay)	71 (sand) 1500 (clay)	0.2 (sand) 1.0 (waste) 20 (clay)	70 (sand) 144 (clay)	66.8 (sand) 410 (organic) 3640 (clay)
Diffusion coefficient [e]	cm^2/sec	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06
Simulation period [f]	years	10,000	10,000	10,000	10,000	10,000	10,000	10,000	1,000	10,000	10,000
Initial mass of contaminant in soil [g]	Ci or g	1.32E+05 (g)	1.47E+06 (g)	5.63E+09 (g)	4.96E+06 (g)	5.63E+06 (g)	1.28E+07 (g)	2.59E+05 (g)	1.08E+00 (Ci)	1.41E-02 (Ci)	4.56E-01 (Ci)
Initial mass of contaminant in concrete [g]	Ci or g	1.83E+05 (g)	3.38E+06 (g)	1.22E+10 (g)	8.93E+06 (g)	2.54E+07 (g)	9.68E+07 (g)	2.83E+05 (g)	7.05E-03 (Ci)	4.24E-01 (Ci)	3.45E+00 (Ci)
Initial mass of contaminant in metal [g]	Ci or g	1.81E+02 (g)	2.38E+03 (g)	4.58E+11 (g)	1.79E+11 (g)	1.10E+08 (g)	1.44E+08 (g)	4.21E+02 (g)	1.05E-02 (Ci)	6.29E-01 (Ci)	5.13E+00 (Ci)
Initial mass of contaminant in lumber and debris [g]	Ci or g	1.37E+05 (g)	2.57E+06 (g)	9.27E+09 (g)	6.78E+06 (g)	1.93E+07 (g)	7.35E+07 (g)	2.15E+05 (g)	5.35E-03 (Ci)	3.22E-01 (Ci)	2.62E+00 (Ci)

Table 4.5. DUST Model input parameters (continued)

Waste Form Parameters

Parameter	Units	Waste Form Type			
		Soil	Concrete	Metal	Lumber and debris
Contaminant release mechanism		Surface Rinse	Surface Rinse	Surface Rinse	Surface Rinse
Height of waste form	cm	366	305	366	305
Width of waste [h]	cm	30,000	30,000	30,000	30,000
Total volume capacity in waste layer	cm^3	3.27E+11	2.73E+11	3.27E+11	2.73E+11
Bulk density	gm/cm^3	1.5	2.0	2.5	1.5
Moisture Content		0.3	0.3	0.3	0.3
Darcy velocity (Operational Period) [i]	cm/s	2.54E-09	2.54E-09	2.54E-09	2.54E-09
Darcy velocity (Institutional Control Period) [i]	cm/s	2.54E-09	2.54E-09	2.54E-09	2.54E-09
Darcy velocity (Post Institutional Control Period) [i]					
year 50 - 90	cm/s	1.78E-08	1.78E-08	1.78E-08	1.78E-08
year 90 - 130	cm/s	9.48E-08	9.48E-08	9.48E-08	9.48E-08
year 130 - 170	cm/s	2.29E-07	2.29E-07	2.29E-07	2.29E-07
year 170 - 210	cm/s	2.84E-07	2.84E-07	2.84E-07	2.84E-07
year 210 - 250	cm/s	2.93E-07	2.93E-07	2.93E-07	2.93E-07
year 250 - 10,000	cm/s	2.95E-07	2.95E-07	2.95E-07	2.95E-07
Dispersivity [j]	cm	253	253	253	253

Table 4.5. DUST Model input parameters (continued)

Soil Parameters

Parameter	Units	Layer Types					
		Native soil	Gravel layer	Clay Barrier	Alluvium Soil	Clay confining unit	Sand layer
Bulk density, r [k]	g/cm^3	1.5	1.2	1.8	1.5	1.76	1.4
Darcy velocity (Operational Period) [i]	cm/s	2.54E-09	2.54E-09	2.54E-09	2.54E-09	2.54E-09	2.54E-09
Darcy velocity (Institutional Control Period) [i]	cm/s	2.54E-09	2.54E-09	2.54E-09	2.54E-09	2.54E-09	2.54E-09
Darcy velocity (Post Institutional Control Period) [i]							
year 50 - 90	cm/s	1.78E-08	1.78E-08	1.78E-08	1.78E-08	1.78E-08	1.78E-08
year 90 - 130	cm/s	9.48E-08	9.48E-08	9.48E-08	9.48E-08	9.48E-08	9.48E-08
year 130 - 170	cm/s	2.29E-07	2.29E-07	2.29E-07	2.29E-07	2.29E-07	2.29E-07
year 170 - 210	cm/s	2.84E-07	2.84E-07	2.84E-07	2.84E-07	2.84E-07	2.84E-07
year 210 - 250	cm/s	2.93E-07	2.93E-07	2.93E-07	2.93E-07	2.93E-07	2.93E-07
year 250 - 10,000	cm/s	2.95E-07	2.95E-07	2.95E-07	2.95E-07	2.95E-07	2.95E-07
Moisture content		0.3	0.3	0.3	0.3	0.3	0.3
Dispersivity [j]	cm	253	253	253	253	253	253

Note that values for the Institutional Control Period were used for both the Institutional Control and Post-Institutional Control Periods under the no failure scenario.

[a] Half-lives of radionuclides were obtained from Disposal Unit Source Term (DUST) default library; half-lives of organics were obtained from Howard et al. (1991).

[b] Values for radionuclides obtained from DUST default library; all other values obtained from the U.S. Environmental Protection Agency (EPA) (1996).

[c] Solubility limits were obtained from EPA (1996).

[d] Values were obtained from Sheppard and Thibault (1990).

[e] Values obtained from DUST model are insensitive to diffusion coefficient if the diffusional release fraction = 0.

[f] Total simulation period (Operational Period = 0 to 20 years, Institutional Control Period = 20 to 50 years, and Post-Institutional Control Period = 50 to 10,000 years).

[g] Values were calculated using contaminant concentration, soil volume, and soil bulk density. Presented values are for the initial inventory (i.e., at start of Operational Period).

[h] Calculated as follows: Width = (surface area of the landfill)$^{1/2}$.

[i] Values for all periods were obtained using the Hydrologic Evaluation of Landfill Performance model for the gradual failure scenario; therefore, it represents constant value for all the layers that are equivalent to the recharge.

[j] Values estimated as 0.1 times the contaminant travel distance from top of waste layers to water table.

[k] Values obtained from U.S. Department of Energy (1999c).

Table 4.6. Inventory of contaminant mass in different waste forms for the chemicals/radionuclides modeled

		Media volume (yd^3)				Volume		Mass of Media (gm)			
		Soil	Concrete [b]	Scrap Metal [b]	Organic [b]	Weighted Average		Soil	Concrete	Scrap Metal	Organic
		313187	293000	356000	224000	1.20E+06		4.30E+11	3.52E+11	4.19E+11	3.57E+11
Indicator Chemicals	**Unit**	**Concentration of Chemicals**					**Unit**	**Mass of Chemicals**			
		Non-Aromatic Straight-Chain Halogenated Hydrocarbons									
Vinyl chloride	mg/kg	0.25	0.002	0	0.002	0.0699	g	1.08E+05	9.40E+02	0.00E+00	7.13E+02
Trichloroethene	mg/kg	0.118	0.068	0	0.058030688	0.0612	g	5.07E+04	3.20E+04	0.00E+00	2.07E+04
		Non-Aromatic Straight-Chain Nonhalogenated Hydrocarbons									
Butanone, 2-	mg/kg	0.0138	2	0	2	0.914	g	5.93E+03	9.40E+05	0.00E+00	7.13E+05
		Aromatic Ring-Structured Nonhalogenated Hydrocarbons									
Benzene	mg/kg	0.00646	0.005	0	0.005	0.00406	g	2.78E+03	2.35E+03	0.00E+00	1.78E+03
		Aromatic Ring-Structured Halogenated Hydrocarbons									
Chlorobenzene	mg/kg	0.00409	1	0	1	0.456	g	1.76E+03	4.70E+05	0.00E+00	3.57E+05
		Light Semi-Volatile Organic Compounds (molecular weight < 200 g/mole)									
Methylphenol, 2-	mg/kg	0.0755	0.2	0.02	1.836070064	0.492	g	3.2E+04	9.4E+04	1.4E+04	6.5E+05
		Heavy Semi-Volatile Organic Compounds (molecular weight > 200 g/mole)									
Pentachlorophenol	mg/kg	0.229	0.229	0.0229	0.467233747	0.228	g	9.85E+04	1.08E+05	1.60E+04	1.67E+05
Total PAH (benzo(a)pyrene)	mg/kg	0.129	1.29	0.013	1.184265192	0.602	g	5.55E+04	6.06E+05	9.07E+03	4.22E+05
		Polychlorinated Biphenyl									
Total PCBs	mg/kg	1.09	1.09	0.109	1.09	0.826	g	4.69E+05	5.12E+05	7.61E+04	3.89E+05
		Pesticides									
Chlordane, gamma-	mg/kg	0.00355	0.002	0	0.002	0.00189	g	1.53E+03	9.40E+02	0.00E+00	7.13E+02
		Inorganic Compounds/Metals (mobile)									
Chromium	mg/kg	1.31E+01	5.40E+01	1.58E+02	5.40E+01	7.07E+01	g	5.63E+06	2.54E+07	1.10E+08	1.93E+07
		Inorganic Compounds/Metals (moderately mobile)									
Uranium	mg/kg	29.7	206	206	206	157.3	g	1.28E+07	9.68E+07	1.44E+08	7.35E+07
		Inorganic Compounds/Metals (less mobile)									
Thallium	mg/kg	0.603	0.603	0.000603	0.603	0.441	g	2.59E+05	2.83E+05	4.21E+02	2.15E+05
		Radionuclides (mobile)									
Technetium-99	pCi/g	2.51	0.015	0.015	0.015	0.704	Ci	1.08E+00	7.05E-03	1.05E-02	5.35E-03
		Radionuclides (less mobile)									
Uranium-238	pCi/g	1.06	7.35	7.35	7.35	5.61	Ci	4.56E-01	3.45E+00	5.13E+00	2.62E+00
		Additional Chemicals / Radionuclides[c]									
Selenium	mg/kg	3.08E-01	3.90E-01	3.08E-04	3.90E-01	2.63E-01	g	1.32E+05	1.83E+05	2.15E+02	1.39E+05
Arsenic	mg/kg	3.42E+00	7.20E+00	3.42E-03	7.20E+00	4.22E+00	g	1.47E+06	3.38E+06	2.39E+03	2.57E+06
Iron	mg/kg	1.31E+04	2.60E+04	6.56E+05	2.60E+04	1.92E+05	g	5.63E+09	1.22E+10	4.58E+11	9.27E+09
Nickel	mg/kg	1.09E+01	1.90E+01	2.57E+05	1.90E+01	6.90E+04	g	4.69E+06	8.93E+06	1.79E+11	6.78E+06
Neptunium-237	pCi/g	3.28E-02	9.02E-01	9.02E-01	9.02E-02	6.62E-01	Ci	1.41E-02	4.24E-01	6.29E-01	3.22E-01

[a]Concentrations for uranium isotopes in non-soil media were estimated using the ratios to total uranium by media.
[b]Non-soil media concentrations are taken from or modified from information in Table 3.4.
[c] Additional chemicals/radio nuclides were selected for modeling based on risk-assessment results

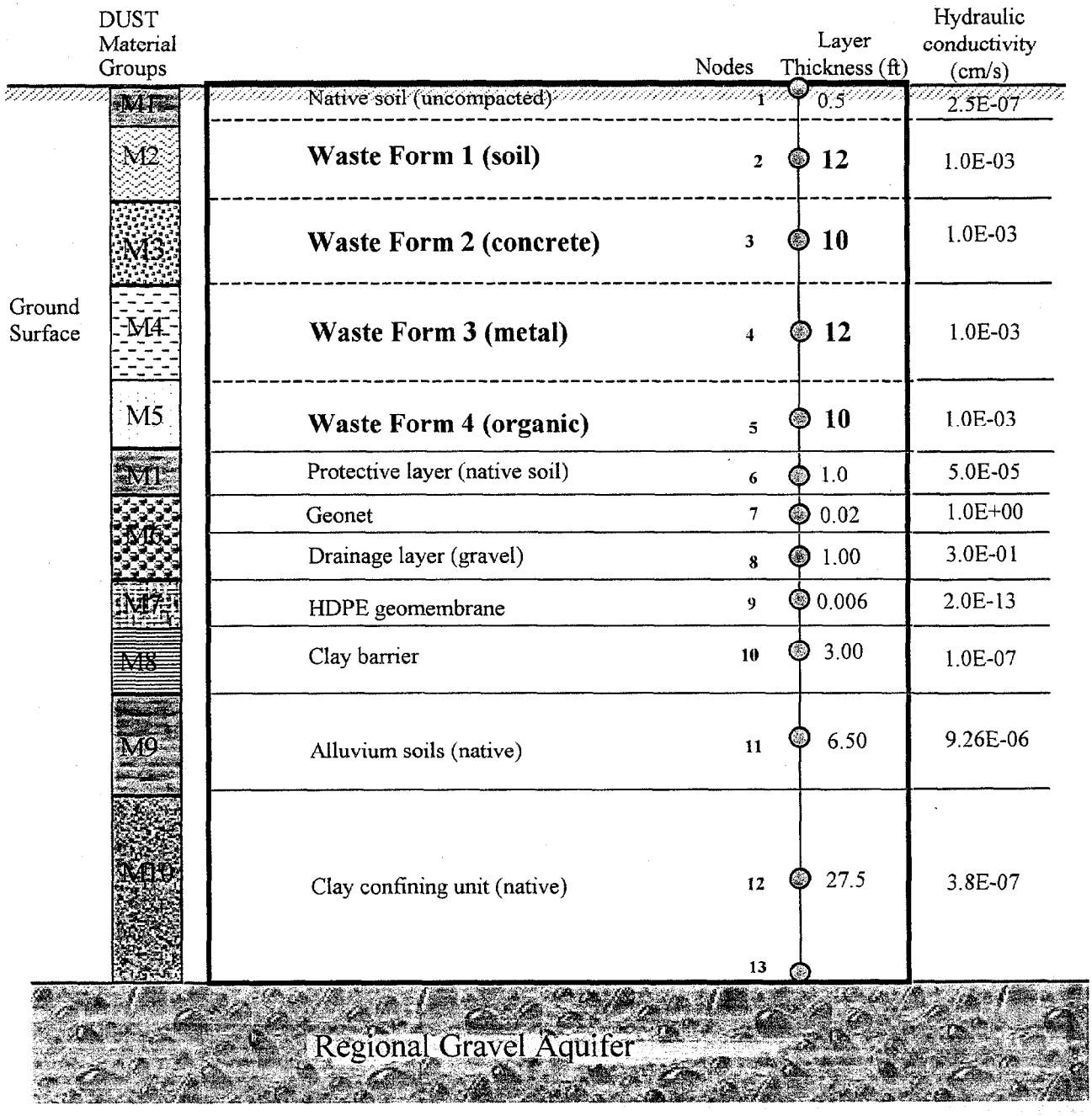
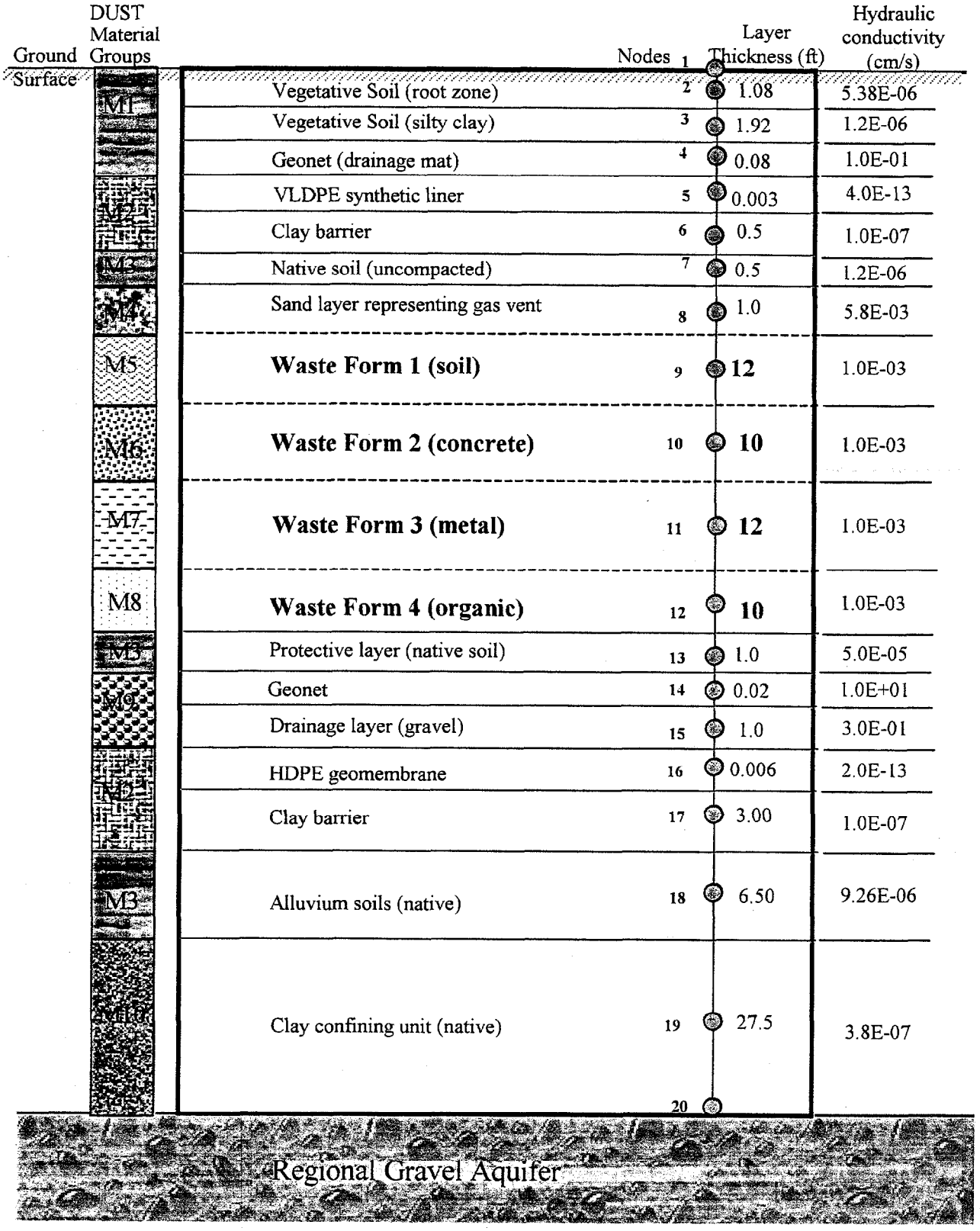
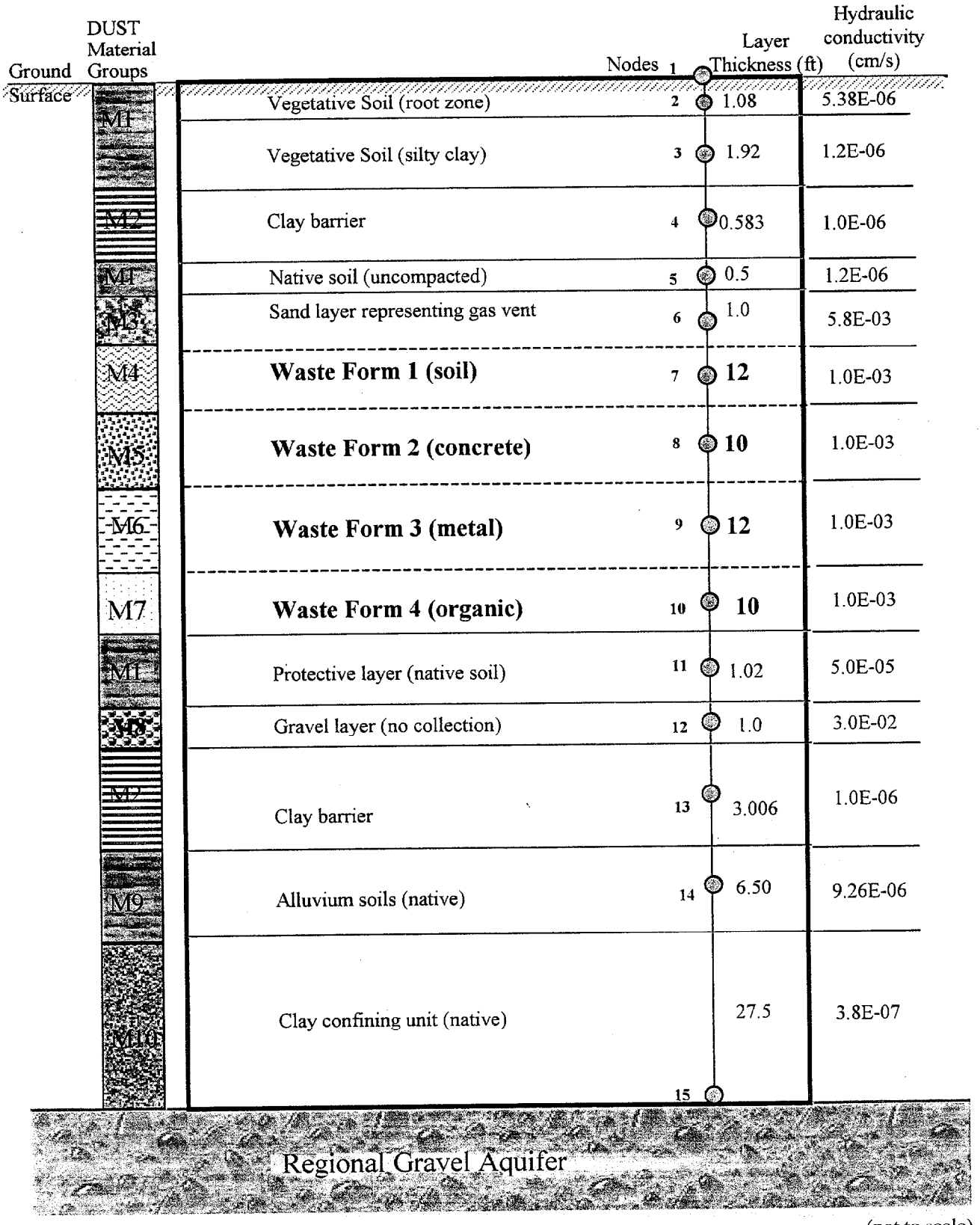


