#4033

PROJECT TASK 6

Health Studies on ROCKY FLATS

PHASE I: HISTORICAL PUBLIC EXPOSURES

R E P O R T

Exposure Pathway Identification & Transport Modeling

MAY 1994

ChemRisk

Colorado Department of Public Health and Environment

Prepared by ChemRisk for the Colorado Department of Public Health and Environment

PROJECT TASK 6 REPORT
EXPOSURE PATHWAY IDENTIFICATION AND TRANSPORT MODELING

MAY 1994

Prepared for:

Colorado Department of Health
Health Studies on Rocky Flats, A-3
4300 Cherry Creek Drive South
Denver, CO 80220
(303) 692-2640 or 692-2700

Prepared by:

ChemRisk®
A Division of McLaren/Hart
1135 Atlantic Avenue
Alameda, CA 94501

This document was prepared as a team effort by the following ChemRisk employees:

Project Manager:

Stephen R. Ripple, Chief Health Scientist

Administrative Support:

Angélica Perea

Principal Authors:

Gregory P. Brorby, Senior Health Scientist

Dante diTommaso, Assistant Health Scientist

Thomas R. Mongan, Principal Environmental Scientist

David Ting, Senior Associate Health Scientist

Thomas E. Widner, Principal Environmental Scientist

TABLE OF CONTENTS

PROJECT BACKGROUND 1

REFERENCES 8

EXECUTIVE SUMMARY 9

REFERENCES 15

1.0 INTRODUCTION 17

1.1 Exposure Pathway Identification 18
1.2 Environmental Transport and Exposure Modeling 18

REFERENCES 19

2.0 EXPOSURE PATHWAY IDENTIFICATION 21

2.1 Identification of Complete Exposure Pathways 21
2.1.1 Air 22
2.1.2 Surface Water 24
2.1.3 Soil and Sediment 25
2.1.4 Groundwater 26
2.1.5 Mother's Milk 28
2.1.6 Summary — Exposure Pathway Selection 29

2.2 Qualitative Evaluation of Complete Exposure Pathways 29

2.2.1 Air 29
2.2.2 Surface Water 31
2.2.3 Soil/Sediment 33
2.2.4 Summary—Qualitative Evaluation of Complete Exposure Pathways 34

REFERENCES 36

3.0 ENVIRONMENTAL TRANSPORT MODELING 39

3.1 Air Dispersion Models and Uncertainty 39
3.2 Releases from Exhaust Filter Plenums 40

3.2.1 Release Estimates 40
3.2.2 Prediction of Airborne Contaminant Concentrations 42

TABLE OF CONTENTS
(Continued)

3.2.3 Uncertainty in Prediction of Airborne Contaminant Concentrations from Filter Plenum Exhaust 43
3.2.4 Prediction of the Deposition of Airborne Contaminants 49
3.2.5 Uranium Release January 24, 1956 51

3.3 Surface-Water-Borne Releases 55
3.4 Nonroutine Contaminant Releases 56

3.4.1 903 Pad Release 57

3.4.1.1 Environmental Monitoring Data 60
3.4.1.2 FDM Modeling of 903 Pad Release Period 73
3.4.1.3 Modeling Results 81

3.4.2 1957 Fire 92

3.4.2.1 1957 Fire Chronology 93
3.4.2.2 Meteorological Data 96
3.4.2.3 Environmental Monitoring Data 98
3.4.2.4 1957 Fire Release Estimating Procedure 108
3.4.2.5 Other Estimates of the 1957 Fire Release 134

3.4.3 1969 Fire 139

3.4.3.1 1969 Fire Chronology 140
3.4.3.2 Meteorological Data 141
3.4.3.3 Environmental Monitoring Data 142
3.4.3.4 1969 Fire Release Estimating Procedure 144
3.4.3.5 Other Estimates of the 1969 Fire Release 157

3.4.4 Burning of Uranium-Contaminated Oil 159

3.5 Resuspension 163

3.5.1 Resuspension of 903 Pad Contamination after 1969 171
3.5.2 Resuspension from Contaminated Sediments 171

3.6 Relative Importance of Releases 173

REFERENCES 177

TABLE OF CONTENTS
(Continued)

APPENDICES

APPENDIX A	Tritium Exposure Modeling
APPENDIX B	Rationale for Selecting Complete Exposure Pathways
APPENDIX C	Groundwater Evaluation
APPENDIX D	Relative Comparison of Pathways for Volatile Compounds
APPENDIX E	Air Dispersion Computer Models
APPENDIX F	Meteorological Data
APPENDIX G	Uncertainty Analysis
APPENDIX H	Information Supporting 903 Pad Release During 1968 and 1969
APPENDIX I	Soil and Air Sampling Information Related to the 903 Pad
APPENDIX J	Creating a Site Map of Soil Contamination Data
APPENDIX K	Data Relative to Soil Particle Size Distribution for 903 Pad Evaluation
APPENDIX L	Studies of Plutonium Concentration as a Function of Soil Particle Size for 903 Pad Evaluation
APPENDIX M	High Readings in the S-8 Air Sampler—November 1968 - January 1969
APPENDIX N	Plume Rise Sensitivity Analysis
APPENDIX O	Background Data on the 1969 Fire
APPENDIX P	Comments and Responses Concerning the Draft Phase I Task 6 Report

UNIT CONVERSION TABLE
GLOSSARY

LIST OF FIGURES

Figure		Page
1	Tasks of the Rocky Flats Toxicologic Review and Dose Reconstruction Project	2
2-1	Elements of a Complete Exposure Pathway	21
3-1	Air Modeling Approach - Routine Releases	41
3-2	Site Map, Rocky Flats	44
3-3	Predicted Annual Average Air Concentrations for a Unit Release of Plutonium or Americium (fCi m^{-3})	45
3-4	Predicted Annual Average Air Concentrations for a Unit Release of Uranium (fCi m^{-3})	46

LIST OF FIGURES
(Continued)

Figure		Page
3-5	Predicted Annual Average Air Concentrations for a Unit Release of Tritium (fCi m^{-3})	47
3-6	Annual Average Air Concentrations for a Unit Release of Beryllium or Volatile Chemical (pg m^{-3})	48
3-7	Predicted Annual Deposition for a Unit Release of Plutonium (mCi km^{-2})	52
3-8	Predicted Annual Deposition for a Unit Release of Uranium (mCi km^{-2})	53
3-9	Predicted Cumulative Deposition from a 30 mCi Release of Plutonium Over 37	54
3-10	Air Modeling Approach - Non-Routine Releases (Accidents)	58
3-11	Soil-Sampling Sites in the Vicinity of Rocky Flats	62
3-12	Polygons Enclosing Sampling Locations Where Measured Contamination Exceeded 10, 50, 100 or 500 mCi km^{-2}	68
3-13	CDH Sectors with CCEI/DOE Sampling Points	70
3-14	Rocky Flats Air Samplers at Rocky Flats	72
3-15	Rocky Flats 903 Pad Modeling Procedure	79
3-16	Estimate of Plutonium Release Outside the Buffer Zone from the 903 Pad	84
3-17	Total Deposition of Plutonium from the 903 Pad Predicted by the Fugitive Dust Model (mCi km^{-2})	85
3-18	Predicted 5-Year Average Air Concentrations of Plutonium on Respirable Particles Released from the 903 Pad (fCi m^{-3})	88
3-19	Vegetation Sampling Data—Post 1957 Fire (dis min^{-1} kg^{-1})	106
3-20	Predicted 13.5-Hour Average Air Concentrations for Plutonium Released During the 1957 Fire (pCi m^{-3})	121
3-21	Fine-Particle Deposition of Plutonium from the 1957 Fire (mCi km^{-2})	122
3-22	1957 Fire Plutonium Release Estimate and Associated Uncertainty	125
3-23	Vegetation Sampling Data—Post 1957 Fire (10^{-3} mCi km^{-2})	128
3-24	Coarse-Particle Deposition of Plutonium from the 1957 Fire (10^{-3} mCi km^{-2})	130
3-25	S-8 Sampler Activity for March, April, and May of 1969	148
3-26	Measured and Predicted Airborne Plutonium Concentrations After the 1969 Fire - Original Meteorological Data	151
3-27	Measured and Predicted Airborne Plutonium Concentrations After the 1969 Fire - Smoothed Meteorological Data	153
3-28	Predicted 17.5-Hour Average Air Concentration Isopleths for Plutonium Released During the 1969 Fire (pCi m^{-3})	154
3-29	Deposition of Plutonium from the 1969 Fire (mCi km^{-2})	155
3-30	1969 Fire Release Estimate and Associated Uncertainty	158
3-31	Oil Burn Pit Locations	160

LIST OF FIGURES
(Continued)

Figure		Page
3-32	Predicted 4-Hour Average Air Concentrations for Uranium Release from the Oil Burn Pits (pCi m^{-3})	162
3-33	Predicted Long-Term Average Air Concentrations of Plutonium on Respirable Particles Associated with Resuspension Following 903 Pad Closure (fCi m^{-3})	165
3-34	Predicted Time-Integrated Air Concentrations for a 30 mCi Release of Plutonium Over 37 Years (μCi sec m^{-3})	175

LIST OF TABLES

Table		Page
1	Contaminants Identified for Quantitative Evaluation	5
1-1	Materials of Concern for the Dose Reconstruction Project	17
2-1	Complete Exposure Pathways Associated with the Air Medium	23
2-2	Complete Exposure Pathways Associated With the Surface Water Medium	25
2-3	Complete Exposure Pathways Associated with the Soil Medium	26
2-4	Milk Transfer Coefficient for the Metals of Concern	28
2-5	Complete Exposure Pathways for the Materials of Concern	30
2-6	Fish Bioconcentration Factors for the Metals of Concern	33
2-7	Potentially Important Pathways for the Materials of Concern	35
3-1	Comparison of CDH Sampling Data (1970-1977) to 1969-1973 Data Set	71
3-2	Comparison of Observed Concentration Ratios to Predicted Concentration Ratios	81
3-3	Comparison of 1969-1973 Soil Data Set to Sector-Averaged Plutonium in Soil Concentration Predicted by the FDM	86
3-4	Summary of 903 Pad Plutonium Estimates	92
3-5	Stability Class Based on Windspeed and Cloud Cover	97
3-6	Stability Class Based on Windspeed and Solar Radiation	97
3-7	Routine Air Monitoring Data During the 1957 Fire	99
3-8	Air Sampling Data from Portable Samplers During the 1957 Fire	100
3-9	Upper-Bound and Best Estimates of Average Air Concentrations At Routine Sampling Locations During the 1957 Fire	114

LIST OF TABLES
(Continued)

Table		Page
3-10	Upper-Bound and Best Estimates of Average Air Concentrations at Portable High Volume Samplers During the 1957 Fire	115
3-11	Comparison of Upper-Bound and Best Estimate Airborne Concentrations During the 1957 Fire to Predicted Airborne Concentrations—Routine Air Samplers	118
3-12	Comparison of Upper-Bound and Best Estimate Airborne Concentrations During the 1957 Fire to Predicted Airborne Concentrations—Portable High Volume Samplers	120
3-13	Comparison of Measured Deposition Following the 1957 Fire to Predicted Deposition of Plutonium from Coarse Particle Release	131
3-14	Release Rates of Plutonium at High Temperatures	138
3-15	Measured Air Concentrations at Routine Sampling Locations During the 1969 Fire	146
3-16	Dust Concentrations Sampled About 100 M Southeast of the Rocky Flats East Gate	166
3-17	Average Plutonium-239 Concentrations from langer (1986)	167
3-18	Calculation of Enhancement Factor for Respirable Particles Based on the Information Provided in Tables 3-16 and 3-17	170
3-19	Time-Integrated Air Concentrations for Releases from the Rocky Flats Plant at Nearest Receptor	176

PROJECT BACKGROUND

The U.S. Atomic Energy Commission (AEC) announced its decision on March 23, 1951 to build the Rocky Flats Plant. The plant was built to increase the quantity and quality of the nation's nuclear arsenal and has played an important role in the U.S. nuclear weapons complex in the years that have followed. Early plant operations were for the most part kept behind a "cloak of secrecy," with the main off-site concern being centered around two fire incidents in 1957 and 1969 that received public attention, an inadvertent release of tritium to surface waters in 1973, and a waste storage practice (waste oil drum storage at the site of the 903 Pad) that resulted in the spread of contamination to nearby soil during the late sixties. After the 1969 fire, the public learned for the first time that plutonium had been released routinely and accidently from the plant. In 1984, the site was proposed to be a Superfund site, and in 1989, it was included on the National Priorities List for cleanup of environmental contamination.

Public concern came to a high point in June 1989 when approximately 100 FBI and U.S. Environmental Protection Agency (EPA) agents raided the plant seeking documentation of alleged criminal acts and mismanagement. The Department of Energy (DOE) subsequently suspended plutonium processing to review and upgrade the plant's safety systems. Following the raid, Colorado's Governor Roy Romer negotiated with Energy Secretary Admiral James Watkins to secure funding for closer scrutiny of the plant's activities by the state and for health studies to address the public's concern of potential adverse health effects.

In June 1989, an Agreement in Principle was signed by Governor Romer and Secretary Watkins that included DOE funding for increased environmental surveillance and oversight, remediation, emergency preparedness measures, accelerated cleanup in areas of imminent threat, and health studies. This report is one of the products of Phase I of the health studies known as the Rocky Flats Toxicologic Review and Dose Reconstruction Project, which is being conducted by ChemRisk under contract to the Colorado Department of Health.

The Rocky Flats Toxicologic Review and Dose Reconstruction Project

The primary purpose of this project is to reconstruct potential doses of the contaminants of concern which might have been received by off-site individuals as a result of past Rocky Flats Plant operations. Two points should be emphasized regarding the project scope. First, this project is designed to address exposures from historical operations, not to estimate doses from present and future operations or anticipate future exposure potentials. Second, this project is concerned with doses to individuals off the plant site, as opposed to occupational exposures to plant workers. Information pertaining to workplace exposures or control devices will in general only be considered if it is also relevant to prediction of off-site releases or exposures. The

period of interest for this study begins in 1953 when production related emissions began and covers the period through 1989.

The technical tasks associated with the Phase I Health Studies are listed in Figure 1. The first several tasks focus on the development of an understanding of potential health impacts of contaminants released from the Rocky Flats Plant through a comprehensive look at all the materials and their quantities used at the plant since 1952.

1. Identify Chemicals & Radionuclides Used
2. Select Materials of Concern
3. Reconstruct History of Operations
4. Identify Release Points
5. Estimate Releases
6. Select and Model Exposure Pathways
7. Characterize Land Uses and Demographics
8. Perform Dose Assessment

FIGURE 1: TASKS OF THE ROCKY FLATS TOXICOLOGIC REVIEW AND DOSE RECONSTRUCTION PROJECT

Task 1 involved identification of chemicals and radionuclides used on the Rocky Flats site. Unlike some similar dose reconstruction studies that have been undertaken for federal nuclear facilities, this project is concerned with not only radionuclide emissions, but also releases of hazardous chemicals and mixed wastes containing both radioactive and non-radioactive components. To identify materials used on the site, the ChemRisk team first reviewed radioactive source registries and inventories and chemical inventories produced by plant staff. Chemical inventories listed thousands of chemicals present in very small quantities and some chemicals used in very large quantities. Examples range from 4 milliliters of vinyl chloride kept in a laboratory refrigerator to over 400,000 pounds of nitric acid used at the plant each year. Classified and unclassified records were also reviewed for evidence of other materials used on the Rocky Flats site. The result of Task 1 was a list of over 8,000 materials used on the site (ChemRisk, 1991a).

The objective of **Task 2** was to select chemicals and radionuclides most likely to have posed an off-site human health hazard under historical routine plant operations. Radionuclides that have been included as contaminants of potential concern are those that were handled in substantial

quantity, were associated with production activities, were found in forms that were likely to be released, or were found to be present in plant effluents or in the environment.

For chemicals, a three-stage screening process was developed to narrow down the list of contaminants of potential concern. In the first stage, 629 compounds were identified for further, more refined screening based on their known toxicologic properties, Rocky Flats release histories, or reported inventory quantities. A second stage of screening was performed to roughly estimate if the quantity of a chemical on-site was sufficient to pose an off-site health hazard. Forty-six potential chemicals of concern emerged from Stage 2 Screening. In the final stage of screening, these chemicals were individually evaluated to determine the likelihood of their release, potential quantity of release based on actual storage and usage practices, likely routes of release, and known behavior in the environment.

Using both qualitative and quantitative screening criteria, and taking into account preliminary knowledge of actual storage and usage practices, 32 contaminants of potential concern were identified in Task 2 that could have been associated with off-site health impacts from normal operations of the Rocky Flats Plant (ChemRisk, 1991b). The initial list of contaminants of potential concern was subject to continuing review. As the work progressed, newly identified compounds were evaluated for possible addition to the list of contaminants of concern.

Concurrent with the identification of materials used on the Rocky Flats site, **Task 3** activities sought to document the history of operations at the facility as it might relate to off-site exposures, and **Task 4** activities sought to characterize emission points for radionuclide and chemical releases to the environment (ChemRisk, 1992a). Tasks 3 and 4 of the Rocky Flats Toxicologic Review and Dose Reconstruction Project involved extensive investigation and collection of information describing past operations of the Rocky Flats Plant. The objectives of the historical investigations were to:

- Document the basic history of the Rocky Flats facility, outlining its physical development and its historical mission,
- Document the nature of historical uses of the contaminants of potential concern identified in Task 2,
- Identify any significant historical uses of materials not evaluated as part of the Task 2 selection of contaminants of potential concern,
- Identify potential points of significant releases of materials of concern to air, surface water, or soil,

- Support work in Tasks 5 and 6 by characterizing the potential for significant uncontrolled radionuclide emissions from normal operations in the past that may have gone undetected by effluent monitoring systems, and,

- Identify any accidents, incidents, or waste disposal practices that resulted in contaminant releases with significant potential for off-site transport, also in support of Tasks 5 and 6.

Tasks 3 and 4 investigations consisted of an extensive campaign of document reviews and personnel interviews targeting active and retired Rocky Flats employees, local citizens, and other interested parties. The major outcomes of the investigations are an understanding of the historical uses of the contaminants of potential concern, identification of accidents that warrant detailed evaluation, and documentation of the nature of associated emission points.

The objective of **Task 5** was to develop historical release estimates for the routine releases and events selected for detail study (ChemRisk, 1994a). This task was divided into the following categories:

- Routine radioactive airborne emissions,

- Routine nonradioactive airborne emissions,

- Routine surfacewater emissions, and

- Nonroutine contaminant releases.

Historical investigations carried out in Tasks 3, 4 and 5 resulted in the identification of the contaminants listed in Table 1 as the subject of quantitative evaluation.

The historical airborne radioactive effluent monitoring program at the plant was reviewed and evaluated to establish the utility of the data for dose reconstruction. Uncertainties in the monitoring data associated with the sampling and analytic practices at the plant were carefully characterized. The review indicated that the effluent monitoring data reported by the plant provided a good basis for estimating airborne releases from the facility provided the identified uncertainties were incorporated in the estimates. One notable exception was the plant's data for uranium emissions prior to 1961, which are underreported in plant summary documents. The uranium emissions for this period were recalculated using raw data from plant log books. The effluent monitoring data were used as the basis for establishing quantitative annual estimates of routine releases of the radioactive materials of concern.

TABLE 1: CONTAMINANTS IDENTIFIED FOR QUANTITATIVE EVALUATION

SOLVENTS	METALS	OTHERS
Carbon Tetrachloride	Americium-241	Tritium
Chloroform	Beryllium	
Methylene Chloride	Plutonium-239/240	
Tetrachloroethylene	Uranium-234/235 (enriched)	
1,1,1-Trichloroethane	Uranium-238 (depleted)	
Trichloroethylene		

Monitoring data for routine airborne emissions of nonradioactive materials are available only for beryllium, and these data served as the basis for the release estimates of this metal. Routine monitoring for organic solvents of concern was not performed by the plant. Estimates of the plausible ranges of historical emissions for these materials were developed using various types of documentation (e.g., Air Pollution Emissions Notifications, special studies conducted by the plant, and inventory quantities) and information obtained from personnel interviews.

Review of information regarding routine contaminant releases to surface water from the plant indicated relatively limited availability of data to directly quantify the releases. Those data that are available were used to examine whether plant releases measurably increased the radioactivity present in water from potentially impacted reservoirs and drinking water. While the data review suggested that it is plausible that plant-related releases may, during some periods of time, have measurably increased gross alpha radioactivity in the waters of the receiving reservoirs, the resulting measured levels were similar to levels found in other, unaffected reservoirs in the area. For tritium, some measured increases were clearly attributable to Rocky Flats.

Information and data associated with releases of contaminants from the plant for major nonroutine release events (1957 and 1969 fires and 903 Pad) were identified in the Task 5 report. The data and information on these accidental events are very limited. As a result, the analysis of these events requires the use of a number of estimates that introduce uncertainties that are accounted for in the final results. The product of Task 5 efforts is historical contaminant release estimates for contaminants routinely released by the plant and information and data regarding accidental releases requiring further analyses in Task 6 to predict historical contaminant concentrations in environmental media.

Project **Task 6** began the process of evaluating how plant releases traveled off-site and could have resulted in exposure of the public by predicting the concentrations of the contaminants in environmental media such as air, soil and foodstuffs. Based on the nature of contaminant releases, physical properties of the contaminants, local hydrogeology and land-use information, the following exposure pathways were identified to be important in Task 6:

- Inhalation of airborne contaminants due to direct release or soil resuspension,
- Incidental ingestion of contaminated soil,
- Consumption of contaminated vegetables, milk and beef, and
- Ingestion of contaminated drinking water.

An exposure model capable of evaluating these exposure pathways is also developed in Task 6.

One of the primary objectives of Task 6 was to predict the concentrations of contaminants in the air in areas around the plant site so that the amount of contaminant that could have been inhaled by people, deposited on the ground that people could come in contact with, and taken up by vegetation or grazing animals that could be eaten by people could be estimated. Air concentrations were estimated for routine releases of contaminants by using computer models, information on the meteorological conditions at the site (such as wind speed and direction) and the conditions and size of the contaminant release (such as height of the stack, temperature of the exhaust air, and amount of contaminant).

A somewhat different technical approach was required to predict contaminant concentrations in off-site areas that resulted from accidental releases. To evaluate these accidental releases, since there were no or incomplete direct measurements of the releases, information was pieced together from the conditions that were reported during the accident and from monitoring data in the form of air, soil or vegetation samples taken during or shortly after the event. Computer air dispersion models were used to determine, under the estimated conditions of the accidental release, the size of the release that would have been necessary to produce the contamination that was measured at the few locations where air, soil or vegetation samples were taken. The model could then be used to predict the likely concentrations of contaminants at other locations where the public could have been exposed. In some cases, model predictions were compared to environmental sampling data that were not used in the initial estimate of the size of the release. These comparisons test the accuracy of the models in predicting environmental concentrations and add to the confidence that can be placed in the modeling.

The results of Task 6 provided the basis for making estimates of the environmental concentrations of contaminants released from the plant from routine operations, accidents, and resuspension to the air from the soil and the identification of the pathways that these contaminants were most likely to have traveled in reaching the public. These are critical pieces of information needed to calculate the doses of contaminants that the public in the vicinity of Rocky Flats would have received as a result of past plant activities. This information was used in Task 8 to calculate doses to the public.

Areas within several miles of Rocky Flats have changed over time in terms of land use and development since the plant first began operations in 1953. The objective of Project **Task 7** was to identify land uses and populations near the Rocky Flats plant during the period of operations from 1953 to 1989 (ChemRisk, 1994b). The task emphasized identification of the locations of nearby residents that would be most highly exposed and the approximate sizes of populations living near the plant. The use of the lands and waters surrounding the plant were also examined, because this can influence the pathways through which contaminants can migrate and ultimately reach people. Typically, land uses of interest include the raising of crops for human consumption, grazing land and hay produced as feed for cattle consumed by people, or the presence of dairies and drinking water or irrigation reservoirs.

A relatively limited amount of detail about land uses and populations was collected for this first phase of the health studies through personal interviews with long-term landowners and review of census data, historical topographical maps produced by the United States Geological Survey, aerial photographs, deed books and county assessor files to establish land ownership and land use, and county and local government records. A number of other types of federal, state and local agency records were also explored for useful information.

The Task 7 work provided preliminary population information that would be required for the purposes of an epidemiological study, but additional information would likely be needed for such studies. The work did not provide detailed agricultural production information; based on the contaminants released by the plant, food-related pathways are known to have made only a minor contribution to the total exposure of the public to contaminants released by the plant.

The last technical task was Project **Task 8**. This task combined the information produced in the preceding tasks on the amount of contaminants that were either estimated to be present or measured in the environment from plant releases with the exposure model developed in Task 6 to estimate radiation and chemical doses potentially received by the public. Dose estimates and the uncertainty in these estimates were provided for each of the contaminants listed in Table 1. While the endpoints of the Phase I studies were dose estimates, and one of the purposes of Phase II is to thoroughly examine what these doses mean in terms of health risk, Task 8 provided some initial interpretations of the doses in terms of health risk in order to provide some perspective on the meaning of the results of Phase I.

REFERENCES

Buffer (1991). Buffer, P. "Highlights in Rocky Flats Plant History." May 1991. Repository Document CR-30.

ChemRisk (1991a). "Task 1 Report (R1), Identification of Chemicals and Radionuclides Used at Rocky Flats." Repository Document TW-362.

ChemRisk (1991b). "Task 2 Report, Selection of the Chemicals and Radionuclides of Concern." Repository Document TA-723.

ChemRisk (1992a). "Reconstruction of Historical Rocky Flats Operations & Identification of Release Points." Project Tasks 3 & 4. Final Draft Report. August. Repository Document TA-1202.

ChemRisk (1994a). "Estimating Historical Emissions from Rocky Flats." Project Task 5 Report. March. Repository Document TA-1240.

ChemRisk (1994b). "Demographic and Land Use Reconstruction of Area Surrounding the Rocky Flats Plant." Project Task 7 Report. April. Repository Document TW-214.

EXECUTIVE SUMMARY

This report describes work performed in three technical areas to address potential human exposures to contaminants released by the Rocky Flats Plant:

- The identification of the environmental pathways through which contaminants may have traveled,
- The determination of the concentrations of contaminants at off-site locations primarily through the use of computerized air transport (dispersion) models and environmental monitoring data, and
- The identification of the exposure models to be used to calculate the uptake of these contaminants as part of the dose assessment in Task 8.

With regard to environmental exposure pathways, complete pathways (i.e., pathways for which a source of contaminant release, an environmental media that will transport the contaminant, and a route of exposure or entry to the body are all present) were identified for each of the contaminants of concern released by the plant to the air, surface waters, and soil or sediment. Exposure pathways associated with plant releases of contaminants to groundwater are not believed to have been complete in the past, and the hydrogeologic basis for this conclusion is described in this report.

Complete exposure pathways were reviewed further to determine, where possible, the relative contribution that the pathway may have made to the total dose received for each of the contaminants of concern. This review led to the identification of the list of exposure pathways that were the subject of a more detailed quantitative evaluation as part of the dose assessment in Project Task 8.

With regard to surface waters and sediments, contaminant concentrations were identified and evaluated in the Task 5 report using environmental sampling data and are not addressed further in this report from the standpoint of modeling, but were the subject of further screening evaluations as part of the dose assessment in Task 8.

Task 6 efforts focused on the determination of contaminant concentrations in off-site air and soil using release estimates developed in Task 5 and environmental transport models. In addition, environmental data were used to reconstruct accidental releases from the 903 Pad and the 1957 and 1969 fires.

Air dispersion models were used slightly differently in modeling routine and nonroutine airborne releases. For routine releases, they were used to estimate the average air concentrations and deposition of contaminants using estimates of contaminant release rate that were developed in Task 5. For nonroutine releases, they were used to develop plausible releases scenarios that led to predicted air concentrations and contaminant deposition consistent with the limited environmental sampling information available to evaluate the major accidental release events (i.e., primarily the 1957 and 1969 fires and the 903 Pad). The air dispersion models used in this effort included the following:

- ISC (Industrial Source Complex model),
- FDM (Fugitive Dust Model), and
- INPUFF (Integrated PUFF model).

Modeling the Transport of Long-Term Releases from the Plant Exhaust Systems

Long-term releases from the plant's exhaust systems were modeled using the ISC model and a validated, five-year meteorological data set for the period of 1987 through 1991. More specifically, plutonium releases from the exhaust systems were modeled assuming that emissions were split between Buildings 771 and 776 (90 percent and 10 percent of emissions, respectively). The dispersion model was run using what is termed a unit emission rate, which means that it is assumed that a total of 1 millicurie of plutonium was released per year (1 mCi y^{-1}), to predict off-site air concentrations. The predicted off-site air concentrations were multiplied by the annual release estimates from the Task 5 report to obtain an estimate of past off-site air concentrations for each year of plant operation. The deposition of plutonium from the air to the ground was estimated from the predicted air concentrations using a deposition model.

A similar approach to that described for plutonium was used to model the releases of other materials of concern from the plant exhaust system. In the case of uranium, the unit emission of 1 mCi y^{-1} was assumed to be evenly split between point sources representing the 444/447 buildings and the 881/883AB buildings. Tritium, beryllium, and the organic solvent releases from the exhaust systems were assumed to have been from a point source near the center of the plant. For tritium, a unit emission rate of 1 mCi y^{-1} was also used; for beryllium and the organic solvents, a unit emission rate of 1 g y^{-1} was used.

The uncertainties associated with the estimates of airborne concentrations include the uncertainties in the estimate of the release (as described in the Task 5 report) and the uncertainty associated with the use of the ISC model. The uncertainties associated with the application of the ISC model are on the order of a factor of 3.

Modeling the Release of Plutonium from the 903 Pad

The 903 Pad accident involved the leakage of drums containing oil contaminated with depleted uranium and plutonium resulting in the contamination of surface soils. These soils were subsequently transported off the pad by the wind. The hazard posed by plutonium in the oil is many times greater than the depleted uranium and therefore was the focus of the evaluation. The reasons that plutonium risks outweigh those from uranium in the 903 Pad contamination center around the following facts:

- More drums stored at the 903 Pad contained plutonium than contained uranium. About three-times as many drums contained plutonium than contained uranium (Seed *et al.*, 1971). As a result, machining fluid contaminated with uranium was likely released to the environment in smaller quantities than fluid contaminated with plutonium.

- The specific activity of depleted uranium is much lower than that of weapons grade plutonium (0.0000004 Ci g^{-1} in depleted uranium compared to 0.07 Ci g^{-1} in plutonium- a factor of 175,000 lower). As a result, the uranium metal retained in the machining fluid contained much less radioactivity on a mass basis than did the retained plutonium.

- Isotopes of plutonium deliver higher doses to exposed individuals than do isotopes of uranium upon inhalation. Committed effective doses (indicating doses comparable to whole-body irradiation) from plutonium-239 are about 3 times higher than those for uranium-238 for relatively insoluble (Class Y) compounds and about 80 times higher than U-238 for moderately soluble (Class W) compounds (USDOE, 1988). The highest organ dose commitment from inhalation of unit Pu-239 activity (9,300 rem μCi^{-1} to bone surfaces) is over nine times the highest organ dose commitment from inhalation of unit U-238 activity (1,000 rem μCi^{-1} to the lung).

- Once released to the environment, plutonium becomes more strongly bound to surface soils than uranium. Uranium is generally more likely to travel downward in the soil to regions where it is less susceptible to resuspension.

An air dispersion model was used to develop a scenario that is consistent with both the limited record of the event and the environmental sampling data. The scenario that is most consistent with the available information was then used to predict plutonium air concentrations and deposition at various off-site locations of interest.

The environmental measurement data used to evaluate the release included soil contamination data and on-site air sampling data. The environmental measurement data were adjusted in a number of ways to make them useful for modeling purposes. The basis for the assumptions used in adjusting the environmental data and in selecting other model inputs is thoroughly described in the report. Since the releases from the pad apparently occurred over a number of years, a five-year validated meteorological data set for the period of 1987 through 1991 was used to represent the range of meteorological conditions for the 903 Pad release.

Plutonium releases associated with the 903 Pad were modeled for the period during which the pad was subjected to active disturbance prior to the pad being covered, i.e., mid-1964 to mid-1969. For this period, the FDM model was used to predict the transport processes leading to the off-site soil contamination pattern observed in late 1969 and the early 1970s.

A variety of possible release scenarios were modeled. The FDM modeling scenario that is consistent with the available information involves a total release of 25 curies (Ci) from the 903 Pad. Of the 25 Ci:

- 11.4 Ci were redeposited on the pad,
- 13.6 Ci escaped from the pad,
- 8 Ci escaped beyond the plant security fence, and
- 6.8 Ci escaped from the buffer zone boundary.

The five-year average airborne concentrations of plutonium associated with these releases were predicted for off-site locations, as was total predicted plutonium deposition. The resuspension of this deposited plutonium is evaluated further in a separate section of the report.

The analysis of the 903 Pad involved the simulation of a very complex transport process that took place over a number of years. A variety of environmental data, a complex transport model, and a number of estimates and assumptions for some key model inputs were made for the purposes of the analysis that all contribute to the overall uncertainty in the predictions. Therefore, the uncertainties associated with the model predictions are considerably larger than those identified for the routine releases. The uncertainties associated with the 903 Pad modeling predictions are on the order of a factor of 12. This means we are quite confident that the actual quantities could be no more than 12 times higher or less than 1/12 of the best estimate.

Modeling the Release of Plutonium from the 1957 Fire—Building 771

Air dispersion models were used to estimate the most plausible release of plutonium as a result of the 1957 fire by developing a scenario that is consistent with both the recorded time-sequence of accident events and the limited environmental sampling data available for the 1957 fire. This scenario was then used to predict plutonium concentrations in air and deposition at off-site locations of interest. The dispersion model used to evaluate the 1957 fire was the INPUFF model. Limited meteorologic data reported in a letter from the plant to the Colorado Department of Health were used in the modeling and analysis process. The environmental data that were collected at the time of the fire are limited in extent and quality, and in many cases, documentation clearly describing sample collection and results is lacking. Since the environmental sampling data represent the only significant source of quantitative information during the time of the fire, considerable effort was devoted to interpreting these data and describing the uncertainties associated with their use in identifying plutonium releases and off-site exposures.

The 1957 fire release was modeled in two stages. One stage addressed the modeling of large or coarse particles believed to have been released by the filter plenum explosion during the fire. This large particle release is believed to have been the primary source of the plutonium contamination measured on on-site vegetation after the fire. These large particles would tend to fall out of the air relatively rapidly, and would have a limited potential to travel off-site. The analysis presented in this report suggests that a relatively small release of 60 μCi of plutonium would be consistent with the observed vegetation contamination.

The other stage of release that was modeled addressed the unfiltered fumes (smoke) from burning plutonium that were released after the destruction of the filters. This second-stage release would have had a greater potential to carry these much smaller plutonium particles off-site. A number of measurements of airborne radioactivity were recorded for a variety of locations during the fire, and these were used to evaluate this second-stage release. The reported radioactivity from the samplers was below the detection threshold of the devices in most cases. As a result, the detection thresholds of the devices were used to bound the possible environmental concentrations of radioactivity from the fire at the location of the samplers. The results of the analysis, to the extent that they rely on these detection thresholds, represent an upper-bound calculation of the release based on the reported environmental data, since the non-detect data only provide information on the highest possible concentrations. The estimated total release of the fine particles from the fire of 0.07 Ci is many times greater than that associated with the coarse particles.

The estimated contribution of the 1957 fire to the total plutonium contamination that was measured in the soil during the 1970s is small when compared to the events associated with the 903 Pad.

The overall uncertainty in the predictions for the 1957 fire is on the order of a factor of 35; it is very large due to the limited and poor quality data available to evaluate the event. This means that the upper bound estimate of the amount of plutonium released from the fire is likely to lie somewhere between 0.002 Ci and 2.4 Ci. A best estimate of the amount of plutonium released cannot be made because the analysis relied on detection thresholds instead of actual measurements.

Modeling the Release of Plutonium from the 1969 Fire—Building 776

The analysis of the 1969 fire release was very similar to that described previously for the 1957 fire. The INPUFF computer model was again used to develop a release scenario that is consistent with the sequence of events and recorded environmental data for the 1969 fire. Limited meteorological data and measurements of airborne radioactivity for a variety of locations are available for the analysis. Unlike the 1957 fire, the measurements of airborne radioactivity were above limits of detection. The analysis described in this report therefore represents a "best" estimate of the release based on the environmental data.

The best estimate of the release from the 1969 fire of 2.8 mCi is much smaller than the release estimated for the 1957 fire. The estimated contribution of the 1969 fire to the total plutonium contamination that was measured in the soil during the 1970s is also very small compared to events associated with the 903 Pad.

The overall uncertainty in the predictions associated with the 1969 fire are relatively large since the analysis simulates a short-term release event using relatively crude meteorologic data. However, the nature and quality of the environmental air sampling data are better than those available for the 1957 fire. The uncertainties associated with the modeling predictions of the 1969 fire are on the order of a factor of 20.

Evaluation of Releases of Depleted Uranium from Oil Burning

Contaminated oil disposal activities that involved burning are described in the project reports for Tasks 3 and 4, and Task 5. Screening estimates that would tend to overestimate the potential off-site airborne concentrations of depleted uranium from these activities are presented based on ISC air dispersion modeling. These estimates are presented for the purposes of evaluating their importance relative to other releases.

Evaluation of the Resuspension of Plutonium from Off-site Soils

A resuspension model based on the mass loading approach was used in conjunction with soil sampling data to quantify airborne concentrations from the resuspension of plutonium in soils. Plutonium is present in off-site soils primarily as a cumulative result of 903 Pad releases that ended after 1969.

Review of Contaminated Shoreline Sediment as a Source of Exposure

The Task 5 report identified the existence of a very limited data set regarding the contamination of sediments in Great Western Reservoir and Standley Lake. The possible range of shoreline sediment plutonium contamination based on the sediment data is very similar to both the predicted and measured levels of plutonium contamination in soils near the reservoirs. Shoreline sediments should therefore not pose a unique additional exposure hazard, since any exposure to the resuspension of shoreline sediments would be similar to that associated with the resuspension of soils in the same area.

Relative Magnitude of Releases

This report concludes by providing a description of the relative magnitude of the various release events. More elaborate comparisons are made as part of the dose assessment in Task 8. The direct release of contaminated soil from the 903 Pad represents the largest source of potential exposure to radioactivity of all the events examined.

REFERENCES

USDOE (1988). U.S. Department of Energy. "Internal Dose Conversion Factors for Calculation of Dose to the Public." DOE/EH-0071, DE88-014297. Washington, D.C. July.

Seed *et al.* (1971). Seed, J.R, K.W. Calkins, C.T. Isley, F.J. Miner, and J.B. Owen. "Committee Evaluation of Plutonium Levels in Soil Within and Surrounding USAEC Installation at Rocky Flats, Colorado." Dow Chemical, Rocky Flats Division, RFP-INV-10. Repository Document AC-726.

This page intentionally left blank.

1.0 INTRODUCTION

The purpose of Task 6 of the Toxicologic Review and Dose Reconstruction Project was to identify environmental exposure pathways associated with the materials released from the Rocky Flats Plant (RFP) and to model the transport of the materials through the identified pathways. This task built upon the work of Tasks 3, 4, 5 and 7 (ChemRisk, 1992, 1994 a-b) and formed the basis for the development of dose estimates in Task 8.

Efforts on Tasks 1 through 4 of the project have resulted in the identification of contaminants for reconstruction of releases from historical operations of the RFP. The contaminants that were the subject of further quantitative evaluation with regard to historical emissions are listed in Table 1-1. The list includes six organic solvents, one nonradioactive metal, three radioactive metallic elements and their isotopes, and tritium, the radioactive form of hydrogen.

TABLE 1-1: MATERIALS OF CONCERN FOR THE DOSE RECONSTRUCTION PROJECT

SOLVENTS	METALS	OTHERS
Carbon Tetrachloride	Americium-241	Tritium
Chloroform	Beryllium	
Methylene Chloride	Plutonium-239/240	
Tetrachloroethylene	Uranium-234/235 (enriched)	
1,1,1-Trichloroethane	Uranium-238 (depleted)	
Trichloroethylene		

In this report, exposure pathways are identified for the contaminants listed in Table 1-1 based on the release characteristics of the contaminants described in the Task 5 report and the land-use information presented in the Task 7 report.

Surface-water-borne releases are not modeled in this report. It was concluded in Task 5 that the available data on surface waterborne releases from the plant were currently insufficient to develop release estimates. However, the Task 5 review of the environmental monitoring data did identify some increases in radioactivity present in the reservoirs that could possibly be

related to Rocky Flats, and that some measured increases in tritium concentration were clearly attributable to releases from Rocky Flats. The potential magnitude of the increases described in Task 5 are identified in this report and are used in screening dose calculations to evaluate their potential importance in Task 8.

1.1 Exposure Pathway Identification

An environmental exposure pathway can be defined as a route through which a radionuclide or chemical released from a source reaches an individual. In this report, those pathways considered complete are identified and their relative importance is discussed. Complete exposure pathways are identified based on the environmental conditions at Rocky Flats, historical off-site monitoring data, and local land-use information.

The relative importance of each complete pathway is evaluated to focus the dose reconstruction efforts on those pathways that contribute most to the overall exposure to the off-site public. The importance of a pathway is related to the method of release and the physical, chemical, and toxicological properties of the contaminant. Pathways that are identified as important in this section are addressed further in the exposure modeling section of this report.

1.2 Environmental Transport and Exposure Modeling

Environmental transport models describe the movement of a contaminant through an environmental medium (e.g., air, surface water, or groundwater) and predict the concentration of a contaminant at an off-site location or in a food chain. In this report, the application of air dispersion models to predict airborne transport of contaminants is discussed in detail. The predicted off-site air and soil concentrations are used in Task 8 to reconstruct doses received by the off-site public.

Other models are used in Task 8 to predict transport in the food chain and human uptake of a contaminant from various environmental and food media. Some exposure routes are simple and direct, such as inhalation of contaminated air or ingestion of contaminated water. Other routes are more complicated and indirect. For example, following an airborne release, a contaminant can be transferred to pasture through deposition, to cattle through grazing, and finally, to humans through milk ingestion. The development and application of a transport and exposure model capable of quantifying radiation and chemical doses are described in this report.

The Rocky Flats Toxicologic Review and Dose Reconstruction Project focuses on past exposures. It is based on past material usage and release information, environmental monitoring data, and model predictions. There are uncertainties associated with this information and the predicted results. Throughout the project, efforts have been made to identify and quantify these uncertainties. The use of Monte Carlo techniques to propagate the estimated uncertainties to determine the overall uncertainty in a dose estimate is discussed in this report.

REFERENCES

ChemRisk (1992). "Reconstruction of Historical Rocky Flats Operations and Identification of Release Points." Project Tasks 3 & 4. Final Draft Report. August. Repository Document TA-1202.

ChemRisk (1994a). "Estimating Historical Emissions from Rocky Flats." Project Task 5 Report. March. Repository Document TA-1240.

ChemRisk (1994b). "Demographic and Land Use Reconstruction of the Area Surrounding the Rocky Flats Plant." Project Task 7 Report. April. Repository Document TW-214.

This page intentionally left blank.

2.0 EXPOSURE PATHWAY IDENTIFICATION

This section identifies important environmental exposure pathways associated with materials of concern at Rocky Flats. The existence of an exposure pathway is determined by environmental conditions (e.g., location of surface water, groundwater, prevailing wind direction), potential for a contaminant to move from one medium (e.g., soil, water, or air) to another, and by the life-styles and activities of the exposed population (e.g., gardening, water recreation). The combinations of media, transport mechanisms, and routes of contact create many possible environmental pathways; however, they are not all necessarily considered complete. In addition, not all complete pathways make a significant contribution to the total potential health risk experienced by an off-site population. An analysis of the relative importance of complete exposure pathways is important for the purpose of focussing dose reconstruction efforts.

Complete exposure pathways for each material of concern at Rocky Flats are identified in the following section. The relative importance of each complete exposure pathway is then evaluated qualitatively based on important physical and chemical characteristics of the materials and environmental monitoring data. The purpose of this process is to identify those exposure pathways warranting detailed dose reconstruction efforts. An earlier analysis provided a semiquantitative evaluation of the relative importance of all pathways for each environmental medium using screening techniques (ChemRisk, 1991). The screening analyses provided some insight to the significance of pathways and are referenced where appropriate. However, the screening analyses are not repeated in this report since doses for the majority of the pathways are rigorously calculated in Task 8.

2.1 Identification of Complete Exposure Pathways

For a radionuclide or chemical used at the Rocky Flats plant to have posed a health hazard to off-site individuals, each of the following elements must have existed (Figure 2-1):

- A **contaminant source** that released the material into the environment,
- A **transport medium** that carried the contaminant off-site to a location where exposure took place, and
- An **exposure route** through which the contaminant entered an individual's body to produce adverse health effects.

FIGURE 2-1: ELEMENTS OF A COMPLETE EXPOSURE PATHWAY

When any one of these three conditions is missing, the pathway is incomplete. However, there is an exception to this rule. Certain radionuclides that emit beta or gamma radiation (which represents only a minor component of the radiation from Rocky Flats) can cause adverse health effects without entering the body, although these radionuclides need to be sufficiently close to the individual to produce external radiation exposure. An incomplete exposure pathway will not pose a health hazard to off-site individuals.

The complete environmental exposure pathways for the materials of concern are identified for air, surface water, soil/sediment, and groundwater in the following sections. Information specific to Rocky Flats is used in the evaluation. It should be noted that complete pathways are identified for this project solely on a retrospective basis. The likelihood of exposure pathways being complete in the future is not considered.

The approaches to the evaluation of environmental transport and exposure for tritium differ from the other materials of concern. When released into the environment, tritium (in the form of tritiated water or hydrogen) is completely mixed with its stable element counterparts in nature. Therefore, specific exposure pathways are not identified for tritium. The conventional method for estimating dose from tritium, the specific activity method, assumes an equilibrium between tritium concentrations in the atmosphere, water, food, and body tissues (Till, 1983). The National Council on Radiation Protection and Measurement (NCRP, 1979) proposed a variation of the specific activity method that can be used when the tritium concentrations in air, water and food products are known or can be estimated. These methods are described in Appendix A, and are used for the dose calculations in Task 8.

2.1.1 Air

Complete exposure pathways for materials released into the atmosphere are identified in this section based on the criteria listed in Figure 2-1.

Contaminant Source

As described in the Task 5 report, historical airborne emissions from the Rocky Flats plant include those from routine facility operations as well as those associated with accidents and incidents (ChemRisk, 1994). Although virtually all airborne effluents emitted from the plant were subjected to filtration to remove the bulk of the radioactive material, some particulates were emitted continually to the atmosphere even when the filtering systems were working as intended. Large quantities of highly volatile solvents were reported to have been used at the plant. Most of these solvents evaporated into the air and were ultimately released in the ventilation exhaust.

There were several accidental or nonroutine releases of contaminants into the air (ChemRisk, 1994). The most important releases with respect to off-site contamination are associated with the 1957 fire and the 903 Pad. In the 1957 fire, plutonium particles were released from the main exhaust duct of Building 771. The 903 Pad was used to store drums of cutting oil containing plutonium and uranium that leaked onto the soil. The suspension and subsequent dispersion of contaminated soil particles represented an important source of off-site contamination.

Transport Medium

Routine operations and accidents resulted in the release to the atmosphere of metals and solvents. All the solvents identified in Table 1-1 are volatile compounds. They are released as vapors and are likely to stay in the atmosphere and travel great distances. All of the identified metals are nonvolatile and are released into the atmosphere as particulates. As described in the Task 5 report, particulates released from the Rocky Flats plant as a result of routine operations were predominately composed of extremely small, submicron-sized particulates (ChemRisk, 1994). Because of the low deposition velocities associated with particulates of this size range, they can be transported long distances by wind before settling.

Contaminant particulates released from the 1957 fire and the 903 Pad were not filtered, and some of them were likely larger in size than those released from routine operations. For example, as described in the Task 5 report, the majority of soil particulates released from the 903 Pad are believed to have been deposited within a short distance from the pad (ChemRisk, 1994). Nevertheless, based on the reported vegetation, soil, and air monitoring data, some particulates released from these accidents reached off-site areas.

Exposure Routes

Table 2-1 presents the complete exposure routes associated with airborne releases from the Rocky Flats plant. The rationale for selecting these routes for one or more of the materials of concern is presented in Appendix B.

TABLE 2-1: COMPLETE EXPOSURE PATHWAYS ASSOCIATED WITH THE AIR MEDIUM

Air - Humans (Inhalation)
Air - Humans (Immersion)
Air - Livestock - Humans (Ingestion)
Air - Vegetation - Humans (Ingestion)
Air - Vegetation - Livestock - Humans (Ingestion)

2.1.2 Surface Water

Complete exposure pathways for materials released into surface waters are identified in this section based on the criteria listed in Figure 2-1.

Contaminant Source

As described in the Task 5 report, wastewater generated by the plant was released into holding ponds on North Walnut Creek and South Walnut Creek (ChemRisk, 1994). Holding ponds on Woman Creek received site runoff that was eventually transported to Standley Lake. Great Western Reservoir and Standley Lake are in the predominant downwind direction of the plant and may also have been affected by deposition of airborne contaminants.

Transport Medium

Both nonvolatile metals and volatile solvents were released into surface waters around Rocky Flats. As discussed in Task 5, volatile solvents readily evaporate from holding ponds and surface waters, and are unlikely to be transported off-site in surface waters to any significant extent (ChemRisk, 1994). In contrast, the metals of concern, which include three radionuclides and beryllium, have low solubility in natural water and tend to adsorb to soil and sediments. These metals are much more likely to be transported as suspended particles than as dissolved ions. Exposure pathways associated with surface water are not complete for the volatile solvents of concern, but surface water is considered a medium of transport for the metals.

Exposure Routes

Table 2-2 presents the complete exposure routes associated with waterborne releases from Rocky Flats. The rationale for selecting these routes for one or more of the materials of concern is presented in Appendix B.

TABLE 2-2: COMPLETE EXPOSURE PATHWAYS ASSOCIATED WITH THE SURFACE WATER MEDIUM

Water - Humans (Ingestion)
Water - Humans (Dermal Contact)
Water - Humans (Immersion)
Water - Livestock - Humans (Ingestion)
Water - Vegetation -Humans (Ingestion)
Water - Vegetation - Livestock - Humans (Ingestion)
Water - Fish - Humans (Ingestion)

Note: Sediment is evaluated with the soil medium

2.1.3 Soil and Sediment

Complete exposure pathways for materials released to soil and sediment are identified in this section based on the criteria listed in Figure 2-1.

Contaminant Source

Soil at off-site locations can become contaminated through contact with contaminants in liquid effluents from the plant or by deposition of airborne contaminants. Contaminated soil particles can also be suspended in surface water and carried off-site. Nonvolatile materials deposited or released to soil may remain and accumulate in surface soil for a long period of time. On the other hand, volatile solvents generally do not remain in surface soil, but evaporate into the atmosphere. Surface soil is therefore not considered an important environmental medium for exposure to solvents.

Transport Medium

To a certain extent, deposited contaminants can be re-entrained by strong winds or as the result of mechanical disturbances and dispersed through the air. This transport mechanism is known as resuspension and is enhanced by the occurrence of small soil particles, low humidity, high wind speed, mechanical disturbance and an exposed ground surface. The dispersion of particulates from the 903 Pad is a good example of this transport process. As discussed in the Tasks 3 and 4 report, cutting oil containing plutonium and uranium leaked from drums stored at the 903 Pad into the underlying soils (ChemRisk, 1992). Contaminated soil particulates were

then transported from the pad by wind. Soil is therefore considered a transport medium for the nonvolatile materials of concern.

Exposure Routes

Table 2-3 presents the complete exposure routes associated with the soil medium. The rationale for selecting these routes for one or more of the materials of concern is presented in Appendix B.

TABLE 2-3: COMPLETE EXPOSURE PATHWAYS ASSOCIATED WITH THE SOIL MEDIUM

Soil/sediment - Humans (Ingestion)
Soil/sediment - Humans (Dermal Contact)
Soil/sediment - Humans (Ground Exposure)
Soil - Livestock - Humans (Ingestion)
Soil - Vegetation - Humans (Ingestion)
Soil - Vegetation - Livestock - Humans (Ingestion)
Soil/sediment - Air - Humans (Inhalation)
Soil/sediment - Air - Humans (Immersion)

2.1.4 Groundwater

Complete exposure pathways for materials released to groundwater are identified in this section based on the criteria listed in Figure 2-1.

Contaminant Source

Groundwater can be contaminated through percolation of liquid effluent discharged to soil or holding ponds and leaching of buried waste. Groundwater contamination has been documented on the Rocky Flats Plant site (EG&G, 1991).

Transport Medium

The hydrogeological conditions of the site has been reviewed and is discussed in detail in Appendix C. The shallow groundwater system in the Rocky Flats Alluvium is unconfined, i.e., not isolated from the surface soil by an impermeable layer. Therefore, contaminants in surface soil can potentially percolate down and contaminate this groundwater system. Beneath the

Rocky Flats Alluvium is the Arapahoe Formation. Water in this system is believed to be in hydraulic communication with the groundwater in the Rocky Flats Alluvium and upper member of the Laramie Formation. The deeper groundwater system is the (lower) Laramie-Fox Hills Formation, separated from the other combined system by a thick layer of relatively impermeable claystone and shale (Hurr, 1976). A detailed evaluation of groundwater as a transport medium of contaminants at Rocky Flats is included in Appendix C. Only a brief summary of the evaluation is provided below.

Municipal wells for the cities east or down-gradient of the Rocky Flats plant draw water from the Laramie-Fox Hills Formation at approximately 1000 feet below ground surface (Nachtrieb, 1991). The Laramie-Fox Hills aquifer is recharged up-gradient of the Rocky Flats plant and is isolated vertically from the Rocky Flats plant and the other groundwater system. It is unlikely that contaminants that originated from the plant reached the Laramie-Fox Hills aquifer and contaminated municipal well water. Accordingly, it is also unlikely that exposure to groundwater from municipal wells represents a complete pathway for down-gradient populations.

With regard to the Alluvium/Arapahoe/Upper Laramie aquifer system, some private wells might have obtained groundwater from this aquifer, which has been potentially impacted by the contaminants released from the plant. However, based on monitoring data, hydrogeology of the area, and physical properties of the materials of concern, this transport route is not considered to have been complete for historical exposures.

Finally, in many areas around the Rocky Flats plant, springs occur where the contact between the alluvium and bedrock intersects the eastward sloping land surface. Many of these springs then lead to streams. Therefore, it is possible that contaminated groundwater in the Rocky Flats Alluvium reached surface water. Great Western Reservoir and Standley Lake are most likely to be affected by this route of transport. Water monitoring data from Great Western Reservoir and Standley Lake are used to evaluate exposures through surface water. Any contaminant transport from groundwater to surface water is therefore included in the surface water evaluation.

In conclusion, the available information that is evaluated in Appendix C indicates that groundwater is not likely to have been an important transport medium of the materials of concern at Rocky Flats with regard to historical exposures. For this reason, exposure pathways associated with groundwater are considered incomplete and are not evaluated further. There are numerous ongoing hydrogeologic studies at the plant that will provide additional information over the next few years that may require the re-evaluation of the potential for historical groundwater transport of contaminants.

2.1.5 Mother's Milk

Exposure to contaminants through mother's milk is a unique pathway, since contaminants can reach breast milk through any of the pathways discussed in the previous sections. This pathway is considered complete at Rocky Flats, since it is likely that some women in the area breast-fed their children. However, this pathway is not likely to be important for either the solvents or metals of concern.

Volatile solvents generally do not accumulate in the human body; once inhaled, they are either exhaled or metabolized. Therefore, exposure to the solvents of concern through mother's milk is not considered an important pathway. With regard to the metals of concern, there are insufficient data to quantify their transfer from mother to mother's milk. Nevertheless, the fraction of the daily intake that is transferred by a cow to the cow's milk (F_m) may indicate the potential importance of this pathway. USEPA (1989) has published screening values of F_m for the metals of concern (Table 2-4):

TABLE 2-4: MILK TRANSFER COEFFICIENT FOR THE METALS OF CONCERN

Element	F_m (d L^{-1})
Americium	4×10^{-7}
Beryllium	9×10^{-7}
Plutonium	1×10^{-7}
Uranium	6×10^{-4}

The F_m of iodine (1×10^{-2} d L^{-1}), an element for which milk ingestion is generally considered an important pathway, is more than an order of magnitude higher than that for the materials of concern.

It should also be noted that F_m depends on the chemical form of an element. For example, when an insoluble form of an element is administered to a cow, the concentration of the element in milk is likely to be less than indicated in Table 2-4. This is because only a small fraction of the ingested amount is absorbed and available to partition into milk when the element is in an insoluble form. As described in the Tasks 3 and 4 report (ChemRisk, 1992), radionuclides and beryllium released from the Rocky Flats plant were mostly in the form of metals and metal oxides with extremely low solubility in water and may have lower F_m values than the values indicated in Table 2-4. Therefore, the mother's milk pathway is not likely to have contributed significantly to total dose.

2.1.6 Summary — Exposure Pathway Selection

Complete exposure pathways at Rocky Flats were identified in this section. Potential pathways that lack one or more of the elements of a complete pathway for the materials of concern are not considered further. Exposure pathways considered complete for the materials of concern are listed in Table 2-5 and evaluated further in the following section.

2.2 Qualitative Evaluation of Complete Exposure Pathways

This section evaluates the relative importance of the identified complete pathways within each environmental medium (i.e., air, surface water, soil/sediment) based on physical and chemical characteristics of the materials of concern.

2.2.1 Air

The complete exposure pathways identified for the air medium are as follows:

Direct Pathways
Air - Humans (Inhalation/Immersion)
Indirect Pathways
Air - Livestock - Humans (Ingestion) Air - Vegetation - Humans (Ingestion) Air - Vegetation - Livestock - Humans (Ingestion)

Although indirect transfer to humans of volatile materials from air through animals and plants is conceptually plausible, this pathway generally does not contribute significantly to the total dose. Volatile organic chemicals (VOCs), such as carbon tetrachloride and trichloroethylene, absorbed by animals are quickly metabolized or excreted through exhalation and do not remain in animal tissues (Sato and Nakajima, 1987). A screening method proposed by McKone and Daniels (1991) was used to compare the dose to humans from direct inhalation of VOCs to the dose associated with ingestion of vegetables, milk, and meat (Appendix D and ChemRisk, 1991). Based on this screening method, a dose received from direct inhalation of the volatile materials of concern is at least 1,800 times higher than from the other three routes combined. Since direct inhalation clearly dominates the other three indirect pathways, only direct inhalation is considered in the dose reconstruction for the volatile materials of concern.

TABLE 2-5

COMPLETE EXPOSURE PATHWAYS
FOR THE MATERIALS OF CONCERN

Air Medium

Pathway	Material of Concern
Air - Humans (Inhalation)	Solvents, Be, Am, Pu, U, Tritium
Air - Humans (Immersion)	Am, Pu, U
Air - Livestock - Humans (Ingestion)	Solvents, Be, Am, Pu, U, Tritium
Air - Vegetation - Humans (Ingestion)	Solvents, Be, Am, Pu, U, Tritium
Air - Vegetation - Livestock - Humans (Ingestion)	Solvents, Be, Am, Pu, U, Tritium

Surface Water Medium

Pathway	Material of Concern
Water - Humans (Ingestion)	Be, Am, Pu, U, Tritium
Water - Humans (Dermal Contact)	Be, Am, Pu, U, Tritium
Water - Humans (Immersion)	Am, Pu, U, Tritium
Water - Livestock - Humans (Ingestion)	Be, Am, Pu, U, Tritium
Water - Vegetation - Humans (Ingestion)	Be, Am, Pu, U, Tritium
Water - Vegetation - Livestock - Humans (Ingestion)	Be, Am, Pu, U, Tritium
Water - Fish - Humans (Ingestion)	Be, Am, Pu, U, Tritium

Soil/Sediment Media

Pathway	Material of Concern
Soil/Sediment - Humans (Ingestion)	Be, Am, Pu, U
Soil/Sediment - Humans (Dermal Contact)	Be, Am, Pu, U
Soil/Sediment - Humans (Ground Exposure)	Am, Pu, U
Soil - Livestock - Humans (Ingestion)	Be, Am, Pu, U
Soil - Vegetation - Humans (Ingestion)	Be, Am, Pu, U
Soil - Vegetation - Livestock - Humans (Ingestion)	Be, Am, Pu, U
Soil/Sediment - Air - Humans (Inhalation)	Be, Am, Pu, U
Soil/Sediment - Air - Humans (Immersion)	Am, Pu, U

Solvents = Carbon Tetrachloride, Chloroform, Methylene Chloride, Tetrachloroethylene, 1,1,1-Trichloroethane, Trichloroethylene
Am = Americium-241
Be = Beryllium
Pu = Plutonium-239, 240
U = Uranium-234, 235, 238

For the nonvolatile materials of concern, indirect pathways are potentially important (ChemRisk, 1991). The relative importance of an indirect pathway depends on the characteristics of the site (e.g., deposition rate of the airborne contaminant, fraction of deposition intercepted by vegetation) and physical and biological properties of the contaminant (e.g., transfer factor between pasture and cattle). For this reason, indirect pathways for the nonvolatile materials of concern are retained as potentially important pathways.

2.2.2 Surface Water

Both direct and indirect exposure pathways were identified as complete pathways for the surface water medium. The relative importance of these pathways is discussed below.

The complete direct exposure pathways for the surface water medium are:

Direct Pathways
Water - Humans (Ingestion)
Water - Humans (Dermal Contact)
Water - Humans (Immersion)

As discussed previously, Great Western Reservoir and Standley Lake supply municipal water for several communities near Rocky Flats. Available surface waterborne contaminant release and environmental monitoring data were used in Task 5 to examine whether plant releases measurably increased radioactivity in potentially impacted reservoirs and drinking waters (ChemRisk, 1994). While the review of the data suggested that it was possible that plant-related releases may on some occasions have measurably increased gross alpha radioactivity in receiving reservoirs, the resulting measured levels were similar to levels found in other unaffected reservoirs in the area. For tritium, some measured increases were clearly attributable to Rocky Flats. Ingestion of surface water is therefore retained as a potentially important complete exposure pathway.

With regard to direct dermal contact, dissolved metal ions generally have very low dermal absorption coefficients. For example, the dermal absorption coefficient for beryllium is 0.001 (CAPCOA, 1991). Although dissolved uranium and plutonium can penetrate human skin to a limited degree, this is not an important pathway due to the low solubility of uranium and plutonium in natural water (ATSDR, 1990a and 1990b). In addition, the duration and frequency of dermal exposure to surface water are low under normal circumstances. Therefore, dermal absorption is not likely to deliver a significant dose of the metals of concern to exposed individuals and is not evaluated further.

Exposure from water immersion occurs when an individual swims in water contaminated with gamma-emitting radionuclides. Great Western Reservoir was not open to the public and swimming was not allowed in the reservoir; however, swimming has been allowed in Standley Lake. Water immersion dose depends on the concentration of radionuclides in the water, exposure frequency, and exposure duration. Normally, water immersion does not contribute significantly to total dose even though the assumed parameters for assessments are very conservative (USEPA, 1979 and ChemRisk, 1991). The significance of this pathway is further reduced by the relatively low water solubility of all the radionuclides of concern except tritium. As such, water immersion is not evaluated further.

The complete indirect pathways for the surface water medium are:

Indirect Pathways
Water - Livestock - Humans (Ingestion)
Water - Vegetation - Humans (Ingestion)
Water - Vegetation - Livestock - Humans (Ingestion)
Water - Fish - Humans (Ingestion)

As discussed in the Task 5 report, water from Great Western Reservoir and Standley Lake contains low concentrations of the nonvolatile radionuclides of concern that are similar to concentrations detected in other area reservoirs not impacted by the RFP (ChemRisk, 1994). There were insufficient data to make a similar comparison for beryllium. All of these materials have low solubility and are poorly absorbed by livestock. Therefore, the nonvolatile materials of concern present in surface water were not likely to be transferred to a significant extent to vegetation or livestock that received water from either reservoir. The indirect pathways for the water medium associated with vegetation and livestock are not evaluated further in this report.

The final indirect exposure pathway for surface water is fish ingestion. Standley Lake is open to the public for sport fishing. In 1989, the Colorado Department of Health (CDH) analyzed fish collected from Standley Lake for selected metals, radionuclides, and priority pollutants (CDH, 1990). None of the radionuclides or beryllium was detected in the fish sampled. These monitoring results may be explained by the low concentrations of radionuclides and metals of concern in the water of Standley Lake and the relatively low bioconcentration factors of these materials. Fish bioconcentration factors for the metals of concern are shown in Table 2-6.

TABLE 2-6: FISH BIOCONCENTRATION FACTORS FOR THE METALS OF CONCERN

Metal of Concern	Bioconcentration Factor	Reference
Americium	—	—
Beryllium	19	CAPCOA (1991)
Plutonium	10[a]	ATSDR (1990a)
Uranium	<38	ATSDR (1990b)

— Not Found
a Plutonium is concentrated in the bones of fish rather than in the edible muscle tissue, ratio of whole fish to muscle tissue is 40:1 (ATSDR, 1990a).

Based on this information, the fish ingestion pathway is not evaluated further.

2.2.3 Soil/Sediment

The complete exposure pathways identified for the soil and sediment media are as follows:

Direct Pathways
Soil/Sediment - Humans (Ingestion) Soil/Sediment - Humans (Dermal Contact) Soil/Sediment - Humans (Ground Exposure)

Indirect Pathways
Soil - Livestock - Humans (Ingestion) Soil - Vegetation - Humans (Ingestion) Soil - Vegetation - Livestock - Humans (Ingestion) Soil/Sediment - Air - Humans (Inhalation) Soil/Sediment - Air - Humans (Immersion)

The relative importance of the direct and indirect pathways for soil is dependent on the transfer factors and dose factors of the contaminants of concern. However, with regard to dermal absorption, this pathway is not likely to be important for the nonvolatile materials of concern. This is because the radionuclides and beryllium were released in the form of metals and metal oxides, which have extremely low solubility in water and solubility is closely related to dermal

absorption potential. Furthermore, dermal absorption of beryllium, americium, and plutonium from dilute solutions is believed to be less than 0.1 % (CAPCOA, 1991; ICRP, 1986). As such, dermal absorption of contaminants in soil and sediments is not evaluated further. The significance of the remaining pathways will be evaluated quantitatively in Task 8.

Secondary soil resuspension (i.e., airborne contaminants deposited on ground surface and then resuspended by wind or mechanical disturbance) is usually of lesser importance in comparison to direct atmospheric transport of a release. It can be of importance, however, when the direct atmospheric transport has ended and the ground surface becomes the primary source of contaminated material. The significance of this pathway is discussed in detail in Section 3.0.

2.2.4 Summary—Qualitative Evaluation of Complete Exposure Pathways

The pathways identified as having the potential to contribute significantly to dose based on the physical properties of the materials of concern and environmental monitoring data are listed in Table 2-7. These pathways are evaluated quantitatively in Task 8.

TABLE 2-7

POTENTIALLY IMPORTANT PATHWAYS
FOR THE MATERIALS OF CONCERN

Air Medium

Pathway	Material of Concern
Air - Humans (Inhalation)	Solvents, Be, Am, Pu, U, Tritium
Air - Humans (Immersion)	Am, Pu, U
Air - Livestock - Humans (Ingestion)	Be, Am, Pu, U, Tritium
Air - Vegetation - Humans (Ingestion)	Be, Am, Pu, U, Tritium
Air - Vegetation - Livestock - Humans (Ingestion)	Be, Am, Pu, U, Tritium

Surface Water Medium

Pathway	Material of Concern
Water - Humans (Ingestion)	Be, Am, Pu, U, Tritium

Soil/Sediment Media

Pathway	Material of Concern
Soil/Sediment - Humans (Ingestion)	Be, Am, Pu, U
Soil/Sediment - Humans (Ground Exposure)	Am, Pu, U
Soil - Livestock - Humans (Ingestion)	Be, Am, Pu, U
Soil - Vegetation - Humans (Ingestion)	Be, Am, Pu, U
Soil - Vegetation - Livestock - Humans (Ingestion)	Be, Am, Pu, U
Soil/Sediment - Air - Humans (Inhalation)	Be, Am, Pu, U
Soil/Sediment - Air - Humans (Immersion)	Am, Pu, U

Solvents = Carbon Tetrachloride, Chloroform, Methylene Chloride, Tetrachloroethylene, 1,1,1-Trichloroethane, Trichloroethylene
Am = Americium-241
Be = Beryllium
Pu = Plutonium-239, 240
U = Uranium-234, 235, 238

REFERENCES

ATSDR (1990a). Agency for Toxic Substances and Disease Registry. "Toxicological Profile for Plutonium." U.S. Department of Health and Human Services, Public Health Service. TP-90-21.

ATSDR (1990b). Agency for Toxic Substances and Disease Registry. "Toxicological Profile for Uranium." U.S. Department of Health and Human Services, Public Health Service. TP-90-29.

CAPCOA (1991). California Air Pollution Control Officers Association. "Air Toxics Hot Spots Program, Risk Assessment Guidelines." January 1991.

CDH (1990). Colorado Department of Health. "Standley Lake Fish Toxics Monitoring Report." January. Repository Document EN-120.

ChemRisk (1991). "Task 6 Draft Plan (P6), Environmental Exposure Pathways." April.

ChemRisk (1992). "Reconstruction of Historical Rocky Flats Operations and Identification of Release Points." Project Tasks 3 and 4. Final Draft Report. August. Repository Document TA-1202.

ChemRisk (1994). "Estimating Historical Emissions from Rocky Flats." Project Task 5 Report. March.

EG&G (1991). EG&G Rocky Flats. "Draft Final Groundwater Protection and Monitoring Plan." June 13, 1991. Repository Document EN-699.

Hurr (1976). Hurr, R.T. "Hydrology of a Nuclear-Processing Plant Site, Rocky Flats, Jefferson County, Colorado." U.S. Geological Survey Open File Report 76-268. Repository Document EN-481.

ICRP (1986). International Commission on Radiological Protection. "The Metabolism of Plutonium and Related Elements." *Annals of the ICRP*. ICRP Publication 48. Pergamon Press. New York.

McKone and Daniels (1991). McKone, T. E., and J. I. Daniels. "Estimating Human Exposure through Multiple Pathways from Air, Water and Soil." *Regul. Toxicol. Pharmacol.*, 13:36-61.

Nachtrieb and Schnoor (1991). Personal Communication with S. Nachtrieb and K. Schnoor, City of Westminster and City of Broomfield. November.

NCRP (1979). National Council on Radiation Protection and Measurements "Tritium in the Environment." NCRP Report No. 62, Washington, D.C.

Sato and Nakajima (1987). Sato, A., and T. Nakajima. "Pharmacokinetics of Organic Solvent Vapors in Relation to Their Toxicity." *Scand. J. Work Environ. Health,* 13:81-93.

Till, J. E. (1983). "Models for Special-Case Radionuclides." In: *Radiological Assessment, a Textbook on Environmental Dose Analysis*, edited by J. E. Till and H. R. Meyer. United States Nuclear Regulatory Commission, Washington D. C.

USEPA (1979). U.S. Environmental Protection Agency. "AIRDOS-EPA: A Computerized Methodology for Estimating Environmental Concentrations and Dose to Man from Airborne Releases of Radionuclides." EPA/520/1-79-009, pp. 38-40.

USEPA (1989). U.S. Environmental Protection Agency. "Risk Assessment Methodology, Environmental Impact Statement. NESHAPS for Radionuclides, Background Information Document — Volume 1." EPA/520/1-89-005.

This page intentionally left blank.

3.0 ENVIRONMENTAL TRANSPORT MODELING

Section 2.0 concludes that materials of concern released from the plant might have reached the off-site public through the processes of air dispersion, deposition, resuspension, and surface water flows. The application of air dispersion, deposition, and resuspension models and environmental monitoring data to estimate off-site contaminant concentrations associated with routine and nonroutine airborne contaminant releases is discussed in this section. Surface-water-borne releases are not modeled in this task. It was concluded in the Task 5 report that available data on surface waterborne releases from the plant were insufficient to develop release estimates (ChemRisk, 1994). An approach to screening estimates of contaminant dose through the drinking water ingestion pathway using surface water and drinking water monitoring data identified in Task 5 is described in Section 3.3.

3.1 Air Dispersion Models and Uncertainty

Three different air dispersion models were employed to predict contaminant concentrations associated with the release of contaminants from the filter plenum exhausts, from fires, and from contaminated soil associated with the 903 Pad. The models included the following:

- ISC (Industrial Source Complex) model,
- FDM (Fugitive Dust Model), and
- INPUFF (Integrated PUFF) model.

It was originally planned to make use of the TRAC model currently under development at Rocky Flats. The TRAC model is a site-specific model for Rocky Flats designed to incorporate the local meteorological/terrain complexities by generating a wind-field based on a relatively extensive network of on-site and off-site meteorologic monitoring stations. The TRAC model has the potential to provide greater accuracy, particularly in the prediction of the location of the maximum concentrations for short-term release events such as fires, provided the meteorologic monitoring network data are available for the event. After further investigation, it was determined that only very basic meteorologic information is available for the historical events of concern. Therefore, the TRAC model did not offer any advantages from the standpoint of accuracy over the less complex dispersion models that were selected. A more detailed discussion of the air dispersion models selected, and the investigation into the TRAC model, is presented in Appendix E.

Successful use of air dispersion models depends on the availability of meteorological data suitable for describing weather conditions during contaminant releases. Meteorological data collected at the site is preferred, and the site-specific meteorological data available for Rocky Flats are discussed in Appendix F.

The results of air dispersion modeling always have a degree of uncertainty. There are many sources of uncertainty in an analysis and we have attempted to identify and characterize these throughout this report. The sources of uncertainty are described in general terms in Appendix G and the specific uncertainties that we have applied to the use of the dispersion models are presented. A method for propagating uncertainties through an analysis known as Monte Carlo simulation is also discussed in Appendix G.

3.2 Releases from Exhaust Filter Plenums

Estimates of the long-term releases of contaminants from the plant's exhaust filter plenums were tabulated in the Task 5 report. This section discusses the application of the ISC air dispersion model to estimate average historical contaminant concentrations in air. The deposition of this contamination to the ground is also addressed in this section. Figure 3-1 is a schematic overview of the modeling approach for routine releases.

In general, ventilation systems at Rocky Flats continuously exhaust air out of production buildings and these buildings are maintained at lower pressure than the surrounding atmosphere. As a result, airflow is into the buildings, except at ventilation system exhausts. Within the buildings themselves, the shielded glove boxes used to handle and machine radioactive metals are at lower pressure than the building, so if a leak occurs, air flows into the glove boxes from within the buildings. Air exhausted from buildings and gloveboxes where radioactive metals and beryllium were handled was filtered through several stages of high efficiency particulate air (HEPA) filters, the last stage usually being large chambers called filter plenums. Therefore, airborne emissions of radioactive materials and beryllium from Rocky Flats during normal operations came from filter plenum exhausts. After exhaust air passed through the HEPA filters, and before it left the exhaust stack, it was sampled by monitoring instruments to determine the concentration of radioactivity and beryllium in the exhausted air. These monitoring data were used to develop the release estimates presented in the Task 5 report.

3.2.1 Release Estimates

Filter plenum release estimates and their associated uncertainties were presented for all the materials of concern in the Task 5 report. The total release of plutonium includes releases from normal operations and from the Building 776 accident involving the 1965 glove box drain fire and the 1974 control valve accident in Building 707A. The Building 776 accident did not bypass

ROUTINE RELEASES

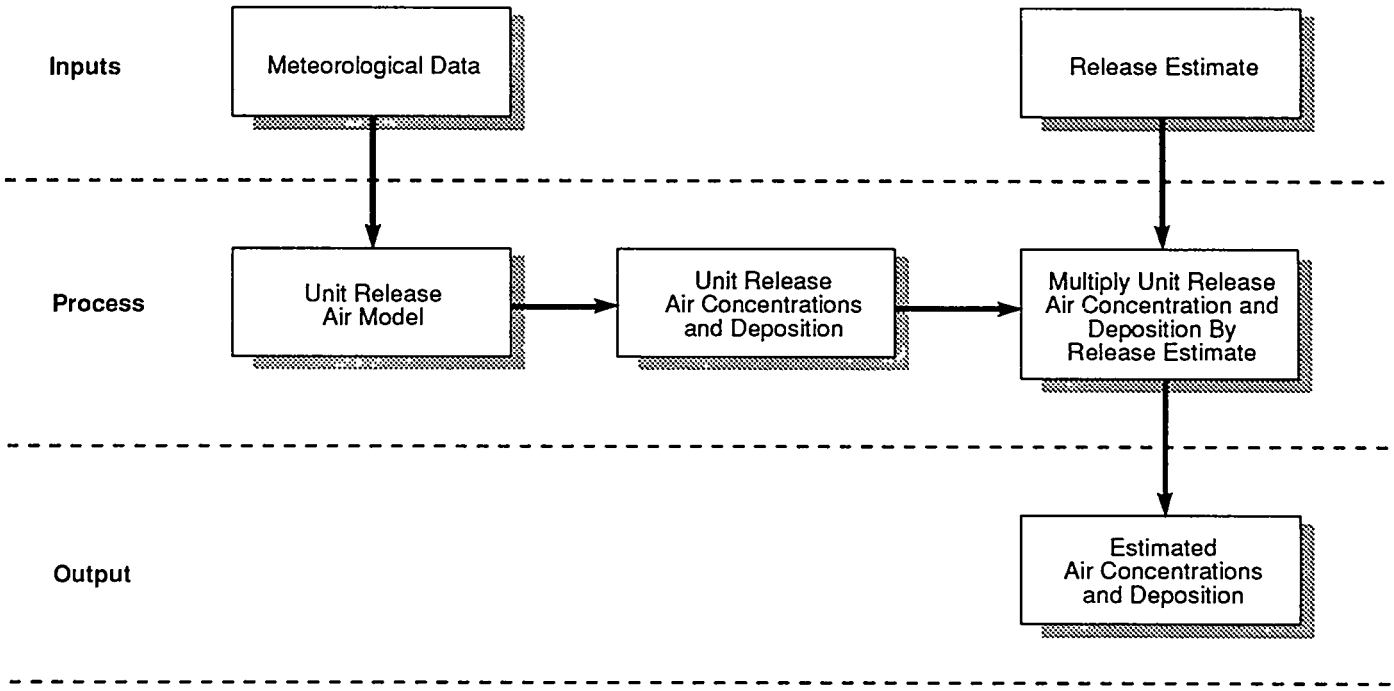


Figure 3-1
Air Modeling Approach
Routine Releases

the HEPA filters, and the release was monitored by stack samplers. The Building 707A control valve accident in 1974 did bypass the HEPA filters, but the release was monitored by a stack sampler before it left the exhaust vent.

3.2.2 Prediction of Airborne Contaminant Concentrations

The releases of contaminants from the filter plenum exhausts were modeled using ISCLT, the version of the ISC model suitable for long-term releases. The model was run a number of times, using different input parameters for stack height, exit velocity and stack location to best represent the characteristics of each of the releases that have been quantified. While the modeling predictions at off-site locations are not very sensitive to the relatively small changes in these input parameters, the assumptions identified below reflect conditions that were associated with the majority of the particular releases based on information compiled in the Tasks 3 and 4 report.

STACK LOCATION	STACK HEIGHT	EXIT VELOCITY
Run 1—plutonium and americium		
Building 771—90 percent of release	44 m	12 m sec^{-1}
Building 776—10 percent of release	13 m	0.01 m sec^{-1}
Run 2—uranium, depleted and enriched		
Building 444/447—50 percent of release	5 m	0.01 m sec^{-1}
Building 881/883A&B—50 percent of release	12 m	1.5 m sec^{-1}
Run 3—tritium, and solvents and beryllium		
Center of the plant (220 m west and 190 m south of Building 771 stack, UTM coordinates 482650E, 4415680N)	5 m	0.5 m sec^{-1}

Further refinements reflecting any annual changes in the parameters are not warranted at this time given the limited sensitivity of the predictions to these assumptions and the limited importance of these emissions when compared to the accidental releases. In cases where a release may have come from more than two buildings, it is assumed to come from the center of the facility. As described in Appendix F, the meteorological input data was the 5-year data set from 1987 through 1991. The modeling runs that serve as the basis for the evaluation of long-

term filter plenum releases are all based on a unit emission rate (1 mCi y^{-1} or 1 g y^{-1}) at ambient temperature (70°F). The model runs all included building downwash corrections.

The predicted annual average air concentrations are presented in the form of concentration isopleths on a map of the site and the surrounding area for each the modeled releases. A base map identifying highways, lakes and residences in the vicinity of the plant is presented in Figure 3-2. Figures 3-3 through 3-6 present the air concentration isopleths for each of the modeling runs indicated above. The isopleth and the accompanying value in fCi m^{-3} (picograms m^{-3} for solvents and beryllium) identify the line along which the predicted air concentration is constant. The predicted air concentrations between isopleth lines would fall somewhere between the values identified for the two nearest isopleths on either side of the point of interest. Because the ISC model does not perform well in mountainous areas, no isopleths are provided within the front range of the Rocky Mountains, which occurs approximately 4 miles due west from the center of the plant. Predicted annual average air concentrations for each of the modeled releases can be calculated for any year by multiplying the isopleth values by the estimated annual release amount in mCi y^{-1} or g y^{-1} as appropriate.

3.2.3 Uncertainty in Prediction of Airborne Contaminant Concentrations from Filter Plenum Exhaust

Annual average air concentrations, [Air], from filter plenum releases of any of the contaminants are calculated as follows:

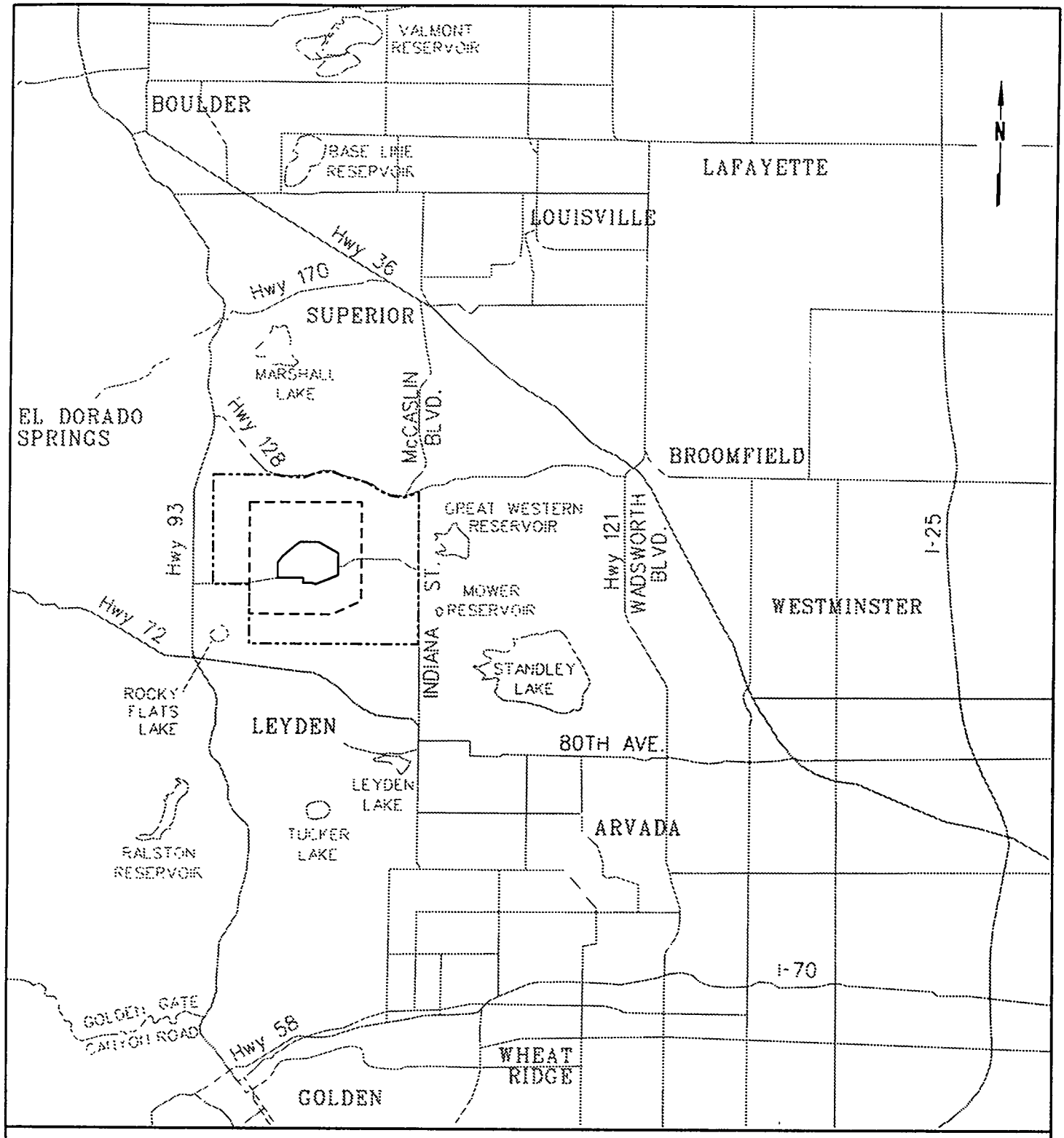
$$[\text{Air}] = [\text{Air}]_{\text{unit release}} \times R$$

where:

$[\text{Air}]_{\text{unit release}}$ = predicted air concentration for a unit release of the contaminant during a year [e.g., fCi m^{-3} per mCi y^{-1}], and

R = annual contaminant release (e.g., mCi y^{-1}).