Fig. 4.3. Schematic diagram of DUST model layers and materials for the Operational Period under all scenarios.



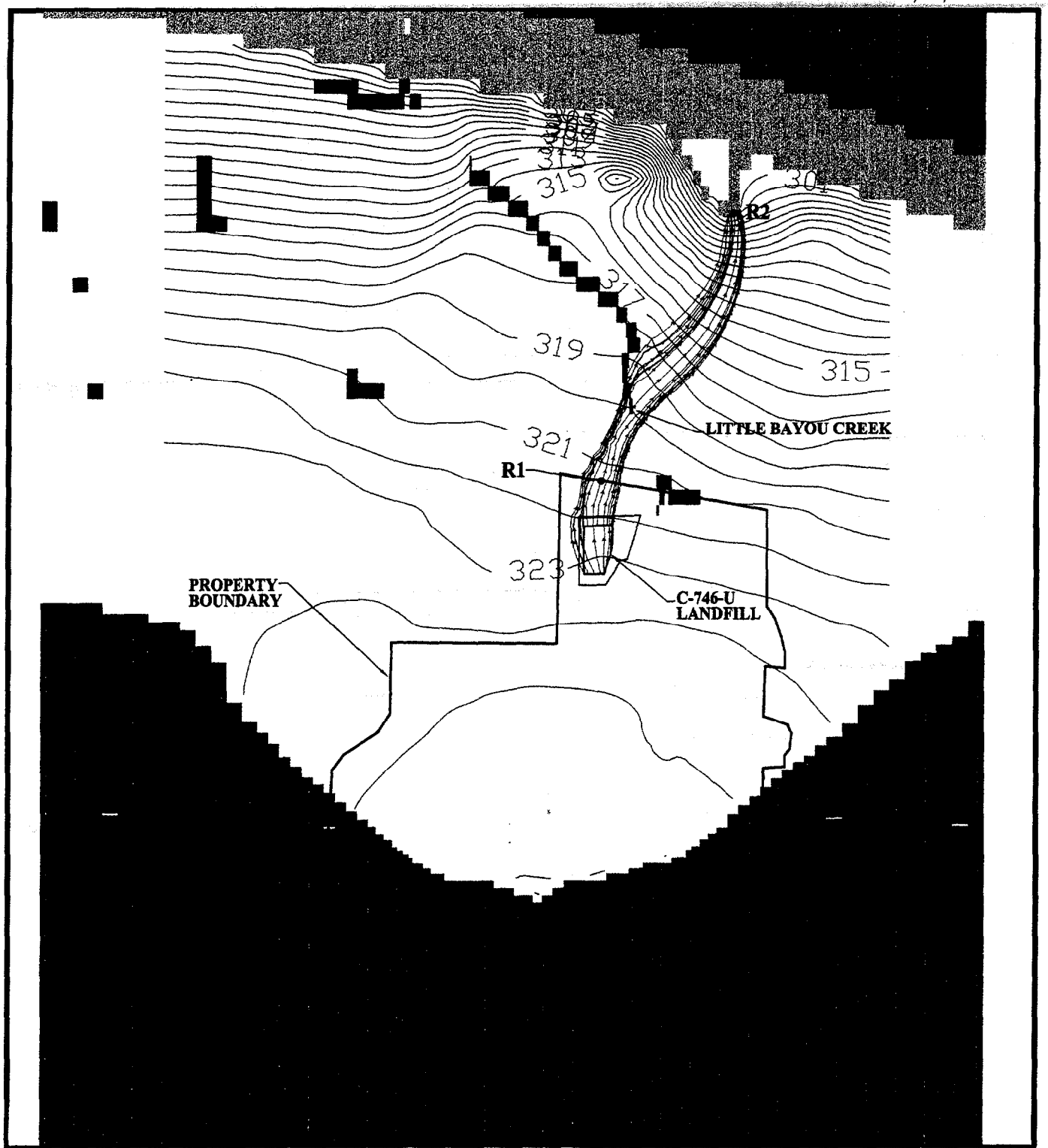
(not to scale)

Fig. 4.4. Schematic diagram of DUST model layers and materials for Institutional Control Period under all scenarios and for the Post-Institutional Control Period under the no failure scenario.



(not to scale)

Fig. 4.5. Schematic diagram of DUST model layers and materials for the Post-Institutional Control Period under the gradual failure and immediate failure scenarios.



SOURCE:
DOE 1997b

0 2000 4000
SCALE: 1" = 4,000'

20°
TRUE NORTH
PADUCAH PLANT

U.S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS
BECHTEL JACOBS COMPANY, LLC
MANAGED FOR THE US DEPARTMENT OF ENERGY UNDER US GOVERNMENT CONTRACT DE-AC-05-98OR22700
Oak Ridge, Tennessee • Paducah, Kentucky • Portsmouth, Ohio

SAIC
Science Applications International Corporation
P.O. Box 2502
Oak Ridge, Tennessee 37831

Fig. 4.6. Preferential flowpath of particles released in RGA.

Figure No. /99049/DWGS/P037UPRT
DATE 08-03-02

Third, the hydraulic gradient along the fastest flowpath associated with the DOE property boundary exposure point was estimated to ensure transit time was conservatively estimated. The heads along the flowpath running from the release point to the property boundary exposure point were determined, and the hydraulic gradient was estimated as the head difference divided by the distance from the release point to the exposure point. Similarly, the hydraulic gradients for the other exposure points were estimated. Fourth, the hydraulic conductivity along the fastest flowpath associated with an exposure point was estimated. The hydraulic conductivities embedded in the MODFLOW model along the flowpath were examined, and the maximum hydraulic conductivity along the flowpath was selected for use in the AT123D model to ensure transit time was not underestimated.

4.1.4 Analytical Transient 1-, 2-, 3-Dimensional (AT123D) Model

The AT123D model was used to model the lateral transport of contaminants in the groundwater to the exposure points. This model is a well-known and commonly used analytical groundwater pollutant fate and transport model that computes the spatial-temporal concentration distribution of chemicals in the aquifer system and predicts the transient spread of a chemical plume through an aquifer. The fate and transport processes accounted for in AT123D are advection, dispersion, adsorption/retardation, and decay. This model estimates the dissolved concentration of a chemical in three dimensions in the groundwater resulting from a mass release (either continuous, instant, or depleting source) over a source area (i.e., point, line, area, or volume source). Predicted contaminant concentrations in groundwater developed by AT123D are subsequently used as inputs for estimating risks and doses to receptors exposed to the contaminated groundwater at each of the exposure points. Therefore, as in the DUST modeling, AT123D modeling was performed from the start of the Operational Period and continued up to 10,000 years.

The model relies on input from HELP, DUST, MODFLOW, and MODPATH. The key parameters required for AT123D modeling include the following:

- predicted contaminant load to the water table from the solid waste landfill for the three periods (from DUST);
- hydrogeologic parameters (from MODFLOW and MODPATH);
- medium-specific K_d values (see Appendix C.3);
- chemical parameters (from DUST); and
- downgradient migration distance to the exposure point (from MODFLOW and MODPATH).

Values for these parameters are listed in Table 4.7.

4.1.5 RESRAD

Because DUST can not model decay chains associated with radionuclide COPCs, the RESRAD model was used to evaluate the uncertainty in results for these radionuclides under the gradual failure scenario. The RESRAD model is also an industry standard model with regulator's and stakeholder's acceptance. RESRAD (Yu et al. 1993) was developed by Argonne National Laboratories and is widely used by DOE and other government agencies to estimate doses from residual radioactive material and to set site-specific cleanup levels for radioactive contaminants. The user interfaces of the program are flexible modeling platforms. RESRAD is primarily used for estimating doses arising from occupancy of land contaminated by radioactive material. RESRAD can model decay chains of many isotopes; its libraries include properties of a large number of isotopes together with their decay chain.

Table 4.7. Parameters used by the AT123D model for saturated zone modeling

Surrogate Chemical/ Radionuclide	Distribution coefficient (K_d) [a] L/kg	Diffusion coefficient [b] cm^2/sec	Diffusion coefficient [b] m^2/hr	Half-life [c] years	Decay constant [d] 1/hr
		Organic			
Vinyl chloride	0.0149	1.23E-06	4.43E-07	7.90E+00	1.00E-05
Trichloroethene	0.0752	9.10E-06	3.28E-06	4.50E+00	1.76E-05
2-Butanone	0.00092	1.02E-05	3.67E-06	1.97E+00	4.02E-05
Chlorobenzene	0.179	8.70E-06	3.13E-06	1.64E+00	4.82E-05
Benzene	0.0496	9.80E-06	3.53E-06	1.97E+00	4.02E-05
2-Methyl-phenol	0.016	8.30E-06	2.99E-06	1.97E+00	4.02E-05
Pentachlorophenol	0.474	6.10E-06	2.20E-06	4.20E+00	1.88E-05
Benzo(a)pyrene	775	9.00E-06	3.24E-06	5.80E+00	1.36E-05
Polychlorinated biphenyl	247	1.00E-06	3.60E-07	1.00E+02	7.91E-07
gamma-Chlordane	47.1	4.37E-06	1.57E-06	7.60E+00	1.04E-05
		Inorganic (metals / radionuclides)			
Selenium	5.00E+00	1.00E-06	3.60E-07	NA	NA
Arsenic	2.00E+02	1.00E-06	3.60E-07	NA	NA
Iron	2.20E+02	1.00E-06	3.60E-07	NA	NA
Nickel	4.00E+02	1.00E-06	3.60E-07	NA	NA
Chromium	19	1.00E-06	3.60E-07	NA	NA
Thallium	71	1.00E-06	3.60E-07	NA	NA
Uranium	66.8	1.00E-06	3.60E-07	4.47E+09	1.77E-14
Technetium-99	0.2	1.00E-06	3.60E-07	2.13E+05	3.71E-10
Neptunium-237	70	1.00E-06	3.60E-07	2.14E+06	2.44E-10
Uranium-238	66.8	1.00E-06	3.60E-07	4.47E+09	1.77E-14

Saturated Zone Parameters

Parameter	Units	Value
Effective porosity [e]	unitless	0.30
Aquifer depth [e]	m	6.10
Hydraulic conductivity [f]	m/day	0.26
Hydraulic gradient [f]	m/m	0.00110
Soil bulk density [e]	g/cm^3	1.67
Longitudinal dispersivity	m	15.00
Vertical dispersivity	m	1.50
Transverse dispersivity	m	0.03

Receptor #	Location	Distance to Receptor (m)
1	Property boundary	407
2	Ohio River	3,275

[a]Noted values were obtained from Sheppard and Thibault (1990) and EPA (1996).
[b]Values obtained from EPA (1996).
[c]Half-lives of radionuclides were obtained from Disposal Unit Source Term default library, half-lives of organics were obtained from Howard et al. (1991).
[d]Decay constants were calculated as $(\ln 2/t_{1/2}) \times$ (1 year/8760 hours).
[e]Values obtained from DOE (2000a).
[f]Values obtained from MODFLOW/MODPATH output.
AT123D = Analytical Transient 1-, 2-, 3-Dimensional Model.
NA = not available.

The RESRAD groundwater model has an unsteady well-mixed linear reservoir in the contaminated zone, a travel time model in the unsaturated zone, and either a mass balance model or non-dispersive model in the saturated zone. The unsaturated zone in RESRAD can be represented with up to five layers with differing properties; however, it has only one cover layer and handles only one contaminated zone. RESRAD simulates the removal of radioactivity from the contaminated zone by leaching, transporting it vertically into groundwater, and by runoff into streams or ponds. RESRAD was not used as the primary model for this task because it can not account for the complexity of contaminant matrix within the landfill, and it can not account for the gradual release of contaminants from the source.