There are uncertainties in both modeled air concentrations for a unit release and in contaminant release estimates. The uncertainty associated with the application of the ISC model to routine releases is a factor of 3 as described in Appendix G. The uncertainties associated with the estimation of routine contaminant releases were described for each of the releases in Task 5. These uncertainties will be incorporated in the dose assessment using Monte Carlo techniques, which are also described in Appendix G.



LEGEND

SECURITY FENCE

ROCKY FLATS PLANT BOUNDARY 1951-1974

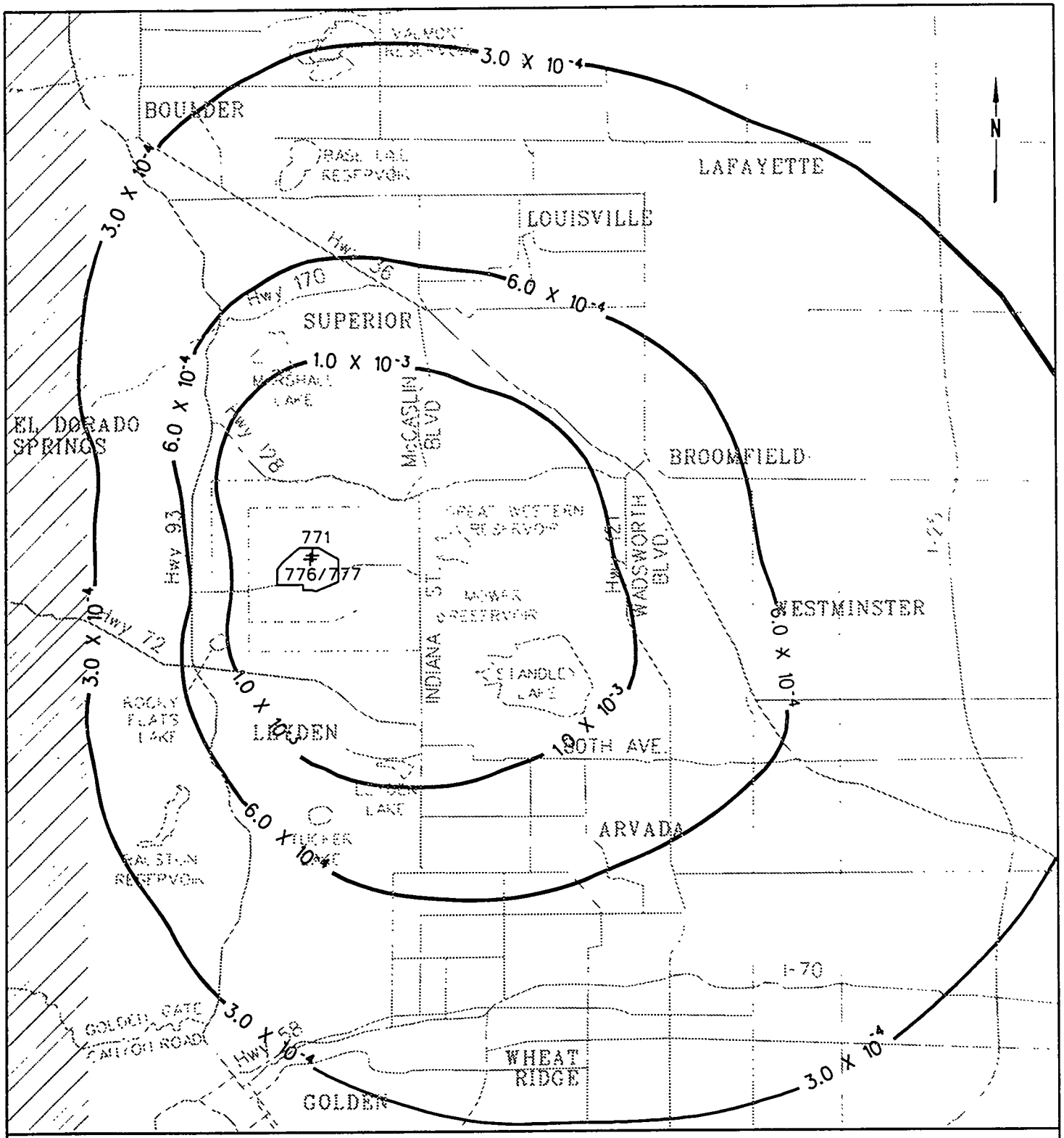
ROCKY FLATS PLANT BOUNDARY 1974-PRESENT (WITH BUFFER ZONE ADDED)

0' 13,200'
SCALE
SCALE: 1"=2.5 Miles

ChemRisk
A Division of McLaren/Hart

FIGURE 3-2
SITE MAP
ROCKY FLATS

Rky0194H/rfh3-2 dgn: Rev 05-17-94



LEGEND

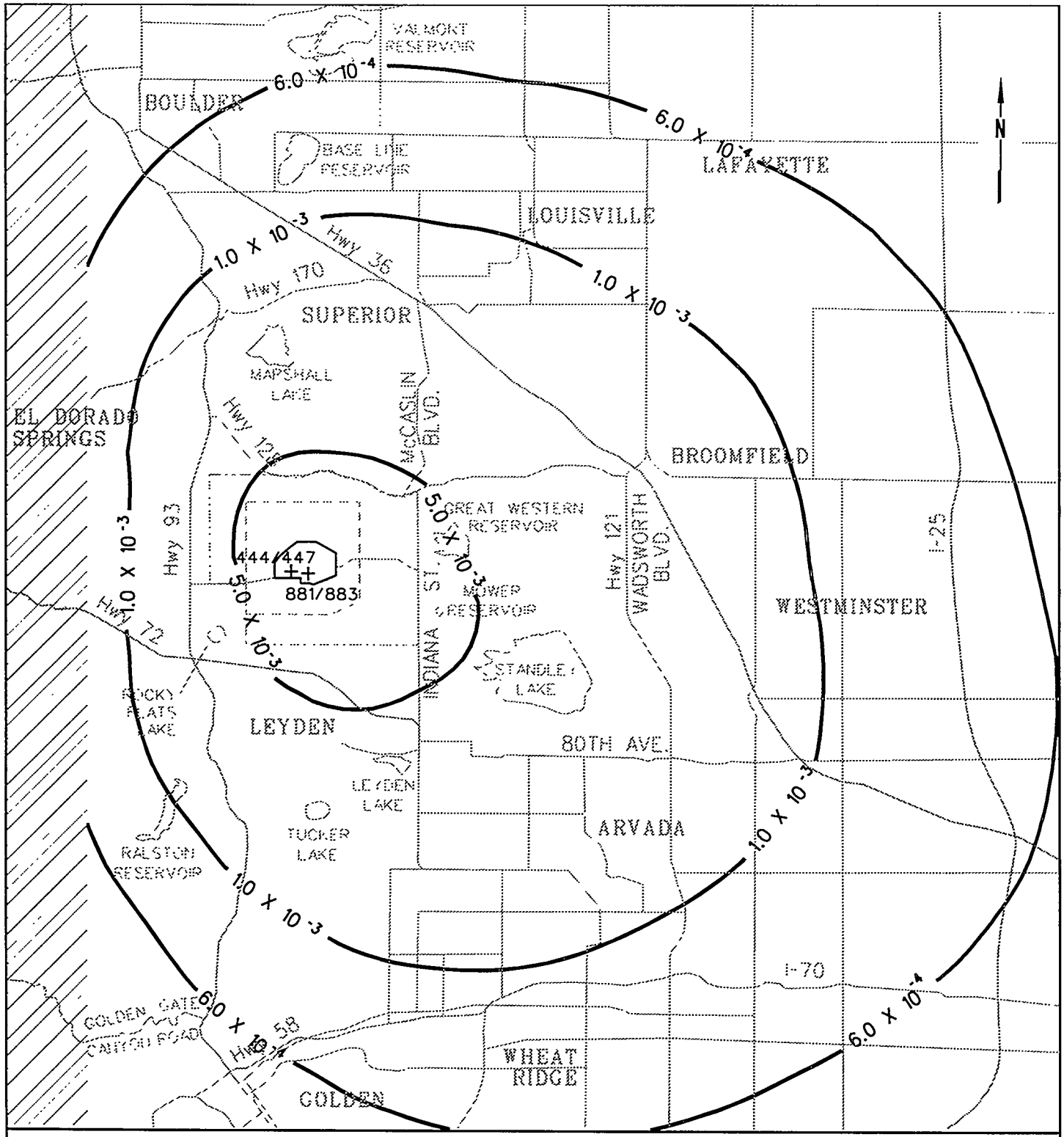
- SECURITY FENCE
- ROCKY FLATS PLANT BOUNDARY 1951-1974
- ROCKY FLATS PLANT BOUNDARY 1974-PRESENT (WITH BUFFER ZONE ADDED)
- FRONT RANGE OF THE ROCKY MOUNTAINS
- + BUILDING 771 STACK
- + BUILDING 776/777 STACK
- ISOPLETH CONCENTRATION LINES, fCi m^{-3}
- 10^{-1} SCIENTIFIC NOTATION: 10^{-1} = 0.1 OR 1/10; 10^{-2} = 0.01 OR 1/100; etc.
- fCi 10^{-15} CURIE

0' 13,200'
SCALE
SCALE: 1" = 2.5 Miles

FIGURE 3-3
PREDICTED ANNUAL AVERAGE AIR CONCENTRATIONS FOR A UNIT RELEASE OF PLUTONIUM OR AMERICIUM (fCi m^{-3})

ChemRisk
A Division of McLaren/Hart

Rky0194h/rfh3-03 dgn: Rev. 05-17-94



LEGEND

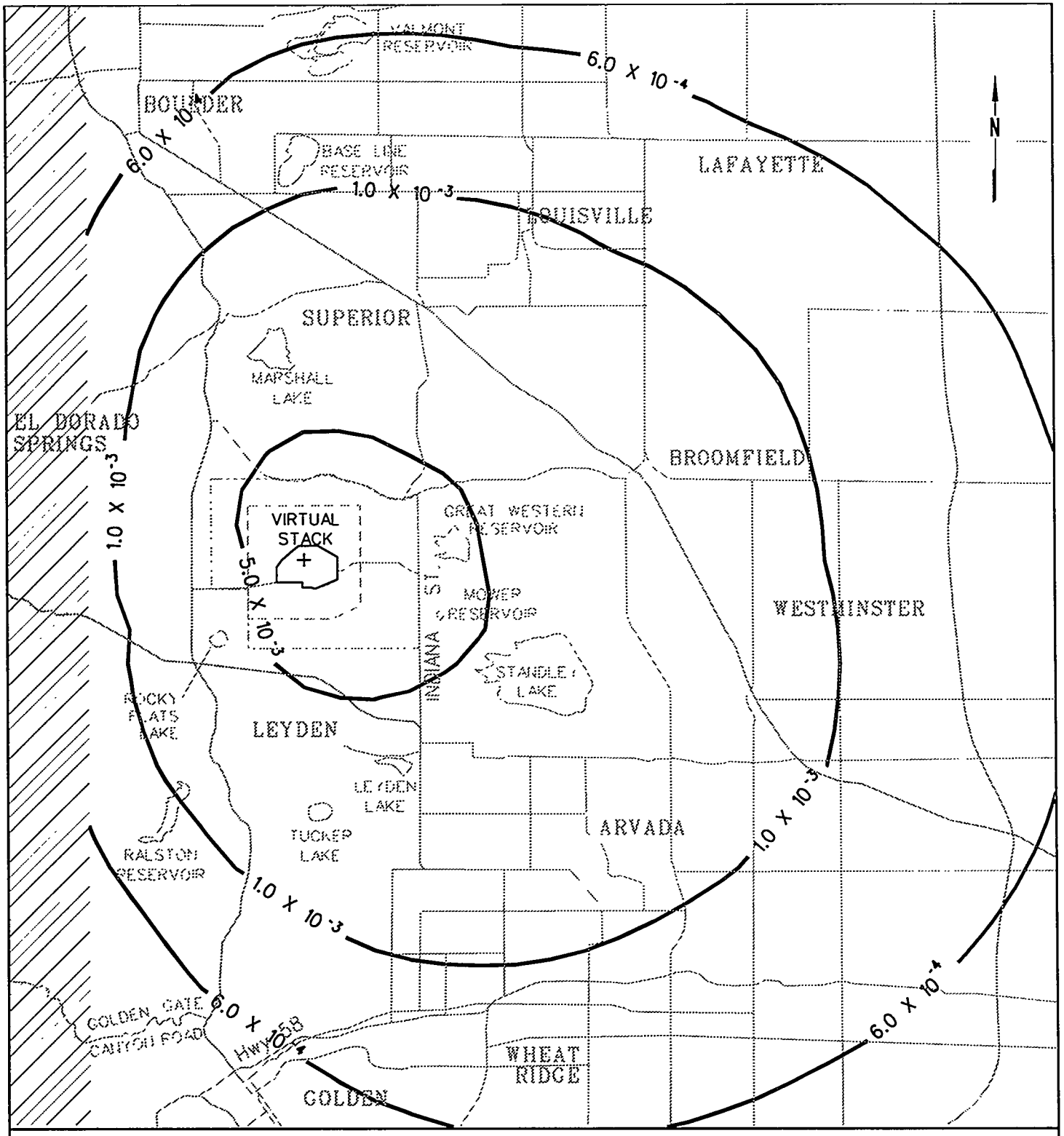
- SECURITY FENCE
- ROCKY FLATS PLANT BOUNDARY 1951-1974
- ROCKY FLATS PLANT BOUNDARY 1974-PRESENT (WITH BUFFER ZONE ADDED)
- FRONT RANGE OF THE ROCKY MOUNTAINS
- + BUILDING 444/447 STACK
- + BUILDING 881/883 STACK
- ISOPLETH CONCENTRATION LINES, fCi m^{-3}
- 10^{-1} SCIENTIFIC NOTATION: 10^{-1} = 0.1 OR 1/10; 10^{-2} = 0.01 OR 1/100; etc.
- fCi 10^{-15} CURIE

0' 13,200'
SCALE
SCALE: 1" = 2.5 Miles

ChemRisk
A Division of McLaren/Hart

FIGURE 3-4
PREDICTED ANNUAL AVERAGE AIR CONCENTRATIONS FOR A UNIT RELEASE OF URANIUM (fCi m^{-3})

Rky0194h/rfh3-04.dgn: Rev: 05-06-94



LEGEND

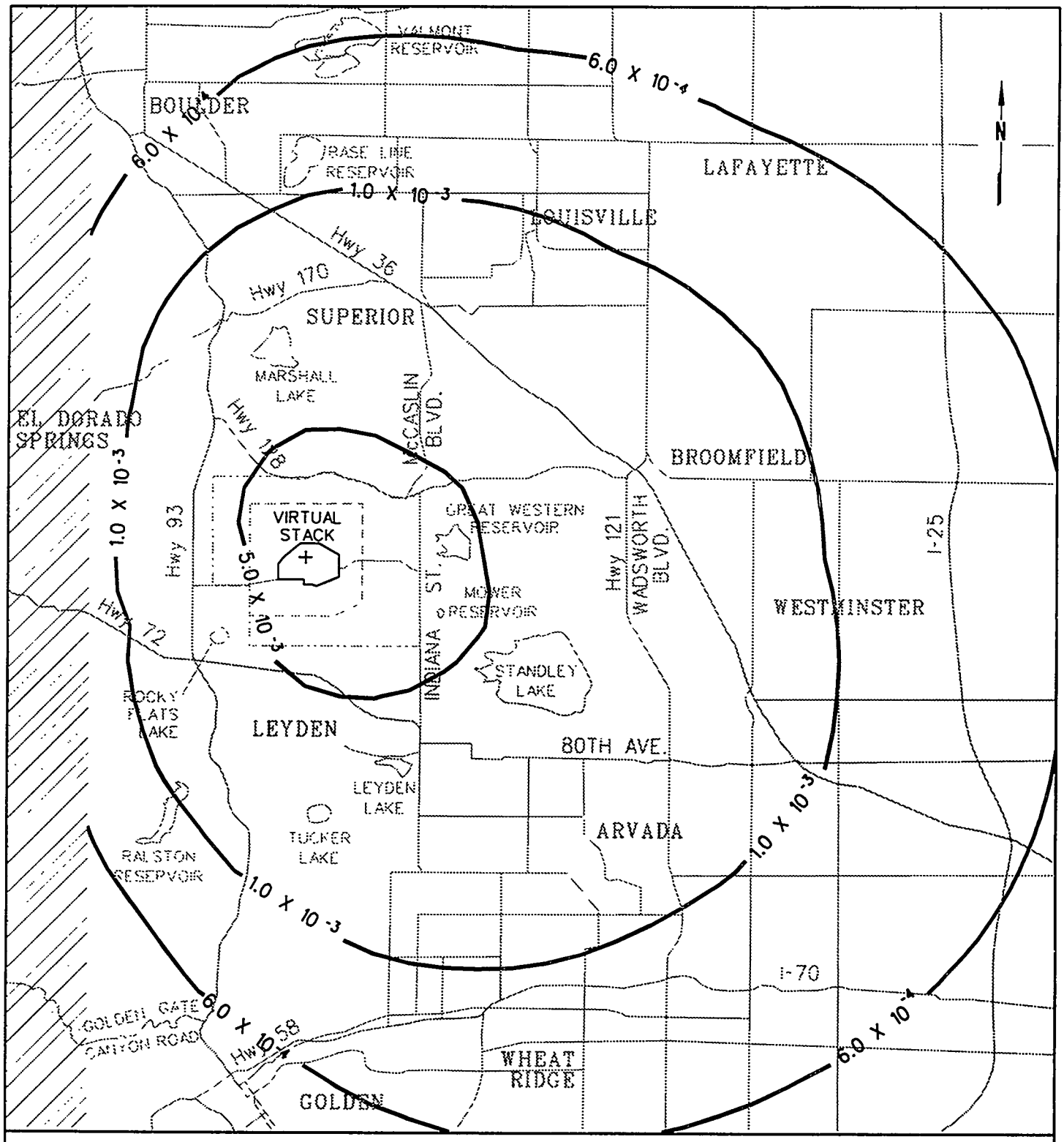
- SECURITY FENCE
- ROCKY FLATS PLANT BOUNDARY 1951-1974
- ROCKY FLATS PLANT BOUNDARY 1974-PRESENT (WITH BUFFER ZONE ADDED)
- FRONT RANGE OF THE ROCKY MOUNTAINS
- ISOPLETH CONCENTRATION LINES, fCi m^{-3}
- 10^{-1} SCIENTIFIC NOTATION: 10^{-1} = 0.1 OR 1/10; 10^{-2} = 0.01 OR 1/100; etc.
- fCi 10^{-15} CURIE

0' 13,200'
SCALE
SCALE: 1" = 2.5 Miles

ChemRisk
A Division of McLaren/Hart

FIGURE 3-5
PREDICTED ANNUAL AVERAGE AIR CONCENTRATIONS FOR A UNIT RELEASE OF TRITIUM (fCi m^{-3})

Rky0194h/rth3-05.dgn: Rev: 05-06-94



LEGEND

- SECURITY FENCE
- ROCKY FLATS PLANT BOUNDARY 1951-1974
- ROCKY FLATS PLANT BOUNDARY 1974-PRESENT (WITH BUFFER ZONE ADDED)
- FRONT RANGE OF THE ROCKY MOUNTAINS
- ISOPLETH CONCENTRATION LINES, pg m^{-3}
- 10^{-1} SCIENTIFIC NOTATION: 10^{-1} = 0.1 OR 1/10; 10^{-2} = 0.01 OR 1/100; etc.
- pg 10^{-12} GRAM

0' 13,200'
SCALE
SCALE: 1" = 2.5 Miles

ChemRisk
A Division of McLaren/Hart

FIGURE 3-6
PREDICTED ANNUAL AVERAGE AIR CONCENTRATIONS FOR A UNIT RELEASE OF BERYLLIUM OR VOLATILE CHEMICAL (pg m^{-3})

Rky1094h/rfh3-06.dgn: Rev: 05-06-94

3.2.4 Prediction of the Deposition of Airborne Contaminants

Particles present in the air have the potential to be deposited onto surfaces near the ground such as vegetation, soil, and surface waters. Evaluation of the deposition of contaminants can be an important consideration in evaluating the ways in which people have been exposed to contaminants in the environment. Large particles have a greater tendency to be deposited, or a higher deposition velocity, than small particles. Therefore, in evaluating the deposition of contaminants, it is important to characterize the size of the contaminant particles.

Of the contaminants of concern, plutonium, americium, uranium, and beryllium are those most likely to be emitted in particulate form. Particulate releases from plant exhausts have all passed through a number of stages of HEPA filtration, leaving only very small particles in the exhaust air stream. As was discussed in the Task 5 report, a number of studies have been performed to characterize the particle size of plutonium contamination in plant exhausts. These studies indicate that the predominant particle size was less than one micron in diameter. While these studies did not specifically address uranium, americium, and beryllium effluent particle size, the similarity in the handling and filtration of these effluents to that of plutonium would be expected to also result in the release of very small particles.

In order to predict the deposition of airborne contaminants, an appropriate deposition velocity must be identified for the contaminants of interest. In this case, we are dealing with very small, sub-micron sized particles for which very small deposition velocities are appropriate (Sehmel, 1984; USEPA, 1979; and Sehmel and Hodgson, 1978). Since releases from the filter plenum exhausts have occurred essentially uninterrupted since operations began, including during periods of rain or snowfall, the materials of concern will have deposited as a result of both wet and dry deposition. Wet deposition results from "precipitation scavenging," a phenomenon in which pollutants or trace contaminants are removed from the atmosphere by various types of precipitation (Slinn, 1984). The primary effect of this phenomenon is to greatly increase deposition of particulate matter during periods of precipitation. Dry deposition, on the other hand, occurs without the aid of precipitation (Randerson, 1984).

A dry deposition velocity of 0.1 cm sec^{-1} has been recommended for particles less than 4 micron in equivalent aerodynamic diameter (Moore *et al.*, 1979). Slinn (1984) estimated that the deposition velocity increases to approximately 10 cm/sec during precipitation events. For the small particles released from the filter plenum exhausts, this represents approximately a 100-fold increase in deposition velocity. The net result would be increased particulate deposition and decreased downwind air concentrations during rain or snowfall events. The greater the number of precipitation events, the greater effect precipitation scavenging could potentially have on the predicted air concentrations and deposition.

As discussed in Appendix F, validated meteorological data for the years 1987 through 1991 were used to predict contaminant air concentrations associated with routine releases. An analysis of this data set revealed that measurable precipitation occurred only 1.7 percent of the time during that period. The annual precipitation ranged from 10 to 16 inches, with an average of approximately 13 inches per year. Annual precipitation for the Denver area between 1936 and 1975 ranged from 12 to 23 inches, with an average of approximately 15 inches per year. These annual precipitation rates are similar to those observed for Rocky Flats during 1987-1991, indicating that, historically, measurable precipitation in the vicinity of Rocky Flats probably occurred only a small percentage of the time.

Based on a dry deposition velocity ($V_{d\text{-}Dry}$) of 0.1 cm sec^{-1} and a wet deposition velocity ($V_{d\text{-}Wet}$) of 10 cm sec^{-1}, the total deposition velocity ($V_{d\text{-}Total}$), assuming that precipitation occurred an average of 2 percent of the time, can be calculated as follows:

$$V_{d\text{-}Total} = [V_{d\text{-}Dry} \times \%\ Dry] + [V_{d\text{-}Wet} \times \%\ Wet]$$

$$= [0.1\ cm\ sec^{-1} \times 0.98] + [10\ cm\ sec^{-1} \times 0.02]$$

$$= 0.098\ cm\ sec^{-1} + 0.2\ cm\ sec^{-1}$$

$$= 0.3\ cm\ sec^{-1}$$

Since there is some uncertainty in our estimate of the actual percentage of the time that precipitation occurred, the above calculated total deposition velocity represents a source of uncertainty in our prediction of deposition from routine releases. For the purpose of this analysis, this uncertainty is represented by a lognormal distribution with a geometric mean (GM) equal to 1 and a geometric standard deviation (GSD) of 1.7. This means that the 95 percent of the distribution falls within a factor of approximately 3 (GSD^2) of the best estimate (0.3 cm sec^{-1}).

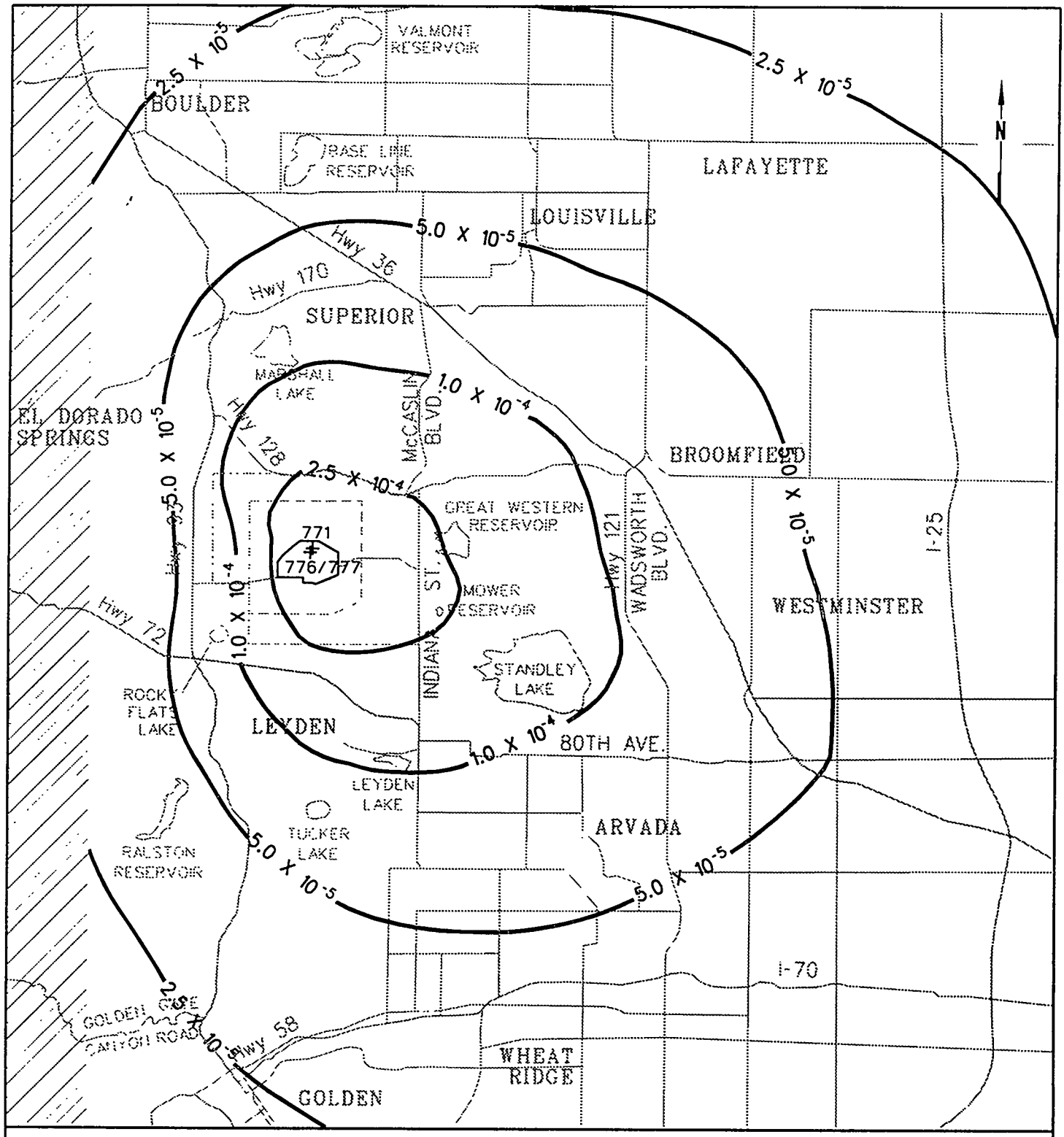
The ISC model can be used to predict contaminant deposition based on the modeling runs performed to estimate air concentrations. The best estimate of the deposition velocity is input to the ISC model for the purposes of generating isopleths of the predicted contaminant deposition. The model is relatively unsophisticated in its calculation of the deposition of contaminants, since it does not account for losses that result from deposition (or what is termed plume-depletion) when making predictions of air concentration. Therefore, the model will tend to overestimate airborne concentrations of contaminants because it does not subtract out the losses from deposition. When losses from deposition are large, as in the case of large contaminant particles, this can be a source of considerable error. However, in the case of the small particles being modeled here, this represents a negligible source of error.

For the purposes of illustrating the limited importance of the deposition of exhaust plenum releases, contaminant deposition isopleths are presented for the unit emission modeling runs for plutonium and uranium in Figures 3-7 and 3-8. Contaminant deposition associated with any of the annual releases can be calculated for a location by multiplying the value identified on the isopleth by the annual release estimate in mCi to obtain the deposited activity in pCi m^{-2}. The predicted total deposition of plutonium from the release of the estimated total of 0.03 Ci of plutonium from the filter plenums over the 37 years of plant operation (ChemRisk, 1994) has been plotted in Figure 3-9. Based on this figure, total deposition from filter plenum exhaust releases over the life of the plant is approximately 0.003 mCi km^{-2} at Indiana Street and 0.006 mCi km^{-2} at the edge of the plant site. These values are substantially lower than soil contamination measured in 1970, which largely resulted from the 903 Pad release (see Section 3.4.1). The measured soil contamination at Indiana Street is about 100 mCi km^{-2}.

3.2.5 Uranium Release January 24, 1956

Data in the Task 5 report indicate that about 20 percent of the enriched uranium released from filter plenum exhausts at Rocky Flats was released in 1956. Most of the 1956 release (about 910 μCi, or 16 percent of the total filter plenum exhaust release of enriched uranium over the 37-year period of 1953 through 1989) was emitted from Building 881 on January 24, 1956. No explanation for this high release has been found. It is not likely to be a sampling, calculation, or reporting error. This is because high readings occurred in all Building 881 exhaust samplers on that day and the readings are surrounded on the data reporting sheets by data for other days that are many orders of magnitude lower.

The release on January 24, 1956 is included in the filter plenum release modeling discussed above. However, inhalation exposure for the one-day (86,400-second) enriched uranium release from Building 881 on January 24, 1956 was also modeled separately using ISC with a constant release rate of 910 μCi/86,400 sec = 0.01 μCi sec^{-1}. Because on-site meteorological data are not available for January 24, 1956, worst-case meteorology of a 1 m sec^{-1} wind from the north for 24 hours with F stability was used. The resulting worst-case, 24-hour average air concentration at Indiana Street near the southeast corner of the buffer-zone (believed to be the location of the nearest residence) was about 1 pCi m^{-3}. The relative magnitude of this worst-case, single-day air concentration from the January 24, 1956 uranium release from the Building 881 filter plenum exhaust is compared to other releases from the plant in a subsequent section of this report (Section 3.6).



LEGEND

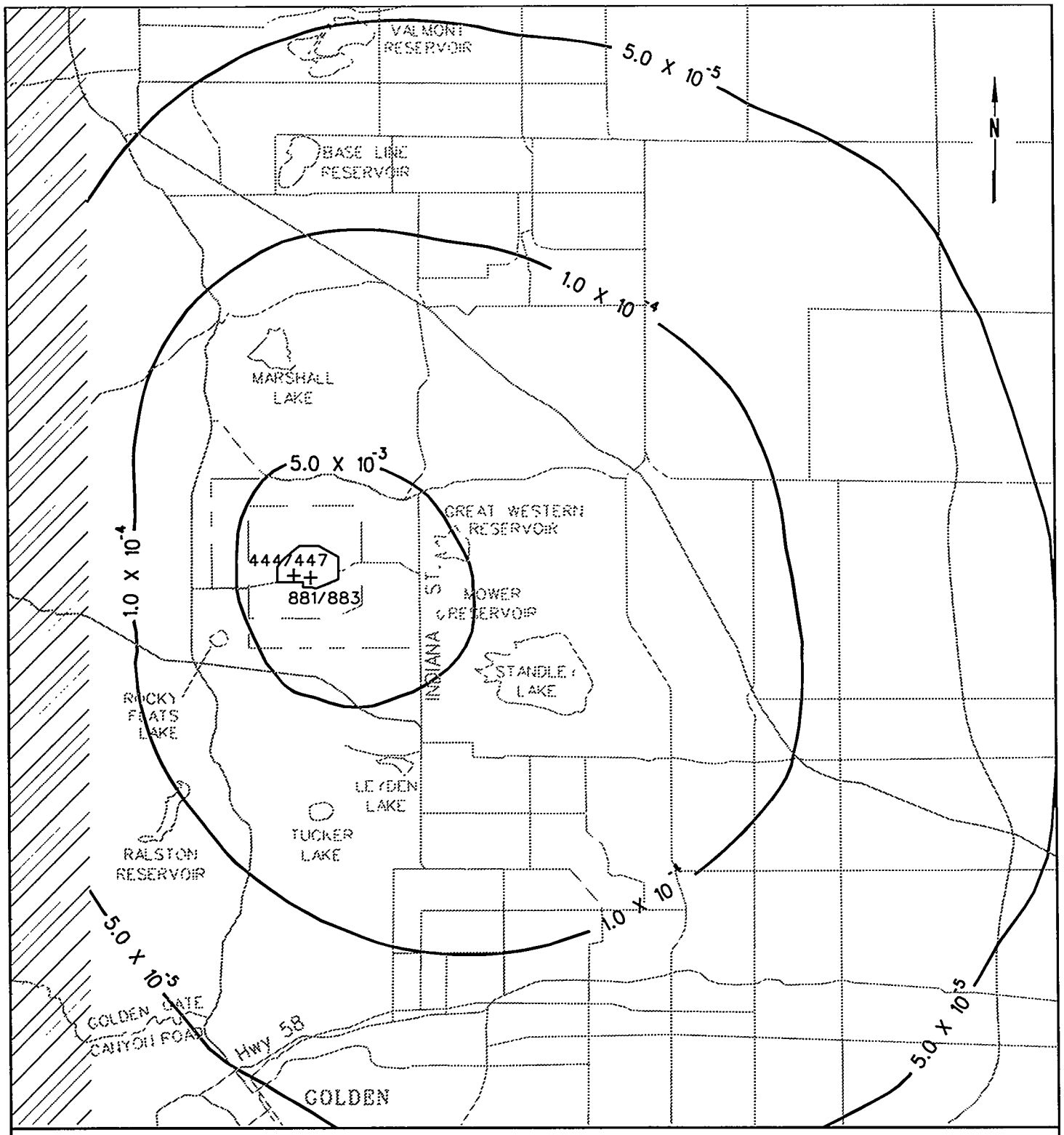
- SECURITY FENCE
- ROCKY FLATS PLANT BOUNDARY 1951-1974
- ROCKY FLATS PLANT BOUNDARY 1974-PRESENT (WITH BUFFER ZONE ADDED)
- FRONT RANGE OF THE ROCKY MOUNTAINS
- + BUILDING 771 STACK
- + BUILDING 776/777 STACK
- ISOPLETH CONCENTRATION LINES, mCi km^{-2}
- 10^{-1} SCIENTIFIC NOTATION: 10^{-1} = 0.1 OR 1/10; 10^{-2} = 0.01 OR 1/100; etc.
- mCi 10^{-3} CURIE

0' 13,200'
SCALE
SCALE: 1" = 2.5 Miles

ChemRisk
A Division of McLaren/Hart

FIGURE 3-7
PREDICTED ANNUAL DEPOSITION FOR A UNIT RELEASE OF PLUTONIUM (mCi km^{-2})

Rky0194h/rfh3-07 dgn. Rev 05-18-94



LEGEND

SECURITY FENCE

ROCKY FLATS PLANT BOUNDARY 1951-1974

ROCKY FLATS PLANT BOUNDARY 1974-PRESENT (WITH BUFFER ZONE ADDED)

FRONT RANGE OF THE ROCKY MOUNTAINS

+ BUILDING 444/447 STACK

+ BUILDING 881/883 STACK

ISOPLETH CONCENTRATION LINES, mCi km $^{-2}$

10^{-1} SCIENTIFIC NOTATION: 10^{-1} = 0.1 OR 1/10; 10^{-2} = 0.01 OR 1/100; etc.

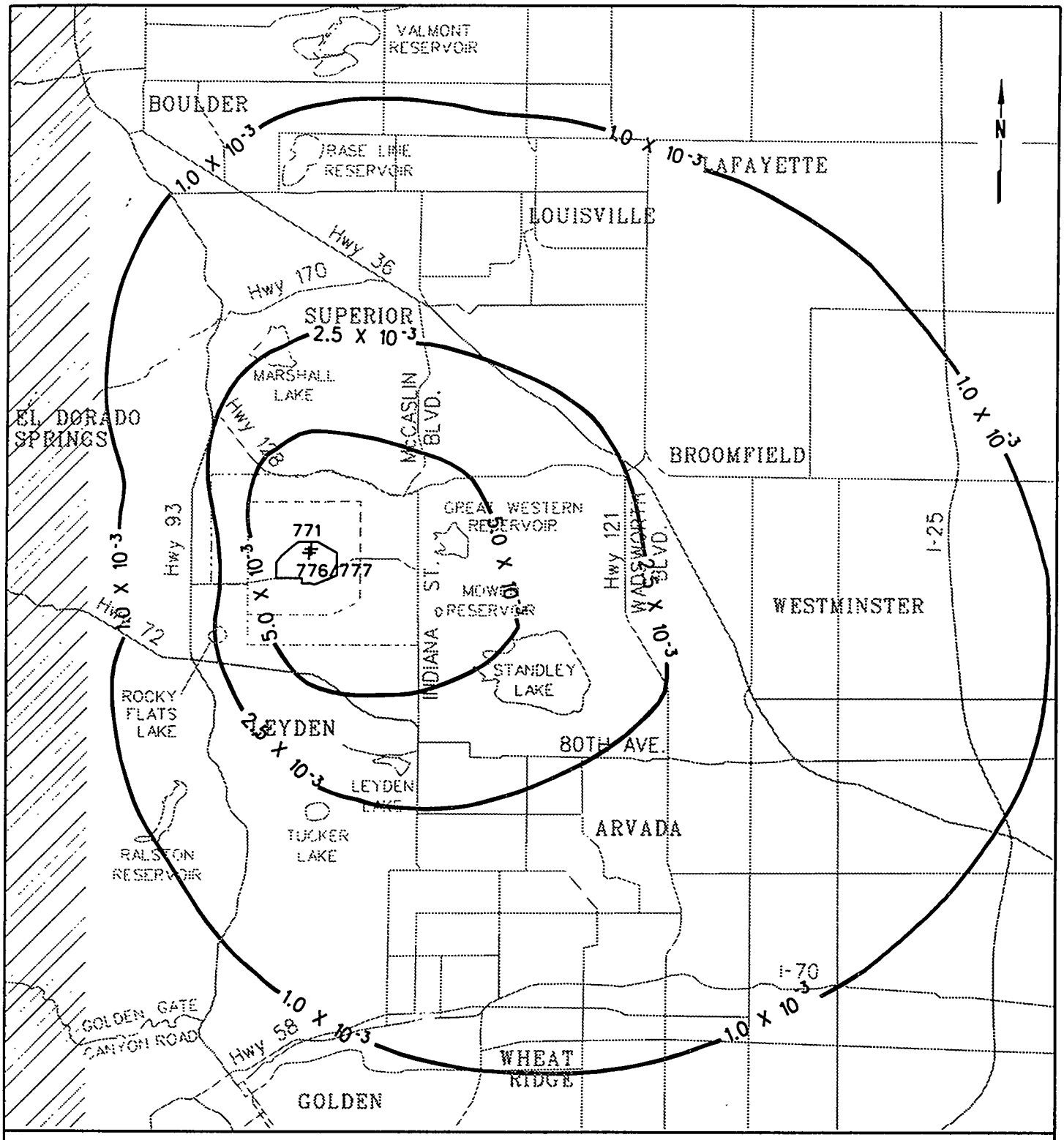
mCi 10^{-3} CURIE

0' 13,200'
SCALE
SCALE: 1"=2.5 Miles

ChemRisk
A Division of McLaren/Hart

FIGURE 3-8
PREDICTED ANNUAL DEPOSITION FOR A UNIT RELEASE OF URANIUM (mCi km^{-2})

Rky0194h/rfh3-08.dgn: Rev: 05-06-94



LEGEND

- SECURITY FENCE
- ROCKY FLATS PLANT BOUNDARY 1951-1974
- ROCKY FLATS PLANT BOUNDARY 1974-PRESENT (WITH BUFFER ZONE ADDED)
- FRONT RANGE OF THE ROCKY MOUNTAINS
- + BUILDING 771 STACK
- + BUILDING 776/777 STACK
- ISOPLETH CONCENTRATION LINES, mCi km $^{-2}$
- 10^{-1} SCIENTIFIC NOTATION: 10^{-1} = 0.1 OR 1/10; 10^{-2} = 0.01 OR 1/100; etc.
- mCi 10^{-3} CURIE

0' 13,200'
SCALE
SCALE: 1" = 2.5 Miles

ChemRisk
A Division of McLaren/Hart

FIGURE 3-9
PREDICTED CUMMULATIVE DEPOSITION FROM A 30 mCi RELEASE OF PLUTONIUM OVER 37 YEARS (mCi km^{-2})

Rky0194h/rfh3-09.dgn: Rev: 05-18-94

3.3 Surface-Water-Borne Releases

As discussed in the Task 5 report, available effluent data on surface-water-borne releases from Rocky Flats were insufficient to develop source terms (ChemRisk, 1994). In addition, modeling of surface water transport can involve relatively large uncertainties. Surface water modeling requires detailed site-specific information on time and duration of releases, amount of water in the system, and associated flow rates. This type of information is generally not available in sufficient detail to carry out surface water modeling for Rocky Flats. Furthermore, the metals of concern have extremely low water solubilities and are likely to be transported with suspended soil particles and sediments. Transport of suspended sediments is affected by episodic events, such as mechanical disturbance of bottom sediment. For example, as described in the Task 5 report, pond reconstruction activities in North Walnut Creek and South Walnut Creek from 1972 to 1974 might have increased plutonium concentration in Great Western Reservoir. Because of the lack of data to support modeling, historical drinking water monitoring data collected from cities near Rocky Flats will be used to evaluate exposure.

The detailed evaluation of surface water contamination in the Task 5 report involved analysis of raw water monitoring data for Great Western Reservoir and Standley Lake and drinking water monitoring data for the cities of Broomfield and Westminster. As discussed in the Task 5 report, tritium concentrations in Broomfield drinking water were above background levels. In single-year fluctuations, this elevation was as much as 8,100 pCi L^{-1}. Over the period 1970-1989, the average elevation in tritium levels in Broomfield drinking water was 840 pCi L^{-1}. It was also concluded that there were occasional occurrences of elevated gross alpha radioactivity in Broomfield and Westminster drinking water. However, these single-year fluctuations of alpha radioactivity were not inconsistent with levels often found in drinking water supplies unaffected by Rocky Flats releases, and it has not been established that the fluctuations in alpha radioactivity in Broomfield and Westminster drinking water were related to activities at Rocky Flats. Finally, there were insufficient data to make similar comparisons for beryllium.

To evaluate the possible importance of fluctuations in radioactivity in surface waters, doses will be calculated for one-year exposures to the following concentrations of radionuclides in drinking water in Task 8:

<u>Based on observations from 1970-1989</u>

Tritium — 8,100 pCi L^{-1}

Plutonium — 0.15 pCi L^{-1}

Based on observations from 1952-1970

Gross alpha — 1 pCi L^{-1} (evaluated as either plutonium or uranium)

3.4 Nonroutine Contaminant Releases

In approaching the evaluation of exposures to contaminants in the environment, data collected in the environment near points of exposure are the most relevant information for estimating dose. Environmental data are frequently of limited use in the evaluation of routine releases that are very small in magnitude, either because of difficulties in detecting very low concentrations of contamination in the environment or the presence of background concentrations of contaminants normally present in the environment. However, in the case of unplanned or accidental events, environmental data can be very important in the evaluation of exposure, since precise direct information on the timing, circumstances, and magnitude of nonroutine releases is often not available. At Rocky Flats, the types of information used to generate estimates of the routine releases, such as measured releases from the exhaust plenums, do not exist for nonroutine events. Therefore, other approaches to evaluating these releases must be developed. Given our objective of characterizing the exposure of the off-site public to contaminants released by these events, the most useful type of information would be measurements of contaminant concentrations in environmental media at off-site locations of exposure. However, such measurements are very limited in either number or in the type of media sampled, and therefore the measurements cannot be used alone to characterize exposures. Consequently, available environmental sampling data and information on the sequence of events associated with the release are used in conjunction with air dispersion models to reconstruct a release scenario that would produce contaminant concentrations that are in general agreement with the measurements that were made. The release scenario and air dispersion models can then be used to predict contaminant concentrations at other locations of interest.

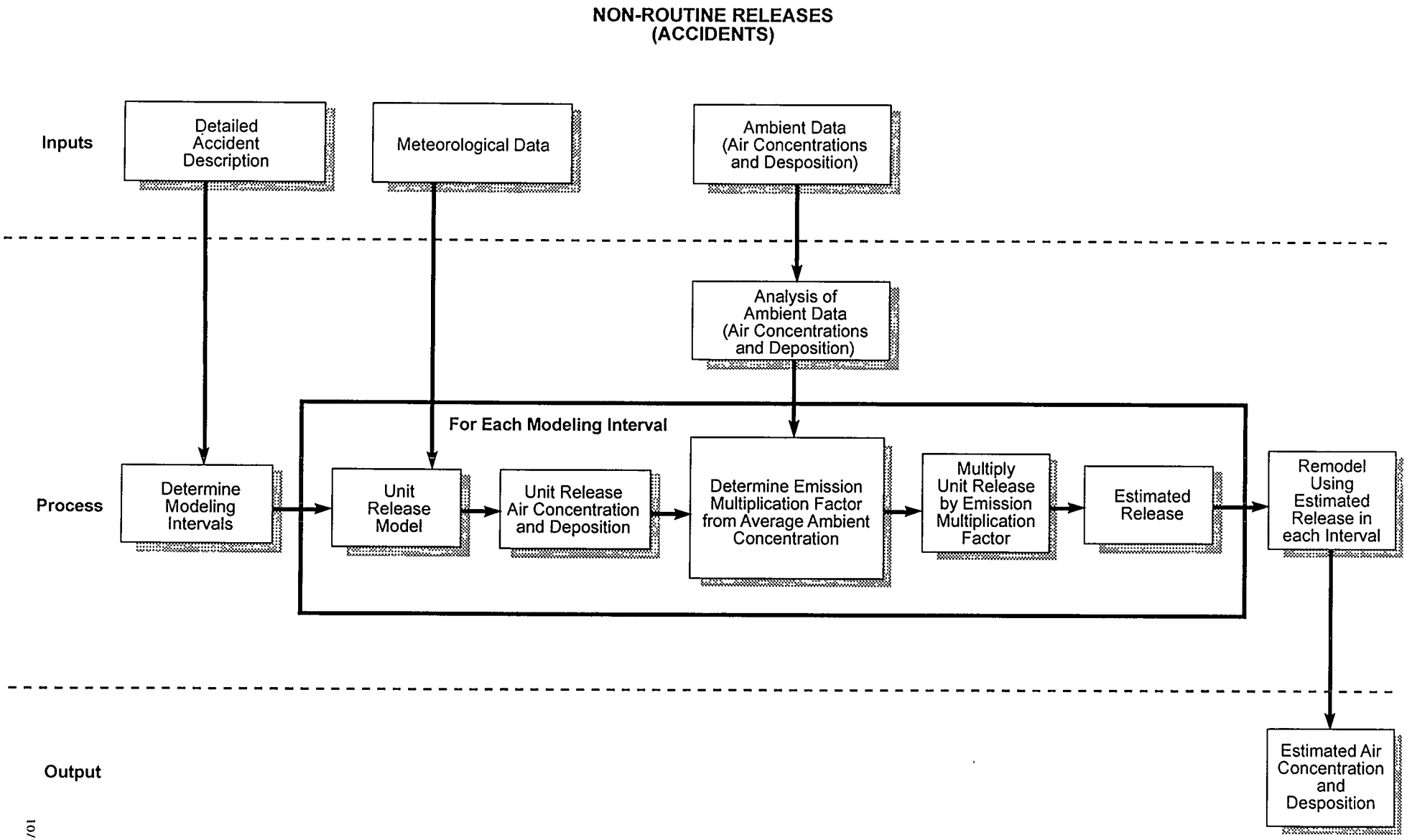
These scenarios do not purport to describe exactly what happened during an accident. Instead, they show one way that accident events could have produced environmental contamination similar to that measured. Similar scenarios could also generate results like those observed. Although other scenarios can be developed and tested, scenarios differing radically from the ones described in the following sections, such as those with greatly different release magnitudes, are less likely to reproduce the observed pattern of environmental measurements under reasonable sets of assumptions.

Figure 3-10 is a schematic overview of the modeling approach for nonroutine releases. The two largest nonroutine release events identified in the Task 5 report are the waste oil storage activities associated with the 903 Pad and the 1957 fire. These two events are evaluated extensively in the following sections. Relatively smaller release events identified in Task 5 are also evaluated and discussed in less detail.

3.4.1 903 Pad Release

The 903 Pad release began when plutonium-contaminated cutting oil (Shell vitrea oil) and solvents, stored in drums to await recycling for recovery of plutonium, leaked into the soil. Cutting oil has the consistency of lightweight motor oil and is used to cool and lubricate parts during machining. Cutting oil used during the machining of plutonium parts at Rocky Flats became contaminated with small particles of plutonium during the machining operations. Because of the high value and safety hazard of plutonium, the cutting oil and solvents were filtered prior to storage on the 903 Pad to remove particles greater than about 2 to 3 microns in size (Hayden, 1974; Little and Whicker, 1978). The filtered cutting oil, still contaminated with micron and submicron sized particles of plutonium, was stored in drums on the 903 Pad awaiting further processing to recover the remaining plutonium. When some of the drums corroded and began leaking, plutonium was released to the 903 Pad soil. Plutonium oxide in the contaminated oil was incorporated in soil particles subsequently carried off-site by the wind. It has been suggested that some of the plutonium in the soil may be in a more soluble form such as plutonium (IV) chloride, possibly as a result of a reaction between plutonium metal and hydrochloric acid formed from carbon tetrachloride present in the oil (Little, 1980). However, Lee *et al.* (1982) suggest that this form of plutonium is not likely to be stable and that a hydrous oxide would more likely be present. In any case, the work of Lee *et al.* regarding the dissolution characteristics of plutonium contaminated soils from Rocky Flats indicated that the results of experimental leaching would not classify the plutonium found in the Rocky Flats soil as soluble.

This release from the 903 Pad is believed to have been the largest release of plutonium from Rocky Flats. The event was described in the Task 3 and 4 report (ChemRisk, 1992) and can be summarized as follows. Widespread drum corrosion and leakage was discovered in January 1964. By January 1967, when removal of the drums began, 5,237 drums were stored on the pad, and 3,572 of them contained plutonium. Other drums on the pad contained cutting oil diluted with solvents and contaminated with depleted uranium (Langer, 1985a). Removal of the drums was completed in June 1968. Grading was started for applying an asphalt cap over the pad in November 1968. The first layer of fill was applied to the 903 Pad on July 23, 1969. An asphalt containment cover over the pad area was completed in November 1969.



REV: 04-28-93
RckyFlts-NonRoutine/4-93/01

ChemRisk
A Division of McLaren/Hart

Figure 3-10
Air Modeling Approach
Non-Routine Releases (Accidents)

A number of sources of information (Appendix H) suggest that the contaminant release from the 903 Pad occurred primarily during 1968 and 1969 prior to the paving of the pad area. Therefore, the initial modeling scenarios began with the assumption that the majority of the releases occurred in 1968 and 1969, possibly on only the few days that grading activities took place. Efforts were made to locate documentation or information regarding the specific days that grading took place, but these were not successful. Therefore, the days for which the downwind air sampler (S-8) indicated the highest readings were modeled and evaluated in constructing a release scenario, since it was believed that these days were likely to be the same days that grading took place and the majority of the release occurred.

Many different release scenarios were analyzed, ranging from one large single day release on the day of the highest measured airborne concentration to releases over the entire life of the pad. The Fugitive Dust Model (FDM) was used to simulate atmospheric processes leading to the soil contamination pattern observed in late 1969 and the early 1970s. The release scenario that gave the best fit to all the available data and assumptions used in the reconstruction was one that extended over a number of years. The following sections of the report describe how this release scenario was constructed. The release scenario that is described suggests that releases from the pad that contributed to the contamination measured in the soil and air around the facility occurred from 1964, when widespread deterioration of the drums at the pad was noted, through the paving of the pad area in 1969.

Actual releases from the pad were likely to have varied from day to day, being closely related to specific activities that led to disturbance of the pad. However, there is insufficient information on these daily activities to permit the evaluation of short time-span releases. The observed distribution of soil contamination, which is the most significant source of information regarding the release, represents the cumulative result of releases from the pad and provides no insight into the time history of the release. Monthly averages of daily airborne contamination measured in the S-8 sampler have been plotted by Seed *et al.* (Figure 3-1, 1971; a copy is included in Appendix H of this report) and indicate the existence of elevated airborne activity throughout the years of 1964, 1967, 1968, and 1969. However, the limitations associated with the air sampler (e.g., particle size sampling efficiency) and effects of meteorology (e.g., wind direction) on the sampling results limit the utility of this information as a sole source for identifying all episodic release events. The analysis presented in this study has therefore focussed on the prediction of releases over the entire release period. The predictions associated with this analysis are presented in terms of the best-estimate and uncertainties associated with the entire five-year release event that is modeled. The estimate of the release from the entire event could potentially be apportioned to specific years or months within the five-year period based on the further analysis of relative air concentrations in all of the on-site air samplers during this period. However, the process of dividing the entire release into smaller time periods

would introduce additional uncertainty into the results of the analysis and has not been pursued at this time.

Another type of release associated with the 903 Pad that continued after the pad was covered in mid-1969 is the resuspension of plutonium-contaminated soil that had moved off the pad. This type of release is addressed in a separate section of this report (Section 3.5).

3.4.1.1 Environmental Monitoring Data

Environmental monitoring data relevant to the analysis of plutonium released from the 903 Pad include off-site soil contaminant data reflecting plutonium deposition and air sampling data that quantify a portion (limited by the particle size collection capabilities of the sampler) of the airborne plutonium.

Soil Sample Locations and Data Sources

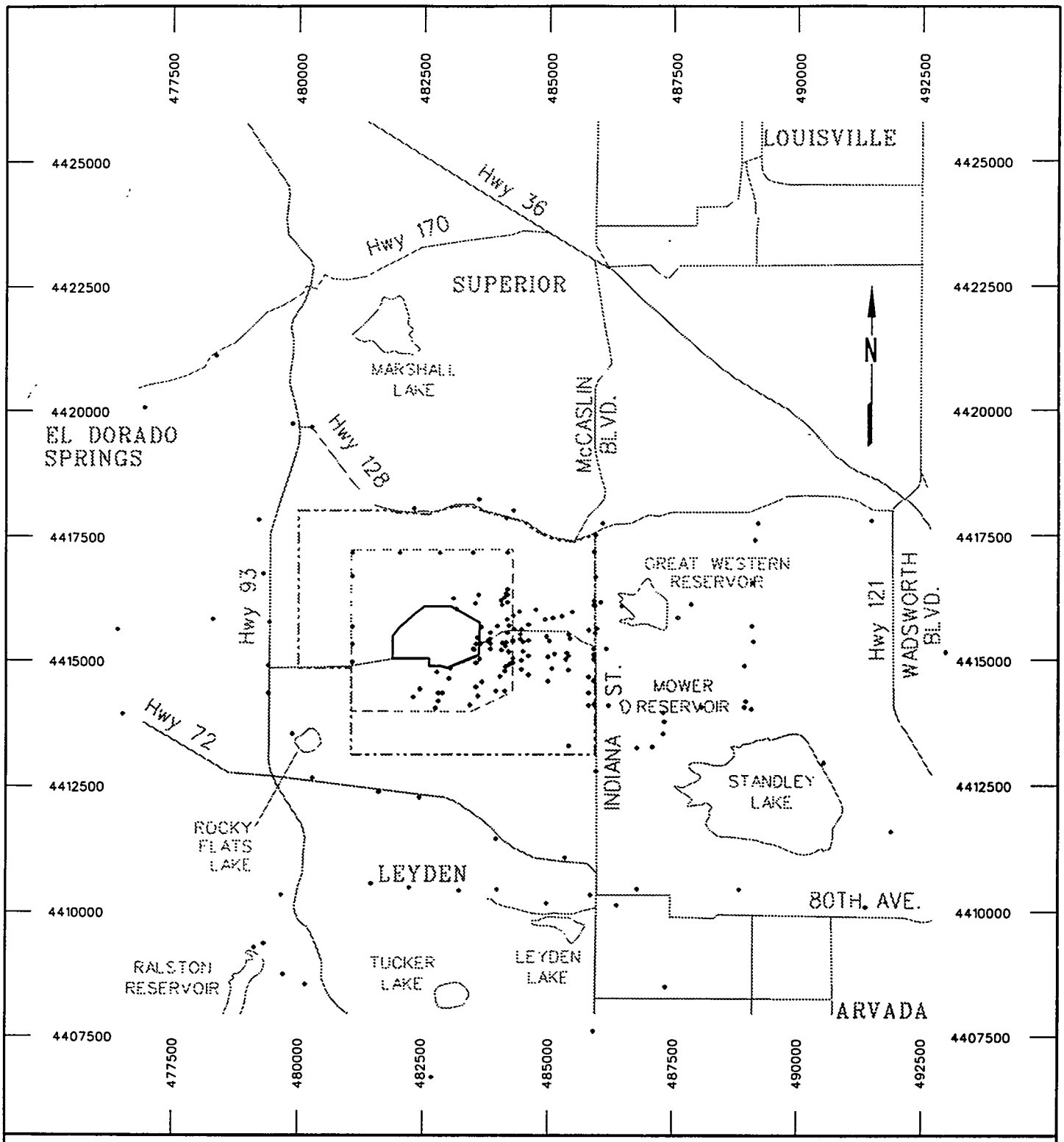
Samples to determine plutonium contamination of soil have been taken periodically at and around the Rocky Flats Plant since it was first built in the early 1950s. However, no large-scale sampling program was undertaken until after the May 11, 1969 fire. Following this fire, soil sampling surveys were undertaken by many different groups, including the Colorado Committee on Environmental Information (CCEI-Poet and Martell), the Department of Energy (USAEC Health and Safety Laboratory [HASL]), Dow Chemical, and the Colorado Department of Health. In many cases, it is difficult to accurately locate exactly where soil samples were taken, because the precise coordinates of soil sample locations were never recorded and the only remaining information concerning these samples are brief narrative descriptions of the sites or symbols recorded on maps. Sample locations were generally to the east of the plant to assess wind transport in the direction of the prevailing winds toward nearby communities. As a result, many regions around the plant were not sampled, since it was assumed that transport of plutonium by wind to these areas would be negligible. In addition, sample locations were in easy access locations, such as along roads and fence lines.

A summary of known plutonium soil surveys between 1969 and 1973 for which specific sampling locations could be identified is given in Appendix I, Table I-1. The summary identifies 249 sites. All of these sites are included in Table I-2, along with their coordinates and plutonium concentrations, with the exception of 12 samples for which no plutonium data are available. There were other soil surveys taken during this time, such as that by the U.S. Public Health Service and the Colorado Department of Health, but either composite samples were taken over large areas or site location information is not given (Loser and Tibbals, 1972; Jacoe, 1976). No soil samples taken since 1973 were included in Table I-2, since they might be affected by resuspension or transport of plutonium down into the soil and would be less likely to represent

total deposition of releases from the pad. Soil samples taken between 1969-1973 should be most indicative of the initial deposition of the 903 Pad releases.

The locations of sampling sites close to Rocky Flats, shown on Figure 3-11, were obtained from the most comprehensive summary of sampling locations between 1969 and 1970 prepared by Loser (1971) for the official Rocky Flats report on the 903 Pad events (Seed *et al.*, 1971) and also from maps in HASL Reports 235 and 304 (Krey and Hardy, 1970; and Krey, 1976). Loser identified 229 soil sampling locations within a seven mile radius of Rocky Flats. Loser then marked these soil sampling sites with various symbols on a USGS 7.5-minute quadrangle map of the Rocky Flats area. The Loser and Seed reports refer to this map, but they only show the resultant isocurie contours of plutonium and not the sampling locations. A copy of Loser's original map is shown in a Rockwell drawing (See footnote e in Appendix I). Only 190 of the sampling locations are given unique identification labels, with another 70 locations marked with a "+" symbol. A more polished version of this map, but with a much smaller scale, is given in the Owen and Steward report (Map 16A, 1974). Loser's map is approximately 21 x 33 inches in size and represents the most accurate depiction of where soil samples were taken. In addition, Loser's map shows many Pu-239 concentrations written by hand next to the sample sites. However, there is no record of where Loser obtained his location information or how he located samples on the map.

The coordinates of the 190 soil sampling sites having a unique identification label were determined by first scaling Loser's map (Rockwell, 1971) using distances between various road intersections and comparing this to more accurate USGS 7.5-minute quadrangle maps of the area (Eldorado Springs, Louisville, Ralston Buttes, and Golden, Colorado). A known reference location at the plant is the southwest corner of Building 707. However, since this building is not shown on Loser's map, the coordinates of the 771 Stack were determined from the Building 707 coordinates. The 771 Stack is the tallest structure at the plant and is easily identified on most USGS maps as a small circle north of the cooling towers. The cooling towers, depicted by a small north-south orientated rectangle on maps, are east of Building 771. All coordinates were then calculated with respect to the 771 Stack. The UTM (Universal Transverse Mercator) coordinate of the reference location as well as the 771 Stack are listed in Appendix I, Table I-3. Estimated coordinates are given in Table I-2, with the measurements rounded off to the nearest 10 meters. The approximate scale of Loser's map is 21 meters per millimeter. Hence, soil locations are accurate to within about 20 meters. The exceptions to this are sites H1, H23, H24, H25, and H26 (Krey *et al.*, 1976), which were taken by Krey in 1973 and hence do not appear on Loser's map. Krey shows a detailed map of these sites near the 903 Pad, using a scale of approximately 3.2 meters per millimeter. It is fortunate that the soil samples with the highest plutonium contamination have the most accurate coordinate locations. The least accurately located soil samples are R22-R33 taken by Krey and Hardy (1970). The scale used to obtain



LEGEND

SECURITY FENCE

ROCKY FLATS PLANT BOUNDARY 1951-1974

ROCKY FLATS PLANT BOUNDARY 1974-PRESENT (WITH BUFFER ZONE ADDED)

• SOIL SAMPLING SITES

UTM COORDINATES SHOWN, METERS N AND E

0' SCALE 9,240'

SCALE: 1"=1.75 Miles

ChemRisk A Division of McLaren/Hart

FIGURE 3-11
SOIL-SAMPLING SITES
IN THE VICINITY OF
ROCKY FLATS

Rky0194h/rfh3-11.dgn: Rev: 05-18-94

coordinates from their map is approximately 450 meters per millimeter, but these sites are over 10 miles from the plant and have very low plutonium concentrations.

In summary, all known references or maps showing soil sampling site locations are listed in Appendix I. Only two of the 190 locations marked by Loser were determined to be in obvious error, where sample sites R16 and R18 were marked in reverse locations. The process used to create a computerized site map containing the soil sampling data is detailed in Appendix J.

Soil Sample Collection and Analysis

Plutonium analysis of soil is difficult to perform and normally requires a large sample of soil to be accurate. Typically, soil locations were chosen that were likely to be undisturbed. Krey and Hardy (1970) used the standard HASL U.S. AEC (Health and Safety Laboratory, U. S. Atomic Energy Commission) technique for sampling plutonium. Ten soil cores, 8.9 cm in diameter, are cut out down to a 20 cm depth and composited. However, the high density of stones in the soil forced most studies (Krey *et al.*, 1976; Poet and Martell, 1972) to use a 1000 cm^2 area that was scooped out to a depth of 1 to 5 cm.

The analytic methods used in the various soil studies identified in Appendix I, Table I-1 are all similar but not identical to the method developed by the U.S. AEC HASL (Krey and Hardy, 1970; Krey *et al.*, 1976) for analyzing plutonium in soil. In the HASL method, soil samples are first leached with solutions of nitric, hydrofluoric, and hydrochloric acids. The plutonium is then isolated by anion exchange (nitrate form) and electrodeposited. Plutonium isotopes are resolved by alpha spectrometry, using standard spikes of Pu-236. Krey and Hardy (1970) discuss a number of aspects of quality control in the analytic and sampling methods that were employed in their studies, including precision and accuracy of the method and the representativity of the soil sampling. They conclude that the uncertainty of the final data is due largely to the imprecision of aliquoting and analysis of the sample and that the overall reliability of the analyses is within ± 20 percent (Krey and Hardy, 1970). Similar levels of uncertainty were also reported in two subsequent plutonium in soil studies (Krey *et al.*, 1976; Poet and Martell, 1972). Since these soil data provide the basis for estimating the total release from the 903 Pad, uncertainty in the analytic results of these studies will contribute to the uncertainty in the estimated release. The contribution of analytic uncertainty to the overall uncertainty in the estimate can be represented by an uncertainty factor that the final release estimate will be multiplied by. The analytic uncertainty factor based on ± 20 percent can be represented by a normal distribution with a most-likely value of 1.0 and a standard deviation of 0.1. In this distribution, the 95 percent confidence interval about the best estimate ranges from approximately 0.8 to 1.2.

Measured concentrations of plutonium in soil are usually expressed in disintegrations per minute per gram (dis min^{-1} g^{-1}) of dry soil. This unit is not convenient for evaluating the areal distribution of plutonium. To convert to units of mCi km^{-2} (millicuries per square kilometer), the density of the soil and depth of soil sample must be considered:

$$\frac{mCi}{km^2} = \frac{dis}{\min g} \times \frac{1\ mCi}{3.7 \times 10^{-7}\ dis\ \sec^{-1}} \times \frac{\min}{60\ \sec} \times \frac{10^{10}\ cm^2}{km^2} \times d \times h$$

where:

d = Density of dry soil (g cm^{-3})
h = Depth of soil sample (cm)

Soil densities measured or assumed for various studies are given in Appendix I, Table I-1 and depths of each sample are given in Table I-2. The soil density assumptions used by the various investigators in reducing their analytic data were not consistent. Krey and Hardy (1970) suggest that the values they employed (1.2 g cm^{-3} for sample depths of 1 to 15 cm; and 2.4 g cm^{-3} for samples from depths of 15 to 20 cm) were obtained as averages of a considerable body of data accumulated at HASL over a 15-year period. Poet and Martell (1972) indicate that the value of 1 g cm^{-3} they employed for their samples taken at depths of 1 cm was an average measured value. The other studies identified in Appendix I assumed a soil dry bulk density of 1 g cm^{-3} for their samples that were primarily collected at depths up to 5 cm. These reports did not provide the actual soil density measurements that were taken that would permit the characterization of the uncertainty associated with the value that was chosen.

Preliminary results of soil sampling being performed by Colorado State University (CSU) were reported by Jim Stone, a member of the CSU sampling team, in an April 1993 telephone conversation. Mr. Stone indicated that soil dry bulk densities for 5 sites located east of the plant site ranged from 0.73 to 1.1 g cm^{-3} for the 0 to 3 cm depth and 1.16 to 1.34 for the 3 to 6 cm depth. These site-specific data suggest relatively good agreement with the values used in the studies that produced the soil sampling data.

Since most of the plutonium soil samples shown in Appendix I were taken at 1 or 5 cm in depth and not accompanied with actual soil density measurements, an uncertainty factor is developed for this parameter. Based on information presented above, it is estimates that soil dry bulk density for soil at 0 to 5 cm in depth ranges from 0.8 to 1.3 g cm^{-3} with a most likely value of 1.0 g cm^{-3}. It is believed that this factor can be used to account for the uncertainty where a generic soil dry bulk density of 1 g cm^{-3} was used by the investigator. This factor is likely to overestimate the uncertainty where actual soil density measurement results were used in calculating plutonium concentrations in soil.

Plutonium soil concentrations were obtained directly from the reports referenced in Appendix I. The greatest number came from Seed *et al.* (1971). Soil concentrations are given by Seed *et al.* in units of dis min^{-1} g^{-1} and mCi km^{-2}. When study results were reported in multiple reports, results were cross-checked to verify the consistency of soil values. The majority of the sample results were identically reported in all references. There were at least 7 inconsistencies with the Dow Chemical (1969) data, 5 in Rockwell International (1971) and 2 in Seed *et al.* (1971). The sampling sites at which discrepancies occurred were B11, B19, B30, B45, B62, B68, and B103. Inconsistencies were either in the measured value or the sampling location. Most differences in the measured values were trivial, consisting of a few percent. The largest error was at site B45, where Seed *et al.* (1971) reported a soil concentration of 12.2 dis min^{-1} g^{-1}, whereas Rockwell International (1971) and Loser (1971) reported 121.5 dis min^{-1} g^{-1}. The value of 121.5 dis min^{-1} g^{-1} was assumed to be correct for site B45, since it was most consistent with neighboring values. Other inconsistencies in sample data or locations were resolved through careful review of the primary reports and other supporting information.

Adjustments to Soil Sample Values for Estimating Total Plutonium Inventory

Krey and Hardy (1970) suggested that, based on their soil sampling results, as much as 60 percent of the total plutonium in the soil may be found at depths greater than 5 cm, but that all the plutonium was likely present in the top 20 cm of soil. In obtaining samples, efforts were reportedly made to avoid disturbed areas. The total plutonium inventory in the top 5 cm (one sample included a depth of 6 cm) for the 7 samples that included a depth analysis ranged from 39 to 91 percent and averaged 62 percent. Krey and Hardy suggested that the range of observed values was a reflection of the different soil types sampled. Krey *et al.* (1976) suggested that 64 percent of the total inventory was likely to be present in the top 5 cm of soil based on the results of the earlier study.

Poet and Martell (1972) examined three undisturbed sampling locations at depths of greater than 1 cm to evaluate the distribution of plutonium with depth. Two of the sites were sampled to a depth of 10 cm while the third was sampled to a depth of only 2.5 cm. These few samples indicated that the majority of the plutonium (approximately 98 percent of the activity) was present in the top 1.3 cm of the soil. Poet and Martell suggested that Krey and Hardy's results, which indicated more of the plutonium inventory was located at greater depths, may have been due to the fact that these samples were at a greater distance from the heavily contaminated area or taken from disturbed soils. Krey (1974) indicated that this was not the case and suggested that Poet and Martell's interpretation of the plutonium distribution with depth was faulty.

Anspaugh *et al.* (1975), using the data generated by Krey and Hardy (1970) and an empirical relationship described by Beck (1966), provided estimates of normalized plutonium profiles with

depth in soil at Rocky Flats that suggest that approximately 20 percent of the total activity is likely to be found in the top 1 cm of soil.

For the purposes of this analysis, soil sampling to a depth of 15 cm or greater was assumed to measure 100 percent of the deposited plutonium (Krey and Hardy, 1970; Krey *et al.*, 1976). Total deposition at locations where soil was sampled to a lesser depth was estimated by assuming that 20 percent of the plutonium is in the top 1 cm of the soil (Anspaugh *et al.*, 1975) and 64 percent of the plutonium is in the top 5 cm of the soil (Krey *et al.*, 1976).

Given the range of reported values of the percent of plutonium inventory associated with sampling depth, the adjustment of sampling results to estimate total plutonium deposited at a site is a source of uncertainty in the analysis. The number of samples collected to characterize the distribution of plutonium with depth are too few to infer a distribution of the actual values. No data are available to directly evaluate a reasonable range of values for the portion of the inventory estimated to be present in the top 1 cm of soil other than the three data points from Poet and Martell that suggest virtually all of the inventory is present in this layer. Adoption of the assumption of virtually all of the inventory in the 1 cm layer is believed to have the potential to result in significant underestimation of the total plutonium inventory. However, for depths of 5 cm, the Krey and Hardy data suggest the plausible range of total plutonium inventory would be consistent with a factor of approximately 1.5, that is, values ranging from 43 to 96 percent are generally consistent with the observed data and a best estimate of 64 percent. If it is also assumed that a factor of 1.5 provides a reasonable bound on the estimate of the average amount of the plutonium in the top 1 cm of soil, then the uncertainty factor associated with the plutonium inventory that would be applied to the final estimate of release can be represented by a lognormal distribution having a geometric mean of 1.0 and a geometric standard deviation of 1.2. The upper and lower bounds on the 95 percent confidence interval about the best estimate would be within a factor of 1.5 of the best estimate.

After adjusting soil sampling data for the sampling depth, a value of 1.7 mCi km^{-2} was subtracted to account for the contribution from weapons testing fallout (Krey, 1974 and 1976). Global fallout is reported to range from 1.5 to 1.8 mCi km^{-2} in the region (Krey, 1974), representing a relatively insignificant source of uncertainty in this evaluation. Therefore, this source of uncertainty is not specifically addressed in the analysis. The adjusted soil data represent the total inventory of plutonium at the sampling site from Rocky Flats.

For the purposes of this analysis, it has been assumed that all Rocky Flats-related soil contamination at the sampling locations listed in Appendix I came from the 903 Pad release. As described in this report, other release events such as the 1957 fire and routine plant exhausts are predicted to have made only minor contributions to the observed soil contamination. Approximately 10 percent of the total estimated plutonium released from Rocky Flats came from

the 1957 fire or filter plenum releases. These other releases would have been associated predominantly with very small particles having very small deposition velocities, as compared to deposition velocities for plutonium on large soil particles for the 903 Pad release. As such, these other emissions would have contributed much less than 10 percent to the deposited activity measured in the soil.

Spatial Distribution of Contamination

Figure 3-12 shows polygons enclosing the soil sampling points where corrected soil contamination greater than 500, 100, 50, and 10 mCi km^{-2} was measured. A large number of contour plotting and smoothing methods were applied to the data in an effort to develop soil contamination isopleths that would reasonably represent the data. However, the scattered nature of the data and the considerable variation between nearby data points did not allow the development of an isopleth representation that was more illuminating than the straightforward polygon representation.

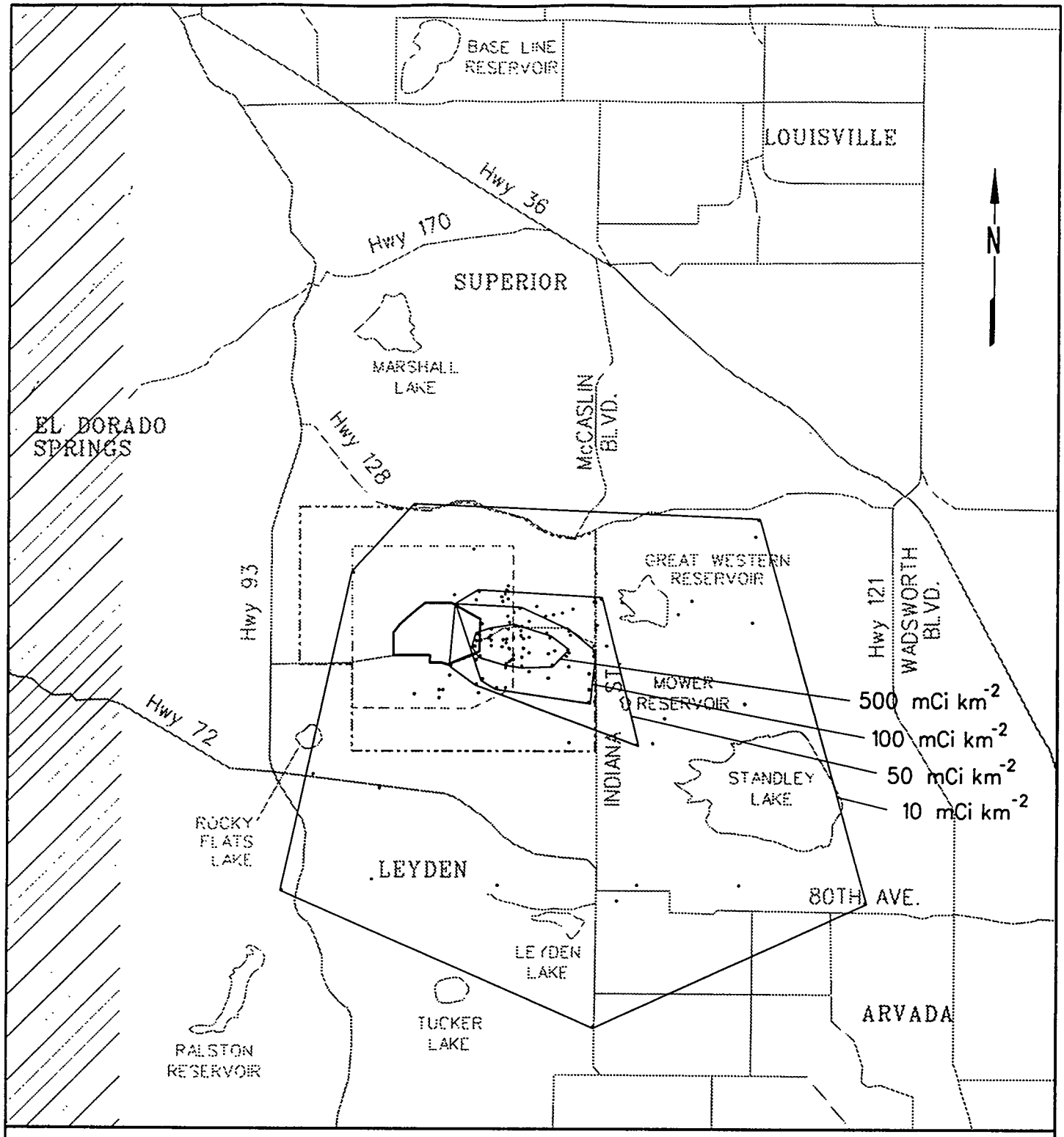
A recent plant-sponsored study that involved on-site soil sampling and elaborate spatial analysis of plutonium activity provides a review of past efforts to develop appropriate soil contamination isopleths and presents an isopleth map for current day on-site soil contamination (Litaor, 1993). Since this report is based on recent-day sampling, it is of limited use in this evaluation; however, it does suggest some of the shortcomings of previous efforts to develop contamination isopleths.

Summary of Uncertainty Associated with the Use of Soil Sampling Data

Two sources of uncertainty that contribute to the overall uncertainty in the estimate of release and exposures associated with the 903 Pad release are associated with the use of the soil sampling data. These sources of uncertainty and the description of the distributions of the correction factors to be applied to the release and exposure estimates are as follows:

Uncertainty	Description of Uncertainty Factor Distribution
Analytic	Normal; Mean=1.0 and Standard Deviation=0.1
Soil dry bulk density	Triangular; 0.8 - 1.0 - 1.3
Inventory distribution in soil	Lognormal; GM=1.0 and GSD=1.2

These distributions, along with the uncertainty associated with the application of the FDM model, will be combined into a single uncertainty factor having a single distribution using Monte Carlo techniques. The single uncertainty factor is described in a later section along with the presentation of the modeling results.



LEGEND

SECURITY FENCE

ROCKY FLATS PLANT BOUNDARY 1951-1974

ROCKY FLATS PLANT BOUNDARY 1974-PRESENT (WITH BUFFER ZONE ADDED)

• SOIL SAMPLING SITES

FRONT RANGE OF THE ROCKY MOUNTAINS

0' 9,240'
SCALE
SCALE: 1"=1.75 Miles

ChemRisk
A Division of McLaren/Hart

FIGURE 3-12
POLYGONS ENCLOSING SAMPLING LOCATIONS WHERE MEASURED CONTAMINATION EXCEEDED 10, 50, 100 OR 500 mCi km^{-2}

Rky0194h/rfh3-12.dgn: Rev: 05-18-94

Comparison with CDH Sector-Averaged Data

The Colorado Department of Health (CDH, 1978) reported sector-averaged soil contamination measurements beginning in 1970. CDH soil concentrations, in dis min^{-1} g^{-1} for the top 0.3 cm of soil, were converted to mCi km^{-2} for comparison to the other soil data by assuming:

- The concentration in the top 0.3 cm was identical to the concentration in the top 1 cm,
- Ratio of surface area to volume of surface soil is equal to 1 (cm^2 cm^{-3})
- The soil dry bulk density of the top 1 cm of soil is 1 g cm^{-3}, and
- 20 percent of the plutonium is in the top 1 cm of the soil (USEPA, 1977, and Anspaugh *et al.*, 1975).

As a result, values in Table V of the CDH report (CDH, 1978, pg. 18) must be multiplied by:

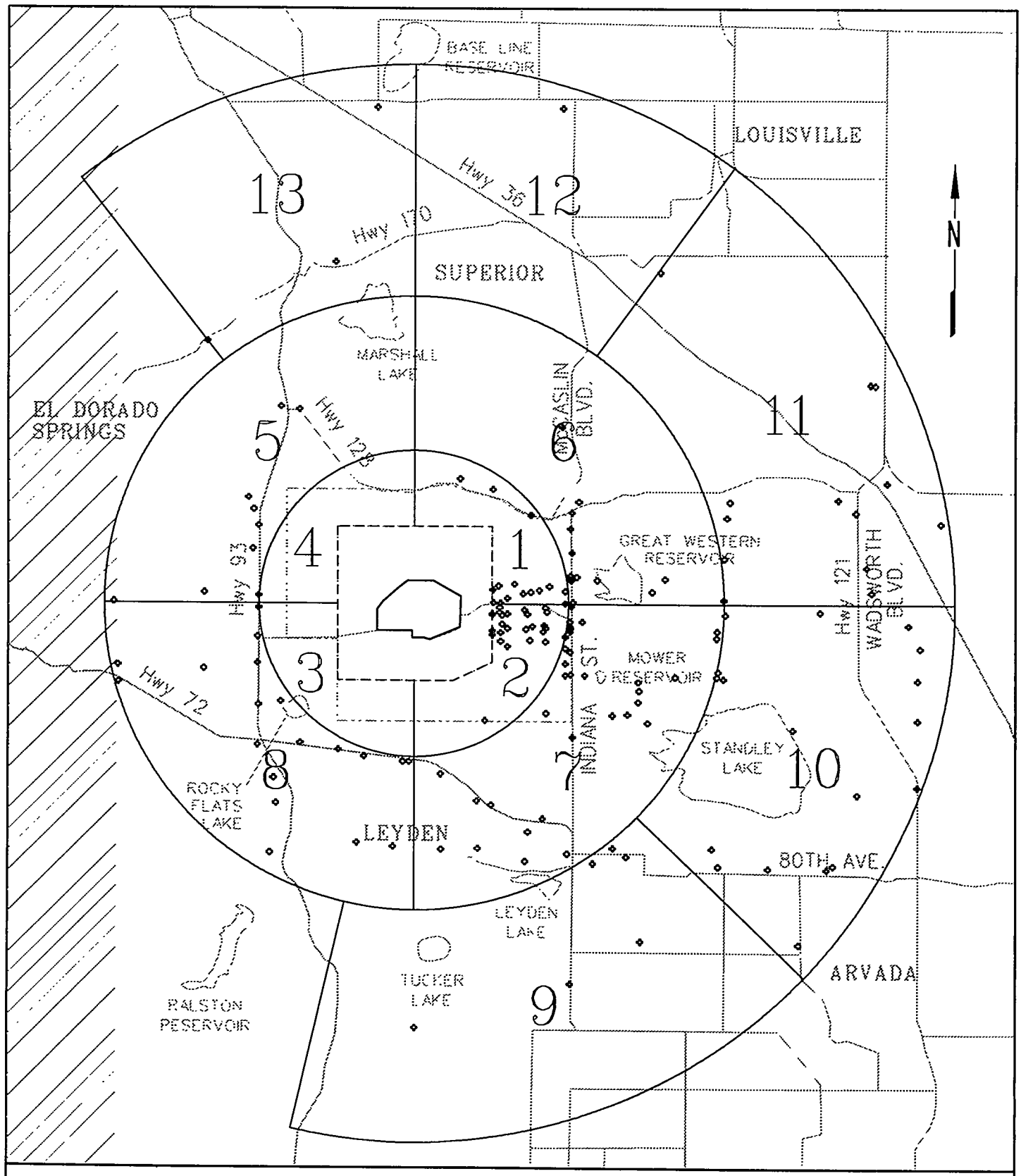
$$(1 \text{ pCi}/2.22 \text{ dis min}^{-1}) \times 1 \text{ g cm}^{-3} \times 1 \text{ cm}^2 \text{ cm}^{-3} \times 10^4 \text{ cm}^2 \text{ m}^{-2} \times 10^6 \text{ m}^2 \text{ km}^{-2} \times 10^{-9} \text{ mCi pCi}^{-1} \times 5$$

$$= 22.5 \text{ g dis}^{-1} \text{ min mCi km}^{-2}$$

In addition, 1.7 mCi km^{-2} is subtracted to account for fallout as was done for the other soil data. Figure 3-13 shows the sectors used by CDH and the sampling points from Appendix I; Table I-2 in each sector. Table 3-1 presents estimated sector-wide average values of soil contamination, based on the median of 1970-1977 CDH soil sampling measurements. The median was used instead of the mean (average), since it is not affected by outlying values. Table 3-1 also shows the median of corrected soil measurements at data points from the data set in Table I-2 in each sector. While the variance, in terms of the difference between the two sets of data, in some cases is as large as nearly a factor of four, the largest variances tend to be for those sectors having the fewest number of data points. The adjusted CDH data are not inconsistent with the data in Table I-2 used in this analysis.