Key parameters for uncertainty analysis using RESRAD include the following:

- Soil characteristics for unsaturated zone – number of layers (limited to a maximum of five layers) in the zone and thickness, density, total porosity, effective porosity, field capacity, hydraulic conductivity, and soil-specific exponential parameter (b) for each layer;
- Soil characteristics for saturated zone – density, total porosity, effective porosity, field capacity, hydraulic conductivity, hydraulic gradient, and b parameter of the zone;
- Radionuclide – influent concentrations, leach rate, and solubility limit;
- Distribution coefficients (K_d) – for each layer in the unsaturated zone as well as in the saturated zone; and
- Climatic parameter – same and HELP.

Values for these parameters are presented in Appendix C.3.

4.2 DERIVATION OF DILUTION ATTENUATION FACTOR

To determine the transport times and concentrations of chemicals within each of the surrogate groups, the DAF for the indicator chemical(s) assigned to each surrogate group was determined, and the DAFs were applied to each chemical's concentration in disposed material. DAF is a numerical value that represents the attempt to mathematically quantify the natural physical, chemical, and biological processes (e.g., advection-dispersion, sorption-retardation, biodegradation, and volatilization) that result in the decrease of a chemical concentration in an environmental medium. In simple terms, the DAF is the ratio of chemical concentration at the source (or the point of origin) to the concentration at the exposure point. The concept used to apply the DAF at the C-746-U Landfill is shown in Fig. 4.7. As shown there, a DAF allows for the calculation of a concentration of a contaminant in groundwater from a concentration of a contaminant in soil or waste. This is based upon the following mechanisms:

- a contaminant released to an unsaturated zone of native soil at a location above the groundwater table is expected to remain in place until water from rainfall or other sources reaches the contaminant through infiltration;
- infiltrating rainwater will release chemicals through surface rinse or another dissolution mechanism and transport the dissolved chemicals (as leachate) through the unsaturated zone, to the water table (the factors that affect leaching rate include a contaminant's solubility and distribution coefficient and the amount of percolation);
- the leachate will enter the water table and migrate with the groundwater to an exposure point; and

- contaminant rate of decay or persistence. [Radionuclides and certain organic compounds decay or breakdown at characteristic rates that are described by the substances half-life. For a given percolation rate, contaminants with a long half-life will have a greater potential to migrate than those with a short half-life. For example, if ^{60}Co and ^{238}U are in waste at equal concentration. It is unlikely that ^{60}Co would even be detected at a point of exposure because of its much shorter half-life (5.3 years) compared to that for ^{238}U (half-life of 4.4 billion years).]

These mechanisms allow the transport of a contaminant through a source-to-exposure point path to be assumed to follow two distinct subpaths discretized with three distinct concentrations. The subpaths are source-to-water table and water table-to-exposure point. The concentrations are the volume-weighted average concentration of contaminant in the solid waste landfill (C_S), the predicted maximum concentration of the contaminant in the leachate just above the water table (C_L), and the predicted maximum concentration of contaminant in groundwater at the exposure point (C_W). The DAF for the source (i.e., solid waste landfill)-to-exposure point path is defined as C_S/C_W. The DAF for the source-to-water table path is $(C_S/K_d)/C_L$ (DAF_1) and for the water table-to-exposure point path is C_L/C_W (DAF_2); therefore, the total DAF for any exposure point is estimated by multiplying the two DAFs, ($DAF = DAF_1 \times DAF_2$). DAFs were developed for the 15 primary chemical groups at the PGDP site indicated in Chap. 3. A surrogate chemical was selected for each group to be used in the quantitative modeling. DAFs developed for the surrogate apply to all chemicals in the group.

Three models were used to estimate the DAFs. The HELP model was used to estimate the water infiltration into the waste cell. The DUST model was used to estimate contaminant loading from the solid waste landfill into the infiltrating water and transport to the water table and, hence, to estimate C_L. The AT123D model was used to estimate contaminant transport from the water table at the source to the exposure point and, hence, to estimate C_W.

4.3 MODEL RESULTS

This section presents the modeling results for the gradual failure scenario subsequently used in Chap. 5 to calculate the preliminary CERCLA-derived waste disposal criteria. Results are presented as concentrations of contaminants at all the relevant exposure points. Cumulative risk and dose for all contaminants are presented in Chap. 5. Uncertainties in these results are discussed in Chap. 6. The final CERCLA-derived waste disposal criteria and the contaminant inventory limits derived from them are presented and discussed in Chap. 7.

Table 4.8 lists the exposure points used for this site. These exposure points are coded as R1 and R2. A description of these exposure points are presented in Sect. 4.1.3. Two additional points representing predicted leachate concentrations also were selected. These points include the exit from the landfill liner system and the water table beneath the landfill.

Table 4.8. Site-to-exposure point distance

Receptor Code	Receptor Name	Distance from the Source (m)
R1	DOE Property Line	407
R2	Ohio River	3275
L1	Liner	3.5 ft below the waste
L2	Water Table	39 ft below the waste

DOE = U.S. Department of Energy.

Table 4.9 shows the DAFs for the exposure points for the indicator chemicals and radionuclides. Chromium has the smallest DAF, while benzo(a)pyrene has the highest DAF among the indicator chemicals and radionuclides.

Table 4.9. Wasteform-to exposure point DAF

Indicator Chemical Groups	Chemical/Radionuclide Subgroup	Indicator Member	$DAF_{above\ liner\ system}$ L1	$DAF_{water\ table}$ L2	DAFs for Exposure Points 407 m R1	3275 m R2
Halogenated Hydrocarbon	Non-Aromatic Straight-Chain	Vinyl Chloride	4.84E+05	2.30E+07	3.19E+08	1.44E+09
Halogenated Hydrocarbon	Non-Aromatic Straight-Chain	Trichloroethene	2.28E+03	8.37E+07	1.06E+09	2.72E+10
Straight-chain, Nonhalogenated Hydrocarbon	Non-Aromatic Straight-Chain	2-Butanone	1.72E+05	8.49E+10	1.60E+12	1.98E+14
Halogenated Hydrocarbon	Aromatic Ring-Structured	Chlorobenzene	3.01E+04	1.64E+10	3.56E+11	3.15E+16
Nonhalogenated Hydrocarbon	Aromatic Ring-Structured	Benzene	1.43E+04	1.49E+10	2.50E+11	1.52E+14
Semivolatile Organic Compound	Light (MW < 200 g/mole)	2-Methylphenol	1.46E+04	2.05E+10	3.40E+11	6.92E+13
Semivolatile Organic Compound	Heavy (MW > 200 g/mole)	Pentachlorophenol	1.43E+04	1.16E+08	2.33E+09	9.22E+12
Semivolatile Organic Compound	Heavy (MW > 200 g/mole)	Benzo(a)pyrene	3.05E+12	6.13E+19	Infinite	Infinite
PCB		PCB	1.46E+04	6.68E+07	1.47E+14	Infinite
Pesticide		gamma-Chlordane	8.13E+07	3.23E+12	1.18E+24	Infinite
Inorganic Compounds/Metals	Highly Mobile	Chromium	2.43E+00	5.23E+00	5.14E+01	6.19E+01
Inorganic Compounds/Metals	Moderately Mobile	Copper	6.51E+00	1.92E+02	2.68E+02	4.97E+02
Inorganic Compounds/Metals	Less Mobile	Thallium	2.22E+01	7.86E+02	1.15E+03	1.01E+04
Radionuclide	Highly Mobile	Technetium-99	7.51E+00	1.43E+01	1.44E+02	1.73E+02
Radionuclide	Moderately Mobile	Uranium-238	6.27E+01	5.49E+02	1.60E+03	2.36E+04

DAF = dilution attenuation factor.
MW = molecular weight.
PCB = polychlorinated biphenyl.

Table 4.10 shows the maximum concentrations at the exposure points for all COPCs. The COPCs are listed by surrogate group, and the chemical or radionuclide listed in bold font is the indicator chemical used for the surrogate group. The information shown with each indicator chemical or radionuclide shows the maximum concentration predicted by modeling. It should be noted that the maximum predicted concentrations in Table 4.10 were not limited by the solubility of the constituent. Therefore, concentrations in water reported in this table are overestimates.

Figures 4.8 through 4.22 show the predicted concentration-time variation for all the indicator chemicals. It should be noted here that for some constituents multiple peaks are predicted. This occurs because the DUST model was applied separately for each period of performance under the gradual failure scenario. That is, the need to divide the early portion of the post-institutional control period into multiple steps to account for gradual failure produced multiple peaks. Also note that some constituents (e.g., uranium) do not reach their peak concentration in the period modeled. For example, Fig. 4.8 shows that vinyl chloride attains maximum concentrations of 1.47×10^{-8} mg/L at R1 at 160 years and 3.26×10^{-9} mg/L at R2 at 180 years after the source material is first placed in the landfill. Similarly, the figures for the remaining chemicals and radionuclides are presented in Appendix C.3. The concentration-time curves of the remaining constituents represented by an indicator chemical were obtained by using a surrogate ratio that was calculated as follows:

$$Cw_{constituent} = Cw_{surrogate} \times \frac{Cs_{constituent} \div Kd_{constituent}}{Cs_{surrogate} \div Kd_{surrogate}}$$

or

$$Cw_{constituent} = Cw_{surrogate} \times \text{Surrogate Ratio}$$

where

$Cw_{constituent}$	=	calculated concentration of contaminant of concern (COC) in groundwater (mg/L or pCi/L),
$Cw_{surrogate}$	=	modeled concentration of indicator chemical or radionuclide in groundwater (mg/L or pCi/L),
$Cs_{constituent}$	=	volume-weighted concentration of COC in waste (mg/kg or pCi/g),
$Kd_{constituent}$	=	distribution coefficient for COC (L/kg),
$Cs_{surrogate}$	=	volume-weighted concentration of indicator chemical or radionuclide in waste (mg/kg or pCi/g),
$Kd_{surrogate}$	=	distribution coefficient for indicator chemical or radionuclide (L/kg).

The surrogate ratios for the C-746-U Landfill COPCs are presented in Table 4.11.

Based on the above results, the list of major COPCs were examined, and if a constituent was determined to be a major COPC but was not an indicator chemical or radionuclide, then modeling to predict the fate and transport of that constituent was performed. The results of this additional modeling were subsequently used in development of the preliminary CERCLA-derived waste disposal criteria. Figures 4.23 through 4.28 show the concentration-time variations for these additional chemicals and radionuclides.

As discussed above, for the immediate failure scenario, two indicator chemicals (vinyl chloride and ^{99}Tc) were chosen for the analysis. The results of this analysis are shown in Table 4.12 and Figs. 4.29 and 4.30. Figure 4.28 shows that vinyl chloride attains maximum concentrations of 4.17×10^{-6} mg/L at R1 at 80 years and 9.18×10^{-7} mg/L at R2 at 90 years after the source material is first placed in the landfill. When compared with results from the gradual failure scenario, the immediate failure scenario produces higher concentrations and shorter arrival times to the receptor locations for vinyl chloride. However, for ^{99}Tc, there is hardly any difference in the predicted concentrations between these two scenarios.

For the no failure scenario, concentrations of all chemicals modeled remained at minimal levels. Table 4.13 and Figs. 4.31 through 4.33 display these results.

Table 4.10. Maximum predicted concentrations for all chemicals at receptor locations based on DAF for indicator chemical

Chemical Groups [a]	K_d (L/kg)	Cs: Volume Weighted Average Concentration in Waste (mg/kg or pCi/g)	Leachate Concentration: Above Liner System	Leachate Concentration: Above Water Table	Maximum Concentration in mg/L or pCi/L at X(m)[b]: Property Boundary 407	Maximum Concentration in mg/L or pCi/L at X(m)[b]: Ohio River 3275
VOLATILE ORGANIC COMPOUNDS						
Non-Aromatic, Straight-Chain Halogenated Hydrocarbons (contains fluorine, chlorine, bromine, and iodine)						
Vinyl chloride	***1.49E-02***	***0.0699***	***9.69E-06***	***2.04E-07***	***1.47E-08***	***3.26E-09***
cis-1,2-Dichloroethene	2.84E-02	0.2220	1.61E-05	3.40E-07	2.45E-08	5.43E-09
1,1-Dichloroethene	5.20E-02	0.0140	5.55E-07	1.17E-08	8.42E-10	1.87E-10
trans-1,2-Dichloroethene	3.04E-02	0.0840	5.71E-06	1.20E-07	8.66E-09	1.92E-09
1,2-Dichloroethane	3.04E-02	0.0034	2.31E-07	4.87E-09	3.51E-10	7.78E-11
Chloroform	4.24E-02	0.0284	1.39E-06	2.92E-08	2.10E-09	4.66E-10
1,2-Dichloroethene (mixed isomers)	6.20E-02	0.00009	2.93E-09	6.17E-11	4.45E-12	9.86E-13
Trichloroethene	***7.52E-02***	***0.0612***	***3.57E-04***	***9.73E-09***	***7.70E-10***	***2.99E-11***
Carbon tetrachloride	1.22E-01	0.0034	1.23E-05	3.34E-10	2.65E-11	1.03E-12
Tetrachloroethene	2.12E-01	0.0053	1.09E-05	2.96E-10	2.34E-11	9.10E-13
Non-Aromatic, Straight-Chain Nonhalogenated Hydrocarbons						
2-Butanone	***9.20E-04***	***0.914***	***5.77E-03***	***1.17E-08***	***6.20E-10***	***5.03E-12***
Aromatic, Ring-Structured Halogenated Hydrocarbons (contains fluorine, chlorine, bromine, and iodine)						
Chlorobenzene	***1.79E-01***	***0.456***	***8.45E-05***	***1.55E-10***	***7.15E-12***	***8.07E-17***
1,4-Dichlorobenzene	4.93E-01	0.057	3.84E-06	7.04E-12	3.25E-13	3.67E-18
Hexachlorobenzene	6.40E+01	0.022	1.12E-08	2.05E-14	9.48E-16	1.07E-20
Aromatic, Ring-Structured Nonhalogenated Hydrocarbons (does not contain fluorine, chlorine, bromine, and iodine)						
Benzene	***4.96E-02***	***0.0041***	***5.74E-06***	***5.48E-12***	***3.27E-13***	***5.39E-16***
Ethylbenzene	1.63E-01	0.0043	1.84E-06	1.76E-12	1.05E-13	1.73E-16
xylene mixture	2.17E-01	0.0046	1.50E-06	1.43E-12	8.54E-14	1.41E-16
m-xylene	1.57E-01	0.0046	2.07E-06	1.98E-12	1.18E-13	1.95E-16
p-xylene	2.49E-01	0.0046	1.31E-06	1.25E-12	7.44E-14	1.23E-16
o-xylene	1.93E-01	0.0046	1.69E-06	1.61E-12	9.60E-14	1.58E-16
SEMIVOLATILE ORGANIC COMPOUNDS						
Light Semivolatile Organic Compounds (molecular weight < 200 g/mole)						
2-Methylphenol	***1.60E-02***	***0.492***	***2.11E-03***	***1.50E-09***	***9.05E-11***	***4.44E-13***
Pyridine	3.49E-03	0.031	6.20E-04	4.41E-10	2.66E-11	1.30E-13
4-Methylphenol	2.88E-02	0.490	1.17E-03	8.30E-10	5.01E-11	2.46E-13
3-Methylphenol	4.56E-02	0.471	7.09E-04	5.04E-10	3.04E-11	1.49E-13
2,4-Dinitrotoluene	7.64E-02	0.022	1.94E-05	1.38E-11	8.31E-13	4.08E-15
Nitrobenzene	9.52E-02	0.031	2.21E-05	1.57E-11	9.47E-13	4.64E-15
2,4,6-Trichlorophenol	2.47E+00	0.068	1.89E-06	1.34E-12	8.11E-14	3.98E-16
2,4,5-Trichlorophenol	2.65E+00	0.969	2.51E-05	1.78E-11	1.08E-12	5.28E-15
Acrylonitrile	1.79E-04	0.002	9.33E-04	6.63E-10	4.00E-11	1.96E-13
Heavy Semivolatile Organic Compounds (molecular weight > 200 g/mole) Mobile Group						
Pentachlorophenol	***4.74E-01***	***0.228***	***3.37E-05***	***4.16E-09***	***2.07E-10***	***5.22E-14***
Naphthalene	9.52E-01	0.056	4.11E-06	5.07E-10	2.52E-11	6.36E-15
Hexachloroethane	1.42E+00	0.035	1.74E-06	2.15E-10	1.07E-11	2.70E-15
Acenaphthene	3.92E+00	0.056	9.96E-07	1.23E-10	6.12E-12	1.54E-15
Acenaphthylene	5.92E+00	0.058	6.82E-07	8.42E-11	4.19E-12	1.06E-15
Fluorene	6.17E+00	0.055	6.24E-07	7.70E-11	3.83E-12	9.66E-16
Phenanthrene	1.12E+01	0.122	7.65E-07	9.44E-11	4.70E-12	1.18E-15
Anthracene	1.88E+01	0.086	3.21E-07	3.97E-11	1.97E-12	4.98E-16
Fluoranthene	3.93E+01	0.152	2.70E-07	3.33E-11	1.66E-12	4.18E-16
Hexachlorobutadiene	4.30E+01	0.023	3.81E-08	4.70E-12	2.34E-13	5.90E-17
Pyrene	5.44E+01	0.143	1.84E-07	2.27E-11	1.13E-12	2.85E-16

Table 4.10. Maximum predicted concentrations for all chemicals at receptor locations based on DAF for indicator chemical (continued)

Chemical Groups [a]	K_d (L/kg)	Cs: Volume Weighted Average Concentration in Waste (mg/kg or pCi/g)	Leachate Concentration: Above Liner System	Leachate Concentration: Above Water Table	Maximum Concentration in mg/L or pCi/L at X(m)[b]: Property Boundary 407	Maximum Concentration in mg/L or pCi/L at X(m)[b]: Ohio River 3275
Heavy Semivolatile Organic Compounds (molecular weight > 200 g/mole) Less Mobile Group						
Total PAH [Benzo(a)pyrene]	***7.75E+02***	***0.098***	***4.14E-17***	***2.06E-24***	***0.00E+00***	***0***
Dioxins/furans	2.64E+03	0.000005	6.01E-22	2.99E-29	0.00E+00	0
PCBs						
PCB	***2.47E+02***	***0.826***	***2.29E-07***	***5.01E-11***	***2.27E-17***	***0***
Pesticides						
gamma-Chlordane	***4.71E+01***	***0.0019***	***4.96E-13***	***1.25E-17***	***3.41E-29***	***0***
alpha-Chlordane	4.71E+01	0.0019	4.93E-13	1.24E-17	3.39E-29	0
Methoxychlor	6.40E+01	0.0466	8.94E-12	2.25E-16	6.15E-28	0
Heptachlor epoxide	6.66E+01	0.0002	3.03E-14	7.63E-19	2.08E-30	0
Toxaphene	7.66E+01	0.0046	7.43E-13	1.87E-17	5.11E-29	0
INORGANIC COMPOUNDS/METALS						
Highly Mobile Metals						
Chromium	***1.90E+01***	***70.66***	***1.53E+00***	***7.11E-01***	***7.24E-02***	***6.01E-02***
Selenium	*5.00E+00*	*0.2626*	*8.07E-03*	*1.93E-03*	*2.55E-04*	*2.12E-04*
Molybdenum	1.00E+01	3.1530	1.30E-01	6.03E-02	6.14E-03	5.10E-03
Moderately Mobile Metals						
Copper	***3.50E+01***	***319.41***	***1.40E+00***	***4.75E-02***	***3.41E-02***	***1.84E-02***
Barium	4.10E+01	281.50	1.05E+00	3.57E-02	2.57E-02	1.38E-02
Antimony	4.50E+01	1.24	4.23E-03	1.43E-04	1.03E-04	5.54E-05
Manganese	5.00E+01	313.08	9.61E-01	3.26E-02	2.34E-02	1.26E-02
Mercury	5.20E+01	0.07	1.98E-04	6.70E-06	4.81E-06	2.59E-06
Uranium	*6.68E+01*	*157.34*	*8.86E-02*	*1.25E-03*	*1.83E-03*	*3.67E-04*
Zinc	6.20E+01	51.60	1.28E-01	4.33E-03	3.11E-03	1.67E-03
Less Mobile Metals						
Thallium	***7.10E+01***	***0.441***	***2.80E-04***	***7.90E-06***	***5.40E-06***	***6.18E-07***
Cadmium	7.50E+01	0.623	3.75E-04	1.06E-05	7.22E-06	8.27E-07
Silver	9.00E+01	0.885	4.43E-04	1.25E-05	8.55E-06	9.78E-07
Arsenic	*2.00E+02*	*4.2223*	*2.45E-03*	*4.93E-04*	*5.14E-05*	*0*
Iron	*2.20E+02*	*191777.7*	*3.80E+01*	*3.63E-01*	*2.20E-02*	*0.00E+00*
Lead	2.70E+02	16.630	2.78E-03	7.83E-05	5.35E-05	6.13E-06
Nickel	*4.00E+02*	*68986.9*	*3.20E+00*	*4.75E-02*	*1.35E-03*	*0.00E+00*
Beryllium	7.90E+02	0.559	3.19E-05	9.00E-07	6.15E-07	7.04E-08
Vanadium	1.00E+03	41.830	1.89E-03	5.32E-05	3.64E-05	4.16E-06
RADIONUCLIDES						
Highly Mobile Radionuclides						
Technetium-99	***2.00E-01***	***0.704***	***9.38E+01***	***4.91E+01***	***4.89E+00***	***4.07E+00***
Neptunium-237	*7.00E+01*	*0.662*	*3.24E+00*	*1.69E+00*	*1.68E-01*	*1.38E-01*
Less Mobile Radionuclides						
Uranium-238	***6.68E+01***	***5.62E+00***	***1.34E+00***	***1.53E-01***	***5.25E-02***	***3.56E-03***
Uranium-234	6.68E+01	5.58E+00	1.33E+00	1.52E-01	5.21E-02	3.54E-03
Uranium-235	6.68E+01	2.76E-01	6.60E-02	7.53E-03	2.58E-03	1.75E-04
Ra-226	5.00E+02	8.99E-01	2.87E-02	3.27E-03	1.12E-03	7.62E-05
Pu-238	5.50E+02	3.86E-02	1.12E-03	1.28E-04	4.38E-05	2.97E-06
Pu-239	5.50E+02	9.18E-02	2.66E-03	3.04E-04	1.04E-04	7.07E-06
Pu-240	5.50E+02	1.15E-01	3.33E-03	3.81E-04	1.30E-04	8.86E-06

Table 4.10. Maximum predicted concentrations for all chemicals at receptor locations based on DAF for indicator chemical (continued)

Chemical Groups [a]	K_d (L/kg)	Cs: Volume Weighted Average Concentration in Waste (mg/kg or pCi/g)	Leachate Concentration		Maximum Concentration in mg/L or pCi/L at X(m)[b]	
			Above Liner System	Above Water Table	Property Boundary 407	Ohio River 3275
Th-230	3.20E+03	4.54E-01	2.26E-03	2.58E-04	8.85E-05	6.01E-06
Th-232	3.20E+03	1.00E+00	4.98E-03	5.69E-04	1.95E-04	1.32E-05

[a] Chemicals in bold, italic font were selected as indicator chemicals from their group. Chemicals in italic font received chemical-specific modeling after examining results derived using indicator chemicals. Chemical in normal font had concentrations estimated using indicator chemical results.

[b] Maximum concentrations for each chemical are calculated as follows:

$Conc._{Max} = (Cs/K_d)/DAF$.

[c] Radionuclide concentrations are presented in pCi/L; all other analyte concentrations are presented in mg/L.

DAF = dilution attenuation factor.

Kd = distribution coefficient.

PAH = polycyclic aromatic hydrocarbon.

PCB = polychlorinated biphenyl.

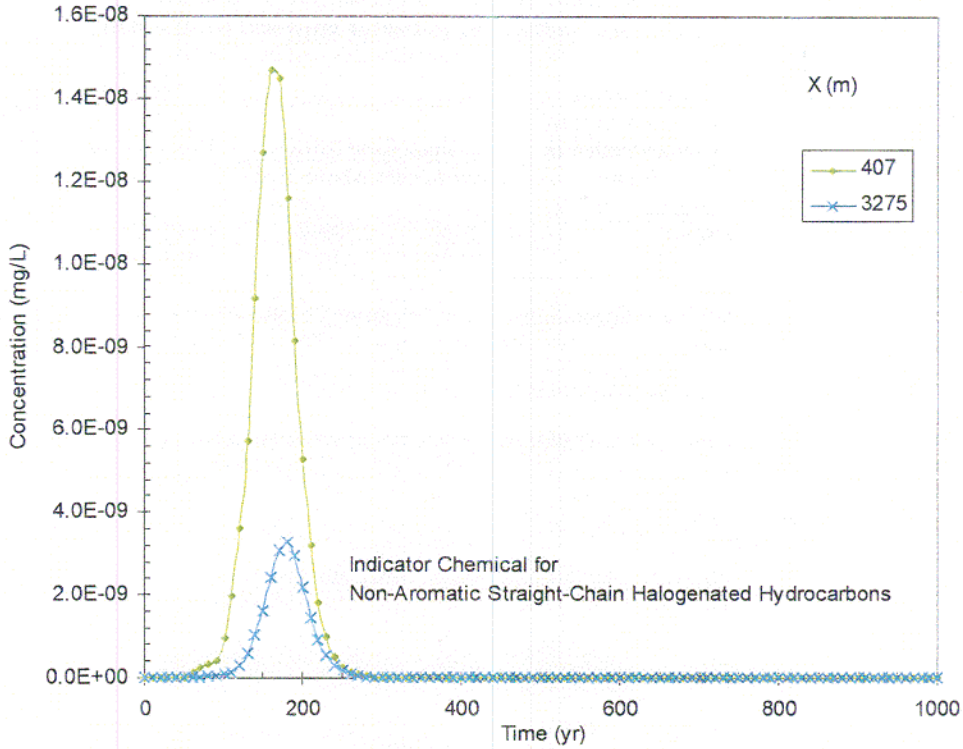


Fig. 4.8. Predicted groundwater concentration of vinyl chloride based on leaching from the C-746-U Landfill waste under the gradual failure scenario.

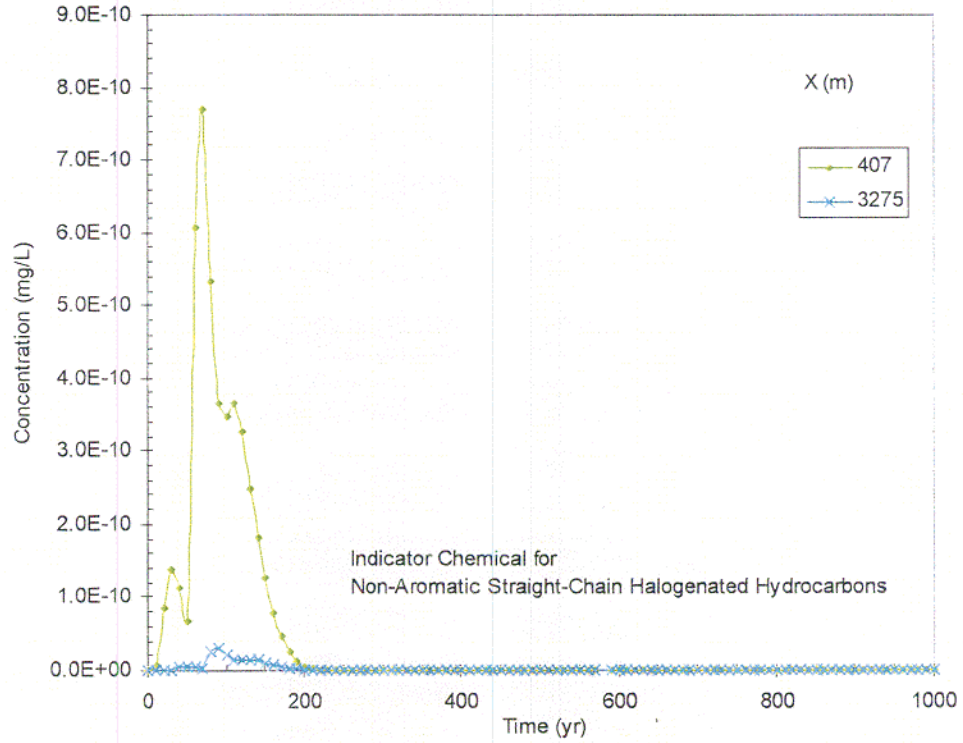


Fig. 4.9. Predicted groundwater concentration of trichloroethene based on leaching from the C-746-U Landfill waste under the gradual failure scenario.

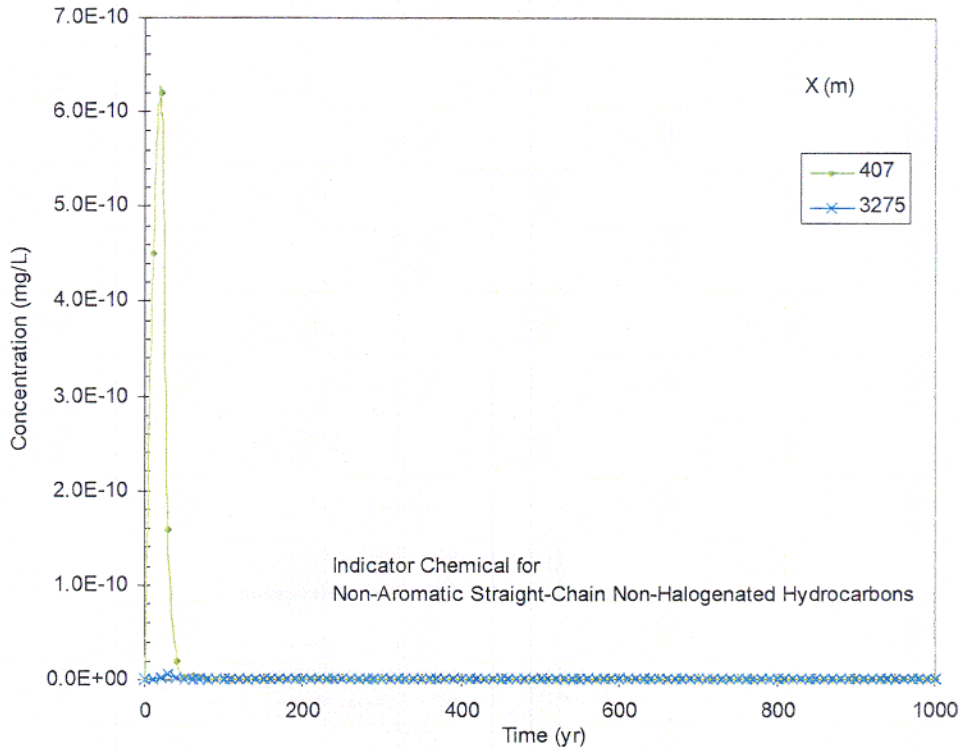


Fig. 4.10. Predicted groundwater concentration of 2-butanone based on leaching from the C-746-U Landfill waste under the gradual failure scenario.

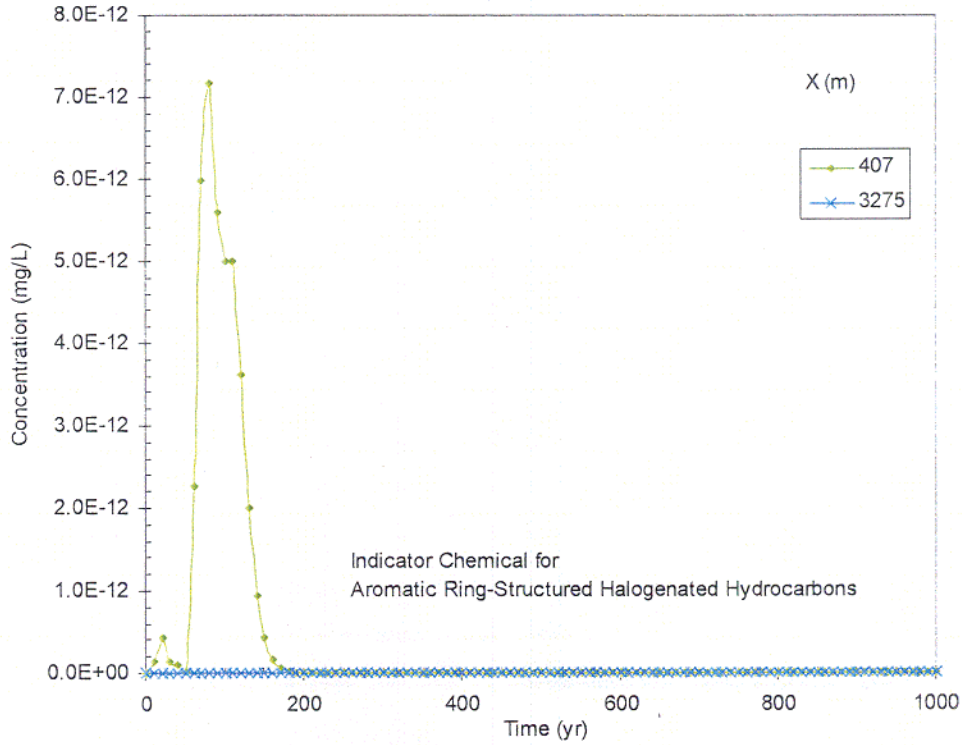


Fig. 4.11. Predicted groundwater concentration of chlorobenzene based on leaching from the C-746-U Landfill waste under the gradual failure scenario.