903 Pad Air Sampling Data

During the 903 Pad releases, 12 on-site air samplers (numbered S1 through S10, S50, and S51) operated at the locations shown on Figure 3-14. These stations sampled at a rate of about 2 cubic feet per minute (cfm or ft^3 min^{-1}) and were analyzed for total long-lived alpha



LEGEND

- SECURITY FENCE
- ROCKY FLATS PLANT BOUNDARY 1951-1974
- ROCKY FLATS PLANT BOUNDARY 1974-PRESENT (WIRH BUFFER ZONE ADDED)
- CCEI/DOE SAMPLING POINTS
- 3 CDH SECTOR NUMBER
- FRONT RANGE OF THE ROCKY MOUNTAINS

0' SCALE 9,240'

SCALE: 1"=1.75 Miles

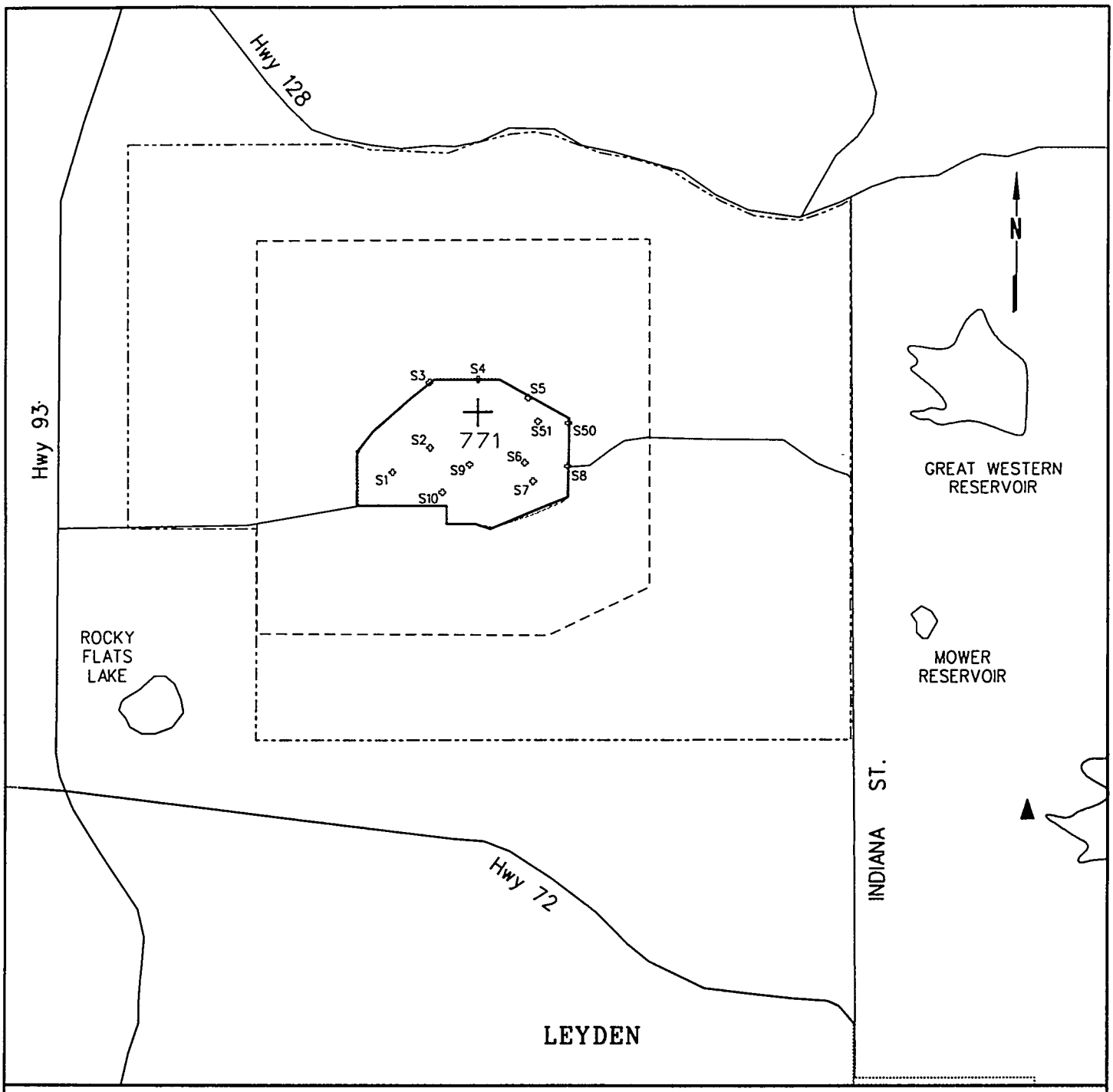
ChemRisk
A Division of McLaren/Hart

FIGURE 3-13
CDH SECTORS WITH
CCEI/DOE SAMPLING POINTS

TABLE 3-1

COMPARISON OF CDH SAMPLING DATA (1970-1977) TO 1969-1973 DATA SET

Sector	Soil Contamination Corrected for Fallout (mCi km^{-2})		
	Median of 1970 to 1977 CDH Data	Median of 1969 to 1973 Data (Table I-2)	Variance 1969 to 1973 vs. CDH
1	65.5	37.7 (16 data points)	-42%
2	549	558 (27 data points)	2%
3	6.53	No samples in sector	
4	6.08	21.6 (2 data points)	255%
5	5.40	4.71 (9 data points)	-13%
6	12.6	25.8 (14 data points)	105%
7	16.2	9.55 (32 data points)	-41%
8	3.60	4.86 (18 data points)	35%
9	2.48	12.0 (6 data points)	384%
10	3.83	7.83 (10 data points)	104%
11	2.70	5.41 (8 data points)	100%
12	1.58	0.8 (1 data point)	-49%
13	1.58	0 (1 data point)	



LEGEND

SECURITY FENCE

ROCKY FLATS PLANT BOUNDARY 1951-1974

ROCKY FLATS PLANT BOUNDRY 1974-PRESENT (WITH BUFFER ZONE ADDED)

BUILDING 771 STACK

ON-SITE SAMPLERS

OFF-SITE AIR SAMPLER AT FORMER WAGNER SCHOOL

0' 3,960'
SCALE
SCALE: 1"=.75 Miles

ChemRisk
A Division of McLaren/Hart

FIGURE 3-14
AIR SAMPLERS
AT ROCKY FLATS

Rky0194h/rfh3-14.dgn; Rev: 05-20-94

concentrations. On-site ambient air monitoring has been conducted since the plant opened in 1953. There were also 9 off-site air samplers at Coal Creek Canyon, Marshall, Boulder, Lafayette, Broomfield, Wagner School, Golden, Denver, and Westminster (Dow Chemical, 1969). The original low-volume air samplers (2 cfm) were not upgraded to high-volume samplers (25 cfm) until 1975. Coordinates of on-site ambient air sampler locations prior to 1974 are given in Appendix I, Table I-3. In addition, locations of some of the off-site ambient air samplers prior to 1974 are also given. Note that the numbering scheme used to identify air samplers was completely revised in 1975. Both the pre- and post-1974 identifiers are given in Table I-3. The 12 on-site air samplers operated 24 hours a day and on weekdays, samples were collected from 8:15 a.m. to 8:15 a.m. of the following day. On weekends, samplers were collected from 8:15 a.m. Friday to 8:15 a.m. Monday. The air samplers used to measure airborne plutonium concentrations at Rocky Flats do not collect particles larger than 30 microns in diameter, and sampling efficiency is not optimal for 15-30–micron-sized particles compared to smaller particles (Langer, 1980). Sampler efficiency also varies with orientation of the sampler with respect to wind direction (Langer, 1980). To account for these sampling inefficiencies, it has been assumed that samplers collected 100 percent of particles less than 15 microns in diameter and 50 percent of particles between 15 and 30 microns in diameter when comparing FDM predictions of particulate air contamination with on-site air sampler data. This approximates the sampler efficiency determined by Hurley (1980) from wind tunnel tests at Colorado State University.

Air sampler data are not used to directly estimate releases from the 903 Pad. Instead, they are used for two purposes: 1) to evaluate the potential for a wind speed dependency for contaminant release based on relative sampler readings, and 2) to determine whether the observed average air sampling results are consistent with the average air concentrations predicted under the estimated release scenario developed using the soil sampling data set and the FDM. The uncertainty in the air sampler data do not directly contribute to the uncertainty in the release estimate. Therefore, the uncertainty in the air sampler data are not elaborated upon here. However, sampling and analytic uncertainties in the air sampler data would be of a similar magnitude to those described for the air sampler data for the 1957 fire, with the additional uncertainty associated with the efficiency of sampling a larger particle size range associated with the 903 Pad release as noted above.

3.4.1.2 FDM Modeling of 903 Pad Release Period

This section discusses the use of the FDM (Fugitive Dust Model) computer program, in conjunction with meteorological and soil contamination data from Rocky Flats, to estimate the amount of radioactivity released from the 903 Pad and concentrations of plutonium on respirable particles in off-site areas.

The FDM was used to simulate all atmospheric transport processes that carried contaminated soil away from the 903 Pad and deposited it in the surrounding area. The resulting soil contamination measured in late 1969 and the early 1970s, after the 903 Pad was covered with fill in July 1969 and subsequently paved, is described in some detail in the preceding sections. The FDM is used to estimate releases from the pad that would be consistent with the observed soil contamination. Particle deposition over the period of pad disturbance from 1964-1969 depended on the distribution of wind speed, direction, and atmospheric stability class over that time period. High quality meteorological data available for 1987-1991 are used to represent meteorological conditions at Rocky Flats during the 1964-1969 release. Five-year average air concentrations necessary to produce the deposition pattern are also predicted by the model for the purposes of evaluating off-site inhalation exposures

Two inputs necessary for modeling transport of contaminated soil away from the 903 Pad are the size distribution of contaminated soil particles blown off the pad and plutonium contamination as a function of soil particle size. Neither of these was measured during the release period, and the data available for estimating these inputs are very limited. While it is known that the plutonium present in the contaminated oil consisted of very small particles, once this oil is spilled on the soil, these very small particles will become associated with larger soil particles. The contaminated soil particle size distribution in air is needed to predict the rate of deposition of contaminated particles to the ground and also to estimate the fraction of the total amount of contaminated particulates in the air that are small enough to be inhaled and reach the lung, resulting in exposure (i.e. respirable fraction). The second input, the relationship between soil particle size and the amount of plutonium contamination that the particle may have incorporated with it, must be estimated in order to predict the amount of plutonium in the air or deposited to the ground. The analysis that is performed here uses the following key estimates.

Estimate 1: The particle size distribution of contaminated soil that becomes airborne from the 903 Pad is represented by the fine particle fraction (less than 150 microns in diameter) of a lognormal particle size distribution for potentially resuspendable soil at Rocky Flats. This soil particle size distribution has been characterized as having a mass median diameter of 200 microns and a geometric standard deviation of 6.2, based on information reported by Krey *et al.* (1974) and Hayden (1977). The basis for this estimate is described in Appendix K and the following section.

Estimate 2: Plutonium contamination is directly proportional to airborne soil particle mass. The basis for this estimate is described in Appendix L and the following section.

Characteristics of Airborne Plutonium Contamination from the 903 Pad

The release of contamination from the 903 Pad was an accident that was not discovered until after it had occurred. No measurements characterizing the particle size distribution of either the surface soil particles contributing to the releases from the 903 Pad or the resulting airborne contamination were made before the pad was covered in 1969. Therefore, we have to rely on measurements taken after the fact to characterize particle sizes of the release. Studies of soil particle size distributions for Rocky Flats soil and particle size distribution of airborne contaminants are described in this section.

A number of studies were made of the particle size distribution of potentially resuspendable soil at Rocky Flats (See Appendix K). The work of Krey *et al.* (1974) and Hayden (1977) indicates that potentially resuspendable Rocky Flats surface soil has a lognormal soil size distribution with a mass median diameter of 200 microns and a geometric standard deviation of about 6.2. These studies provide the primary basis for the estimate of contaminated particle size distribution for the purposes of modeling releases from the 903 Pad. With this soil size distribution, 5 percent of the soil mass has particle diameters less than 10 microns.

The amount of contamination carried on small particles is of interest, since it is these particles that can be inhaled and represent the respirable fraction of the release. Little or no deposition in the alveolar region of the lungs takes place for particles with an aerodynamic diameter greater than 8 microns. Hinds (1982) says "Particles larger than this size (8-micron equivalent aerodynamic diameter) do not reach the alveolar region and are non-hazardous with respect to alveolar injury." The aerodynamic diameter of a particle is the square root of the particle density multiplied by the diameter of the particle (Hinds, 1982). Rocky Flats soil particle density is estimated to be 2.4 g cm^{-3} (this is not the same as dry bulk density of soil), the approximate midrange of commonly encountered soil particle densities (Morris and Johnson, 1967). Therefore, soil particles with a diameter of less than 5 microns or having an equivalent aerodynamic diameter of less than 8 microns would be considered to be respirable. Particles with a diameter between 5 and 10 microns are inhalable, but they do not lodge in the alveoli. They are generally cleared from the lungs and eliminated through the digestive tract.

FDM modeling with the soil particle size distribution specified above indicates that the respirable fraction (i.e., fraction <5 microns) of airborne activity released from the pad is about 20 percent in areas outside the buffer zone. Airborne respirable activity measurements taken in the vicinity of Rocky Flats after the 903 Pad releases can be used to further evaluate the reasonableness of the estimate of particle size distribution based on soil studies.

Langer (1989) sampled respirable airborne activity near Rocky Flats using methods to minimize the chance of coarse particles bouncing through the cascade impactors, a problem that had been reported previously (Langer, 1980). Langer suggested that previous measurements may have overestimated the respirable fraction of airborne activity, because larger particles bounced through cascade impactors and were retained on the final filter meant to measure respirable particles only. Langer found that respirable airborne activity in 1980-1985 was mostly of fallout origin and represented less than 10 percent of total airborne activity. However, Volchok *et al.* (1972) found a respirable fraction of 25 percent in two samples of plutonium-bearing airborne dust taken near Rocky Flats in October 1971. Sehmel (1976) claimed that 20 percent of airborne activity around Rocky Flats in 1973 was respirable. The USEPA (1977) suggested that about 30 percent of the total airborne dust (not limited to contaminated dust) near Rocky Flats was inhalable (less than 10 microns). In summary, a number of studies performed to quantify the respirable fraction of contaminated particles present in the air after the 903 Pad was paved found that the fraction ranged from approximately 10 to 25 percent.

A factor affecting the particle size distribution of releases from the 903 Pad that is not addressed by the modeling is the presence of the cutting oil at the pad. The contaminated cutting oil spilled on the 903 Pad probably agglomerated the underlying soil particles, incorporating micron- and submicron-sized plutonium particles into larger soil particle associations that would reduce the respirable fraction of the released contaminated soils. This reduction in the fraction of fine particulates is similar to the effect of oiling a dirt road to reduce the dust. The extent of agglomeration produced by the cutting oil is unknown, but it may have reduced the respirable fraction. Weathering and mechanical disturbance of the soil may have acted to reduce some of the agglomeration over time. The potential effects of the cutting oil have not been quantified, but contribute to the uncertainty in estimates of respirable fraction.

The values of the respirable fraction predicted by FDM (20 percent outside the plant buffer zone) fall within the range of values of respirable activity measured in the air after the paving of the pad. The measurements discussed above suggest that other values of the respirable fraction that are within ± 50 percent (10 to 30 percent) of the best estimate are equally likely. The uncertainty in the estimate of the respirable fraction reflects the uncertainty in the soil particle size distribution upon which the prediction of respirable airborne contaminant concentration is based. The uncertainty in the respirable airborne contamination will be represented in the analysis by a uniform distribution having a lower bound of 0.5 and an upper bound of 1.5.

With regard to the second key estimate, involving the relationship between soil particles and plutonium contamination, no measurements of plutonium concentration as a function of particle size in airborne contaminated soil released from the 903 Pad are known to have been taken during the release. It is believed that the very finely divided sub-micron sized plutonium dioxide

particles contained in the cutting oil that leaked onto the soil beneath the 903 Pad were absorbed into soil particles or incorporated in soil particle agglomerates, so that plutonium content was proportional to the mass of the transported soil particles. The available measurements of plutonium contamination in soils or in airborne particles taken after the release, as discussed in Appendices K and L, do not conflict with the assumption that plutonium content of particles transported off the 903 Pad was proportional to particle mass. For example, airborne particulate measurements show plutonium concentrations increasing with particle mass, even in the small soil particle size range (Langer, 1974, and undated). Although other studies of off-pad soil contamination show more plutonium in the finer soil fractions (Krey *et al.*, 1974; USEPA, 1977; Little and Whicker, 1978; and CDH, 1978), this observed relationship of contamination with the finer soil fractions is as expected, because only the finer fraction of plutonium bearing soil particulates released from the 903 Pad can be transported significant distances.

Fitting Deposition to Obtain Release Estimates

The FDM can be used in conjunction with the estimates of particle size distribution and particle contamination to predict a deposition pattern from a unit release (1 Ci) of contaminated soil particles less than 150 microns in diameter from the 903 Pad. Since the amount released and the resulting deposition pattern are related in a linear fashion (i.e., doubling the amount released doubles the predicted deposition at any point in the pattern), the unit release can be scaled to obtain the best fit between the soil contamination data and the deposition pattern.

Another factor considered by FDM is wind speed. As discussed by Sehmel (1980 and 1982a), wind erosion is proportional to wind speed (v) raised to the nth power, where n is greater than 3. A review of hourly weather observations and daily air monitoring data for on-site samplers S-6, S-7 and S-8 from 1968-1969 indicates that the releases from the pad were wind speed dependent. This was the period of highest monthly average readings in the S-8 sampler and high work activity on the pad. It was found that high daily S-8 air sampler readings occurred most often on days when there were observations of wind from the west at 30 mph or greater (Appendix M). These data support Sehmel's observations that greater release and transport of contamination occurs at high wind speeds.

Based on the apparent dependence of the release on wind speed, FDM was used to generate multiple deposition patterns based on wind dependencies varying from v^0 to v^6. All of the deposition patterns were then scaled to determine the best fit to the environmental data.

Use of Air Sampler Data

The air sampler data were used in two ways to evaluate the 903 Pad release estimate developed from the available soil data. First, the ratios of long-term average air concentrations were used to evaluate the potential for a wind speed dependence in deriving the release estimate. Air concentration ratios were used, because measured air concentrations in the samplers could be biased on the low side if clogging of the filters reduced the actual air volume sampled (Chapman, 1960). Clogging was most likely on windy days when high dust loadings and therefore high readings would be most likely to occur, making the reliance on the actual readings or changes in the actual readings from day to day questionable for the purposes of this analysis. However, ratios of long-term averages observed in different air samplers probably indicate relative air concentrations in the different sampler locations, since all the samplers on any given day were subject to similar dust loadings. Over the four years in which data are available during the five- year period from August 1964 through July 1969 (when the first coat of fill was applied to the 903 Pad), the S-8 sampler, east of the 903 Pad, had much higher readings than the other samplers, even though it is the farthest away from the pad of the three samplers. The S-7 sampler, very close to the 903 Pad but in a southwesterly direction, averaged about 6 times lower than S-8 (S8/S7=6.1), and the S-6 sampler, at an intermediate distance to the northwest, averaged about 9 times lower than S-8 (S8/S6=8.8). These ratios were used to evaluate the potential for a wind speed dependence in deriving the best estimate of the release from the pad using the FDM model.

The air sampler data was also used to evaluate whether the air sampling results are consistent with the FDM model predictions of the release. Based on the estimated soil size distribution, particles collected by the air samplers (all particles less than 15 microns in diameter and half the particles between 15 and 30 microns in diameter) were estimated to comprise about 26 percent of the soil particle mass (and therefore the estimated radioactivity) released from the 903 Pad. The FDM model was used to predict the transport of only this fine particle fraction away from the 903 Pad using the same meteorological and emission estimates used in modeling deposition to estimate the measurable air concentrations at the sampler locations for comparison to actual measured values.

Each of the elements needed to estimate releases of plutonium from the 903 Pad and to predict off-site respirable airborne concentrations from the release has been described. A summary of the modeling approach is provided in the adjoining text box and in Figure 3-15. The results of this approach are described in the following section.

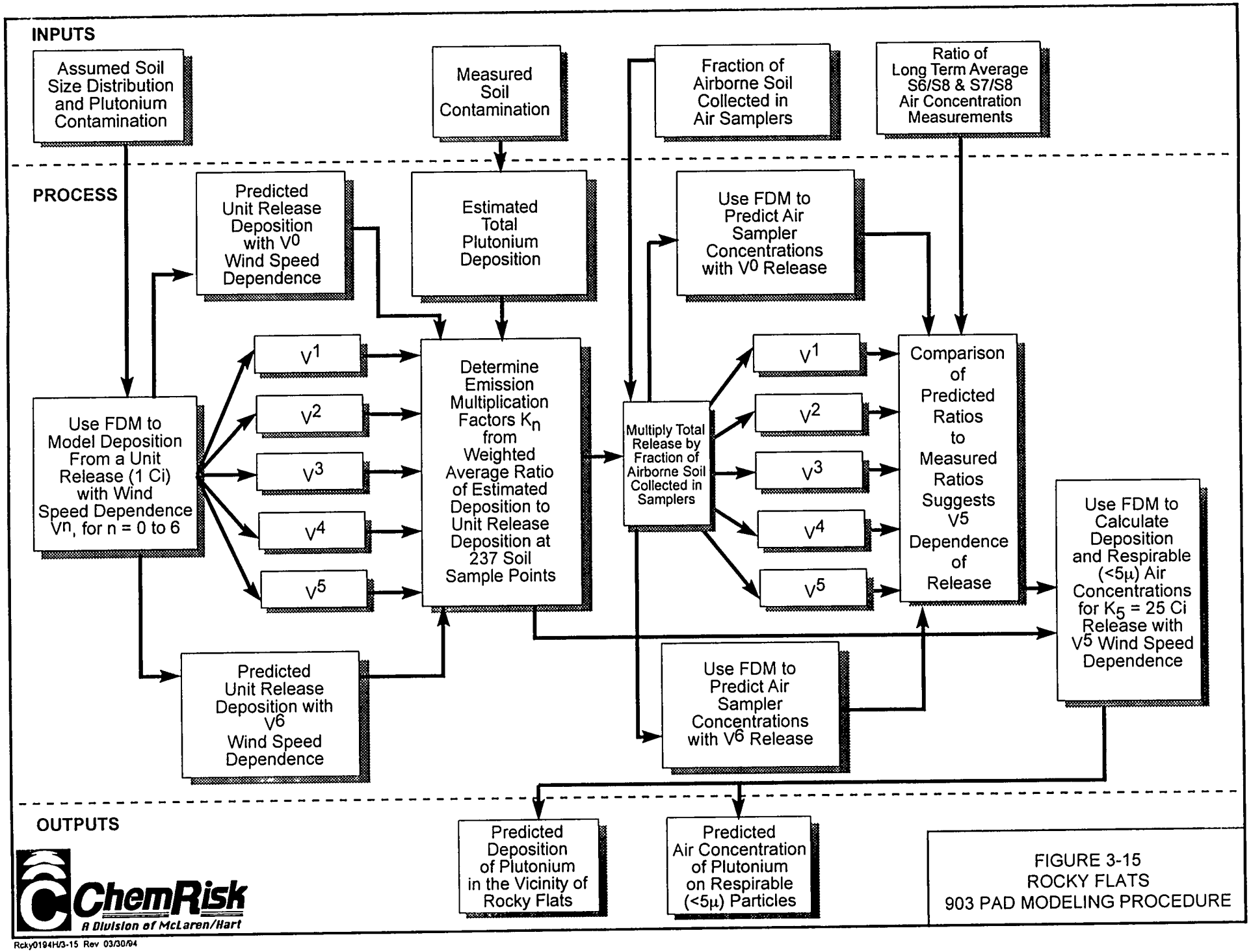


FIGURE 3-15
ROCKY FLATS
903 PAD MODELING PROCEDURE

Rcky0194H/3-15 Rev 03/30/94

FDM MODELING TO ESTIMATE TOTAL RELEASE FROM THE 903 Pad

Step 1. Select an appropriate soil size distribution and identify the relationship between soil particles and plutonium loading or contamination.

- The airborne soil is the fraction less than 150 microns in diameter of an assumed lognormal, potentially resuspendable soil size distribution with a median diameter of 200 microns and geometric standard deviation of 6.2 (Krey, 1974; Hayden, 1977).
- Plutonium contamination is estimated to be proportional to soil particle mass.

Step 2. Use FDM to predict deposition from a unit release of 1 Ci from the 903 Pad for releases varying with different powers of wind speed, from v^0 to v^6.

Step 3. For each power of wind speed dependence, determine the factor that scales the unit release and deposition predictions to give the best fit to the measured soil contamination data.

Step 4. Use FDM to predict long-term average air concentrations at the S-6, S-7, and S-8 air samplers near the 903 Pad. The modeling is performed for all airborne particles less than 15 microns in diameter plus half of the airborne particles between 15 and 30 microns in diameter for each power of wind speed dependence. This is the fraction of the release that is likely to be collected in the air samplers, and based on the estimated soil particle size distribution, these particles carry about 26 percent of the total release.

Step 5. Select the wind speed dependence and the associated total release, in Ci that comes closest to the long-term average of the S-8/S-7 and S-8/S-6 air concentration ratios.

3.4.1.3 Modeling Results

The FDM model was first used to establish the total release of contaminated soil necessary to approximate the observed distribution of plutonium in the soil around the plant. Then a release of 26 percent of the contaminated soil needed to approximate the observed soil deposition pattern, representing the fine particle fraction that would be collected in the air samplers, was modeled with FDM to calculate five-year average air concentrations at the air sampler locations.

The FDM model predicts air concentrations and deposition from a contaminant release that varies as a power of wind speed. As discussed in the preceding section, air concentrations measured in the S-8 sampler were highest when high winds blew toward the sampler. To investigate the wind speed dependence of the release, FDM was run with contaminant release proportional to various powers of wind speed from zero (no variation of release with wind speed) to six (release proportional to the sixth power of wind speed).

The sum of absolute deviations of predicted values from measured values at soil deposition data points did not indicate a strong wind speed dependence. The sum of absolute deviations was highest for a release independent of wind speed (release proportional to v^0), but it only declined by 6 percent as wind speed dependence was increased to v^6. However, ratios of average air concentrations in the S-6, S-7, and S-8 air samplers were sensitive to the power of wind speed as summarized in the following table:

TABLE 3-2: COMPARISON OF OBSERVED CONCENTRATION RATIOS TO PREDICTED CONCENTRATION RATIOS

Samplers	Power of Wind Speed	Observed Ratio	Predicted Ratio
S8/S7	0	6.1	0.8
	4		2.6
	5		3.8
	6		5.2
S8/S6	0	8.8	2.0
	4		7.1
	5		11.4
	6		18.2

Since predictions did not change greatly when the power of wind speed dependence was varied from v^4 to v^6, releases dependent on fractional powers of wind speed were not modeled. A v^5 dependence was selected as the best value, since the predicted ratio for S8/S7 was approximately

40 percent low, while the predicted ratio for S8/S6 was approximately 30 percent high. Using a release proportional to the fifth power of wind speed, the total release from the 903 Pad that gave the best fit to soil deposition measurements at the sampling locations listed in Appendix I was 25 Ci.

The uncertainty associated with the predictions is a combination of the uncertainty associated with the soil sampling data and the uncertainty associated with the use of the FDM model in this application. The uncertainty associated with the use of the soil sampling data was identified as being a result of analytic uncertainty, uncertainty in soil dry bulk density, and uncertainty in the distribution of plutonium inventory in the soil. This uncertainty was previously summarized in terms of three different uncertainty distributions.

As described in Appendix G, studies of the performance of the FDM model in predicting long-term averages involving the transport of particles in the TSP size range (Total Suspended Particulates, approximately <30 microns in equivalent aerodynamic diameter) using actual meteorological data suggest uncertainties on the order of a factor of 2 (Winges and Gomber, 1990a and b). The application of the FDM model in the analysis described here differs considerably from that used to evaluate model performance. Our application of the FDM model extended into a larger particle size range (150 microns), assigned greater importance to short-term events (high wind speed events), and used a surrogate meteorological data set for the analysis. These differences in the application of the FDM introduce uncertainties that the model developer suggested may be as large as a factor of 10. The uncertainty in the application of the FDM model to this analysis is represented by a lognormal distribution having a GM of 1.0 and a GSD of 3.2.

Combining the uncertainties associated with the use of the soil sampling data and the FDM model using Monte Carlo techniques results in total uncertainty represented by a lognormal distribution having a GM of 1 and a GSD of 3.3. Therefore, our model predictions represent the best estimate of the release, and the 95 percent confidence interval about the best estimate is the best estimate multiplied by $1/GSD^2$ (lower bound) and by GSD^2 (upper bound).

FDM deposition modeling indicates that, of the total of 25 Ci released from the 903 Pad:

- 11.4 Ci were redeposited on the pad,
- 13.6 Ci escaped from the pad,
- 8 Ci escaped beyond the security fence, and
- 6.8 Ci escaped from the buffer zone boundary.

Figure 3-16 illustrates the estimate of the total release of plutonium for areas beyond the buffer zone boundary and the uncertainty associated with the estimate. Using the total uncertainty distribution defined above, the best estimate is equal to 6.8 Ci and the upper and lower bounds of the 95 percent confidence interval about the best estimate are 74 Ci and 0.62 Ci, respectively.

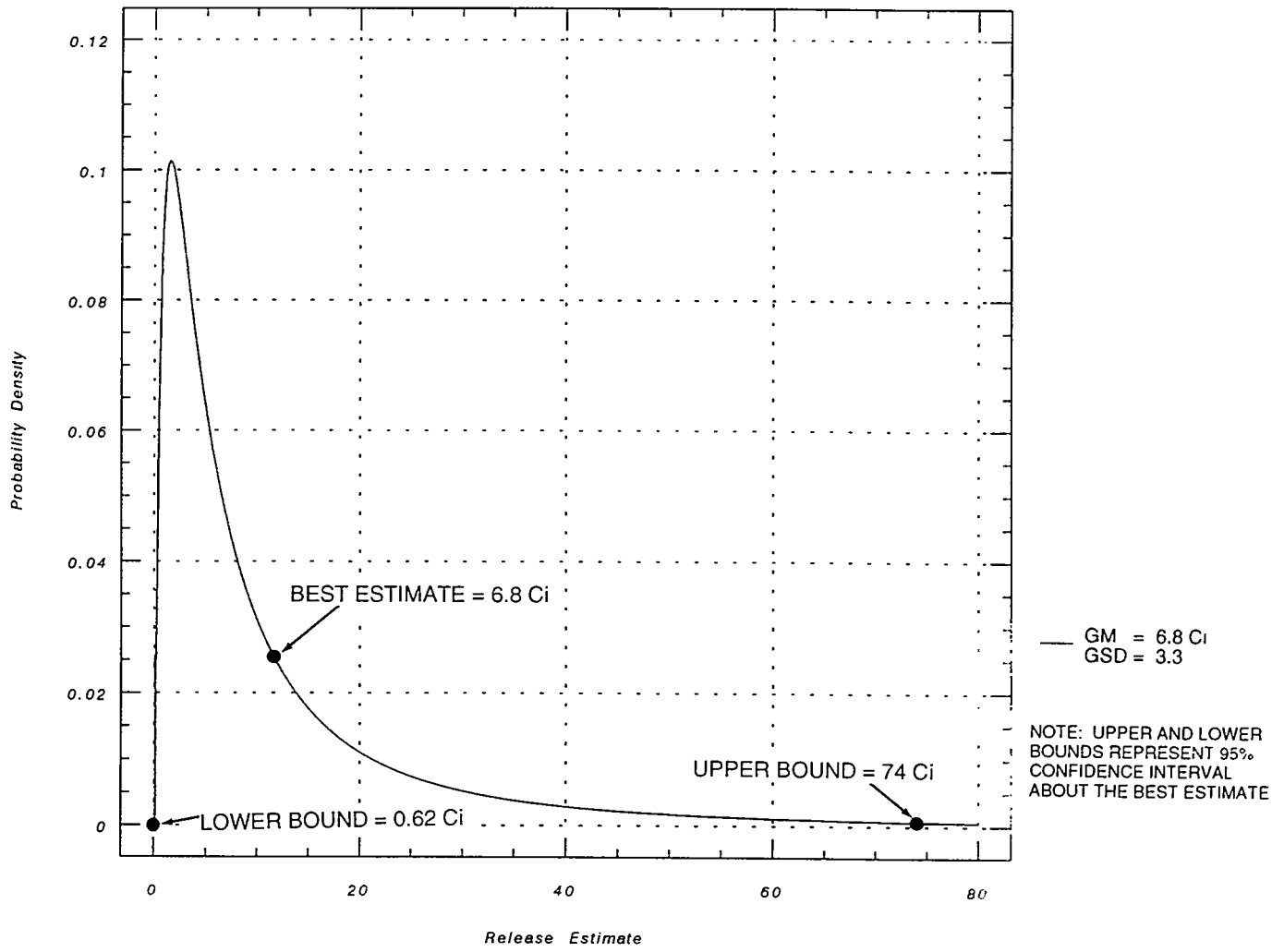
The predicted deposition contours (with a v^5 wind speed dependence) are shown in Figure 3-17. To compare the FDM predictions to the sector-averaged sampling results reported by CDH, the average deposition predicted by FDM in the soil sampling sectors used by CDH is shown in Table 3-3. The deviation of the predicted values from measured values ranges up to a factor of nearly four, which is well within the range of predicted uncertainty.

With regard to the predicted airborne concentrations of plutonium using a v^5 wind speed dependence for the release, the five-year average S-8 air concentration calculated by FDM is 0.45 pCi m^{-3}, about 4 times higher than the measured value of 0.12 pCi m^{-3}. The calculated average for S-6 is 0.040 pCi m^{-3}, about 3 times higher than the measured value of 0.014 pCi m^{-3}, and the calculated average for S-7 is 0.12 pCi m^{-3}, about 6 times higher than the measured value of 0.02 pCi m^{-3}. Again, the observed values are within the range of predicted uncertainty.

The fact that all of the FDM predictions of air concentrations in the S-8, S-7, and S-6 air samplers exceed the observed values suggests that the air sampling data may be biased on the low side or the release estimate is biased on the high side. Bias in the air sampling results could be a result of reduced sampler flow rates from such things as filter clogging, or additional self-absorption losses in counting heavily loaded filters. There could be at least two other possibilities:

- The 903 Pad release occurred over a longer time period.

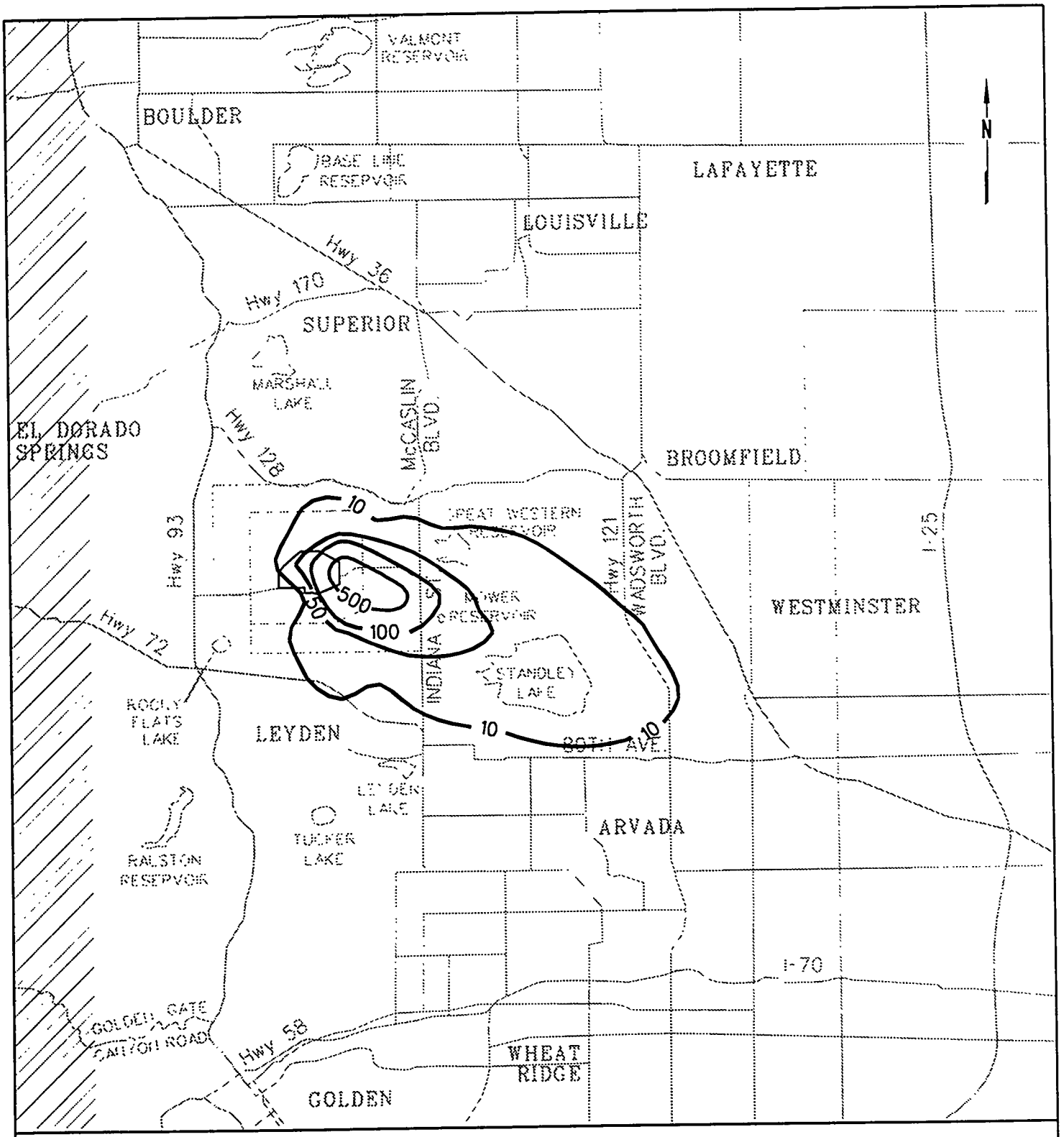
  A given total release could produce the same deposition pattern as the result of a higher air concentration for a shorter time, or a lower air concentration for a longer time, so average air concentrations are inversely proportional to the release time. However, even a 10-year release (covering the whole active life of the 903 Pad) gives calculated air concentrations greater than the five-year average measurements. Also, the 10-year average of the measured airborne concentrations would be lower than the five-year measured average, because of the lower air concentrations measured in the earlier years.



ChemRisk
A Division of McLaren/Hart

FIGURE 3-16
ESTIMATE OF PLUTONIUM RELEASE OUTSIDE THE PLANT BUFFER ZONE FROM THE 903 PAD

Rcky0194H/3-16 Rev 03/30/94



LEGEND

SECURITY FENCE

ROCKY FLATS PLANT BOUNDARY 1951-1974

ROCKY FLATS PLANT BOUNDARY 1974-PRESENT (WITH BUFFER ZONE ADDED)

ISOPLETH CONCENTRATION LINES, mCi km^{-2}

mCi 10^{-3} CURIE

FRONT RANGE OF THE ROCKY MOUNTAINS

0' 13,200'
SCALE
SCALE: 1"=2.5 Miles

FIGURE 3-17
TOTAL DEPOSITION OF PLUTONIUM FROM THE 903 PAD PREDICTED BY THE FUGITIVE DUST MODEL (mCi km^{-2})

ChemRisk
A Division of McLaren/Hart

Rky0194h/rfh3-17.dgn: Rev: 05-18-94

TABLE 3-3

COMPARISON OF 1969-1973 SOIL DATA SET TO SECTOR-AVERAGED PLUTONIUM IN SOIL CONCENTRATIONS PREDICTED BY FDM

Sector	Median of 1969-1973 Soil Data* (Corrected Values) (mCi km^{-2})	Sector-Averaged Plutonium in Soil Concentration Predicted by FDM (mCi km^{-2})	Variance Predicted vs. Measured
1	37.7 (16 data points)	33.4	-11%
2	558 (27 data points)	224	-60%
3	NO DATA	2.92	
4	21.6 (2 data points)	2.04	-91%
5	4.71 (9 data points)	0.6	-87%
6	25.8 (14 data points)	10.4	-60%
7	9.55 (32 data points)	47.1	390%
8	4.86 (18 data points)	1.22	-75%
9	12.0 (6 data points)	2.31	-80%
10	7.83 (10 data points)	14.6	86%
11	5.41 (8 data points)	2.31	-57%
12	0.8 (1 data point)	0.53	-34%
13	0 (1 data point)	0.44	

* Data from Table I-2.

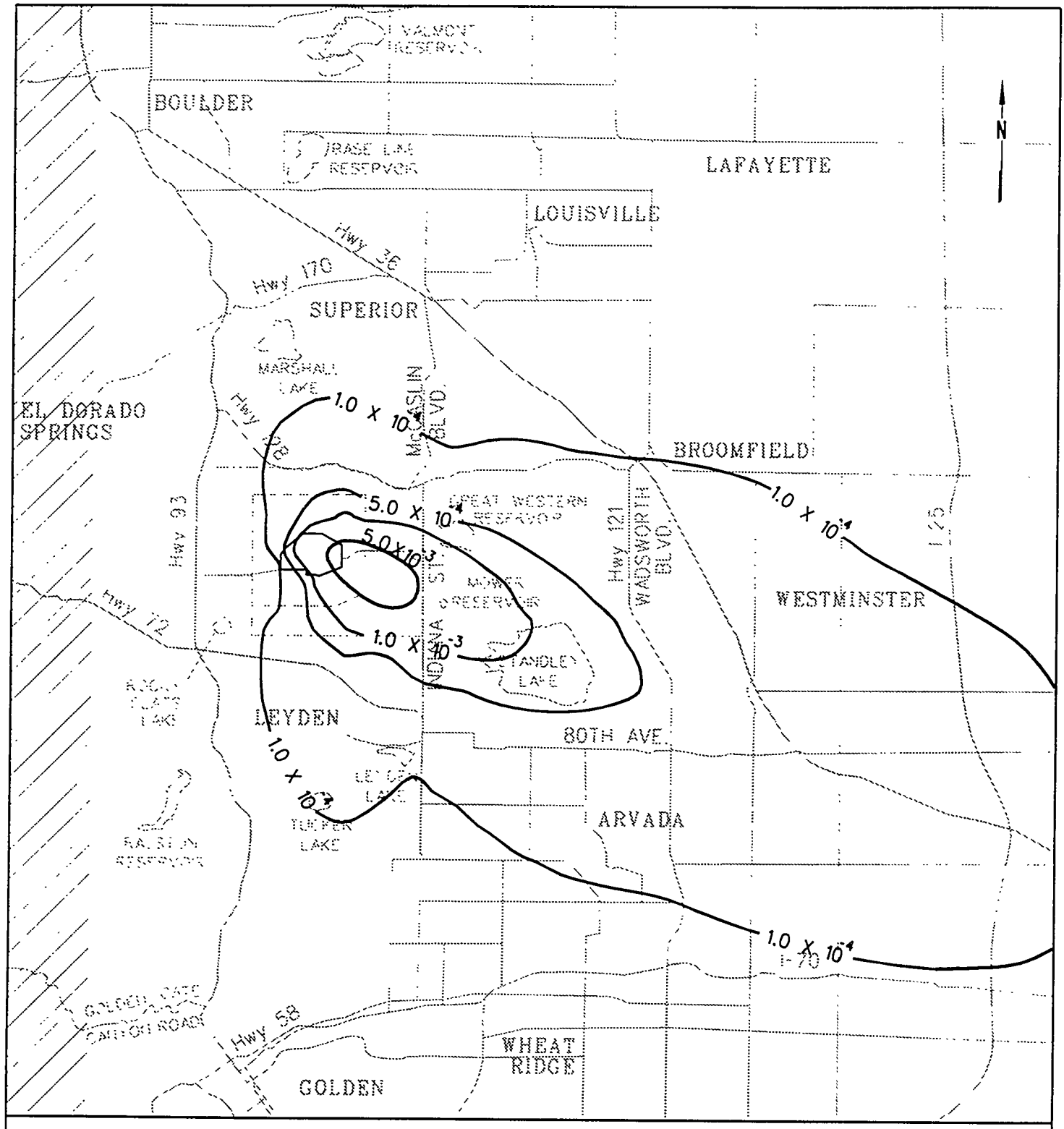
- The potentially resuspendable particle size distribution and the assumption that plutonium contamination is proportional to soil particle mass do not accurately reflect the particle size distribution of contamination transported away from the 903 Pad. If this is the case, since the air concentrations predicted by FDM for particles less than 30 microns is smaller than those actually measured, there may have been less contamination spread on a smaller particles below 30 microns in size, perhaps as a result of agglomeration of fine soil particles into large soil particles by the cutting oil. This would result in lower inhalation exposure from the 903 Pad releases than has been estimated by this analysis.

The air sampling data suggest that the FDM predictions may be biased to some extent on the high side in regards to estimates of the 903 Pad-related airborne concentrations of plutonium. On the other hand, there have been arguments that the air samples data are biased on the low side as a result of clogging and inefficiencies in particle sampling. In any case, the potential error associated with this discrepancy in the results with respect to the air sampling data is well within the overall uncertainty identified for the analysis.

The average annual air concentrations during the five-year release period of plutonium contamination on respirable particles less than 5 microns in diameter, which will be used in Task 8 to estimate doses from the 903 Pad release, are shown in Figure 3-18, based on the FDM calculation with a wind speed dependence of v^5. The uncertainty associated with these estimates of average airborne concentrations of respirable particles includes the uncertainty described for the estimate of the release of plutonium from the pad and the uncertainty associated with the estimate of the respirable fraction of the releases. As described in an earlier section of this report, the uncertainty in the respirable fraction is represented by a uniform distribution ranging between 0.5 and 1.5. Combining this uncertainty distribution with the uncertainty from the soil sampling data and the application of the FDM model yields an overall uncertainty in the estimates of respirable airborne concentration that is described by a lognormal distribution having a GM of 1 and a GSD of 3.4.

Two other approaches to estimating 903 Pad releases were investigated:

- FDM allows the use of a release rate that is zero below a specified threshold wind speed. FDM was run with several different threshold wind speeds to see if introducing a wind speed threshold would produce a better fit to the measured soil deposition pattern than the models discussed above without a threshold velocity. Better fits were not achieved.



LEGEND

- SECURITY FENCE
- ROCKY FLATS PLANT BOUNDARY 1951-1974
- ROCKY FLATS PLANT BOUNDARY 1974-PRESENT (WITH BUFFER ZONE ADDED)
- FRONT RANGE OF THE ROCKY MOUNTAINS
- ISOPLETH CONCENTRATION LINES, fCi m $^{-3}$
- 10^{-1} SCIENTIFIC NOTATION: 10^{-1} = 0.1 OR 1/10; 10^{-2} = 0.01 OR 1/100; etc.
- fCi 10^{-15} CURIE

0' 13,200'
SCALE
SCALE: 1" = 2.5 Miles

ChemRisk
A Division of McLaren/Hart

FIGURE 3-18
PREDICTED 5-YEAR AVERAGE AIR CONCENTRATIONS OF PLUTONIUM ON RESPIRABLE PARTICLES RELEASED FROM THE 903 PAD (fCi m^{-3})

Rky0194h/rfh3-18.dgn: Rev: 05-18-94

- As described in the introduction to this discussion of the 903 Pad releases, in order to investigate the possibility that the 903 Pad release occurred over a very short time, releases over periods of days were modeled. The periods chosen were:

  1. January 30-31, 1969, when the highest reading ever observed in the S-8 sampler occurred (see Appendix M), and

  2. The eight highest (nonconsecutive) days of S-8 sampler readings.

  Hourly meteorological observations taken in 1968 and 1969 were used for short-term modeling. The best-fitting deposition patterns from these short-term releases had a sum of absolute deviations about 40 percent higher than the long-term average models, so the fit to the soil deposition data was not as good as for the long-term release. Predicted air concentrations in the S-8 air sampler were still 3 or 4 times higher than observed. Since there were high readings in the S-8 sampler over a period of several years, it did not seem reasonable to further pursue the idea of the majority of the release taking place over a few days.

Other Estimates of the 903 Pad Release

A number of other reports and studies have developed estimates of the total amount of plutonium that has been deposited to the soil as a result of the releases from the 903 Pad. The results of these other studies are described here and summarized in Table 3-4. These estimates differ from the estimates made in this analysis in that they attempt to estimate the total amount of plutonium that has been deposited on the ground based on soil data and do not attempt to directly account for the total pad release. The majority of the uncertainty associated with these previous estimates is due only to uncertainty in the soil data.

The plant has estimated that approximately 85 grams of plutonium were released from the drums to the soil at the pad site based on the number of leaking barrels and the plutonium concentrations in the barrels (Seed *et al.*, 1971).

Seed *et al.* (1971) (same as Loser, 1971) provide the following estimates of plutonium inventory in soils:

- Page 18: The quantities of plutonium were calculated by integrating the areas between the 2,000 mCi km^{-2} contour and the 13 mCi km^{-2} contour:

— The total quantity of plutonium-239 dispersed in soil other than that contained by the asphalt pad was calculated to be 14.3 $\pm$ 2 grams.

— The quantity of plutonium-239 inside the Rocky Flats boundary is estimated to be 6.7 $\pm$ 0.4 grams.

— The amount of plutonium-239 on public and private property is estimated to be 7.6 $\pm$ 1.8 grams.

No attempt to simulate the natural conditions which spread plutonium in soil was made. Wind direction and velocity were not considered, neither were natural washes in the foothills, which dilute or accumulate plutonium concentrations. The source of plutonium in the soil was assumed strictly to be the barrel storage area. Other sources such as stack effluent, world-wide plutonium fallout, and the September 11, 1957 fire were not considered.

Krey and Hardy (1970) present the following estimates:

- p33: Based on the areas within the various soil contamination contours determined by planimetry:

  — The total Rocky Flats Pu-239 burden in the soil bounded by the 3 mCi km^{-2} contour is estimated to be 4.5 Ci. Few samples were taken on the plant site, consequently the estimate of plutonium within the plant area is poor and may be low.

  — The amount of Rocky Flats plutonium on public and private lands not controlled by the U.S. AEC and within the 3 mCi km^{-2} contour is estimated to be 2.6 Ci.

  — There is no question that Rocky Flats plutonium extended beyond the 3 mCi km^{-2} contour, but the extent of this low level contamination is difficult to define. An extreme and unlikely estimate of plutonium contamination of remote areas (40 miles east and north of plant) would be an additional 3.2 Ci.

- p35: The distribution of Rocky Flats plutonium suggests that the leaking barrels were the source of the contamination. The plutonium within the 3 mCi km^{-2} contour is estimated to have been deposited on particles in excess of 10 microns in diameter [particle size information on routine releases was not available to

Krey and Hardy, but this rules out routine stack releases as the source given the very small particle size of these releases]. The May 11, 1969 fire is not considered the source, since winds on that day were mostly in the opposite direction to the contamination pattern. The September 11, 1957 fire would have released submicron-sized particles from burning plutonium, and the sharp gradient and relatively short downwind extent of the contours are not compatible with deposition of submicron-sized particles.

Poet and Martell (1972) estimate:

- Page 546: Mentioned Krey and Hardy estimate for area within the 3 mCi km^{-2} contour (2.6 Ci) and suggested an additional 4.0 Ci of plutonium-239 from Rocky Flats beyond the 3 mCi km^{-2} contour out to 64 km in the northeast quadrant.

- Noted that the assessment of the total off-site plutonium-239 contamination was very incomplete.

Krey *et al.* (1976) suggest:

- Table 13: Estimated total plutonium based on measured values and adjustment for plutonium present at depth out to the measured contour of 250 mCi km^{-2} (which falls within the limits of the current plant buffer zone) was 8.5 Ci.

Krey (1976) re-evaluated earlier data and estimated:

- The total off-site inventory was 3.4 Ci.

- The total plutonium released to the environment was 11.4 Ci.

The Seed *et al.* estimates represent the initial efforts at calculating the soil inventory from the pad, with later reports providing what might be considered better estimates of the plutonium soil inventory.

TABLE 3-4: SUMMARY OF 903 PAD PLUTONIUM ESTIMATES (Ci)

Source	Basis	Total Inside Security Fence	Total Outside Security Fence	Total Outside of 903 Pad
Seed *et al.*, 1971	soil inventory	0.4	0.5	0.9
Krey & Hardy, 1970	soil inventory		>2.6 ≤5.8	>4.5
Poet & Martell, 1972	soil inventory		>6.6	
Krey, 1976	soil inventory	8	3.4	11.4
ChemRisk	release simulation	5.6	8	13.6

3.4.2 1957 Fire

The 1957 fire, which is described in this section, represents the second largest plutonium release event at Rocky Flats, the 903 Pad being the largest. The 1957 fire began in Building 771 at about 10:10 p.m. on September 11, 1957 when metallic plutonium casting residues spontaneously ignited in a glove box in Room 180. The fire then spread to an exhaust filter plenum and Rooms 281 and 282, consuming a considerable quantity of filters and damaging the ductwork and fan system.

Environmental samples collected during and following the 1957 fire provide data and information that can be used to estimate plutonium releases from the fire and predict off-site exposures. The data that were collected are limited in extent and quality, and in many cases documentation clearly describing sample collection and results is lacking. Since the environmental sampling data represent the only quantitative information during the time of the fire, considerable effort was devoted to interpreting these data and describing the uncertainties associated with their use in identifying plutonium releases and off-site exposures.

The following sections present a discussion of the approach and results of the analysis of the fire release based on the environmental data. Following these discussions is a review of previous fire-related evaluations which utilized alternative information. Other approaches to the evaluation of the fire releases may yield estimates that differ from those developed based on the environmental data. However, releases that were significantly larger than those estimated using the environmental data would contradict the only available data representing conditions during the fire.

The release estimates developed in this report represent the results of initial comprehensive efforts to quantify the magnitude of releases from the plant site for the purpose of developing preliminary estimates of contaminant doses received by the off-site public. These release estimates will be the subject of further investigation in Phase II of the Health Studies that could lead to the identification of other relevant data and the adoption of different approaches and estimates of release.

3.4.2.1 1957 Fire Chronology

As discussed in the reports of Tasks 3, 4, and 5, a major fire at Rocky Flats began at about 10:10 p.m. on September 11, 1957. The fire probably resulted from spontaneous ignition of metallic plutonium casting residues in a glove box in Room 180 of Building 771 (called Building 71 at the time). Although the initial fire in Room 180 was put out by 10:38 p.m., the fire had spread to an exhaust filter plenum. At about 10:40 p.m., an explosion in the filter plenum breached the HEPA filters, permitting the direct release of contaminants up the building stack. The HEPA filter fire was not under control until 2:00 a.m. on September 12, and there were several rekindlings in Room 180. The final plutonium fire was not out until about 11:30 a.m. on September 12.

Because the samplers in the 771 Building stack were disabled by the HEPA filter plenum explosion during the early stages of the 1957 fire, there are no measurements of the release from the 771 stack during the fire. The limited data available from ambient air and vegetation monitoring during and after the fire are used in this analysis to estimate the releases and resulting air concentrations experienced during the 1957 fire.

It has been reported by C. Barrick that Building 771 fans were turned on 15 days after the fire, and that considerable amounts of ash disappeared at that time. Based on the information reviewed during the Phase I investigation, the effluent samplers of Building 771 were turned on on 9/19/57, i.e., 7 or 8 days after the fire. Therefore, contaminant released 15 days after the fire should have been monitored by the stack samplers and included in the total release estimates of 1957. All off-site air samples collected for the period of 9/13/57 to 9/24/57 were below the detection limit. This result indicates that if there were releases after the fire, it is likely that the amount of contaminant reached off-site was much less than that during the fire itself.

Historical information (Dow Chemical, 1957) about the fire lead to the identification of the following general events:

Period 1. 10:10 p.m. to 10:40 p.m. on 9/11/57 (from the beginning of the fire in Room 180 of Building 771 until the Building 771 HEPA filter plenum explosion)

During this period, HEPA filters were filtering air released from the 771 stack, so plutonium released during this period was probably not significant compared to releases later in the fire. The fire in Room 180 was reported to be out by 10:38 p.m. (Dow Chemical, 1957), but plutonium fires rekindled several times during the night.

Period 2. 10:40 p.m. on 9/11/57 (approximate time of the explosion in the Building 771 HEPA filter plenum).

Stack samplers for the 771 stack were disabled at this time, so no stack release measurements are available for the remainder of the fire. The exhaust fans went off almost immediately following the explosion, so that the heat of the fire was the primary mechanism moving air up the exhaust stack and out of the building. The HEPA filter plenum explosion is believed to have released primarily coarse particles that would present a limited inhalation hazard. Therefore, this coarse particle release will be discussed separately from the fine particle releases.

Period 3. 10:40 p.m. on 9/11/57 to 2:00 a.m. on 9/12/57 (from the time of the HEPA filter plenum explosion until the fire in the filter plenum was controlled).

Period 4. 2:00 a.m. to 11:30 a.m. on 9/12/57 (from the time the HEPA filter fire was controlled until the time when the last fire was out).

As a result, a two-stage release is evaluated in this analysis:

Stage 1. Coarse particles released by the filter plenum explosion that breached the HEPA filters at about 10:40 p.m on 9/11/57 (i.e., Period 2). These particles were primarily deposited within relatively short distances, leading to the plutonium contamination on vegetation observed in a direction trending toward the southeast. Prior to this time, the filters were intact.

Stage 2. Unfiltered smoke from burning plutonium escaped through the breached HEPA filters after the filter plenum explosion, in addition to unfiltered smoke from the burning HEPA filters themselves. This smoke carried respirable plutonium dioxide particles off-site during the fire. This stage of the release was further divided into two periods based on when the fire in the filter plenum was controlled. The first period extends from 10:40 p.m. on 9/11/57 to 2:00 a.m. on 9/12/57 (i.e., Period 3) and the second period extends from 2:00 a.m. until 11:30 a.m. on 9/12/57 (i.e., Period 4).

A discussion by Langer (1979) supports the idea that coarse particulates were released from the filter explosion. Langer says:

> "[P]lutonium particles collected by the filters in routine operations are either the oxide or plutonium salts. These materials are quite refractory and will not burn, but have to be vaporized at rather high temperatures to be transformed into a fine aerosol. In any conceivable accident, the plutonium would become airborne from the fire-induced mechanical breakup of the filter matrix and a rather coarse aerosol will result."

The second component of the 1957 fire release requiring particle size characterization is the particulate matter released from burning plutonium. For particulates produced in a plutonium fire, Kathren (1974) assumes a lognormal distribution and a mass median aerodynamic diameter of 1 to 2 microns with a geometric standard deviation of 1.5 to 2.0.

Kathren says:

> "This implies a count mean aerodynamic diameter of 0.5 to 1.0 [micron]. This particle size distribution, although not the 'worst possible case' from an inhalation standpoint, is conservative and has been inferred from experimental studies (Andersen, 1964; Ettinger *et al.*, 1967; Stewart, 1963; Stewart, 1965).
>
> "Stewart (1963, 1965), for example, in experiments in which metallic plutonium was burned, found that the mass median diameter of the airborne fraction of plutonium ranged from 0.3 to 29 [microns]. Similar particle size distributions were reported by Ettinger *et al.* (1967) and Andersen (1964). Note that the particle size distribution of [plutonium dioxide] will vary with ignition temperature; the higher the ignition temperature, the larger the particle size."

Martell (1975, page 13) says:

> "For airborne particles resulting from the accidental combustion of plutonium metal in laboratory air at the Rocky Flats plant, Mann and Kirchner (1966) report a plutonium dioxide mass median diameter (MMD) of 0.32 micron, with 97 percent of the activity associated with sub micron sized particles. ...Ettinger *et al.* (1967)...report that size distributions of aerosols over burning plutonium metal and plutonium alloy ranged from 0.03 to 0.14 micron MMD...."

The other types of information and data that are needed and available for evaluating the contaminant releases fall into two categories: meteorological data and environmental monitoring data. The availability of each of these types of information is discussed in the following sections.

3.4.2.2 Meteorological Data

On-site meteorological data reported as fifteen minute average wind speed and direction are available from 10:00 p.m. on 9/11/57 to 10:00 a.m. on 9/12/57 (note that the fire was not finally out until 11:30 a.m.). The data are provided in Dow Chemical's letter to Dr. Roy Cleere, Executive Director of the Colorado Department of Health, dated March 20, 1970 (Dow Chemical, 1970a) and shown in Appendix F. The actual strip charts from the meteorologic data recorders were reportedly destroyed at the end of the federally mandated records retention period.

Another important meteorological parameter for air dispersion modeling is termed stability class. Atmospheric stability refers to the amount of turbulent energy that is present in the atmosphere and is a measure of the degree of dispersion that is likely to occur. Atmospheric stability can be determined in a number of ways. Stability can be inferred from cloud cover, ceiling height, surface wind speed, and period of day (day or night time), or it can be measured as the standard deviation of either the horizontal or vertical wind direction fluctuations. Atmospheric stability is typically defined in terms of stability class ranging from class A through F, with F being the most stable, or low dispersion conditions. (An additional class, G, is occasionally used as a hypothetical worst-case condition.)

The meteorological data reported for the site do not include any measures of atmospheric stability. Therefore, stability classes had to be inferred for the various periods of the fire based on:

- Wind speeds and meteorological conditions recorded at the plant site and in the Denver area during the fire, and
- Meteorological conditions that are known to typically prevail at Rocky Flats during the night and early morning hours.

Based on the wind speed and direction data recorded at Rocky Flats and cloud cover data recorded at Stapleton Airport and Lowry Airforce Base, relatively stable, nighttime conditions prevailed from the beginning of the fire shortly after 10:00 p.m. on September 11 until shortly after sunrise. However, it has been reported that the inversion layer broke up soon after sunrise, and unstable conditions (on a scale of neutral—unstable/neutral—unstable) ensued (Dow Chemical, 1957; Fairfield *et al.*, 1978). Therefore, from 10:00 p.m. until 6:45 a.m. (1 hour after sunrise at 5:45 a.m.), atmospheric conditions representative of night-time conditions with less than 50 percent cloud cover were used. Stability class was inferred from windspeed and cloud cover using the following table:

TABLE 3-5: STABILITY CLASS BASED ON WINDSPEED AND CLOUD COVER

Surface wind speed (w) at a height of 10 m (mph)	Nighttime Conditions*	
	≥ 50 percent Cloud Cover	<50 percent Cloud Cover**
w<5	---	---
5≤w<7	E	F
7≤w≤11	D	E
11<w≤13	D	D
w>13	D	D

* Stability classes for winds between 5 and 7 mph used for winds less than 5 mph.
** Listed as ≤ 3/8 cloud cover in the source document. Presumed to include anything less than 50 percent in this analysis.
Source: USEPA (1970). *Workbook of Atmospheric Dispersion Estimates*

After sunrise, the intensity of solar radiation also affects atmospheric stability. Since no measures of solar radiation are available for the morning of September 12, 1957, Rocky Flats meteorological data from September 1989 were used to identify representative conditions. These data indicate that moderate solar radiation typically prevailed until approximately 8:30 a.m., followed by strong solar radiation. Therefore, from 6:45 a.m., 1 hour after sunrise, through the end of the modeling period, stability class was inferred from windspeed and solar radiation using the following table:

TABLE 3-6: STABILITY CLASS BASED ON WINDSPEED AND SOLAR RADIATION

Surface wind speed (w) at a height of 10 m (mph)	Solar Radiation (Insolation) Daytime Conditions—Incoming		
	Slight	Moderate	Strong
w<5	B	A-B	A
5≤w<7	C	B	A-B
7≤w≤11	C	B-C	B
11<w≤13	D	C-D	C
w>13	D	D	C

Source: USEPA (1970). *Workbook of Atmospheric Dispersion Estimates*

As stated previously, there are no meteorological data after 10:00 a.m. on September 12. For the purposes of this analysis, it was assumed that the morning upslope wind pattern observed from 8:00 a.m. to 10:00 a.m. (gentle upslope winds to the southwest at 1—6 mph) continued from 10:00 a.m. to noon, because this is a common morning wind pattern at Rocky Flats (Crow, 1974; Rockwell Technical Report, 1985). In further support of this assumption, Crow (1974) notes that air flow typically shifts from downslope to upslope about an hour earlier at Rocky Flats than at Stapleton Airport. Weather data from Stapleton Airport on 9/12/57 show winds

blowing from the east (upslope) at 3 to 9 mph from 9 a.m. through 1 p.m., suggesting that upslope winds probably occurred at Rocky Flats from 8 a.m. to noon on 9/12/57.

The atmospheric stability class assigned to each 15-minute period during the fire is presented in Appendix F. No additional weather stations closer to Rocky Flats than Stapleton Airport that operated during this event could be located for the purpose of comparison to the weather observations taken by the plant.

3.4.2.3 Environmental Monitoring Data

The environmental monitoring data that are relevant to the analysis of the 1957 fire release include on-site and off-site air sampling data as well as vegetation sampling data reflecting plutonium deposition.

Air Monitoring—On-Site and Off-Site

Air monitoring data have been reported from eight samplers (designated S-1 through S-8) that were routinely operated on-site and one sampler that was operated off-site at a location known as Wagner School (Figure 3-14). The Wagner School site was no longer an operational school at the time of the 1957 fire. Hill (1957) reports that for these samplers:

> "Results are given as percent MPL long lived activity based on the 71 Building tolerance level (MPL) of 9 dpm/m^3. ...The eight on-site air samplers for the period 0815 on September 11 to 0330 on September 12 *all showed 0 percent MPL as did the off-site sample at Wagner School,* which ran from 1150 on September 10 to 0215 on September 12. ...Off-site samplers which ran from September 10 to 13 revealed *only the station at Wagner School to have any long-lived activity.* This sample was 0.56 percent MPL."

The abbreviation MPL refers to maximum permissible level for workers. The periods of time identified in the quote reflect the periods over which the filters were in place in the samplers. The italicized portions of the statement are confusing in that they seem to contradict each other. In a telephone conversation on July 14, 1992, Mr. John Hill cleared up the potential confusion in the quote from his 1957 report by stating that the filter on the Wagner School sampler was changed at 2:15 a.m. on 9/12/57, during the fire, because Wagner School was the nearest downwind off-site air sampler to the Building 771 stack (3.3 miles). The report does not explicitly state at what time the filter that was placed in the Wagner School site sampler at 2:15 a.m. on 9/12/57 was removed for the analysis that resulted in the reading of 0.56 percent MPL. However, in the absence of any information to the contrary, it is believed that the filter was changed on 9/13/57 at about 12:00 p.m., which is approximately the same time it had been changed on 9/10/57.

Table 3-7 presents a summary of the sampling data for the routine samplers. It should be noted that a range of 0-0.28 percent MPL was reported for the on-site samplers for the period from 3:30 a.m. to 1:30 p.m. on 9/12/57. Hill (1957) does not specify which or how many on-site samplers collected measurable levels of plutonium during this period of the fire.

TABLE 3-7: ROUTINE AIR MONITORING DATA DURING THE 1957 FIRE

Location	Time On	Time Off	Sampling Time (minutes)	Reported Results (percent MPL)
S1 through S8	9/11/57 8:15 a.m.	9/12/57 3:30 a.m.	1155	0
S1 through S8	9/12/57 3:30 a.m.	9/12/57 1:30 p.m.	600	0 - 0.28
Wagner "School" Site	9/10/57 11:50 a.m.	9/12/57 2:15 a.m.	2305	0
Wagner "School" Site	9/12/57 2:15 a.m.	9/13/57 Not Reported	Unknown	0.56

Source: Hill (1957).

In addition to the routine samplers that operated during the fire, portable samplers were deployed on-site. Short-term average air concentrations observed on-site by the portable air samplers during the 1957 fire ranged from 0 to 56 percent MPL (Hill, 1957), and are shown in Table 3-8. In a telephone conversation on September 17, 1992, Mr. John Hill stated that Gate 2, also called the clock room, was next to Building 81 and that Gate 6 was designated as the East Entrance to the Rocky Flats Plant.

Records relating to sampling during or after the 1957 fire were identified in listings of holdings of the Federal Records Center in Denver. However, the boxes identified as likely relevant were retrieved to the Rocky Flats Plant according to FRC records. Rocky Flats personnel were not able to locate these missing records at the plant during Phase I investigation.

Details on Sampling Equipment and Analytic Methods

The following discussions provide information that describe the equipment and methods used to produce the air monitoring data. The description of the methods and equipment used for the routine and portable air sampling that was obtained from plant documents and interviews is generally consistent with guidance provided in the "American National Standard Guide to Sampling Airborne Radioactive Materials in Nuclear Facilities," ANSI standard N13.1-1969.

TABLE 3-8

AIR SAMPLING DATA FROM PORTABLE SAMPLERS
DURING THE 1957 FIRE

September 12, 1957

Location	Time On	Time Off	Sampling Time (Minutes)	Reported Results (% MPL)
Gate 2	12:40 a.m.	3:05 a.m	145	0
Gate 6	1:20 a.m.	3:20 a.m.	120	0
Gate 2	3:10 a.m.	5:10 a.m.	120	0
Gate 6	3:20 a.m.	5:25 a.m.	125	0
Gate 2	5:10 a.m.	7:04 a.m.	114	0
Building 91[a]	5:30 a.m.	5:45 a.m.	15	25.6
N. of Bldg. 71 at Main E.W. Road	6:15 a.m.	6:20 a.m.	5	0
N. of Bldg. 71 at Main E.W. Road	6:25 a.m.	6:28 a.m.	3	55.6
Building 23[b]	7:00 a.m.	10:12 a.m.	192	0.8
Gate 2	7:04 a.m.	10:20 a.m.	196	2.7
Gate 6	8:15 a.m.	10:00 a.m.	105	0
Gate 6	10:05 a.m.	2:40 p.m.	275	0.1
Gate 2	10:23 a.m.	2:45 p.m.	267	0.9

Source: Hill (1957).

[a] Currently designated as Building 991.
[b] Currently designated as Building 123.

The information is used to develop appropriate uncertainty estimates for the air monitoring data to be used in the reconstruction of the fire releases.

Sampling flow rates and volumes—Routine samplers: The sampling equipment used to collect the routine samples consisted of a GAST brand vacuum pump drawing air at a target flow rate of 2 cubic feet per minute (ft^3 min^{-1}), which is equivalent to approximately 57 liters per minute or 81.5 cubic meters per day (Hill, 1993a and 1993b; Angell, 1955 and 1956). The on-site samplers were installed in February 1953 (Kittinger, 1953a) and the off-site samplers were installed between March and June 1953 (Kittinger, 1953b-e). The samplers were calibrated to the target flow rate of 2 ft^3 min^{-1} in July and August 1953 (Kittinger, 1953f and g). In addition, air sampling pump flow rates were reportedly calibrated to 2 ft^3 min^{-1} both prior to and after each sampling period (Hill, 1993a), but none of the documentation reviewed noted that such calibrations had occurred. In fact, air sampling data sheets were often preprinted with a standard of 81.5 m^3 air sampling volume per day. There was also no evidence of air volume adjustment based on the post-calibration results.

Following installation of the routine samplers, air samples were collected continuously over a 24-hour period (Kittinger, 1953a and b). Beginning in January 1954, off-site samples were collected on a weekly basis (Kittinger, 1954a), while on-site samples were collected on a biweekly basis beginning in August 1954 (Kittinger, 1954b). Although the term "biweekly" can mean either twice a week or once every two weeks (according to Webster's dictionary), it is presumed to mean twice a week based on an interview of a former plant employee (Hill, 1993c). It should also be noted that a pre-trial statement for what is known as the Church litigation (Fairfield and Woods, 1978) indicated that the off-site samplers did not sample continuously at the time of the 1957 fire. These samplers were said to have operated ten minutes out of each hour and that modifications in the 1970s were made so that the samplers operated continuously (Trial Exhibit 3503). Given the potential importance of this claim to the reconstruction of 1957 fire release, an extensive review of plant documents was undertaken to clarify this point.

As discussed above, the Monthly Progress Reports for February and March 1953 state that air samples were collected continuously on a daily basis (Kittinger, 1953a and b). Although the term "continuous" was not explicitly used in any of the subsequent Monthly Progress Reports during the 1950s, no indication was given that the sampling methods had changed from continuous to intermittent sampling. Beginning in 1960, environmental sampling results were summarized by Dow Chemical Company in quarterly or semi-annual Environmental Survey Reports. The term "continuous" was used to describe the on-site and off-site air samples beginning in the report for October-December 1961 and continued through the report for January-June 1969. Sample collection practices for the off-site samplers did apparently change during the second half of 1969. In the Environmental Survey Report for July-December 1969, Dow reported that the off-site samplers were programmed to sample 5 minutes of each hour

(Dow Chemical, 1969). The sampling period was apparently increased to 10 minutes of each hour at the beginning of 1970 (Dow Chemical, 1970b), which remained in effect until March 1973 when continuous sampling was resumed (Dow Chemical, 1974). This reported series of changes in the off-site sampling procedures is consistent with information obtained in interviews of two former plant employees, both of which stated that the off-site samplers sampled air continuously at the time of the 1957 fire, but were changed to sample air intermittently in later years (Hill, 1993b; Kittinger, 1992).

Additional questions have been raised regarding the actual flow rate of the samplers as a result of the potential for filter clogging. Chapman (1960) suggested that the air sampling data could under–predict by as much as a factor of ten as a result of filter clogging:

> "...dust loading restricts the air flow and gives an unrealistically low computed value for air activity. ...the data are about an order of magnitude lower than those reported from the sampling stations of other observers."

The Chapman argument is based on the theory that, while the off-site sampling results were similar to the on-site sampling results when the sampling period was 24 hours, the dust loading on the filters caused a substantial decrease in the air flow rates when the off-site samplers were allowed to run for a week or more. Although some decrease in the air flow rate would be expected due to increased airflow resistance caused by filter loading, Chapman's suggested decrease of an order of magnitude is not supported by any data. Furthermore, such a large decrease in air flow is also not reasonable to expect, because, as resistance is applied to an air sampling pump, the pump works harder, usually overheats, and then fails to operate. These types of problems were not recorded by Rocky Flats technicians or recalled by interviewees. In addition, the longest sampling time for samples collected during or immediately after the fire was less than 48 hours.

While there is a potential for the flow rate to have decreased during the sampling period due to filter loading, there is no evidence that the recorded air volumes were ever adjusted to account for such a decrease. In any case, the sampling flow rate represents a source of uncertainty in the air sampling data collected during the 1957 fire. No data have been located that would permit the quantitative evaluation of the uncertainty in the sampling flow rate. Professional experience with air sampling devices suggest that if desired sampling rates are not maintained, the largest deviance from the target rate will be towards lower collection rates. It is estimated, based on professional experience, that the actual annual average sampling flow rates would very likely be bounded by a range of 1 and 2.5 cfm (-50 percent to +25 percent of the target value of 2 ft^3 min^{-1}). In the uncertainty analysis, the factor that the results will be multiplied by to account for this uncertainty is represented by a triangular distribution with the best estimate equal to 1.0, a lower bound of 0.8 and an upper bound of 2.0.

Sampling flow rates and volumes—Portable Samplers: Portable high-volume sampling equipment was maintained for deployment during such incidents as the 1957 fire. The samplers were Staplex brand samplers that draw air at rates in the range of 12 to 40 ft^3 min^{-1} through a 4 inch diameter or 8 by 10 inch rectangular Whatman–41 cellulose filter (Hill, 1957 and 1993b; Dow Chemical, 1978; ANSI, 1969). No original data sheets have been located for these samplers that would provide details of their operation. While the variability in the flow rate of these devices is likely to differ from that of the routine samplers, the range of uncertainty described for the routine sampler volumes is relatively large and is believed to encompass the expected uncertainty associated with the operation of the portable samplers.

Sampling filters and efficiencies—Routine Samplers: The available records do not identify the type of filters used for each individual sample collected during the fire. In general, samples were collected on either a 47 mm diameter Hollingsworth & Vose HV–70 asbestos/cellulose filter or a 47 mm diameter Whatman–41 cellulose filter (Hill, 1993a and 1993b). The off-site samplers reportedly employed only the Whatman–41 filter starting in February of 1954 due to periodic filter paper failures (ruptures) when using the HV–70 filters for the week-long sampling periods (Kittinger, 1954b). Each filter type has some differences in air flow resistance, collection efficiency, and self absorption (i.e, burial loss).

The HV-70 asbestos/cellulose filter has a higher collection efficiency and air flow resistance than the Whatman-41 cellulose filter when used at the air flow rates reported above. Based on data reported by the manufacturers, the Whatman-41 filter collection efficiency is expected to have been approximately 84 percent efficient at an air flow rate of 2 ft^3 min^{-1} compared with an expected collection efficiency of approximately 99 percent for the HV-70 filter (ANSI,1969). Two other studies of the Whatman-41 filter indicate that the collection efficiency can range from 92 to 95 percent (interpolated values from Lindekin *et al.*, 1963) or from 86 to 99 percent (Rimberg, 1969), depending on the size of the aerosol. Therefore, the air sample results may have under-reported the airborne concentrations by as much as 15 percent if the Whatman-41 filters were used. Since there is no indication that any of the air sampling results were corrected for collection efficiency, this represents a source of uncertainty in the reported results. The factor that the results will be divided by to account for this uncertainty will be represented by a uniform distribution ranging from 0.85 to 1.0 in the uncertainty analysis.

With regard to self absorption, cellulose filters such as the Whatman-41 filter are subject to significant burial of radioactive particles (ANSI, 1969). One study that tested a number of filters including the Whatman-41 and HV-70 filters for measuring alpha radiation at a flow rate of 3 ft^3 min^{-1} reported a burial loss of 40 percent for the Whatman-41 filter and 18 percent for the HV-70 filter, as compared to a Millipore AA filter (Lindekin, 1961). An earlier study had demonstrated that the Millipore AA filter was subject to very little (i.e., 3 percent) self absorption (Setter and Coats, 1961). As described in the Task 5 report, the plant routinely

adjusted measured airborne concentrations by a factor of 70 percent (i.e., a 30 percent loss) to account for filter self absorption, regardless of filter type. This value lies in between the reported range of approximately 20 to 40 percent (correction factors of 0.80 and 0.60, respectively) for the types of filters used by the plant. Since the amount of burial loss should be related to the type of filter (as well as filter loading), this factor also represents a source of uncertainty in the reported results.

Unlike the uncertainty distribution described for collection efficiency, the distribution for burial loss is not simply a uniform distribution ranging from 0.60 to 0.80. This is because the correction factor of 0.70 has already been taken into account in the data, and the uncertainty in the reported results lies in how far off this correction factor could have been. The percent difference between the upper and lower bounds of the plausible range and the value used in the data reduction of 0.70 can be calculated using the following equation:

$$\%\ Difference = \left[\frac{1}{Value\ Used/Plausible\ Value} - 1\right] \times 100$$

Using a value of 0.70 and a plausible value of 0.60 or 0.80, the reported airborne concentrations could have been overestimated or underestimated by as much as 14 percent. In the uncertainty analysis, the factor that the results will be divided by to account for this uncertainty is represented by a uniform distribution ranging from 0.86 to 1.14.

Sampling filters and efficiencies—Portable samplers: Collection efficiency and burial loss of the Whatman–41 filter have already been described for the routine samplers. It is believed that the range of uncertainty previously described for these parameters should also be applicable to the portable samplers.

Analytic Method: The analytical methodology used for air samples collected during the period of the 1957 fire is described in the Task 5 report. An alpha scintillation counter, Model MAC 5, was used. In addition to the aforementioned adjustment for self absorption, measured airborne concentrations from routine samplers were adjusted by a factor of 30 percent to account for the efficiency of the counting device. This correction factor was verified by daily measurements of electroplated sources traceable to the National Bureau of Standards which were believed to be accurate to within 10 percent of the true activity (i.e., uncertainty of $\pm$ 3 percent in the 30 percent counting efficiency correction factor). The uncertainty in the counting efficiency can be defined in a manner similar to that used for burial loss. Therefore, a uniform distribution ranging from 0.9 to 1.1 will be used in the uncertainty analysis.

Overall uncertainty—Air monitoring data: Four sources of uncertainty have been identified for the air monitoring data from the 1957 fire. They are: flow rate, filter collection efficiency, filter burial loss, and counter efficiency. The individual uncertainties that have been assigned to each of these sources can be combined into a single uncertainty factor that model predictions will be multiplied by using Monte Carlo techniques. This overall uncertainty factor can be represented by the following equation:

$$U_{air} = \frac{U_{flow}}{U_{collection} \times U_{burial} \times U_{counter}}$$

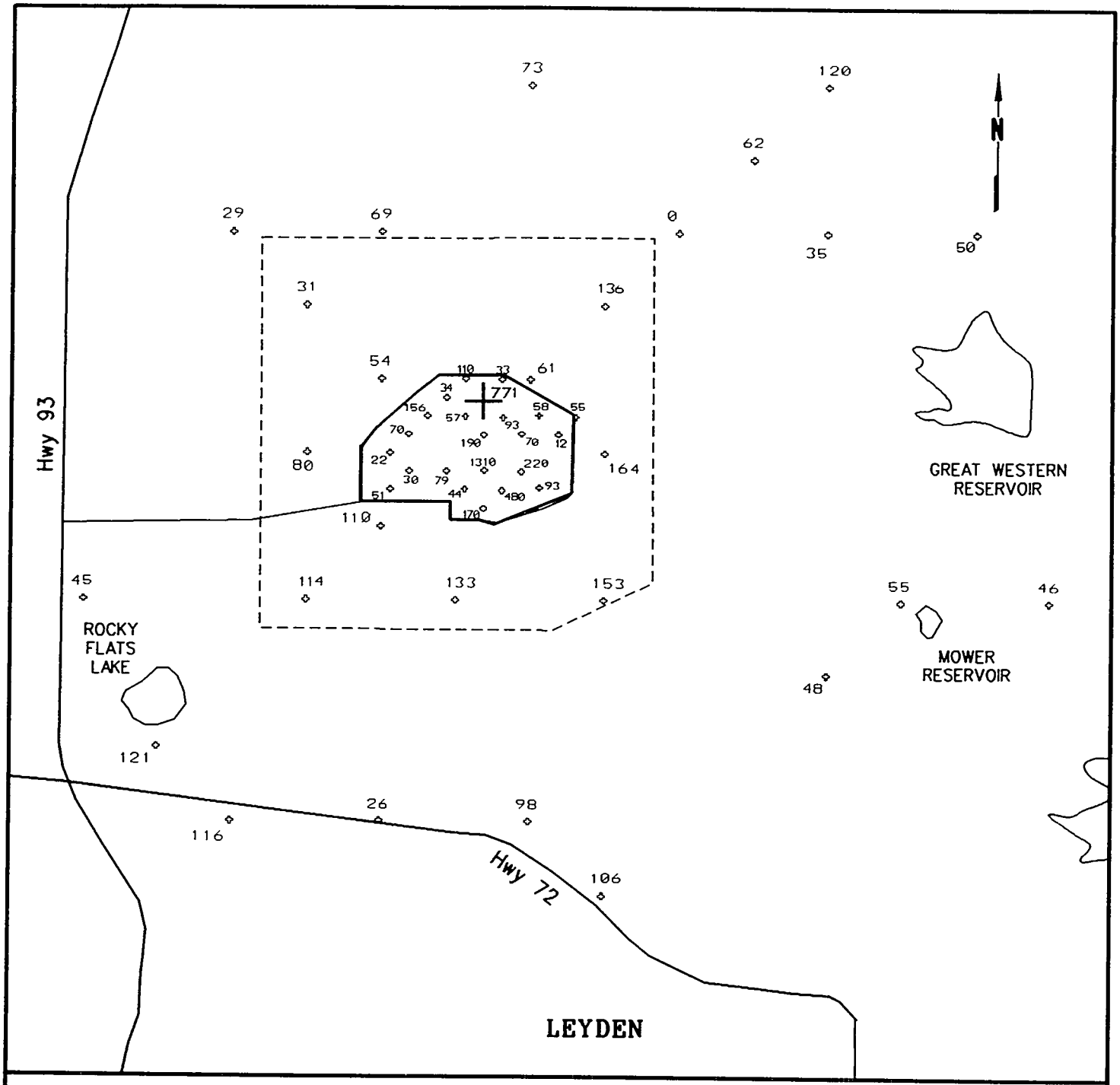
where:

U_{air}	=	Overall uncertainty in the air monitoring data
U_{flow}	=	Uncertainty in flow rate (triangular; 0.8—1.0—2.0)
$U_{collection}$	=	Uncertainty in filter collection efficiency (uniform; 0.85—1.0)
U_{burial}	=	Uncertainty in burial loss (uniform; 0.86—1.14)
$U_{counter}$	=	Uncertainty in counter efficiency (uniform; 0.9—1.1)

The resulting overall uncertainty factor can be defined as a lognormal distribution with a GM of 1.4 and a GSD of 1.3. This means that 95 percent of the distribution is within a factor of approximately 1.7 of the best estimate.