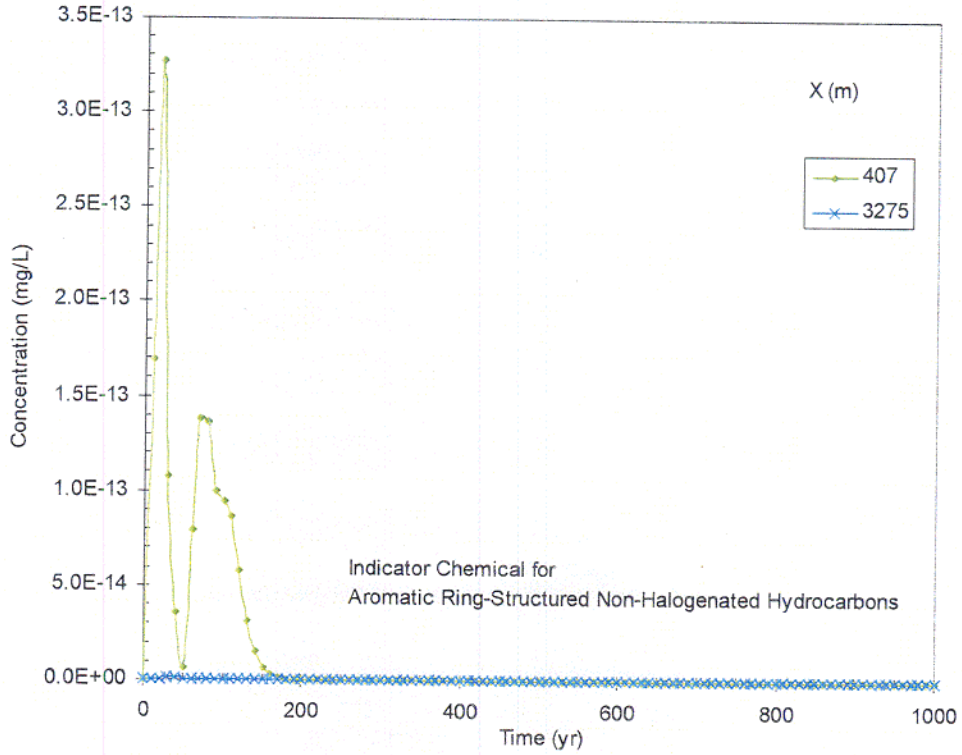


Fig. 4.12. Predicted groundwater concentration of benzene based on leaching from the C-746-U Landfill waste under the gradual failure scenario.

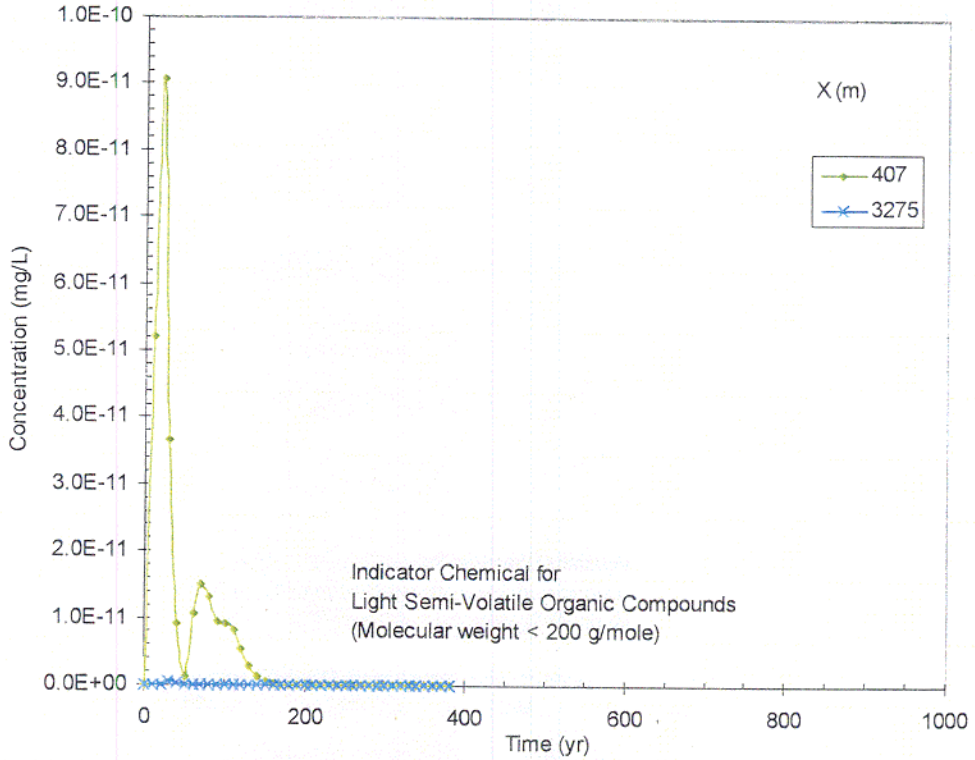


Fig. 4.13. Predicted groundwater concentration of 2-methylphenol based on leaching from the C-746-U Landfill waste under the gradual failure scenario.

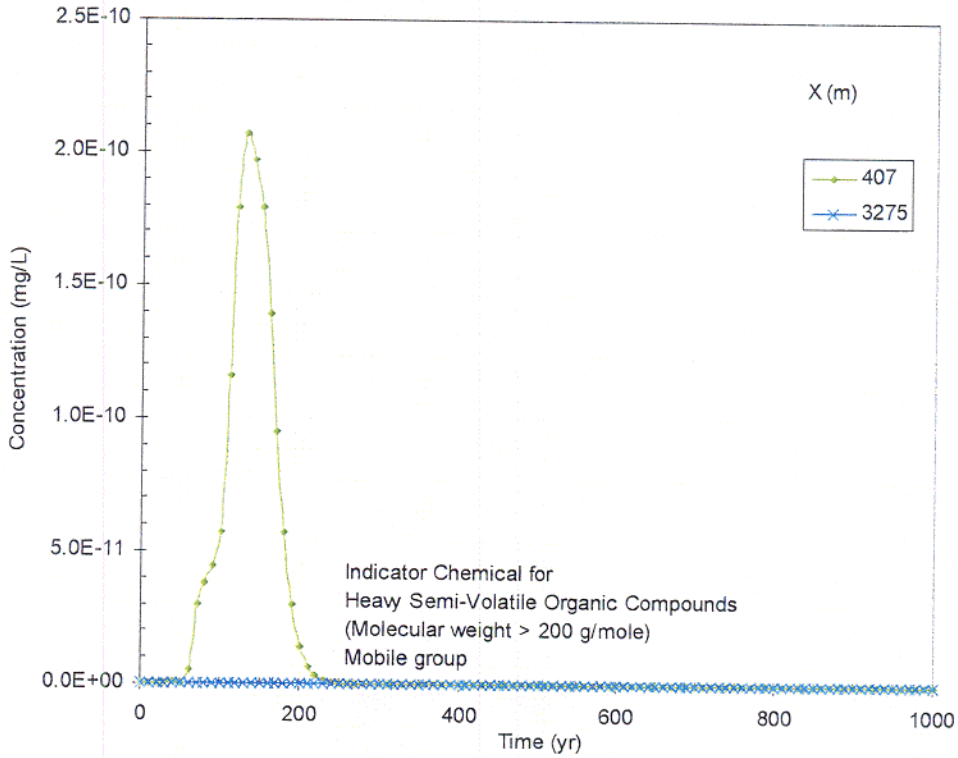


Fig. 4.14. Predicted groundwater concentration of pentachlorophenol based on leaching from the C-746-U Landfill waste under the gradual failure scenario.

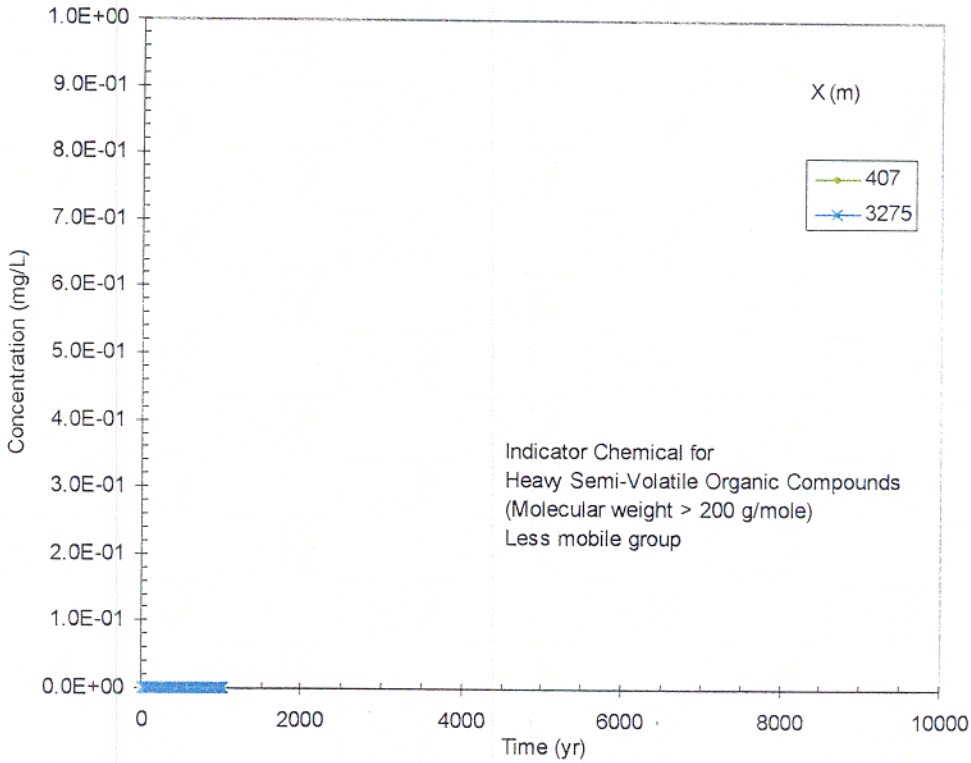


Fig. 4.15. Predicted groundwater concentration of benzo(a)pyrene based on leaching from the C-746-U Landfill waste under the gradual failure scenario.

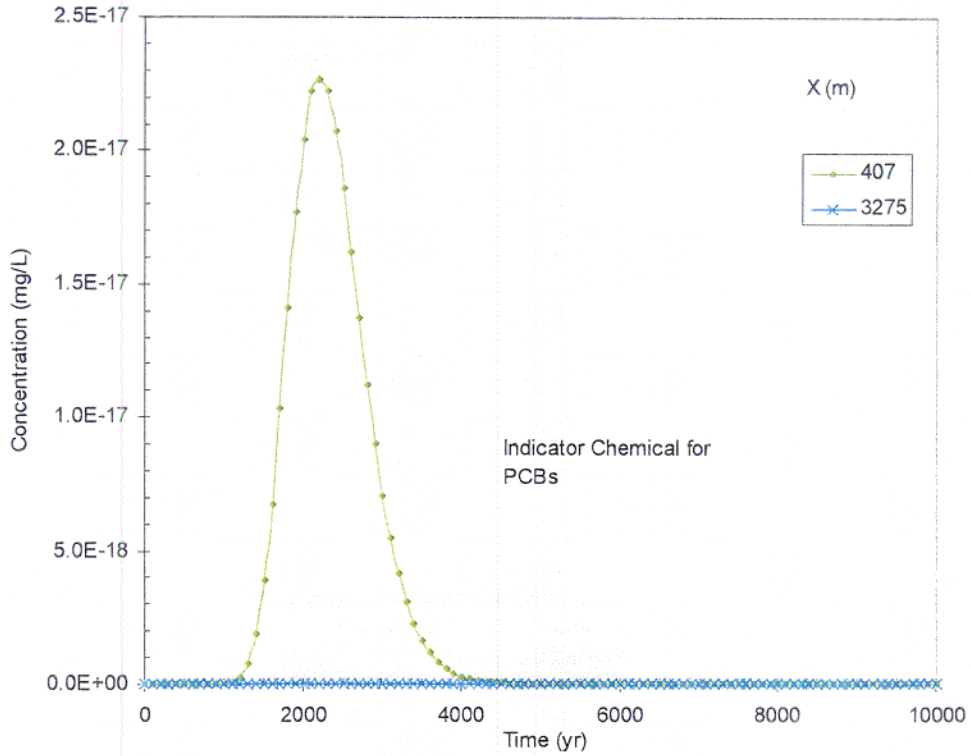


Fig. 4.16. Predicted groundwater concentration of PCBs based on leaching from the C-746-U Landfill waste under the gradual failure scenario.

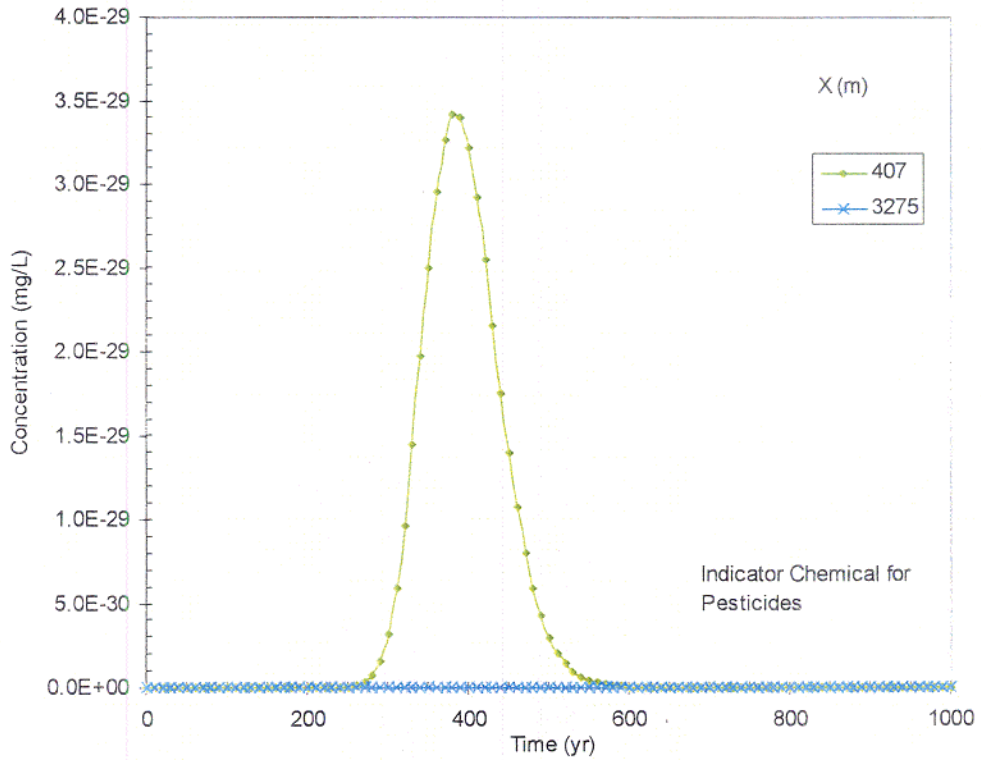


Fig. 4.17. Predicted groundwater concentration of gamma-chlordane based on leaching from the C-746-U Landfill waste under the gradual failure scenario.

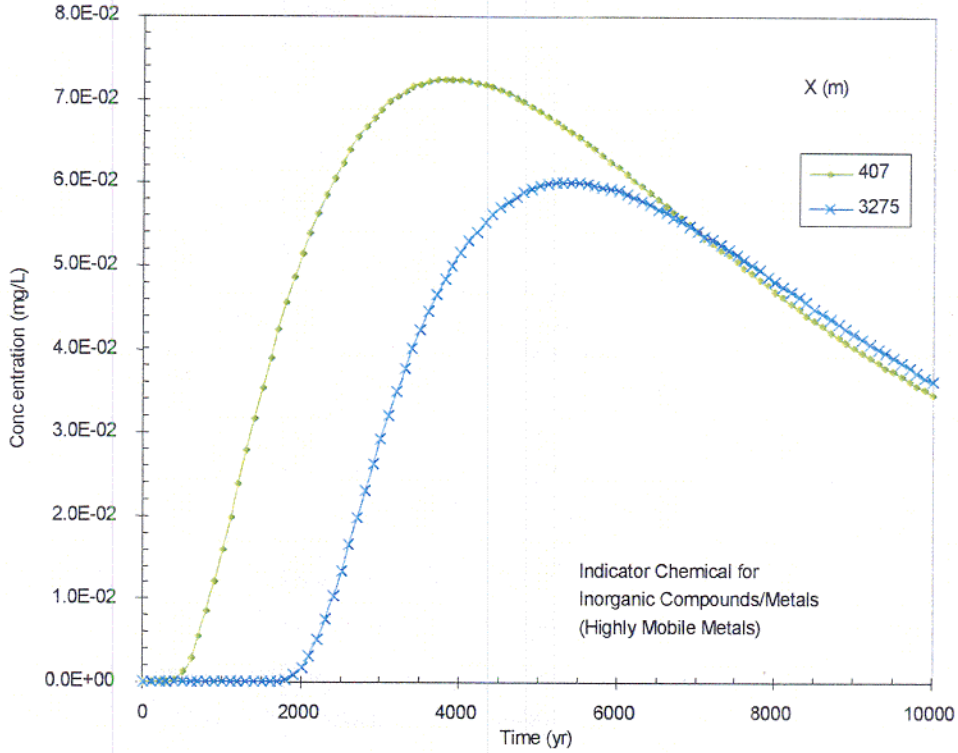


Fig. 4.18. Predicted groundwater concentration of chromium based on leaching from the C-746-U Landfill waste under the gradual failure scenario.