Vegetation Monitoring

Handwritten records of vegetation sampling results from 1952 to 1971 are available (Dow Chemical, 1953-1971). During this time, vegetation samples were taken periodically at numerous locations around the plant site and the surrounding areas. Some samples were taken on regularly spaced grids, while others were taken at widely spaced, individual locations. Vegetation samples were routinely analyzed for total alpha radioactivity. However, in the months following the 1957 fire, the majority of the vegetation samples taken on two grids were also analyzed by pulse height analysis to determine the portion of the total alpha radioactivity that was due to plutonium. Data from these two grids, i.e., a 2000-foot grid established to monitor off-site contamination and a 500-foot grid established to monitor on-site contamination, were used to model the coarse particle release from the 1957 fire. These data, mainly from September and October 1957, are shown in Figure 3-19.



LEGEND

SECURITY FENCE

ROCKY FLATS PLANT BOUNDARY 1951-1974

VEGETATION SAMPLING LOCATION

73 PLUTONIUM CONCENTRATION IN VEGETATION SAMPLE, dis $min^{-1}kg^{-1}$ (dry weight)

BUILDING 771 STACK

0' 3,960'
SCALE

SCALE: 1"=.75 Miles

ChemRisk
A Division of McLaren/Hart

FIGURE 3-19
VEGETATION SAMPLING DATA-
POST 1957 FIRE (dis $min^{-1}kg^{-1}$)

Rky0194h/rfh3-19.dgn: Rev: 05-06-94

Prior to modeling the coarse particle release, any background levels of plutonium present in vegetation around the RFP would ideally be subtracted from the levels measured in samples taken shortly after the 1957 fire. However, the results from earlier sampling efforts, including background data from pre-plant construction (1952-1953), were generally reported in terms of gross alpha radioactivity. For example, levels of total gross alpha radioactivity ranged from less than 20 to 1850 dis min^{-1} kg^{-1} for samples collected in 1952 prior to plant operation (Dow Chemical, 1953-1971). In addition, adjustment of vegetation data for background from previous years may not be appropriate given the fact that vegetation is a renewable resource. Therefore, all of the activity measured on the vegetation located in the path of the airborne plume from the fire has been attributed to the fire release.

Uncertainties in the vegetation data would be expected to be related primarily to collection and analytical techniques. Detailed information on collection methods was not located in the documentation reviewed. However, the type of vegetation (e.g., broad vs. narrow leaved) and handling procedures (e.g., rinsed vs. non-rinsed) may contribute to the overall uncertainty in the result. In a study on the resuspension of plutonium from soil, Langer (1985b) analyzed the dust rinsed from grass samples and unrinsed grass samples. The measured plutonium concentrations were approximately the same, indicating that the primary source of the plutonium was associated with dust that could be removed by rinsing. These results are not surprising given the relative insolubility of plutonium. Since vegetation samples collected for the purpose of establishing background plutonium levels would not have been rinsed, the results of this study indicate that handling procedures should not contribute significantly to the overall uncertainty in the vegetation monitoring data.

With regard to analytical methods, a study of the recovery of plutonium from vegetation samples was conducted on samples collected at the Savannah River Plant (Geiger, 1959). In this study, approximately 64 to 97 percent of the plutonium was recovered from 78 spiked vegetation samples. The mean recovery was 73 percent. For the purpose of this analysis, a triangular distribution with as best estimate of 0.73, a lower bound of 0.64 and an upper bound of 0.97 is included in the overall uncertainty estimate for the coarse particle release.

Other Environmental Monitoring Data

Efforts to characterize environmental contamination of soil and water in addition to vegetation from the fire are briefly described in a rough draft report authored by S. E. Hammond (Hammond, 1958a). The report indicates that there is no evidence from water samples of off-site contamination; however, it does report off-site soil contamination results as "possible" enriched uranium and plutonium (e.g., Ralston and Semper Schools), but does not indicate what the designation of possible means. A report published much later by Hammond (1971) appears to provide an answer with the following quote:

> "While we could detect plutonium by alpha spectrometry in some of the on-site samples, there were other alpha emitters present, the spectra were smeared, and we were unable to quantify the results."

Due to the questionable quality and very limited extent of these data, they could not be used in the analysis. Some limited additional soil and groundwater data collected after the fire can be found in the plant Monthly Progress Reports, Site Surveys for September—December 1957 (Hammond, 1957a-c, 1958b). The monthly reports suggest only small differences between the post-fire samples and samples taken in 1952 prior to plant construction.

3.4.2.4 1957 Fire Release Estimating Procedure

Coarse particles released during Stage 1 of the 1957 fire would have subsequently deposited on vegetation and fine particles released during Stage 2 would have been sampled by on-site and off-site air samplers. The approach adopted here to estimate this two-stage release involves the use of an air dispersion model (INPUFF) to estimate release rates that result in predictions of deposited activity on vegetation and air concentrations at downwind sampler locations that are consistent with the results from these sampling locations.

As indicated in the air sampling data summaries presented earlier, much of the data employed in the reconstruction consists of non-detect results and can therefore only provide an indication of how high the contaminant concentration and, to a certain extent, the release could have been. This analysis relies on some of the best data available to characterize the release; however, the available data are very limited and are relatively poorly documented for this fire that took place over 35 years ago. While we believe that the analysis provides a reasonable estimate of the actual release, the uncertainties associated with the estimate are large and, there are many questions that cannot be answered by the available information.

Fine Particle Release—Data Analysis

The releases that are predicted to produce air concentrations equal to measured results or just at or below the reporting or detection limit for non-detect (0 percent MPL) results are identified in the analysis. Since all of the routine samplers reported 0 percent MPL for the first stage of the fire (10:10 p.m. till 2:00 a.m.), actual releases could have been lower than this and still have been consistent with the environmental data being used. Therefore, the first-stage fire release should be characterized as a bounding estimate of release as opposed to a best-estimate.

A number of calculations and assumptions must be made in order to predict air concentrations that are consistent with the data reported as a percent of the MPL for the routine air samplers. The following discussion describes these calculations and assumptions and the uncertainty that they introduce into the analysis.

Analysis of Ambient Air Sampler Data

All of the analyses that are performed are based on the following assumptions:

Assumption 1: All plutonium either collected on the air sampling filters or estimated as possibly present on the filters (threshold amount) is assumed to have been released during the fire.

This assumption implies that background airborne concentrations are negligible compared to the potential contribution from the fire. A review of the Monthly Progress Report Site Surveys for the months preceding the fire indicated that air monitoring results were not routinely included. This may indicate that the results were not remarkable. The site survey report from January 1956 reported that a total of 224 air samples were collected during December 1955. Based on these samples, it was concluded that "There was no apparent long-lived alpha activity." (Angell, 1956).

This is the only assumption necessary to translate the measured air concentrations, reported in percent MPL, to an average air concentration during the fire (C_T). For example, a value of 0.28 percent MPL was reported for one or more of the on-site sampling locations based on the analysis of filters that were in place from 3:30 a.m. to 1:30 p.m. on September 12 (sampling time equal to 10 hours). The MPL used by the plant at the time of the fire was 4 pCi m^{-3}. Therefore, the average air concentration would appear to be simply 4 pCi m^{-3} multiplied by 0.28 percent or 0.011 pCi m^{-3}. However, since the fire ended at approximately 11:30 a.m., or two hours before the filter was removed, the average air concentration during the fire (sampling time equal to 8 hours) would actually be equal to:

$$C_T = \%\ MPL \times MPL \times \frac{Total\ Sampling\ Time}{Sampling\ Time\ During\ Fire}$$

Using the same example, the average plutonium concentration in ambient air at one or more of the on-site samplers between the hours of 3:30 a.m. and 11:30 a.m. on September 12 would be:

$$C_T = 0.28\% \times 4\ pCi\ m^{-3} \times \frac{10\ hours}{8\ hours}$$

$$= 0.014\ pCi\ m^{-3}$$

Assumption 2: Airborne concentrations of plutonium at sampling stations reporting 0 percent MPL are assumed to be the highest airborne concentrations possible during the hours of the fire that would not result in the reporting of a positive result.

This second assumption requires that a number of calculations be performed to translate the sampling results in terms of 0 percent MPL to air concentrations for each of the sampling sites and sampling periods. The starting point for these calculations is the amount of plutonium that could be collected on the sampling filter to produce a reading of 0 percent MPL. Several different methods that rely on different sources of information were explored, each of which is described briefly below.

Reported Limit of Detection

C.W. Barrick reviewed the 1957 fire incident as part of a larger report addressing multiple incidents that have occurred at the RFP (Barrick, 1981). As part of his review, Barrick stated that "The detection limit was 0.009 dis min^{-1} m^{-3} for three day air samples." This detection limit would be consistent with 0.004 pCi m^{-3}. The amount of plutonium that would have been collected on the filter can be determined from the following equation:

$$\text{Amount of Plutonium} = \text{Air Concentration} \times \text{Sampling Flow Rate} \times \text{Sampling Time}$$

Assuming that the flow rate was equal to the target of 2 ft^3 min^{-1} or 3.4 m^3 hr^{-1} (81.5 m^3 d^{-1}),

$$\begin{aligned}\text{Amount of Plutonium} &= 0.004 \text{ pCi m}^{-3} \times 3.4 \text{ m}^3 \text{ hr}^{-1} \times 72 \text{ hr} \\ &= 1 \text{ pCi}\end{aligned}$$

Minimum Detectable Amount

Another way to estimate the lowest amount of plutonium that can be detected on a filter is to use the lowest counts per minute (c min^{-1}) reading that can be detected and the analytical and/or measurement error. Raw analytical data sheets for the 1957 fire were not found in the documentation reviewed. However, raw analytical data sheets from 1964 through 1969 were examined to determine the minimum activity, in c min^{-1}, that was recorded during this period. In 1964, the lowest entry recorded on the data sheets is 0.1 c min^{-1} (Dow Chemical, 1978). Since the same counting equipment was used from 1956 through 1964 (ChemRisk, 1992a), this information should be applicable to the 1957 fire. Assuming that 21 percent of the ambient alpha activity collected on the filter was detected (correction factor of 0.21), which accounts for the burial losses (correction factor of 0.70) and counter efficiency (correction factor of 0.30)

discussed previously, the lowest amount of plutonium that can be detected is determined as follows:

$$\text{Amount of Plutonium} = \frac{0.1 \text{ c min}^{-1}}{0.21 \times 2.22 \text{ dis min}^{-1} \text{ pCi}^{-1}}$$

$$= 0.21 \text{ pCi}$$

It should be noted that 0.1 c min^{-1} was the lowest positive entry recorded on any of the raw data sheets examined from 1964 through 1969. However, beginning in 1968, data sheets that summarized analytical results for several sampling locations and/or time periods contained a value of 0.21 c min^{-1} for any raw data value less than 0.2 c min^{-1}. In fact, the value of 0.21 c min^{-1} was listed on several Rocky Flats forms as the "MDA," or minimum detectable amount. The amount of plutonium associated with an MDA of 0.21 c min^{-1} is 0.45 pCi.

NBS Lower Limit of Detection

In 1984, the National Bureau of Standards issued a report that addressed the issue of estimating a lower limit of detection for radiological effluent and environmental measurements (NBS, 1984). An equation developed from this guidance was used in the Task 5 report to assess the sensitivity of the analytical method used in the effluent monitoring program. Since the routine sampling devices were similar in design (Kittinger, 1992), this equation should also be applicable to data collected during the 1957 fire:

$$LLD = \frac{4.66 \times S_b}{E \times C \times S \times F \times 2.22}$$

where:

LLD = Lower limit of detection (pCi m^{-3})

S_b = Standard deviation of the background count rate (c min^{-1})

$$S_b = \sqrt{N/t}$$

where:

N = Background count rate (c min^{-1})
t = Background count time (min)

E = Counting efficiency (c min^{-1} per dis min^{-1})

C = Collection efficiency (dimensionless)

S = Self-absorption (dimensionless)

F = Total sampled air volume (m^3)

2.22 = Conversion factor (dis min^{-1} pCi^{-1})

If the term for total sampled air volume is removed from the equation, the result will be in pCi of plutonium on the filter. Using a background count rate of 0.1 c min^{-1} and a sample count time of 60 minutes (ChemRisk, 1992a), a factor of 0.30 for counting efficiency and a factor of 0.70 for collection efficiency and self-absorption, the amount of plutonium on the filter is 0.41 pCi.

In summary, the range of estimates of the lowest amount of plutonium that could be detected on the sampling filter from the above described methods are as follows:

Method	Amount of Plutonium
Reported Limit of Detection	1 pCi
Minimum Detectable Amount 0.1 c min^{-1} 0.21 c min^{-1}	 0.21 pCi 0.45 pCi
Lower Limit of Detection	0.41 pCi

For the purposes of this analysis, a value of 0.45 pCi, which is based on a minimum detectable amount of 0.21 c min^{-1}, is used for the following reasons.

- The value of 1 pCi calculated from Barrick's review is not consistent with other data collected during the fire.
- The remaining estimates are all within a factor of 2, and any uncertainty in using a value of 0.45 pCi is overwhelmed by the other sources of uncertainty described in detail later in this section.

This value of minimum detectable amount of plutonium on a filter (Pu_f), in pCi, can then be used to identify average airborne concentrations (C_T) at sampling locations with non-detect results during the fire that would have been consistent (at or below the detection limit) with the reporting of 0 percent of MPL using the following equation:

$$C_T = \frac{Pu_f \times 60}{Rate \times Time}$$

where:

C_T	=	Average airborne concentration (pCi m^{-3})
Pu_f	=	Amount of plutonium on filter (pCi)
60	=	Conversion factor (min hr^{-1})
Rate	=	Sampling flow rate (m^3 hr^{-1})
Time	=	Sampling time during fire (min)

Tables 3-9 and 3-10 present the estimated average airborne concentrations for the routine and portable high volume samplers, respectively. In cases where the sampling results were reported as 0 percent of MPL, these estimates represent upper-bound air concentrations, and where they are reported as positive values, they represent best estimates. It should be noted that the data from the three high volume samples collected at Building 91 and north of Building 71 have not been used, because the sampling times were too short (3, 5 and 15 minutes) to be of use in the analysis, since the time resolution of other available information is not as fine. Additionally, average air concentrations were not estimated for the last samples collected at Gates 2 and 6, since the sampling interval began at 10:00 a.m. or later, a period for which no meteorological data are available.

The uncertainties associated with these estimates of average air concentrations are those described and quantified for the air sampling devices and analytic process used for these air samples. The following section describes the use of the average airborne concentrations of plutonium presented in Tables 3-9 and 3-10 in estimating a fine particle release from the fire. This is followed by a discussion of the approach used to estimate a coarse particle release based on vegetation sampling data.

TABLE 3-9

UPPER-BOUND AND BEST ESTIMATES OF AVERAGE AIR CONCENTRATIONS AT ROUTINE SAMPLING LOCATIONS DURING THE 1957 FIRE

Location	Total Sampling Time (min)	Sampling Time During Fire (min)	Sample Rate (m^3 hr^{-1})	% MPL	Estimated Plutonium on Filter (Pu_f) (pCi)	Estimated Average Air Concentration (C_T) (pCi m^{-3})
First Set of Sampling Filters						
S1 through S8	1155	290	3.4	0	≤0.45	≤0.027[a]
Wagner School	2305	215	3.4	0	≤0.45	≤0.037[a]
Second Set of Sampling Filters						
S1 through S8	600	480	3.4	0.28[c]	≤0.38[f]	≤0.014[b]
Wagner School	2025[d]	585	3.4	0.56	2.6[f]	0.078[b,e]

a $C_T = Pu_f \times 1/\text{sampling rate} \times 1/\text{sampling time during fire} \times 60 \text{ min hr}^{-1}$

b $C_T = \%\text{MPL} \times 4 \text{ pCi m}^{-3} \times \text{Total Sampling Time / Sampling Time During Fire}$

c 0.28 percent of MPL assumed for all on-site routine samplers since information on which and how many on-site samplers collected measurable levels of plutonium was not provided (Hill, 1957). The resulting estimated average air concentrations could represent either upper-bound or best estimates.

d Filter is assumed to have been removed at 1200 on September 13.

e This is the only routine sample location for which a positive detect result was specifically reported. Therefore, this would not be an upper-bound estimate but a best estimate.

f For samplers with measured concentrations, $Pu_f = \%\text{ MPL} \times 4 \text{ pCi m}^{-3} \times \text{sampling rate} \times \text{total sampling time / 60 min hr}^{-1}$.

0104ALR8

TABLE 3-10

UPPER-BOUND AND BEST ESTIMATES OF AVERAGE AIR CONCENTRATIONS AT PORTABLE HIGH VOLUME SAMPLERS DURING THE 1957 FIRE

Location	Total Sampling Time (min)	Sampling Time During Fire (min)	Sample Rate[a] (m^3 hr^{-1})	% MPL	Estimated Plutonium on Filter (Pu_f) (pCi)	Estimated Average Air Concentration (C_T) (pCi m^{-3})
Gate 2	145	145	51	0	≤0.45	≤0.0037[b,d]
Gate 6	120	120	51	0	≤0.45	≤0.0044[b,d]
Gate 2	120	120	51	0	≤0.45	≤0.0044[b,d]
Gate 6	125	125	51	0	≤0.45	≤0.0042[b,d]
Gate 2	114	114	51	0	≤0.45	≤0.0046[b,d]
Building 23	192	192	51	0.8	5.2[f]	0.032[c,e]
Gate 2	196	196	51	2.7	18[f]	0.11[c,e]
Gate 6	105	105	51	0	≤0.45	≤0.0050[b,d]

a Assumed to equal 30 cubic feet per minute (51 m^3 hr^{-1}), the low end to the range reported by Hill (1957)

b $C_T = Pu_f \times 1/\text{sampling rate} \times 1/\text{sampling time during fire} \times 60 \text{ min hr}^{-1}$

c $C_T = \%\text{MPL} \times 4 \text{ pCi m}^{-3} \times \text{Total Sampling Time / Sampling Time During Fire}$

d Upper-bound estimates

e Best estimate

f For samplers with measured concentrations, $Pu_f = \%\text{ MPL} \times 4 \text{ pCi m}^{-3} \times \text{sampling rate} \times \text{total sampling time / 60 min hr}^{-1}$.

Fine Particulate Release—Emission Rate Estimate

The process of identifying average release rates of plutonium during the fire that are consistent with the upper bound and best estimates of the air concentrations based on the environmental data involved the use of the INPUFF computer model, which was run to simulate the dispersion of contaminants during the event. The model used the meteorological data and atmospheric stability estimates to predict the movement and dispersion of "puffs" of contaminants released by the fire and to predict average airborne concentrations of contaminants at the locations of the air samplers and at any other locations of interest. Since the meteorological data are in 15-minute intervals, INPUFF predicted 15-minute average air concentrations throughout the duration of the fire. The analysis proceeded by developing estimates of the average releases for two periods of the fire (between 10:40 p.m and 2:00 a.m.; and after 2:00 a.m.) that are consistent with the information obtained from the routine on-site samplers and the off-site sampler at the Wagner "School" site. Once release rates that are consistent with the routine sampling information were identified, the estimated air concentrations at the locations of the portable samplers were then predicted as a check to determine whether there is general agreement.

As described above, average release rates from the Building 771 stack can be identified that would produce the upper bound and best estimate average air concentrations associated with the air sampling locations. It is important to note that this analysis can only estimate the *average* release rates over many hours of the fire release, since the environmental samplers only provide us with average air concentration estimates. The actual rate of release of contaminants could have varied considerably throughout the fire. However, the primary objective of the analysis is to predict contaminant doses to the off-site public that were present during the entire fire event, and such exposures are the same whether they are calculated from either the average air concentration or the time varying air concentration given relatively uniform meteorologic conditions.

The INPUFF model can also account for contaminant removal from the air as a result of deposition to the ground (plume-depletion). In the modeling of the fine particle releases from the fire, it has been assumed that this removal mechanism plays a very minor role by assuming a settling velocity of zero (implies that the particles essentially behave as a gas) and a deposition velocity consistent with submicron-size particles of 0.1 cm sec^{-1} (Sehmel, 1984; USEPA, 1979; Sehmel and Hodgson, 1978). However, since the actual particle size distribution for the fine particle release is not known, an uncertainty factor of 10 (GM of 1 and GSD of 3.2) was incorporated into the dose calculations in Task 8 for those pathways related to deposition (e.g., soil ingestion). This uncertainty factor is in addition to that described later in this section for the overall release estimate.

Precipitation scavenging did not have to be taken into account for the 1957 fire, because no precipitation was recorded in the region around the time of the fire. For example, meteorological data collected at Stapleton Airport indicate that light rain occurred on the evening of September 10, but no precipitation (i.e., thunderstorm, rain, rain showers, snow pellets, snow showers, sleet, fog or smoke) occurred on the days of the fire, September 11 or 12. Light rain and rain showers were next reported at approximately 2:00 p.m. on September 13. Weather observations from the Fort Collins Station of the U.S. Department of Commerce, Weather Bureau, indicate similar conditions. No precipitation was reported on September 10, 11 or 12 at Fort Collins. Rain was first reported at Fort Collins at approximately 3:00 p.m. on September 13.

In order to simulate the transport of the contaminants, the height of the release was also specified in the modeling. The height of the Building 771 stack from which the contaminants were released is approximately 145 feet. In addition, eyewitness accounts (Dow Chemical, 1957) reported the observation of a plume of smoke rising from 80 to 100 feet above the Building 771 stack during the early hours of the fire. Therefore, the release for the first period of the fire (from 10:40 p.m. to 2:00 a.m.) has been modeled assuming an effective stack height of 245 feet, which is consistent with a plume rising and cooling to ambient temperature at 100 feet above the 145-foot stack. For the second period of the fire, i.e., after the filter plenum fire was controlled at 2:00 a.m., an effective stack height of 145 feet was used. This assumes that without the force generated by an active fire in the main exhaust plenum, the plume cooled to ambient temperature before exiting the stack. The sensitivity of the analysis to these plume height assumptions is discussed in Appendix N.

Table 3-11 presents a comparison of the upper-bound and best estimate air concentrations derived from the routine samples to the average air concentrations predicted by INPUFF based on a release rate of 4 μCi sec^{-1} from 10:40 p.m. on September 11 to 2:00 a.m. on September 12 and a release rate of 0.07 μCi sec^{-1} from 2:00 a.m to 11:30 a.m. on September 12. These release rates are believed to result in the best "fit" of release to the environmental data.

For the first period of the fire, the selected release rate produces a predicted average air concentration at the Wagner "School" site that is approximately equal to the upper-bound concentration based on the reporting threshold for the sampler, while the predicted concentrations for the on-site samplers are significantly lower than the upper-bound concentrations. As stated previously, the upper-bound concentration represents the highest concentration that would not result in a positive sampling result; therefore, the actual concentration could be much lower. As such, these predicted air concentrations are consistent with the environmental data and the relatively stable atmospheric conditions during this first period that would have resulted in very little of the plume reaching the on-site samplers.

TABLE 3-11

COMPARISON OF UPPER-BOUND AND BEST ESTIMATE AIRBORNE CONCENTRATIONS DURING THE 1957 FIRE TO PREDICTED AIRBORNE CONCENTRATIONS—ROUTINE AIR SAMPLERS

Period Modeled	Location	Average Plutonium Concentration from Routine Samplers (pCi m^{-3})	Predicted Plutonium Concentration from INPUFF Model (pCi m^{-3})
First Set of Sampling Filters			
Fire Releases from approximately 10:40 p.m to 3:30 a.m.	S1 S2 S3 S4 S5 S6* S7* S8*	≤ 0.027 For All Samples	0 0 0 0 0.005 0.00004 0.0012 0.002
Fire releases from approximately 10:40 p.m. to 2:15 a.m.	Former Wagner School Site	≤ 0.037	0.036
Second Set of Sampling Filters			
Fire releases from approximately 3:30 a.m. to 11:30 a.m.	S1* S2* S3 S4 S5 S6* S7* S8*	≤ 0.014 For All Samples	0.072 0.23 0.0021 0.0008 0.0008 0.042 0.031 0.014
Fire releases from approximately 2:15 a.m. to 11:30 a.m.	Former Wagner School Site	Best Estimate - 0.078	0.002

* Downwind from the Building 771 stack during a significant portion of this period.

During the second period of the fire, the selected release rate resulted in predicted average air concentrations for the downwind on-site samplers (i.e., S-1, S-2, S-6—S-8) that are equal to or greater than the upper-bound concentrations, while the predicted concentrations at the upwind on-site samplers and at Wagner "School" are significantly lower. Hill's 1957 fire report did not specify which or how many of the on-site samplers had measured concentrations of 0.28 percent MPL, only that the measurements ranged from 0 to 0.28 percent. Therefore, the average air concentration for these samples are all based on 0.28 percent MPL and should be treated as upper-bound estimates. The apparent poor fit for the Wagner "School" sampler for this time period is not so easily understood, and possible explanations are discussed in greater detail in the following uncertainty section. Increasing the average release rate over the second period of the fire to better fit the single Wagner "School" sampler would result in predicted airconcentrations at the multiple on-site samplers that greatly exceed the measured or upper-bound values. Additional support for the selected release rates comes from the portable high volume samplers. As shown in Table 3-12, for five of the eight data points, the model predicts values that are nearly equal to or exceed the upper-bound or measured values at the sample locations by up to a factor of approximately 7 at different times during the fire. Again, increasing the average release rate over the second period of the fire to better fit the Wagner "School" sampler would also result in predicted concentrations at the portable samplers that further exceed the measured or upper-bound values.

Fine Particle Release—Air Concentration and Deposition Isopleths

The predicted 13.5-hour average air concentration isopleths based on the two "best fit" emission rates are shown in Figure 3-20. The resulting deposition pattern, assuming a deposition velocity of 0.1 cm sec^{-1}, is shown in Figure 3-21. As stated previously, precipitation scavenging does not apply to the 1957 fire. The total deposition from the 1957 fire should also include a component from the coarse particle release, which is discussed in the next section. However, since the coarse particles were larger in size and subjected to greater gravitational force than the fine particles, they are believed to have deposited primarily within relatively short distances. As a result, the deposition isopleths predicted for the fine particle release at off-site locations can be considered to be representative of total deposition from the 1957 fire. The estimated deposition shown in Figure 3-21 is much lower than the soil contamination measured in late 1969 and the early 1970s after the 903 Pad release. For example, the measured soil contamination is about 100 mCi km^{-2} near Indiana Street at the eastern edge of the buffer zone, while the maximum predicted deposition from the 1957 fire is 0.01 mCi km^{-2}.

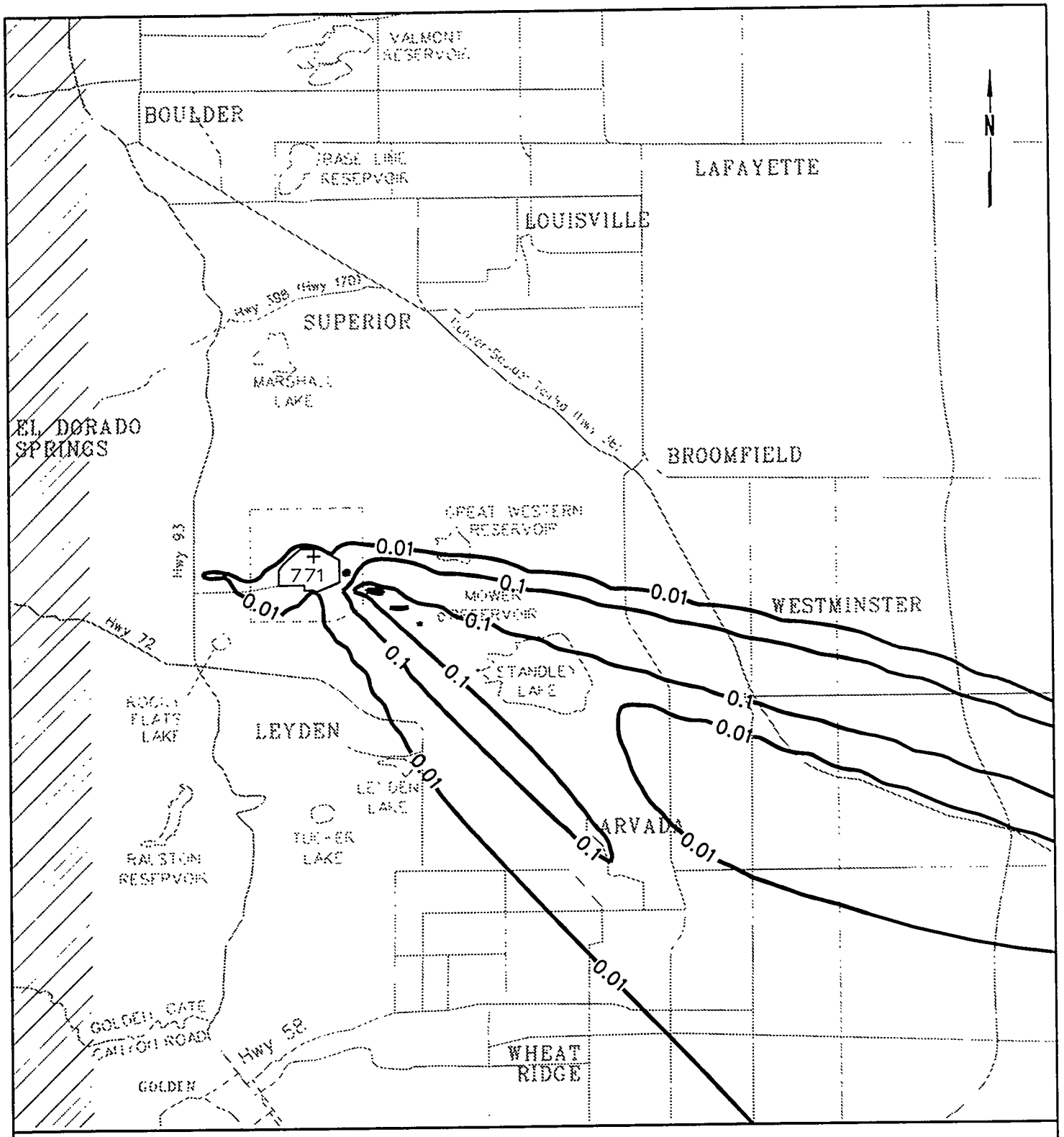
The fact that much of the estimating process has relied on the use of threshold or detection limit results must again be emphasized, since such approaches are more likely to produce bounding estimates rather than best estimates of the release.

TABLE 3-12

COMPARISON OF UPPER-BOUND AND
BEST ESTIMATE AIRBORNE CONCENTRATIONS DURING THE 1957 FIRE
TO PREDICTED AIRBORNE CONCENTRATIONS—PORTABLE HIGH VOLUME SAMPLERS

Period Sampled	Location	Average Plutonium Concentration from High Volume Samplers ($pCi\ m^{-3}$)	Predicted Plutonium Concentration from INPUFF Model ($pCi\ m^{-3}$)[a]
0040-0305	Gate 2	≤ 0.0037	0
0120-0320	Gate 6	≤ 0.0044	0
0310-0510	Gate 2	≤ 0.0044	0.004
0320-0525	Gate 6	≤ 0.0042	0.003
0510-0704	Gate 2	≤ 0.0046	0.0086
0700-1012	Building 23	0.032	0.14
0704-1020	Gate 2	0.11	0.73
0815-1000	Gate 6	≤ 0.0050	0

[a] Average of 15-minute model prediction intervals that encompass entire sampling time.



LEGEND

SECURITY FENCE

ROCKY FLATS PLANT BOUNDARY 1951-1974

FRONT RANGE OF THE ROCKY MOUNTAINS

+ BUILDING 771 STACK

ISOPLETH CONCENTRATION LINES, pCi m $^{-3}$

pCi 10^{-12} CURIE

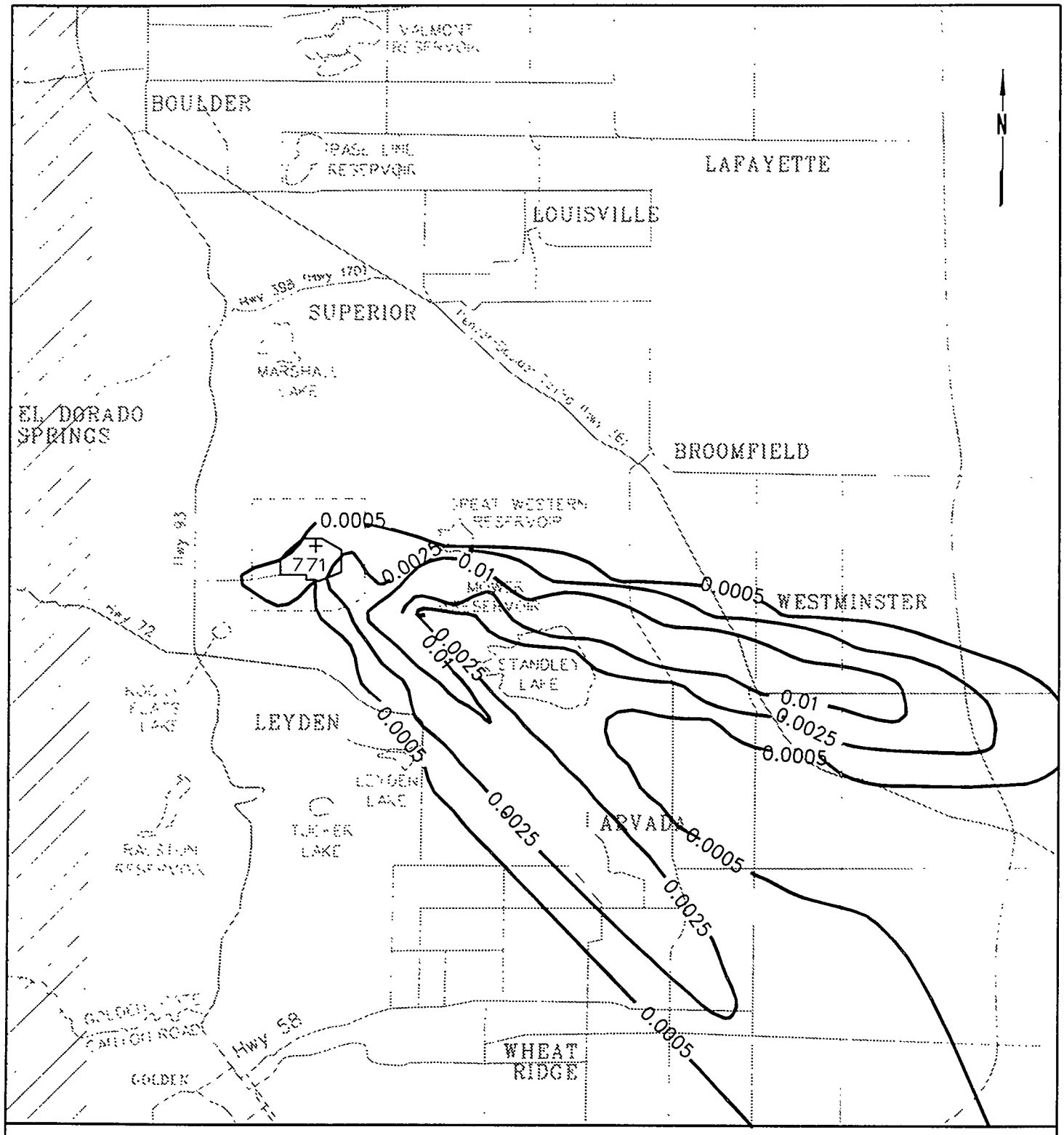
0' 13,200'
SCALE

SCALE: 1" = 2.5 Miles

FIGURE 3-20
PREDICTED 13.5-HOUR AVERAGE AIR CONCENTRATIONS FOR PLUTONIUM RELEASED DURING THE 1957 FIRE (pCi m^{-3})

ChemRisk
A Division of McLaren/Hart

Rky0194h/3-20.dgn: Rev: 05-18-94



LEGEND

SECURITY FENCE

ROCKY FLATS PLANT BOUNDARY 1951-1974

FRONT RANGE OF THE ROCKY MOUNTAINS

+ BUILDING 771 STACK

ISOPLETH CONCENTRATION LINES, mCi km^{-2}

mCi 10^{-3} CURIE

0' 13,200'
SCALE

SCALE: 1" = 2.5 Miles

FIGURE 3-21
FINE-PARTICLE DEPOSITION OF PLUTONIUM FROM THE 1957 FIRE
(mCi km^{-2})

ChemRisk
A Division of McLaren/Hart

Rky0194h/rfh3-21 dgn: Rev 05-20-94

Fine Particle Release—Uncertainty

The "goodness-of-fit" of the predicted concentrations to the upper-bound or measured concentrations calculated from the sampler information must be evaluated in light of the rather large overall uncertainty associated with this analysis. The uncertainty associated with the prediction of models such as the INPUFF model in applications such as this (which are discussed in Appendix G) is relatively large, being on the order of a factor of 10. As such, we have assigned a lognormal distribution with a GM of 1 and a GSD of 3.2 to the uncertainty in this aspect of the analysis. The uncertainties associated with the sampling devices and analytic techniques used to generate the air sampling data were previously combined into a single lognormal distribution with a GM of 1.4 and a GSD of 1.3 (Section 3.4.2.3). The final element of uncertainty in the 1957 fire release estimate relates to the limited time resolution and number of data points available for reconstruction. The most difficult type of prediction for any air dispersion model is for a specific location at a specific point in time. This is exactly the type of prediction that has been attempted for the 1957 fire in making comparisons to sampling locations. Furthermore, only a few data points are available and, in most cases, they represent very short periods of time. These limitations in data and time resolution add further uncertainty than was assigned to the air dispersion model itself. For the purposes of this analysis, an additional factor of 10, represented by a loguniform distribution ranging from -2.3 to 2.3, has been included.

These individual components can be combined into an overall uncertainty estimate for the 1957 fire release using Monte Carlo techniques. The total uncertainty can be represented by the following equation:

$$U_{\text{Total-Fine Particle}} = U_{\text{model}} \times U_{\text{Air}} \times U_{\text{Data}}$$

where:

$U_{\text{Total-Fine Particle}}$	=	Total uncertainty in the fine particle release
U_{Model}	=	Uncertainty in the INPUFF model (lognormal; GM=1.0, GSD=3.2)
U_{Air}	=	Uncertainty in the air monitoring data (lognormal; GM=1.4, GSD=1.3)
U_{Data}	=	Uncertainty related to limited time resolution and number of data points (loguniform; -2.3—2.3)

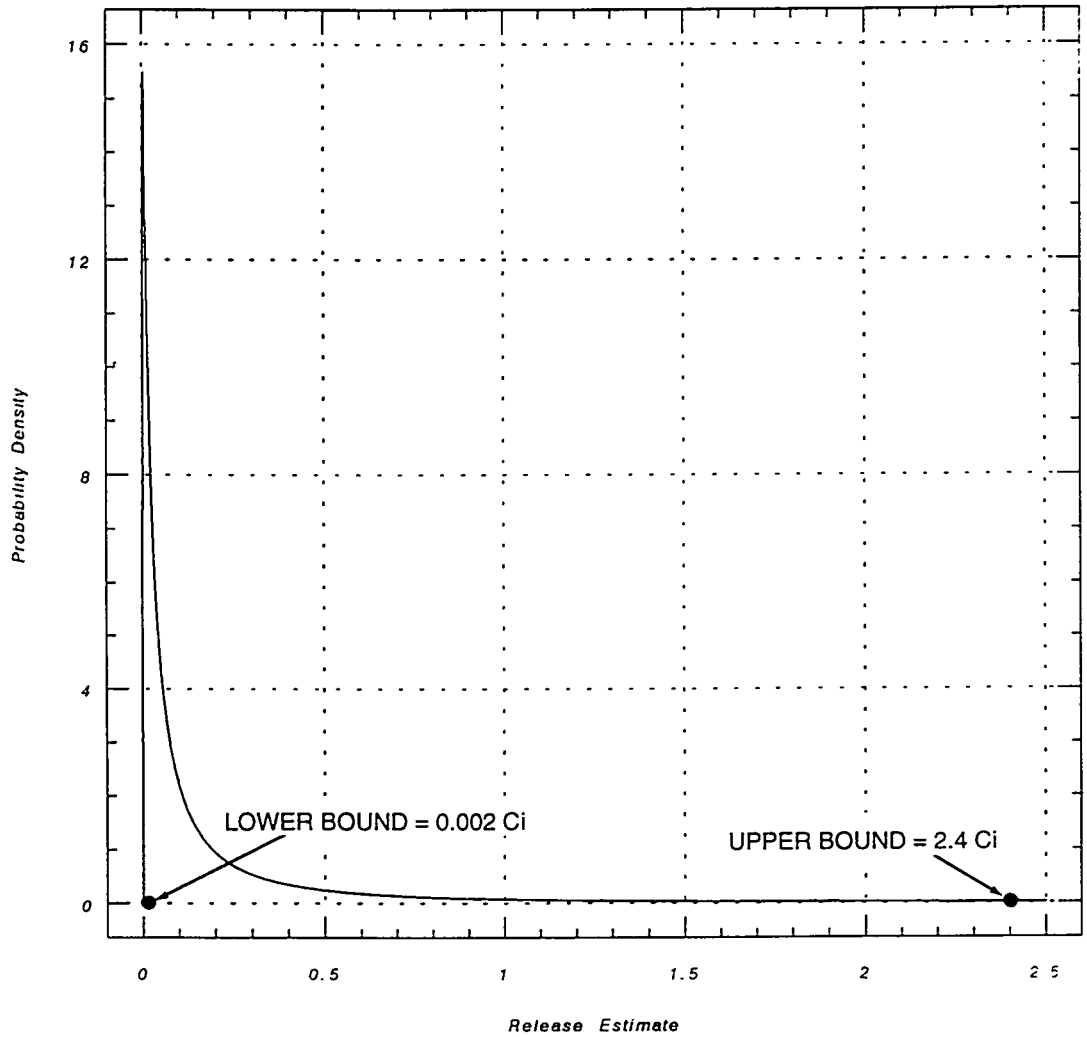
The resulting distribution is best described by a lognormal distribution with a GM of 1.4 and a GSD of 5.9. This means that 95 percent of the distribution falls within a factor of approximately 35 (GSD^2) of the predicted value.