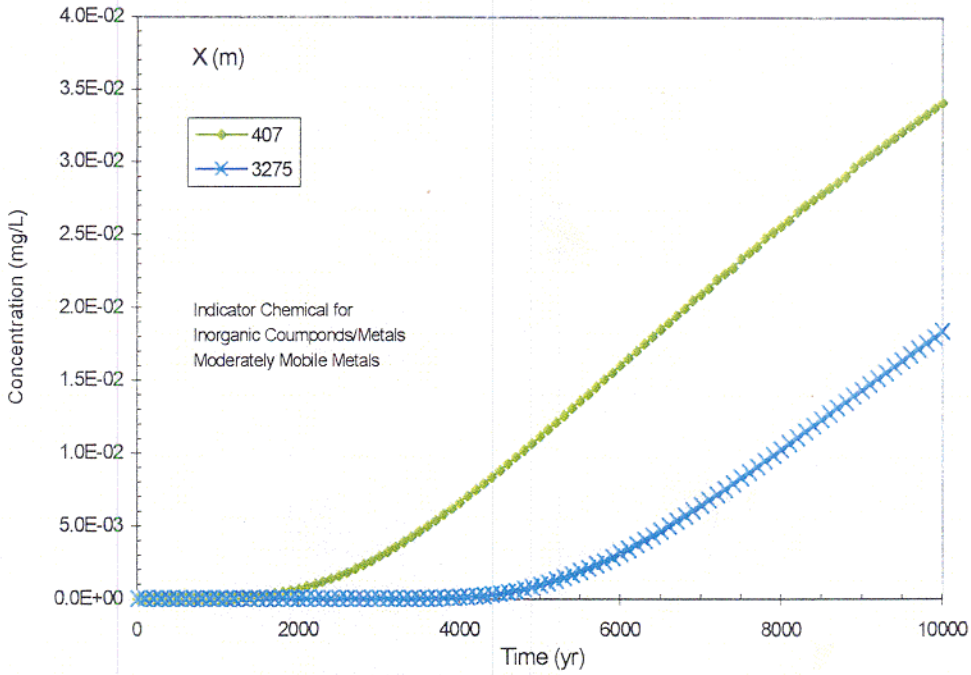


Fig. 4.19. Predicted groundwater concentration of copper based on leaching from the C-746-U Landfill waste under the gradual failure scenario.

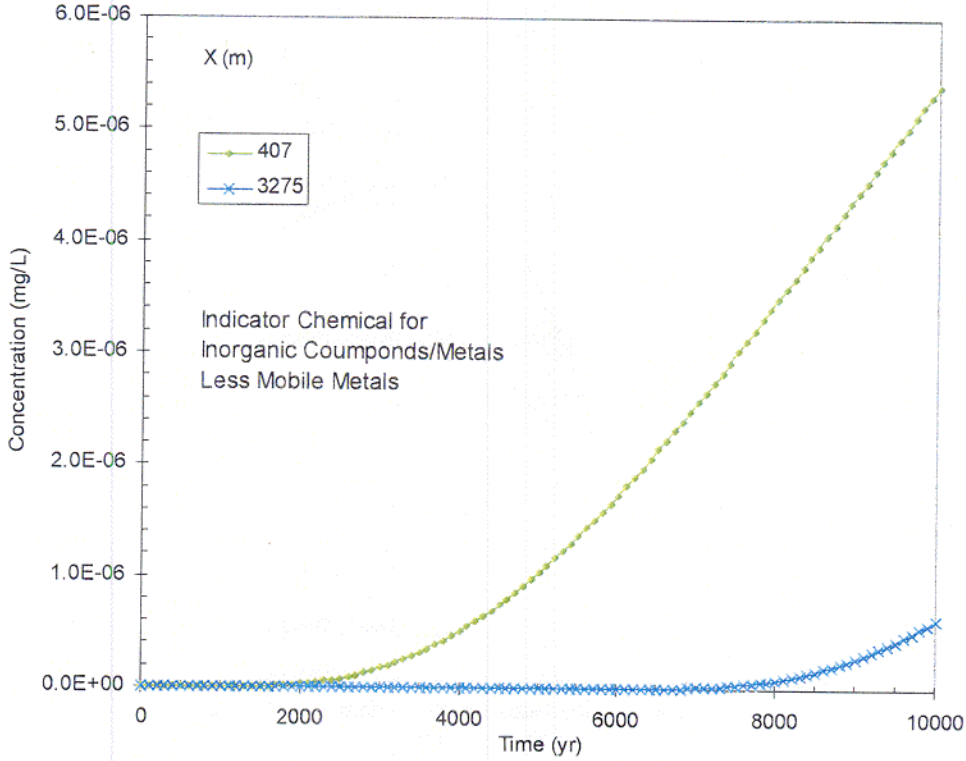


Fig. 4.20. Predicted groundwater concentration of thallium based on leaching from the C-746-U Landfill waste under the gradual failure scenario.

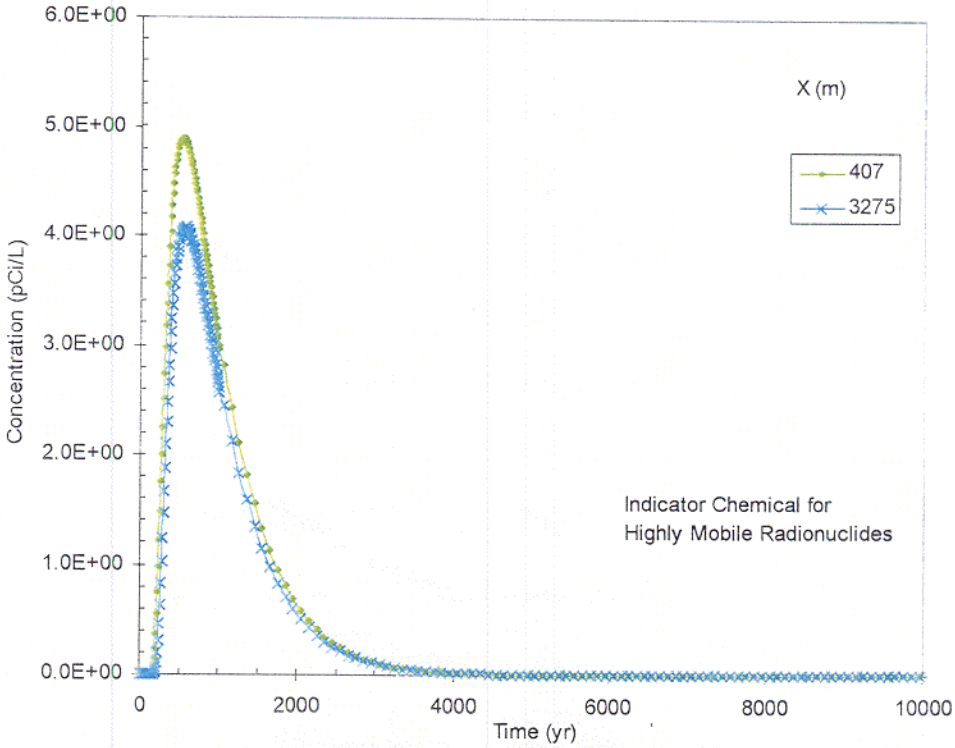


Fig. 4.21. Predicted groundwater concentration of ^{99}Tc based on leaching from the C-746-U Landfill waste under the gradual failure scenario.

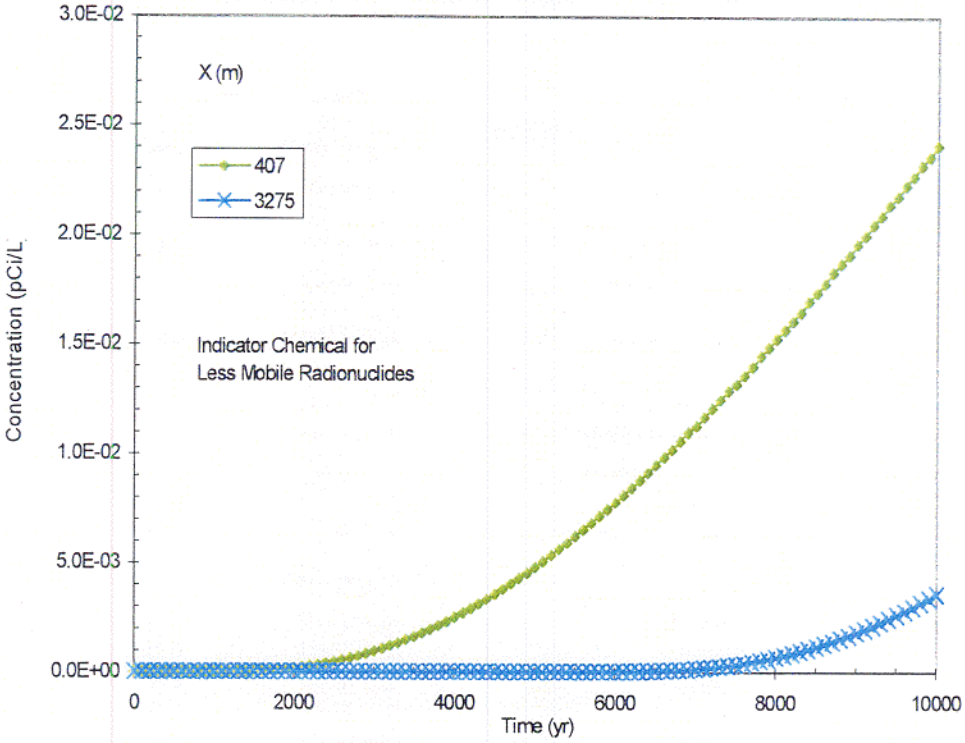


Fig. 4.22. Predicted groundwater concentration of ^{238}U based on leaching from the C-746-U Landfill waste under the gradual failure scenario.

Table 4.11. Summary of surrogate ratios for C-746-U Landfill COPCs

COPCs[a]	Indicator Chemical	K_d (L/kg)	Volume-Weighted Average Concentration (mg/kg or pCi/g)	Surrogate Ratio
Vinyl chloride	***Vinyl chloride***	**1.49E-02**	**6.99E-02**	**1.00E+00**
cis-1,2-Dichloroethene	*Vinyl chloride*	2.84E-02	2.22E-01	1.67E+00
trans-1,2-Dichloroethene	*Vinyl chloride*	3.04E-02	8.40E-02	5.89E-01
1,2-Dichloroethane	*Vinyl chloride*	3.04E-02	3.41E-03	2.39E-02
Chloroform	*Vinyl chloride*	4.24E-02	2.84E-02	1.43E-01
1,1-Dichloroethene	*Vinyl chloride*	5.20E-02	1.40E-02	5.73E-02
1,2-Dichloroethene (mixed isomers)	*Vinyl chloride*	6.20E-02	8.80E-05	3.03E-04
Trichloroethene	***Trichloroethene***	***7.52E-02***	***6.12E-02***	**1.00E+00**
Carbon tetrachloride	*Trichloroethene*	1.22E-01	3.41E-03	3.44E-02
Tetrachloroethene	*Trichloroethene*	2.12E-01	5.25E-03	3.04E-02
2-Butanone	***2-Butanone***	9.20E-04	9.14E-01	1.00E+00
Chlorobenzene	***Chlorobenzene***	***1.79E-01***	***4.56E-01***	**1.00E+00**
1,4-Dichlorobenzene	*Chlorobenzene*	4.93E-01	5.71E-02	4.55E-02
Hexachlorobenzene	*Chlorobenzene*	6.40E+01	2.16E-02	1.33E-04
Benzene	***Benzene***	***4.96E-02***	***4.06E-03***	***1.00E+00***
Ethylbenzene	*Benzene*	1.63E-01	4.29E-03	3.21E-01
xylene mixture	*Benzene*	2.17E-01	4.64E-03	2.61E-01
m-xylene	*Benzene*	1.57E-01	4.64E-03	3.61E-01
p-xylene	*Benzene*	2.49E-01	4.64E-03	2.28E-01
o-xylene	*Benzene*	1.93E-01	4.64E-03	2.94E-01
2-Methylphenol	***2-Methylphenol***	***1.60E-02***	***4.92E-01***	**1.00E+00**
Pyridine	*2-Methylphenol*	3.49E-03	3.15E-02	2.94E-01
4-Methylphenol	*2-Methylphenol*	2.88E-02	4.90E-01	5.53E-01
3-Methylphenol	*2-Methylphenol*	4.56E-02	4.71E-01	3.36E-01
2,4-Dinitrotoluene	*2-Methylphenol*	7.64E-02	2.16E-02	9.18E-03
Nitrobenzene	*2-Methylphenol*	9.52E-02	3.06E-02	1.05E-02
2,4,6-Trichlorophenol	*2-Methylphenol*	2.47E+00	6.81E-02	8.96E-04
2,4,5-Trichlorophenol	*2-Methylphenol*	2.65E+00	9.69E-01	1.19E-02
Acrylonitrile	*2-Methylphenol*	1.79E-04	2.43E-03	4.42E-01
Pentachlorophenol	***Pentachlorophenol***	***4.74E-01***	***2.28E-01***	**1.00E+00**
Naphthalene	*Pentachlorophenol*	9.52E-01	5.58E-02	1.22E-01
Hexachloroethane	*Pentachlorophenol*	1.42E+00	3.54E-02	5.17E-02
Acenaphthene	*Pentachlorophenol*	3.92E+00	5.58E-02	2.95E-02
Acenaphthylene	*Pentachlorophenol*	5.92E+00	5.77E-02	2.02E-02
Fluorene	*Pentachlorophenol*	6.17E+00	5.50E-02	1.85E-02
Phenanthrene	*Pentachlorophenol*	1.12E+01	1.22E-01	2.27E-02
Anthracene	*Pentachlorophenol*	1.88E+01	8.63E-02	9.53E-03
Fluoranthene	*Pentachlorophenol*	3.93E+01	1.52E-01	8.01E-03
Hexachlorobutadiene	*Pentachlorophenol*	4.30E+01	2.34E-02	1.13E-03
Pyrene	*Pentachlorophenol*	5.44E+01	1.43E-01	5.46E-03
Total PAH [Benzo(a)pyrene]	***Total PAH [Benzo(a)pyrene]***	***7.75E+02***	***9.78E-02***	**1.00E+00**
Dioxins/furans	*Total PAH [Benzo(a)pyrene]*	2.64E+03	5.00E-06	1.45E-05
PCB	***PCB***	***2.47E+02***	***8.26E-01***	**1.00E+00**
gamma-Chlordane	***gamma-Chlordane***	***4.71E+01***	***1.89E-03***	**1.00E+00**
alpha-Chlordane	*gamma-Chlordane*	4.71E+01	1.89E-03	1.00E+00
Methoxychlor	*gamma-Chlordane*	6.40E+01	4.66E-02	1.81E+01
Heptachlor epoxide	*gamma-Chlordane*	6.66E+01	1.64E-04	6.14E-02
Toxaphene	*gamma-Chlordane*	7.66E+01	4.63E-03	1.51E+00
Chromium	***Chromium***	***1.90E+01***	***7.07E+01***	***1.00E+00***
Selenium	*Chromium*	5.00E+00	2.63E-01	1.41E-02

Table 4.11. Summary of surrogate ratios for C-746-U Landfill COPCs (continued)

COPCs[a]	Indicator Chemical	K_d (L/kg)	Volume-Weighted Average Concentration (mg/kg or pCi/g)	Surrogate Ratio
Molybdenum	*Chromium*	1.00E+01	3.15E+00	8.48E-02
Copper	***Copper***	***3.50E+01***	***3.19E+02***	***1.00E+00***
Barium	*Copper*	4.10E+01	2.82E+02	7.52E-01
Antimony	*Copper*	4.50E+01	1.24E+00	3.02E-01
Manganese	*Copper*	5.00E+01	3.13E+02	6.86E-01
Mercury	*Copper*	5.20E+01	6.69E-02	1.41E-04
Uranium	*Copper*	*6.68E+01*	*1.57E+02*	*2.58E-01*
Zinc	*Copper*	6.20E+01	5.16E+01	9.12E-01
Thallium	***Thallium***	***7.10E+01***	***4.41E-01***	**1.00E+00**
Cadmium	*Thallium*	7.50E+01	6.23E-01	1.34E+00
Silver	*Thallium*	9.00E+01	8.85E-01	1.58E+00
Arsenic	*Thallium*	2.00E+01	4.22E+00	3.40E+00
Iron	*Thallium*	2.20E+02	1.92E+05	1.40E+05
Lead	*Thallium*	2.70E+02	1.66E+01	9.91E+00
Nickel	*Thallium*	4.00E+02	6.90E+04	2.78E+04
Beryllium	*Thallium*	7.90E+02	5.59E-01	1.14E-01
Vanadium	*Thallium*	1.00E+03	4.18E+01	6.73E+00
Technetium-99	***Technetium-99***	**1.00E+00**	**7.04E-01**	**1.00E+00**
Neptunium-237	*Technetium-99*	5.00E+00	6.62E-01	1.88E-01
Uranium-238	***Uranium-238***	**6.68E+01**	**5.62E+00**	**1.00E+00**
Uranium-234	*Uranium-238*	6.68E+01	5.58E+00	9.93E-01
Uranium-235	*Uranium-238*	6.68E+01	2.76E-01	4.92E-02
Radium-226	*Uranium-238*	5.00E+02	8.99E-01	1.12E-02
Plutonium-238	*Uranium-238*	5.50E+02	3.86E-02	4.37E-04
Plutonium-239	*Uranium-238*	5.50E+02	9.18E-02	1.04E-03
Plutonium-240	*Uranium-238*	5.50E+02	1.15E-01	1.30E-03
Thorium-230	*Uranium-238*	3.20E+03	4.54E-01	8.84E-04
Thorium-232	*Uranium-238*	3.20E+03	1.00E+00	1.95E-03

[a] Italicized, bold chemicals/radionuclides represent the indicator/surrogate chemical/radionuclide from their individual groups. Simple italicized were modeled separately.

COPCs = contaminants of potential concern.

PAH = polycyclic aromatic hydrocarbon.

PCB = polychlorinated biphenyl.

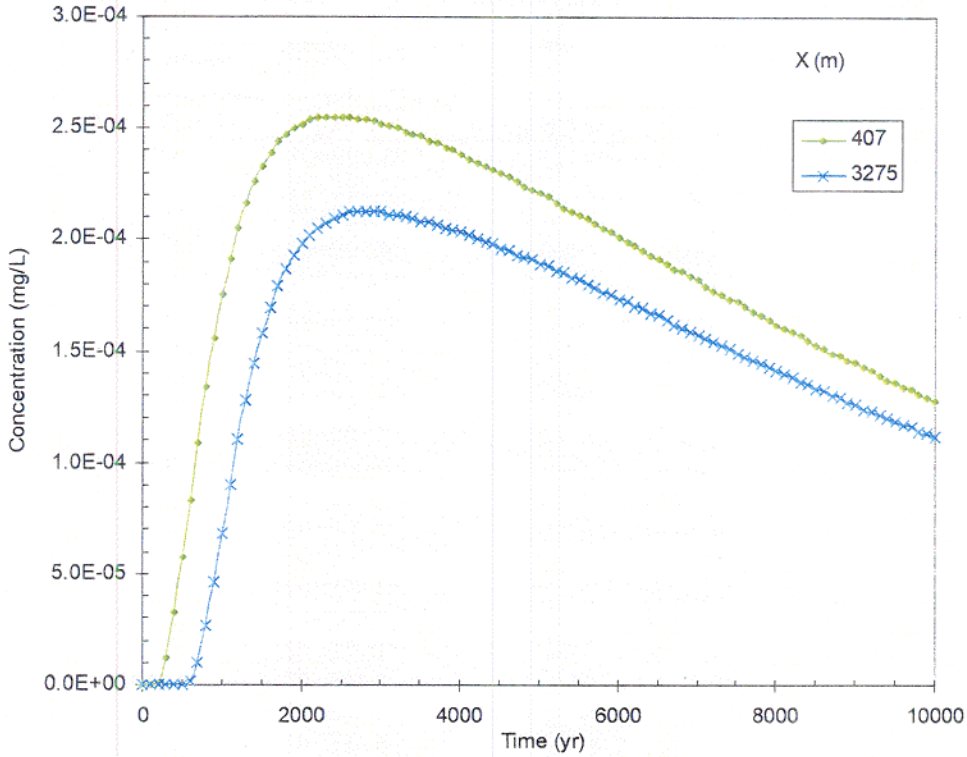


Fig. 4.23. Predicted groundwater concentration of selenium based on leaching from the C-746-U Landfill waste under the gradual failure scenario.

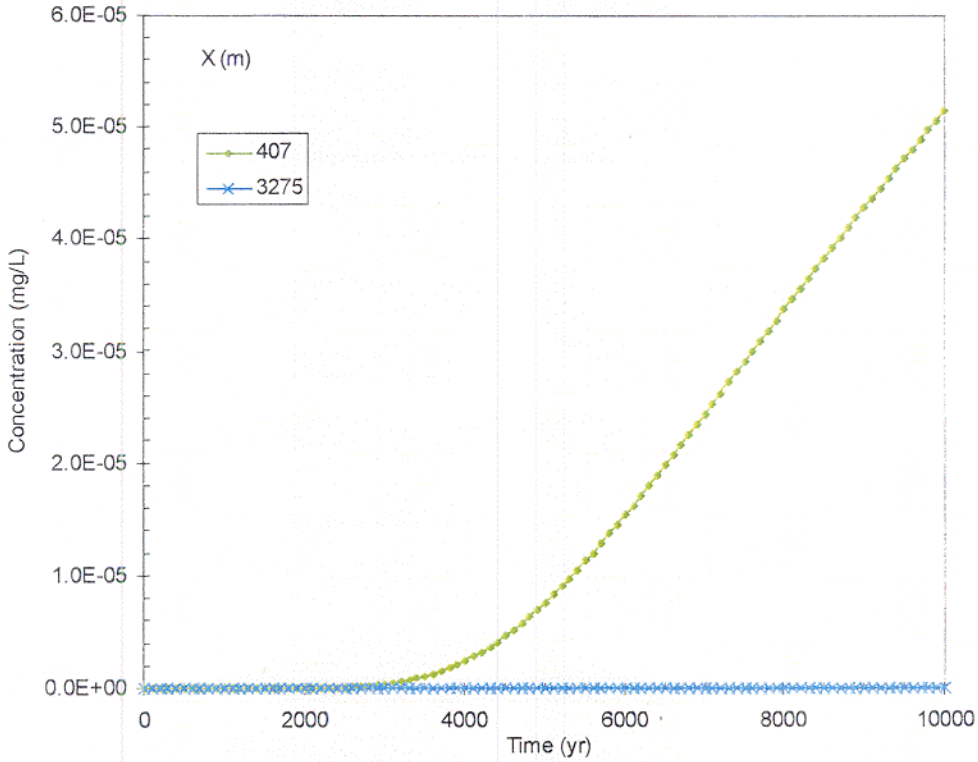


Fig. 4.24. Predicted groundwater concentration of arsenic based on leaching from the C-746-U Landfill waste under the gradual failure scenario.

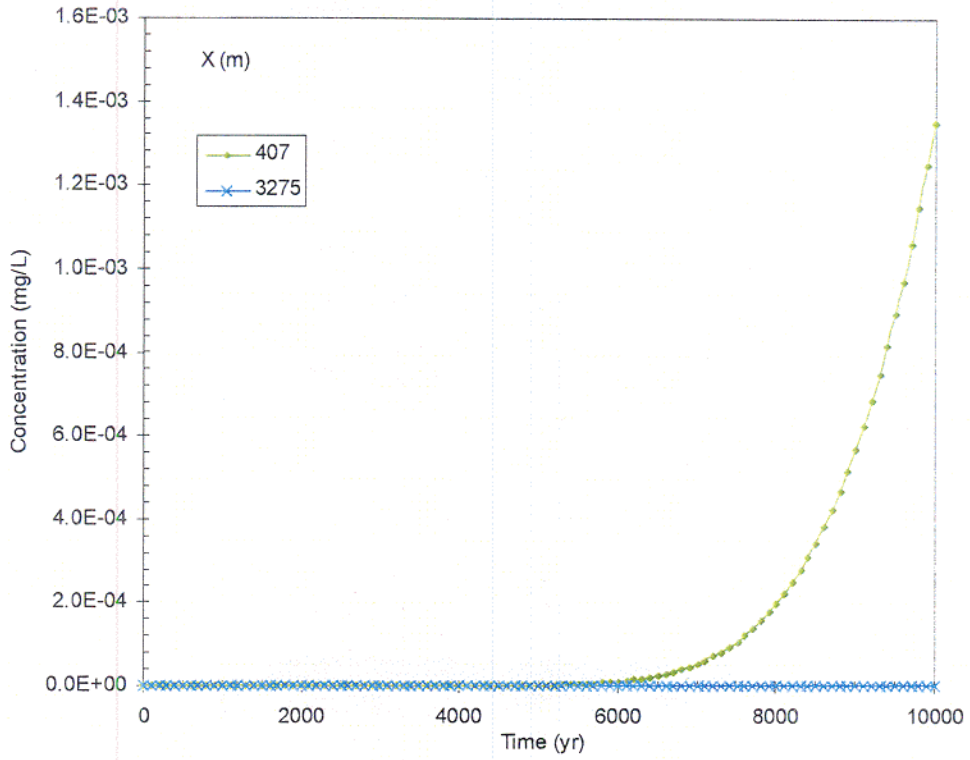


Fig. 4.25. Predicted groundwater concentration of nickel based on leaching from the C-746-U Landfill waste under the gradual failure scenario.

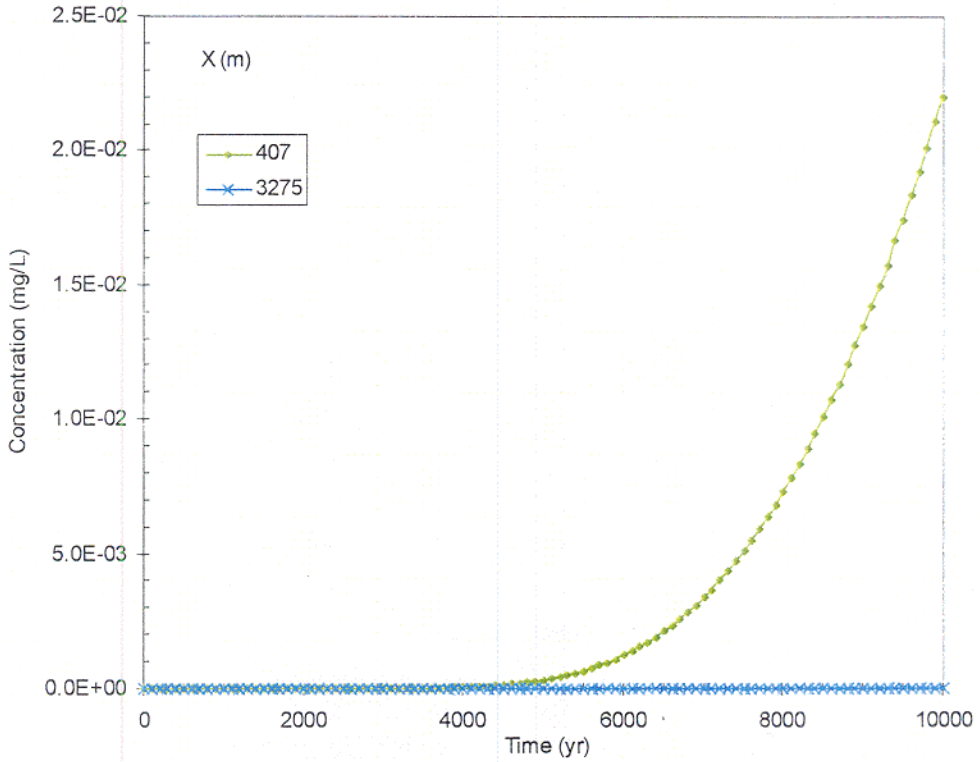


Fig. 4.26. Predicted groundwater concentration of iron based on leaching from the C-746-U Landfill waste under the gradual failure scenario.

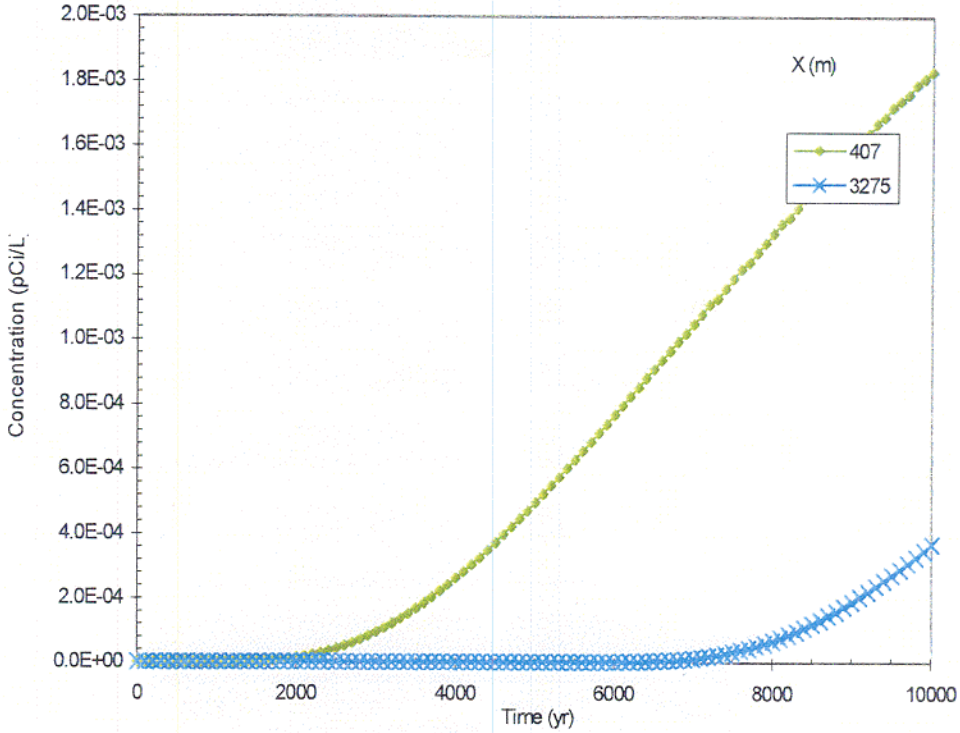


Fig. 4.27. Predicted groundwater concentration of uranium based on leaching from the C-746-U Landfill waste under the gradual failure scenario.

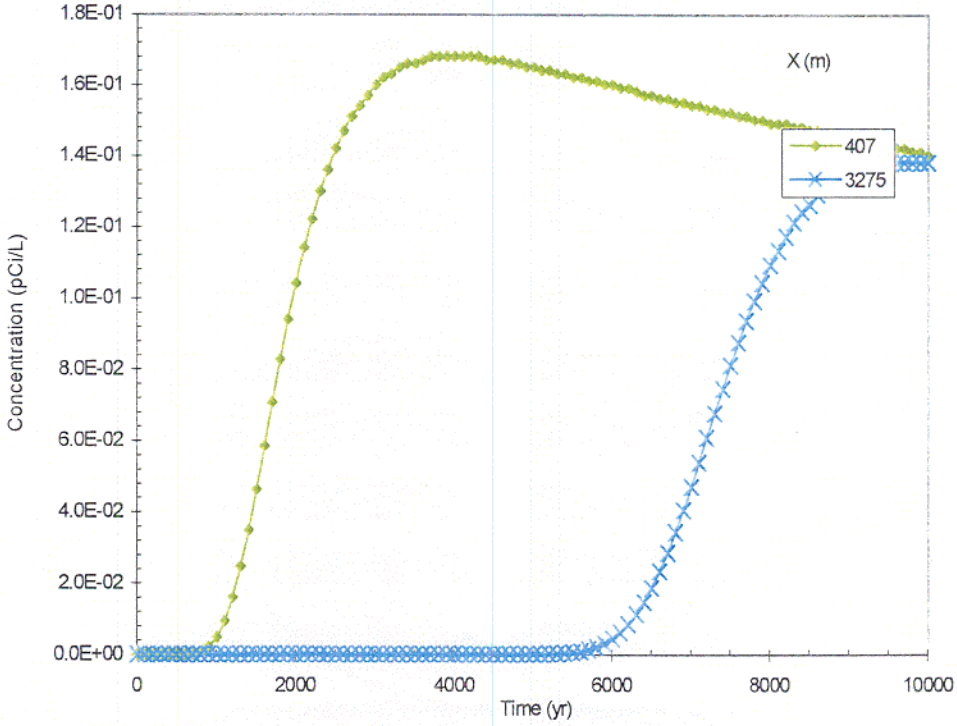


Fig. 4.28. Predicted groundwater concentration of Np-237 based on leaching from the C-746-U Landfill waste for immediate failure scenario.

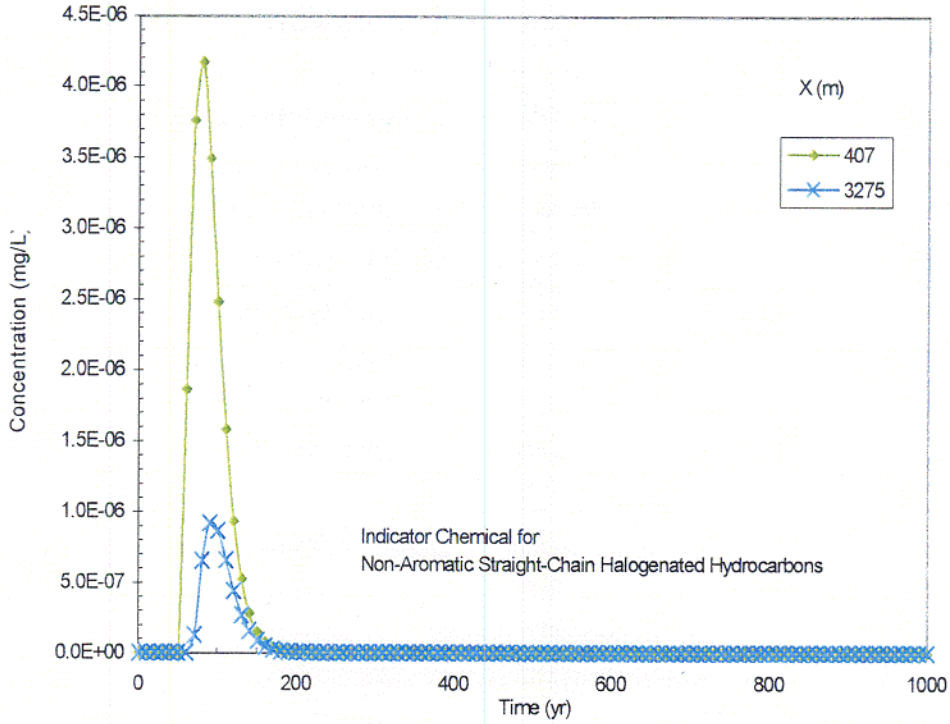


Fig. 4.29. Predicted groundwater concentration of vinyl chloride based on leaching from the C-746-U Landfill waste for immediate failure scenario.

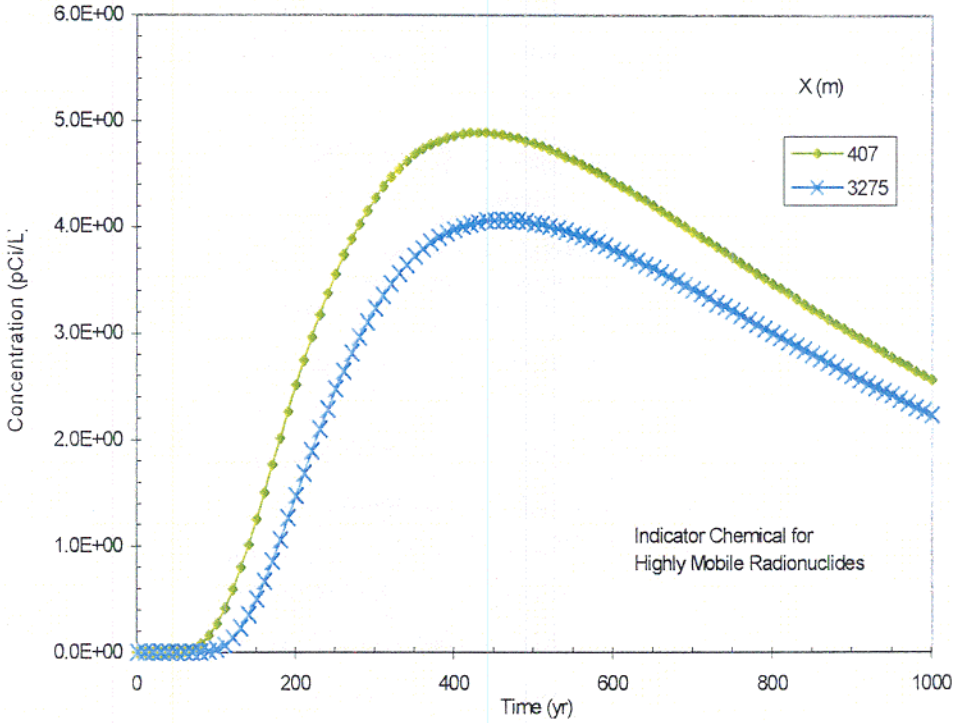


Fig. 4.30. Predicted groundwater concentration of ^{99}Tc based on leaching from the C-746-U Landfill waste for immediate failure scenario.

Table 4.12. Maximum predicted concentrations for all PGDP COPCs at receptor locations based on DAF for indicator chemical[a] immediate failure scenario

Chemical Groups [b]	K_d (L/kg)	Cs: Volume-Weighted Average Concentration in Waste (mg/kg or pCi/g)	Leachate Concentration Above Liner	Leachate Concentration Above Water Table	Maximum Concentration in mg/L or pCi/L at X(m)[b] Property Boundary 407	Maximum Concentration in mg/L or pCi/L at X(m)[b] Ohio River 3275
		Volatile Organic Compounds				
Non-Aromatic, Straight-Chain Halogenated Hydrocarbons (contains fluorine, chlorine, bromine, and iodine)						
Vinyl chloride	***1.49E-02***	***0.0699***	***1.91E-04***	***4.10E-05***	***4.17E-06***	***9.18E-07***
cis-1,2-Dichloroethene	2.84E-02	0.2220	3.18E-04	6.83E-05	6.95E-06	1.53E-06
1,1-Dichloroethene	5.20E-02	0.0140	1.09E-05	2.35E-06	2.39E-07	5.26E-08
trans-1,2-Dichloroethene	3.04E-02	0.0840	1.12E-04	2.41E-05	2.46E-06	5.41E-07
1,2 Dichloroethane	3.04E-02	0.0034	4.56E-06	9.79E-07	9.96E-08	2.19E-08
Chloroform	4.24E-02	0.0284	2.73E-05	5.86E-06	5.96E-07	1.31E-07
1,2-Dichloroethene (mixed isomers)	6.20E-02	0.00009	5.78E-08	1.24E-08	1.26E-09	2.78E-10
		Radionuclides[c]				
Highly Mobile Radionuclides						
Technetium-99	***0.2***	***0.704***	***9.37E+01***	***4.90E+01***	***4.89E+00***	***4.06E+00***

[a] Maximum concentrations for each chemical are calculated as follows:
$Conc._{Max} = (Cs/K_d)/DAF$.
[b] Maximum concentrations for each chemical are calculated as follows:
$Conc._{Max} = (Cs/K_d)/DAF$.
[c] Radionuclide concentrations are presented in pCi/L; all other analyte concentrations are presented in mg/L.
COPCs = contaminants of potential concern.
DAF = dilution attenuation factor.
PGDP = Paducah Gaseous Diffusion Plant.

Table 4.13. Maximum predicted concentrations for all PGDP COPCs at receptor locations based on DAF for indicator chemical for No Failure Scenario

Chemical Groups[a]	K_d (L/kg)	Cs: Volume-Weighted Average Concentration in Waste (mg/kg or pCi/g)	Leachate Concentration Seep	Leachate Concentration Above Water Table	Maximum Concentration in mg/L or pCi/L at X(m)[b] Property Boundary 407	Maximum Concentration in mg/L or pCi/L at X(m)[b] Ohio River 3275
		Volatile Organic Compounds				
Non Aromatic Straight-Chain Halogenated Hydrocarbons (contains fluorine, chlorine, bromine, and iodine)						
Vinyl chloride	***1.49E-02***	***0.0699***	***9.69E-06***	***1.03E-09***	***4.37E-11***	***1.12E-11***
cis-1,2-Dichloroethene	2.84E-02	0.2220	1.61E-05	1.72E-09	7.28E-11	1.87E-11
1,1-Dichloroethene	5.20E-02	0.0140	5.55E-07	5.90E-11	2.50E-12	6.42E-13
trans-1,2-Dichloroethene	3.04E-02	0.0840	5.71E-06	6.07E-10	2.57E-11	6.60E-12
1,2 Dichloroethane	3.04E-02	0.0034	2.31E-07	2.46E-11	1.04E-12	2.67E-13
Chloroform	4.24E-02	0.0284	1.39E-06	1.47E-10	6.25E-12	1.60E-12
1,2-Dichloroethene (mixed isomers)	6.20E-02	0.00009	2.93E-09	3.12E-13	1.32E-14	3.39E-15
		Inorganic Compounds/Metals				
Highly Mobile Metals						
Chromium	***1.90E+01***	***70.66***	***1.54E-01***	***1.56E-04***	***3.93E-06***	***2.06E-06***
Selenium	5.00E+00	0.2626	2.17E-03	2.20E-06	5.55E-08	2.91E-08
Molybdenum	1.00E+01	3.1530	1.31E-02	1.32E-05	3.33E-07	1.75E-07
		Radionuclides[c]				
Highly Mobile Radionuclides						
Technetium-99	***2.00E-01***	***0.704***	***3.38E+01***	***3.94E+00***	***4.27E-02***	***3.30E-02***
Neptunium-237+D	7.00E+01	0.662	4.54E-01	5.29E-02	5.74E-04	4.43E-04

[a] Chemicals in bold, italic font were selected as indicator chemicals from their group. Chemicals in italic font received chemical-specific modeling after examining results derived using indicator chemicals. Chemical in normal font had concentrations estimated using indicator chemical results.
[b] Maximum concentrations for each chemical are calculated as follows:
$Conc._{Max} = (Cs/K_d)/DAF$
[c] Radionuclide concentrations are presented in pCi/L; all other analyte concentrations are presented in mg/L

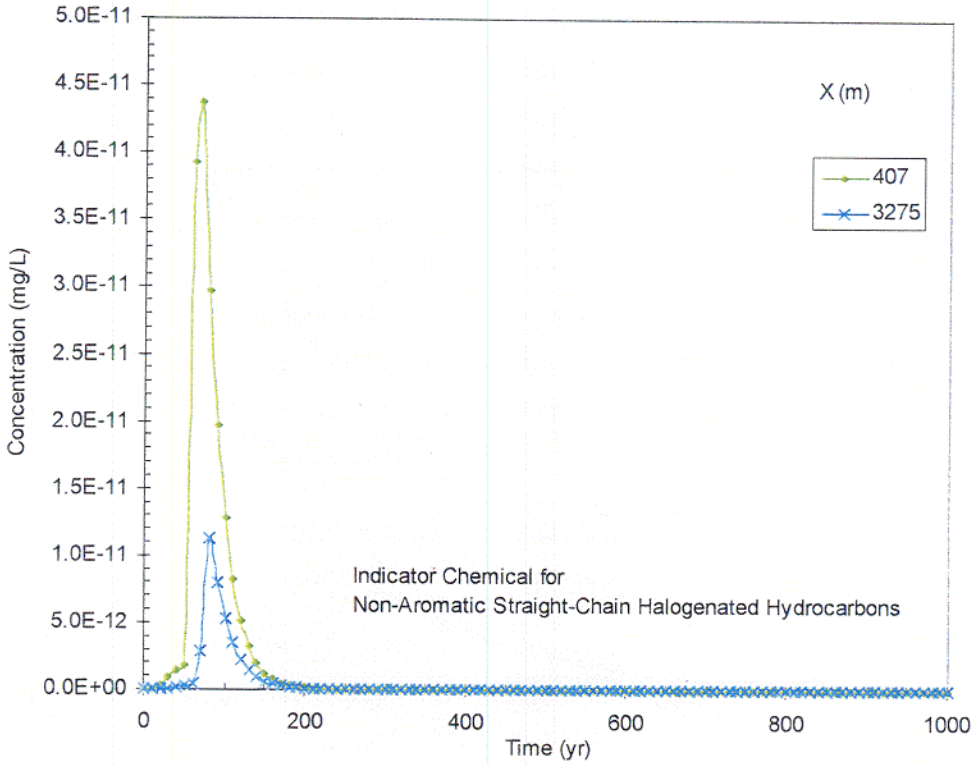


Fig. 4.31. Predicted groundwater concentration of vinyl chloride based on leaching from the C-746-U Landfill waste under the no failure scenario.

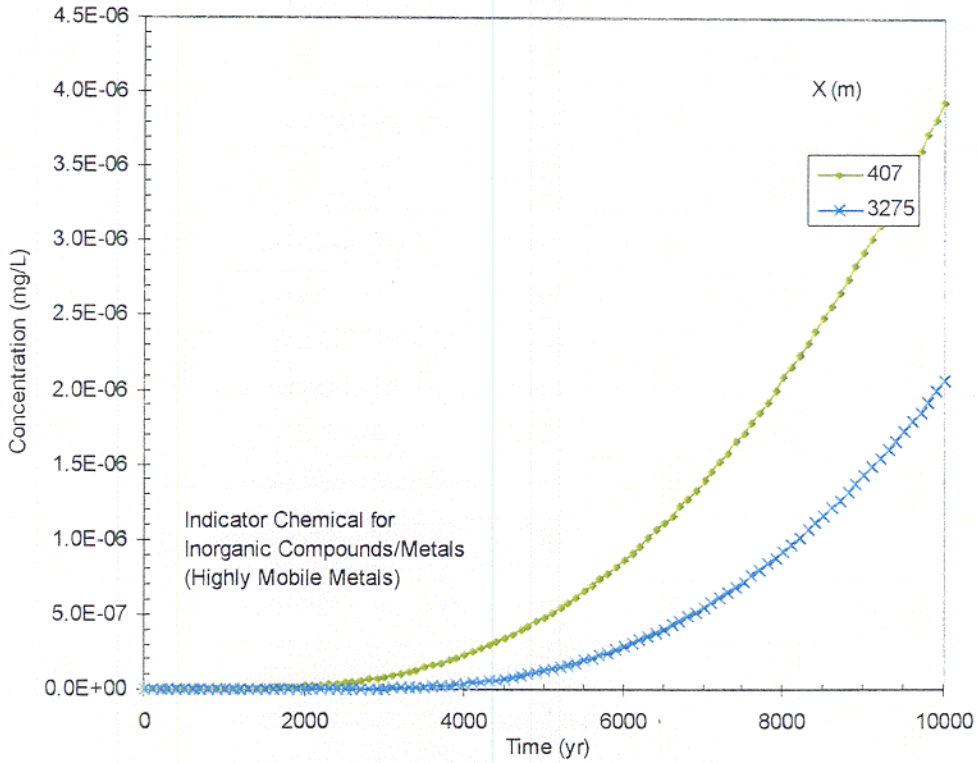


Fig. 4.32. Predicted groundwater concentration of chromium based on leaching from the C-746-U Landfill waste under the no failure scenario.

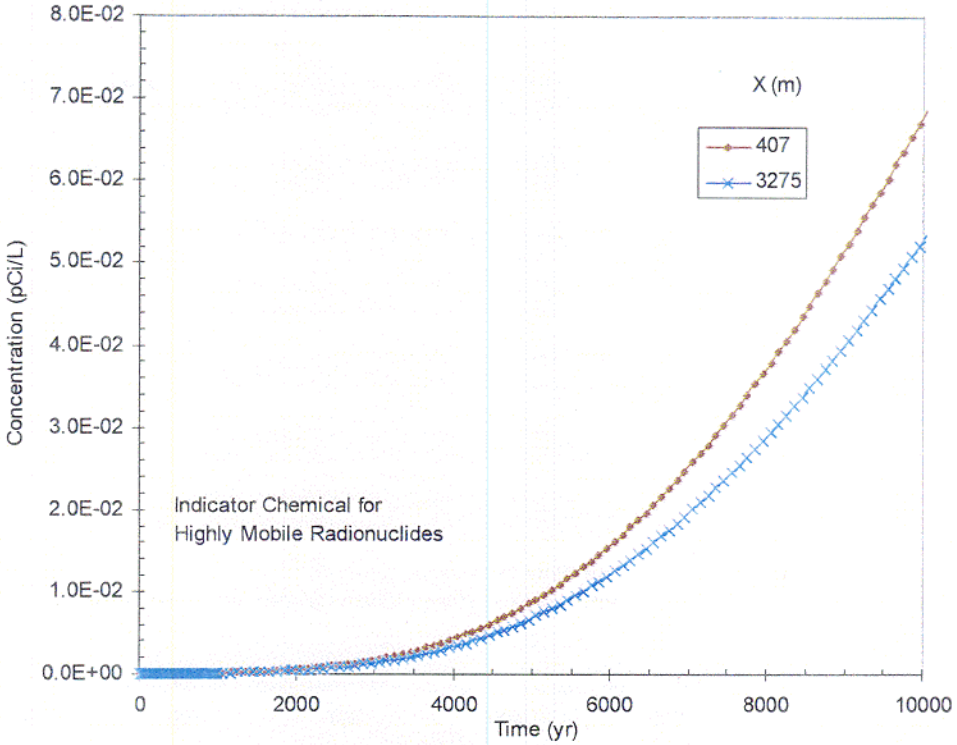


Fig. 4.33. Predicted groundwater concentration of ^{99}Tc based on leaching from the C-746-U Landfill waste under the no failure scenario.