The conclusions that can be drawn from this analysis are that average release rates of fine particles of plutonium of 4 μCi sec^{-1} and 0.07 μCi sec^{-1} for the two periods of release during the fire would be consistent with the air sampling and meteorologic data that have been reported during the fire (total fire release of 0.05 Ci over 13.5 hours). Based on these average release rates, the total estimated release of fine particles from the fire is 0.07 Ci, (0.05 Ci multiplied by the geometric mean of the overall uncertainty distribution of 1.4). The estimates of the upper and lower bounds of the 95 percent confidence interval about this estimate are 2.4 Ci and 0.002 Ci, respectively (Figure 3-22).

As discussed previously, the predicted concentration at the Wagner "School" site for the second sampling period is significantly lower (by approximately a factor of 40) than the reported value. However, increasing the average release rate for the latter part of the fire so that the predicted concentration at the Wagner "School" site matches the measured concentration results in predicted values at the routine on-site and high volume samplers that greatly exceed the measured or upper-bound concentrations. Upon further evaluation of the meteorological data, it was determined that the Wagner "School" sampler was in the plume of contamination from the fire for only a single 15-minute release period from 3:50 a.m. to 4:05 a.m. This means that the Wagner "School" results could be greatly affected by a transient change in the emission rate during this 15-minute period that would have a less significant effect on the results from the other samplers. Transient, short-term variations from the assumed average release rate would not be unexpected, since the actual release rate presumably fluctuated throughout the duration of the fire. If the release rate had been approximately 40 times higher, or 3 μCi sec^{-1}, between 3:50 a.m. and 4:05 a.m., the air concentration predicted by the model at Wagner "School" would equal the measured value. Since the increase occurs over such a short time, there is relatively little effect on the routine on-site samplers and a slightly greater effect on some of the high volume samplers. As such, a short-term increase in the release rate is not inconsistent with the sampling data. It should also be noted that this increased release has little effect on the estimate of the total amount of plutonium released during the fire. The amount of plutonium that would have been released during this 15-minute period can be calculated as follows:

$$\begin{aligned}\text{Plutonium released} &= 3\ \mu\text{Ci sec}^{-1} \times 15\ \text{min} \times 60\ \text{sec min}^{-1} \\ &= 3 \times 10^3\ \mu\text{Ci or } 0.003\ \text{Ci}\end{aligned}$$

This represents less than 10 percent of the current estimate of the total amount of plutonium released during the fire (0.07 Ci).



NOTE: UPPER AND LOWER BOUNDS REPRESENT 95% CONFIDENCE INTERVAL ABOUT THE ESTIMATE

ChemRisk
A Division of McLaren/Hart

FIGURE 3-22
1957 FIRE PLUTONIUM
RELEASE ESTIMATE
AND ASSOCIATED UNCERTAINTY

Rcky0194H/3-22 Rev 03/30/94

A second possible explanation of the low predicted concentration at the Wagner "School" site during the second sampling period may be associated with continued releases after the fire was extinguished. In this analysis, it has been assumed that all of the plutonium collected on the filter at Wagner "School" during the second sampling period had been collected by 12:00 noon on 9/12/57 (30 minutes after the fire was out), even though the filter was not removed until 12:00 noon on 9/13/57. If it were assumed that some of the plutonium present on the filter had been collected in the period after the fire, the estimated average air concentration during the fire would be lower and therefore more consistent with the predictions of the model. Results from the routine on-site samplers for filters in place from 1:30 p.m. on 9/12/57 to 4:00 p.m. on 9/13/57 indicate that this may have been the case in that measurable levels of plutonium were present in ambient air at one or more of the sampling locations (Hill, 1957). However, since no meteorological data are available after 10:00 a.m. on 9/12/57, this information could not be taken into account in the modeling, nor could it be determined if the Wagner "School" sampler was downwind during this period.

The period between the time when the fire was declared out at 11:30 a.m. on 9/12/57 and when the effluent stack samplers were again functional on 9/19/57 has been the subject of little discussion, documentation or study. Whereas the period of the fire received formal study by the plant, information that could be used to assess any releases prior to the re-establishment of the effluent samplers is virtually non-existent. The information relating to this period of time consists of the following:

- 0-0.67 percent MPL reported for on-site samplers for the period of 1:30 p.m. on 9/12/57 to 4:00 p.m. on 9/13/57. The high value of 0.67 percent MPL was reported for on-site sampler S-4. No other information as to which or how many other on-site samplers collected measurable levels of plutonium was provided (Hill, 1957).

- 0-0.2 percent MPL reported for on-site samples for the period of 4:00 p.m. on 9/13/57 to 9:00 a.m. on 9/16/57. No information as to which or how many on-site samplers collected measurable levels of plutonium was provided (Hill, 1957).

- <0.1 percent MPL was reported for the off-site samplers for the period of 9/13/57 to 9/24/57. The number of samples collected during this period is not specified (Hill, 1957).

Some of these pieces of information suggest the potential for continuing or periodic releases during this period; however, there is insufficient information to formally evaluate or quantify these events. While few, if any, conclusions can be drawn from this scattered information in the absence of any meteorologic data, the data do not immediately suggest that any release greatly in excess of those estimated for the fire itself occurred during this period.

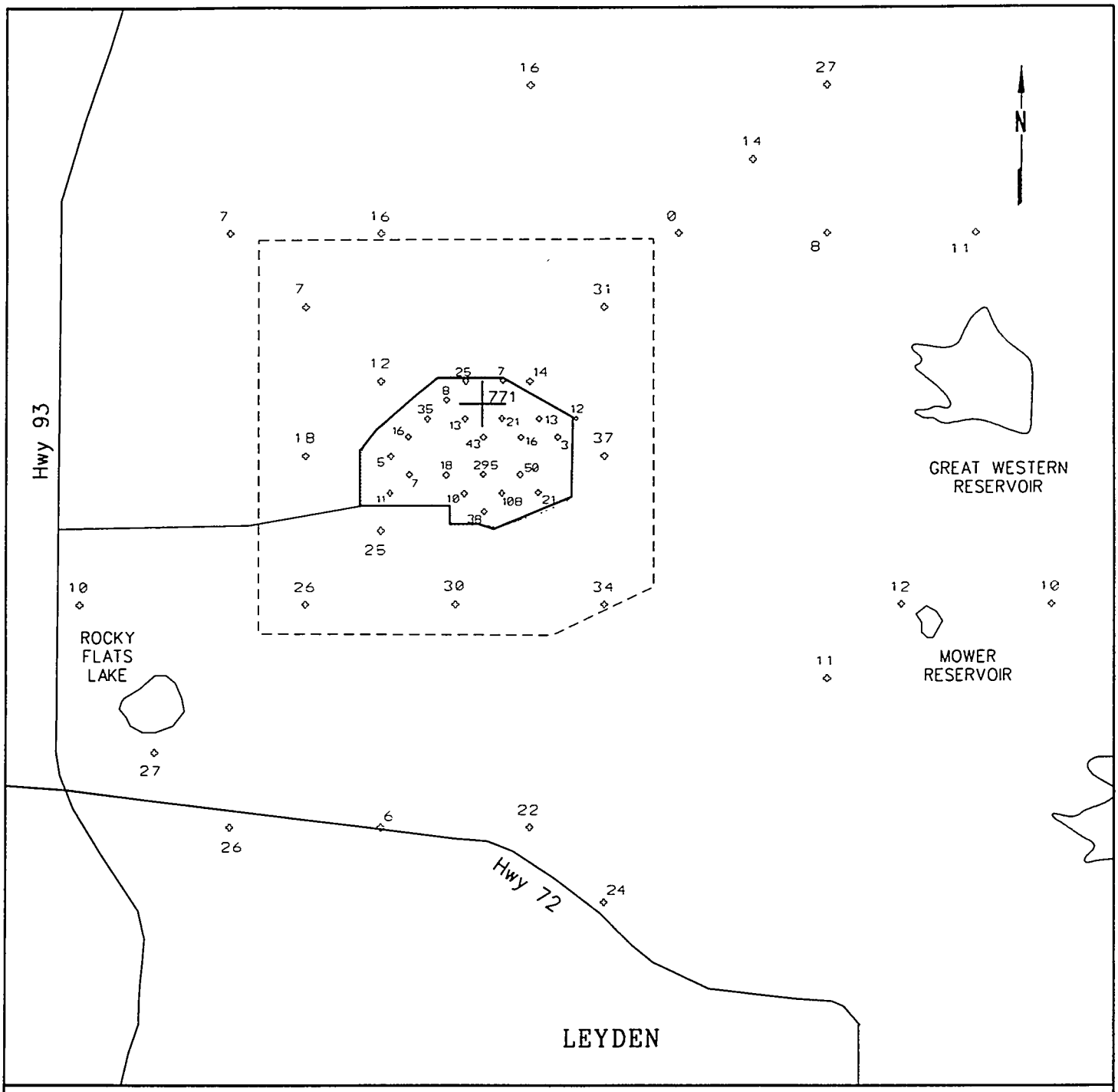
Coarse Particle Release—Data Analysis

The explosion in the main filter plenum during the first period of the fire is assumed to have ejected relatively large particles from the Building 771 Stack. These "coarse" particles, being of larger size and subjected to greater gravitational force than fine particle emissions released during the remainder of the fire, are believed to have deposited primarily within relatively short distances, resulting in the observed plutonium contamination on vegetation. As such, the coarse particle release is not expected to have contributed to off-site exposures, only to the overall release estimate.

Plutonium concentrations in vegetation samples were reported in dis min^{-1} kg^{-1} (dry weight). In order to more easily estimate the amount of plutonium that was released by the explosion and deposited on vegetation, the recorded contamination readings are converted into the units of mCi km^{-2}, which will allow for a direct comparison of the sampling results to deposition predicted by the model. The measured concentrations in dpm kg^{-1} are divided by 2.22×10^9 dis min^{-1} mCi^{-1} and a vegetation interception factor of 2×10^{-6} km^2 kg^{-1} (dry weight). The vegetation interception factor is the ratio of two parameters, the interception fraction and mass vegetation yield. The interception fraction (unitless) describes the fraction of airborne contaminant that is typically intercepted by vegetation. The mass yield parameter (units of kg m^{-2}) describes the mass of vegetation produced on a typical area of soil. The vegetation interception factor 2×10^{-6} km^2 kg^{-1} is the mean value for dried forage grasses in National Council on Radiation Protection and Measurements (NCRP) Report 76 (1985). The sampling locations and measured plutonium concentrations, in mCi km^{-2}, are shown in Figure 3-23. The largest measured deposition occurred approximately 2000 feet due south of the Building 771 stack.

Coarse Particle Release—Emission Estimate

The process of identifying a release of plutonium that is consistent with the available vegetation data involves the use of the INPUFF computer model in a slightly different manner than was used for the fine particle release. In this case, the instantaneous release capability of the model, in conjunction with the same meteorological data and atmospheric stability used for the fine particle release, is used to simulate the deposition of the coarse particles following the explosion in the filter plenum. The key differences between model runs for the coarse and fine particle releases are the timing of the release and the deposition and settling velocities associated with the emissions. For the coarse particle release, a single "puff" of coarse particles is assumed to have been released at 10:40 p.m. on September 11 to coincide with the explosion in the main filter plenum. A modeling interval of one hour was used to allow ample time for the majority of the large particles to deposit. The deposition and settling velocity parameters were set equal to each other as suggested by Peterson (1986) for medium and large particle deposition; for the fine particle release, the settling velocity was set equal to zero. Based on these changes in the



LEGEND

SECURITY FENCE

ROCKY FLATS PLANT BOUNDARY 1951-1974

VEGETATION SAMPLING LOCATION

16 PLUTONIUM CONCENTRATION IN VEGETATION SAMPLE, 10^{-3} mCi km^{-2}

BUILDING 771 STACK

0' 3,960'
SCALE
SCALE: 1"=.75 Miles

ChemRisk
A Division of McLaren/Hart

FIGURE 3-23
VEGETATION SAMPLING
DATA-POST 1957 FIRE
(10^{-3} mCi km^{-2})

Rky0194h/rfh3-23.agn. Rev 05-20-94

model, the coarse particle release of plutonium that is consistent with the vegetation data can then be identified.

Based on an estimated instantaneous release, INPUFF can estimate average ground-level air concentrations, in pCi m^{-3}, over the one-hour time interval. These air concentrations can be converted to ground deposition, in pCi m^{-2}, using the method discussed by Rao (1981), which depends on the deposition velocity associated with the transported particles. Essentially, particles distributed in the air at ground level will regularly deposit to the ground, according to the deposition velocity, for the entire time period over which the air concentration is averaged. That is:

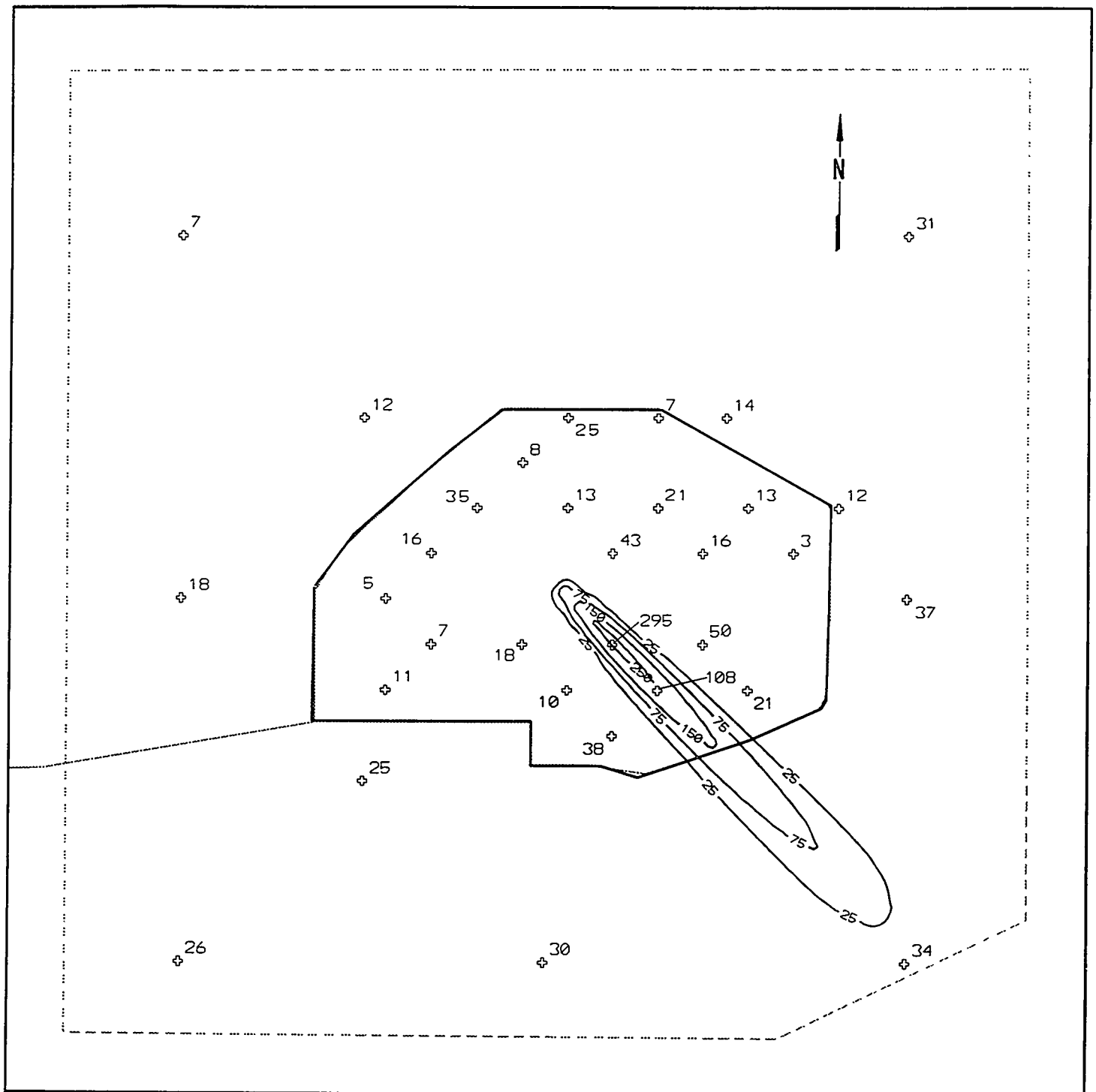
$$\text{Deposition} = [\text{AIR}] \times V_d \times T$$

where:

Deposition	=	Ground deposition (pCi m^{-2})
[AIR]	=	Average ground-level air concentration (pCi m^{-3})
V_d	=	Deposition velocity (m sec^{-1})
T	=	Time over which air concentration is averaged (sec)

No data on the particle size distribution of the coarse particle release are available. In order to obtain an estimate of the average deposition velocity best fitting the environmental data, the model was run a number of times for an instantaneous unit release of 1 μCi with increasing deposition velocities until the location of highest predicted deposition coincided with the location of the highest detected plutonium deposition on vegetation. The resulting deposition velocity was 18 cm sec^{-1}. However, when we assume that the average wind speed of 3 mph reported at 10:45 p.m. was a constant wind speed throughout the preceding 15-minute period, the model predicted maximum deposition at a location southwest of the highest vegetation sample. Therefore, the simple assumption that the average wind speed of 3 mph prevailed throughout the preceding period was examined to determine whether a better fit with the data could be obtained. If the wind speed for the period 10:40 p.m. to 10:45 p.m. immediately following the filter plenum explosion is assumed to be 1 mph (which was the average wind speed reported for the 15-minute period ending at 10:30 p.m.), a predicted deposition pattern that roughly coincides with the vegetation data is predicted. Since the reported wind speeds represent an average of fluctuating meteorological conditions, it is plausible that this less-than-average wind speed provided for at least a portion of the 15-minute period.

Since the instantaneous release and predicted deposition are related in a linear fashion (i.e., doubling the release will double the deposition), the unit release was scaled so that the magnitude of the predicted maximum deposition corresponded to the measured value. Based on a time period of 1 hour and a deposition velocity of 18 cm sec^{-1}, an instantaneous release of



LEGEND

SECURITY FENCE

ROCKY FLATS PLANT BOUNDARY 1951-1974

VEGETATION SAMPLING LOCATION

12 PREDICTED DEPOSTION, 10^{-3} mCi km^{-2}

0' 1,584"
SCALE
SCALE: 1"=.3 Miles

ChemRisk
A Division of McLaren/Hart

FIGURE 3-24
COARSE-PARTICLE DEPOSITION OF PLUTONIUM FROM THE 1957 FIRE (10^{-3} mCi km^{-2})

Rky0194h/rfh3-24.dgn; Rev: 05-20-94

TABLE 3-13

COMPARISON OF MEASURED DEPOSITION FOLLOWING THE 1957 FIRE TO PREDICTED DEPOSITION OF PLUTONIUM FROM COARSE PARTICLE RELEASE

Sample Site Label	Distance from 771 Stack (m)	Measured Deposition (pCi m^{-2})	Predicted Deposition (pCi m^{-2})
VAG 375-205	187	12.8	0
VAG 370-210	270	42.8	0
VAG 360-210*	575	295.1	290
VAG 360-200	647	17.8	0
VAG 360-220	654	49.6	0
VAG 355-205	741	9.9	0
VAG 355-215*	744	108.1	240
VAG 355-225	863	21	1
VAG 350-210	880	38.3	0
V2S-2E*	1922	34.5	14

* Sample locations lying in path of predicted plume.

approximately 50 μCi plutonium would result in a ground deposition of approximately 0.29 mCi km^{-2} 2000 feet south of the stack.

The predicted deposition isopleths are shown in Figure 3-24 and a comparison of measured deposition to predicted deposition for several sampling points lying in or near the predicted path of the coarse particle release is presented in Table 3-13. As can be seen in the table, only a few of the samples lie in the predicted path of the plume (sampling locations VAG 360-210, VAG 355-215, and V2S-2E). For these few sample locations, the deposition predicted by the model is within about a factor of 2 of the measured values. At the other sample locations outside the predicted plume, measured concentrations are an order of magnitude lower than those inside the plume and approach what might be considered local (i.e., within the plant boundary) background. Previous measures of background (i.e., prior to the fire) were total gross alpha radioactivity and could not readily be subtracted out from the measured results. The "fit" of the release estimate to the clearly elevated samples indicates that an instantaneous release of approximately 50 μCi is in general agreement with the available environmental data.

It should also be noted that the predicted deposition pattern is very sensitive to atmospheric stability. As shown in Appendix F, stability class E was assigned to the period between 10:30 p.m. and 10:45 p.m. based on the measured wind speed and a presumed level of cloud cover based on observations of clear conditions in Denver. If there had been a greater degree of cloud cover during this period at Rocky Flats, stability class D would be more appropriate. This change in stability class results in predicted deposition of 295, 140, and 15 pCi m^{-2} for sampling locations VAG 360-210, VAG 355-215 and V2S-2E, respectively. These results, which are in somewhat better agreement with the measured data, correspond to a slightly lower deposition velocity of 16 cm sec^{-1} and a release of 20 μCi plutonium.

Coarse Particle Release—Uncertainty

There are three primary sources of uncertainty in the modeling of the coarse particle release and subsequent estimate of the source term. The first source of uncertainty is associated with the vegetation monitoring data. As discussed previously, only the portion that is related to the analytic techniques for recovering plutonium from vegetation has been quantified. This uncertainty is characterized by a triangular distribution with a best estimate of 0.73, a lower bound of 0.64 and an upper bound of 0.97 (Section 3.4.2.3). The second source of uncertainty is associated with the INPUFF model. As with the fine particle release, a factor of 10 has been assigned to this portion of the uncertainty estimate (lognormal distribution with GM of 1 and GSD of 3.2). The final source of uncertainty is related to the limited number of data points available for reconstruction and the very short modeling period (i.e., 1 hour) of the coarse particle release. This represents the same type of data uncertainty as discussed previously for the fine particle release; therefore, a factor of 10 is also applied (loguniform distribution ranging from -2.3 to 2.3). As with the fine particle release, the individual components can be combined

into a single uncertainty factor using Monte Carlo techniques. This total uncertainty factor can be represented by the following equation:

$$U_{Total\text{-}Coarse\ Particle} = \frac{U_{model} \times U_{Data}}{U_{Vegetation}}$$

where:

$U_{Total\text{-}Coarse\ Particle}$	=	Total uncertainty in the coarse particle release
U_{Model}	=	Uncertainty in the INPUFF model (lognormal; GM=1.0, GSD=3.2)
U_{Data}	=	Uncertainty related to limited time resolution and number of data points (loguniform; -2.3—2.3)
$U_{Vegetation}$	=	Uncertainty in analytical techniques (triangular; 0.64—0.73—0.97)

The resulting distribution is best described by a lognormal distribution with a GM of 1.2 and a GSD of 5.7. As a result, 95 percent of the distribution will be within a factor of approximately 32 of the predicted value.

It can be concluded from this analysis that an instantaneous release of 60 μCi plutonium (50 μCi multiplied by the geometric mean of the overall uncertainty of 1.2) would be consistent with the vegetation sampling and meteorologic data that have been reported. The estimates of the upper and lower bounds of the 95 percent confidence interval about the best estimate are 1900 μCi and 1.9 μCi, respectively.

Summary—1957 Fire Release

The reconstruction of the 1957 fire release was divided into two stages, one addressing coarse particles released at the time of the filter plenum explosion and a second addressing the release of fine particles during the remainder of the fire. Based on the limited air sampling and meteorological data collected during the fire, an estimated 0.07 Ci of plutonium were released as fine particles during the course of the 13.5-hour fire event, while an estimated 60 μCi (0.00006 Ci) were released as coarse particles. There is considerable uncertainty in these estimates as a result of the numerous assumptions that have been made and the generally poor quality of the available data. In addition, much of the estimating process for the fine particle

release relied upon threshold or detection results, which would produce bounding estimates rather than best estimates of the release.

The 13.5-hour average air concentrations previously presented in Figure 3-20 will be used in Task 8 to predict off-site exposures. The modeling indicated that the coarse particle release deposited primarily within relatively short distances, and would not contribute to off-site exposures.

3.4.2.5 Other Estimates of the 1957 Fire Release

In a document that addresses contaminant releases from major accidents at Rocky Flats, Barrick (1981) provides a brief summary of what he terms as four different release estimates for the 1957 fire. These estimates are based on the following sources which are not fully cited in the Barrick document:

1. J. Epp, 771 Building Fire Report,

2. The 1980 Environmental Impact Statement (1980 EIS) and its predecessor draft document and Omnibus document,

3. A 1971 LASL (Los Alamos Scientific Laboratory) Meeting Report LA-4576 (Hammond, 1971), and

4. A 1980 report by Barrick.

The first release estimate from the official fire report is limited to a qualitative statement "detectable but insignificant" which Barrick interprets to mean insignificant compared to the 1957 industry and governmental standards. The standards that are cited consist of maximum permissible exposure levels for workers and off-site removable activity levels. There is no actual release estimate identified from this source.

The second source of a fire release estimate (reported by Barrick as 25,618 μCi) is from the 1980 EIS for the plant and its predecessor documents. This estimate is based on various manipulations of the stack sampler data for the last quarter of 1957. Barrick (1981) notes that the EIS estimate was obtained by subtracting the average of stack sampler readings from those months of 1957 unaffected by the accident from the amount of total alpha radioactivity (assumed to be all plutonium) recorded by the Building 771 stack sampler from September through December 1957. However, this approach neglects the fact that the Building 771 stack samplers were not operating from one hour after the fire began until eight days later on September 19, 1957. Barrick (1981) says that, for the above reasons, the estimate provided in the USDOE

1980 EIS cannot be supported. We would concur with this observation, since the building exhaust fans were off during the early stages of the fire and the loss of building power led to the failure of the effluent sampling systems. A release estimate based only on the effluent sampling data does not address all the emissions that occurred during the fire.

The third source of a fire release estimate (reported by Barrick as 1 gram [approximately 0.06 Ci]) of plutonium off-site is a LASL meeting report attributed to S. E. Hammond, 1971. Barrick interpreted off-site to mean outside the cattle fence which, in 1957, was the facility property line enclosing the approximately four square mile plant site. Barrick indicated that monthly progress reports and personal data files were searched, but no statement of basis, assumptions, method or calculation were found to indicate the actual derivation of the estimate. Search activities undertaken for this project found no information that would permit any further evaluation of this reported release estimate.

The fourth estimate, summarized by Barrick as 1.0 ± 0.3 Ci, is based on a reference to a 1980 report that he prepared. Efforts to locate the 1980 report led to the identification of handwritten notes that may have served as the basis for the report; however, no formal report was located and it apparently never went beyond an initial draft stage. Barrick indicates in his 1981 summary report that the release estimate was made by assuming that the southern most branch of the observed soil deposition, best illustrated by Krey (1976), was due to the 1957 fire. Using the 15-minute wind speed and direction data from atop Building 123, Barrick predicted an expected path of release from the Building 771 stack. These assumptions reportedly were further checked against the vegetation contamination data. Barrick's calculations attempted to separate the portion of the total plutonium contamination observed in soils in the 1970s that was due to the 1957 fire from the much larger portion that was due to the 903 Pad by attributing soil contamination along the expected path of release to the 1957 fire. Barrick's estimate of the release, while higher than the estimate developed in this study, falls within the 95 percent confidence interval about the estimate developed in this study. Barrick's higher estimate could well be the result of the difficulty of completely eliminating the influence of the 903 Pad releases from the soil data collected in the 1970s.

Pre-trial statements ("statements") in civil actions brought against the corporations that had operated the plant and the U.S. Government during the 1970s, which have been collectively referred to as the Church litigation, include a number of estimates of the amount of plutonium involved in the 1957 fire. These estimates include the amount of plutonium in Room 180 during the fire, which was suggested to range from several kilograms to 42 kilograms. The statements also indicate that the filters in the main plenum had not been changed since they had been installed (four years earlier) and that they may have contained anywhere from 20 to 250 kilograms of plutonium. The statements cite two Dow studies, Hagan and Miner, 1970 and Woodard, 1971, as containing information regarding the potential filter plenum loading at the

time of the 1957 fire; however, the range of 20-250 kilograms appears to be based solely on data from the Woodward study. It should be noted that the statements do not suggest an amount of plutonium that was released into the environment, but only what is believed to be the amounts that might have been present in the areas involved in the fire.

The approach used in this report for estimating the release of plutonium from the 1957 fire has not been based on estimates of the potential quantities of plutonium present in the areas involved in the fire and the fraction of these materials that may have been released from the building during the fire. The data available to support this type of analysis of the fire are at least as limited as the environmental data that are used in this study to develop a release estimate. The development of a fire release estimate based on the potential quantities of plutonium involved in the fire is being considered by the Phase II Health Studies investigators as an alternative approach to the analysis. If pursued, this alternative approach will permit further evaluation of the release estimate from this study, which has been developed using some upper-bound assumptions.

While this study has not attempted to evaluate in detail the alternative approach involving the evaluation of the amount of plutonium present in the fire, there are a number of reasons to suggest that use of the data presented in the Woodard (1971) study to directly estimate the amount of plutonium potentially involved in the 1957 fire, as suggested in the pre-trial statements, is inappropriate.

The Woodard study quantifies the buildup of plutonium during a period in 1970 on the Booster System 3 filters in Building 771. These filters handle exhaust air from chemical processing operations for plutonium recovery. The exhaust from Booster System 3 (which has passed through HEPA filters in the booster system) feeds into the main exhaust plenum. The report notes that the chemicals, moisture and particulate matter that the filters in this system are subjected to shorten their service life and lead to the need for frequent replacement. Booster system 3 consisted of four stages of HEPA filtration in 1970, and the first stage of filters was changed 6 times, the second stage was changed twice, and the third and fourth stages were changed once in 1970.

A number of reasons why the Woodard data may be inappropriate for use in estimating plutonium filter loading in the main plenum at the time of the 1957 fire without some adjustment are:

1. The main filter plenum receives effluent air only after it has been subjected to some initial HEPA filtration. The rates of buildup cited in the pre-trial statements relate to first-stage filters that receive air that has not had any previous filtration. A single stage of HEPA filtration should remove over 99 percent of the

radioactive particulates in the air stream. The Woodard study notes that radioactivity leaving the single stage of HEPA filtration in the main plenum is reduced to a hundredth or thousandth (0.01 to 0.001) of that leaving Booster System 3 through a combination of dilution and filtration. Therefore, the main plenum filters, which the pre-trial statements indicated had been in place for over four years at the time of the 1957 fire, would have been accumulating plutonium at only a fraction of the rate that was measured on the first stage of Booster System 3 in 1970.

2. The amount of production activity and plutonium handling in 1957 and the preceding years was likely to be very different from that occurring in 1970 when the Woodard study was conducted. A weapons design change in 1957 resulted in the incorporation of more plutonium in the pit than had been used in earlier years. The expansion of the production facility in Building 771 throughout the 1960s increased the throughput capability by a factor of 20 over the original facility (ChemRisk, 1992b, p60).

A further indication of the relative amount of plutonium that would have likely accumulated on the filters in the main plenum prior to 1957 compared to the later years of higher production when the Woodard study was performed is the annual amount of plutonium released from the facility. The total plutonium effluent measured during the first four years of plant operation (approximately 1,100 μCi for 1953 through August 1957) was less than 40 percent of the average annual release of plutonium for the higher production years from 1958 through 1965 (approximate annual average of 3,000 μCi). (The total amount of plutonium released by the facility falls after 1965, because two additional HEPA filtration stages were added to the building.) Therefore, based on total measured effluent from the plant, the average annual rate of plutonium accumulation on the main filter plenum at the time prior to the 1957 fire was likely to have been approximately 10 percent of that occurring in 1970.

One direct method of developing an initial estimate of the amount of plutonium on the main plenum filters is to use the total estimate of plutonium effluent from the plant prior to the fire (approximately 1,100 μCi) and an assumed efficiency of the HEPA filters. Assuming a high HEPA filter efficiency will result in a conservative or upper-bound estimate of the amount of plutonium that would be retained on the filters. If it is assumed that the filter bank was performing well or at high efficiency, the filters would retain approximately 99.99 percent of the contamination from the air that passed through them, and only 0.01 percent would have escaped and been measured in the effluent. Therefore, if the total effluent from the plant measured prior to the 1957 fire represents 0.01 percent of the contamination collected by the main plenum HEPA filters, the filters could have retained as much as 11 Ci of plutonium, or

somewhat less than 200 g. (filtration efficiencies of 99.9 percent or less are more commonly attributed to the plant's system, which would reduce this estimate by a factor of 10 or more.)

A more complete analysis of the potential loading of the main filter plenum prior to the fire would include an estimate of the actual HEPA filter efficiencies and the uncertainty associated with this estimate, along with the uncertainty associated with the effluent measurements. In addition, the initial HEPA filtration that takes place outside of the main filter plenum in either booster systems or glovebox filters would also have to be addressed, since these systems would have collected the majority of the plutonium in the effluent air stream and would represent a portion of the total inventory of plutonium involved in the fire. The specifics regarding the operation of these initial filters, such as frequency or time of change, are important considerations in evaluating potential plutonium filter loading at the time of the fire. To-date, specifics regarding these initial filters have not been located.

A critical point that the pre-trial statements entirely ignore is the estimate of the fraction of the total inventory of plutonium that was present in the fire area that was ultimately released from the building. This a very difficult factor to estimate, because of the highly complex conditions of any fire, particularly one taking place in a building and a ventilation system. Clearly, just because the plutonium was involved in the fire does not mean that it was released from the building during the fire, since a large amount of the plutonium was recovered after the fire. A study performed by Schwendiman *et al.* (1968) examined the release of plutonium at high temperatures and found the release rate to be highly dependant on the amount and physical form of the plutonium (e.g., solid or powdered). The Schwendiman study observed the release fractions indicated in Table 3-14 for the identified types of materials.

TABLE 3-14: RELEASE RATES OF PLUTONIUM AT HIGH TEMPERATURES

Material	Release Fraction in Weight % Per Hour
Solid pieces of Pu metal (temperatures to 900°C)	
—air flow of 3.3 to 50 cm sec^{-1}	0.000003 to 0.00005
—air flow of 525 cm sec^{-1}	0.0045 to 0.032
Powdered compounds—plutonium oxide from metal rods (700 to 1,000°C and air flow rates from 10 to 117 cm sec^{-1})	0.0000032 to 0.025

Source: Schwendiman *et al.*, 1968

These data suggest that plutonium subjected to fire conditions would produce airborne releases at widely varying rates, from approximately one-hundred-millionth to one-ten thousandth of its total weight per hour, depending on the physical size and characteristics of the plutonium as well as the air flow rate over the material. The results of this study suggest that the involvement of large quantities of plutonium (kilogram quantities) in the 1957 fire in Building 771 is not inconsistent with the release of relatively small amounts (gram quantities or less) to air in the building and ultimately the environment.

The further investigation of alternative approaches to estimating the releases of plutonium from the fire, based on material inventories and fire conditions, may provide additional estimates of the fire release that can be compared to the results of the approach based on the use of environmental data and air dispersion models that has been described in this report.

3.4.3 1969 Fire

The 1969 fire described in this section represents a much smaller plutonium release than either than 903 Pad or the 1957 fire. The 1969 fire began in Building 776 at about 2:30 p.m. on Sunday, May 11, 1969 when pressed plutonium briquettes spontaneously ignited in a storage cabinet in the North Foundry Line. The fire burned for several hours and spread through combustible materials in several hundred inter-connected glove boxes, causing considerable damage to the building and its equipment.

The ventilation system for Building 776 is divided into four components: the main filter plenum and three booster systems. Stack releases from the main filter plenum, which services the main building, were monitored continuously throughout the fire. However, the stack samplers in the three booster systems servicing the glove boxes were disabled in the early stages of the fire, and subsequent releases from these systems were not monitored. As a result, only plutonium released through the main filter plenum can be estimated from the stack monitoring data alone. Environmental samples were also collected during and following the 1969 fire. These samples provide data and information that can be used to estimate the total amount of plutonium released from the fire. As with the 1957 fire, considerable effort has been devoted to interpreting these data and describing the uncertainties associated with their use in identifying plutonium releases and off-site exposures.

The following sections present a discussion of the approach and results of the analysis of the fire release based on the environmental data. Following these discussions is a review of previous fire-related evaluations that used alternative information.

3.4.3.1 1969 Fire Chronology

As discussed in the Tasks 3 and 4 report, a major fire at Rocky Flats began at about 2:30 p.m. on May 11, 1969. The fire is believed to have resulted from the spontaneous ignition of pressed plutonium briquettes in a glove box in the North Foundry glove box line in Building 776. The fire subsequently spread through the Foundry Conveyor Line, interconnecting conveyor lines and into the Center Fabrication Line. Considerable damage was done to the building and its equipment. During the early stages of the fire, Booster System #2, which serviced the North Foundry line, became clogged. Air from this portion of the building was then processed through Booster System #1. The majority of the fire was controlled by 6:40 p.m. and was extinguished by 8:00 p.m., except for small rekindlings that occurred in the North Foundry Line throughout the night. Releases from the main filter plenum were monitored throughout the fire. Releases from the booster systems were monitored until 4:00 p.m., at which time the samplers were disabled. It was reported that the first two of the four HEPA filter banks in Booster #1 were breached and that the gaskets which contained the third and fourth filter banks were also breached (Dow Chemical, 1970a).

Because the stack samplers in the booster systems were disabled during the fire, measurements of the releases from Building 776 during the fire are incomplete. The data from ambient air monitoring during and after the fire are used to estimate the releases and resulting air concentrations experienced during the 1969 fire. The 1969 fire report (USAEC, 1969) identifies the following sequence of events:

- Alarm received at Fire Station at 2:27 p.m. on 5/11/69
- Fire in North Foundry Line observed at 2:29 p.m.
- Fire spread to North-South Conveyor line by 2:50 p.m.
- Smoke observed coming from exhaust vents on the roof of Building 776 between 3:20 p.m. and 4:10 p.m.
- Stack samplers in booster systems disabled by power failure at 4:00 p.m.
- Fire contained by 6:40 p.m.
- Fire extinguished by 8:00 p.m., except for small fires in North Foundry line, which continued to reoccur throughout the night.
- Last fire observed in North Foundry line at approximately 9:00 a.m. on 5/12/69.

The exact time at which the last fire was extinguished in the North Foundry line is not known; however, it was presumably not long after the last flareup was observed at 9:00 a.m. Since the majority of the fire was extinguished by 8:00 p.m. on 5/11/69, with only small fires reoccurring sporadically throughout the night, it would appear that there were two distinct release periods during the fire. Period 1 would extend from the start of the fire at 2:30 p.m. until 8:00 p.m. on 5/11/69. Period 2 would extend from 8:00 p.m. on 5/11/69 until the fire was completely extinguished on 5/12/69, which, for the purpose of this analysis, is assumed to be 10:00 a.m. on 5/12/69. Since the filters were changed in the on-site samplers at 8:00 a.m. on 5/12/69, Period 2 will be assumed to end at that time for modeling purposes. However, the last two hours will be included in the estimate of the total release from the fire by assuming that a similar level of release occurred for an additional two hours.

There were no measurements of particle size of emissions during the fire. However, since the HEPA filters in the main filter plenum and booster systems were largely intact, it is assumed that the majority of the particles emitted during the fire were very small in size (less than one micron). The availability of meteorological and environmental data for evaluating contaminant releases are discussed in the following sections.

3.4.3.2 Meteorological Data

On-site meteorological observations of average wind speed and wind direction are available beginning 12:00 p.m. on 5/11/69 through 2:30 p.m. on 5/12/69. These observations are reported primarily at one-hour intervals, on the hour, except during the initial hour of the fire. Between 2:30 p.m. and 3:30 p.m., 5-minute wind observations were recorded. The data were provided in Dow Chemical's letter to Dr. Roy Cleere, Executive Director of the Colorado Department of Health (Dow Chemical, 1970a) and are shown in Appendix F. It should be noted that the wind blew in predominantly two directions during the course of the fire. From 2:30 p.m. until 8:50 p.m. on 5/11/69, the predominant wind direction was from the northeast. After 8:50 p.m. on 5/11/69 until the end of the fire on the morning of 5/12/69, the predominant wind direction was from the west.

As was the case for the 1957 fire, atmospheric stability was not measured, and stability class was again inferred from wind speeds and meteorological conditions recorded at the site and in the surrounding areas during the fire. Cloud cover observations at Stapleton Airport were less than 50 percent for the afternoon and night of 5/11/69 extending through the morning of 5/12/69, with the exception of 7:00 p.m. to 9:00 p.m. on 5/11/69. Meteorological information available from Jefferson County Airport (approximately 3.5 miles east of the RFP) for 5/11/69 indicated heavier cloud cover in the vicinity of the plant. Broken clouds covered approximately 75 percent of the sky until approximately 7:00 p.m. on 5/11/69. Meteorological observations from Jefferson County Airport are not available for 5/12/69. Based on these observations,

daytime conditions with slight solar radiation were assumed between 2:30 p.m., when the fire began, and 8:00 p.m. Based on the recorded wind speeds and the U.S. EPA's guidelines on atmospheric stability (USEPA, 1970) presented in Section 3.4.2.2, stability class B was used during this period, with the exception of 10 minutes from 2:40 p.m to 2:50 p.m. when wind velocities were measured at 6 mph, which corresponds to stability class C. Nighttime conditions were assumed to prevail from 8:00 p.m. on 5/11/69 until 7:00 a.m. on 5/12/69. During this period, stability classes ranging from D to E were inferred from the measured windspeeds and the U.S. EPA's guidelines for nighttime conditions. Following sunrise, morning conditions associated with slight solar radiation were assumed for the final hour of simulation, 7:00 a.m. to 8:00 a.m., which corresponds to the time that filters were changed in the on-site air samplers.

The atmospheric stability class assigned to each 5 to 60 minute period during the fire is presented in Appendix F.

3.4.3.3 Environmental Monitoring Data

The environmental data that are most relevant to the analysis of the 1969 fire release are the on-site air sampling data. Additional environmental data are available from off-site air samplers and vegetation, soil and water samples; however, they do not appear to have been measurably affected by the fire release. A short discussion regarding these samples follows the detailed discussion of the on-site air sampling data.

Air Monitoring—On-Site

Air monitoring data have been reported from 12 samplers (designated S-1 through S-10, S-50 and S-51) that were operating on-site at the time of the 1969 fire (see Figure 3-14) (Dow Chemical, 1964-1970). Filters were collected from the samplers on weekday mornings and were counted for gross alpha radioactivity. Each week is represented by four 24-hour samples (filters collected Tuesday, Wednesday, Thursday and Friday) and one 72-hour weekend sample (filter collected Monday). The results, in counts per minute, are first recorded on "Health Physics On-Site Site Survey Routine Air Sample Results" sheets and then combined on a monthly basis onto "Results Sheet for On-Site Air Samples." Air concentrations from 5/8/69 through 5/23/69, in μCi/ml (equivalent to pCi m^{-3}) are summarized in a table presented in Appendix I-2 (page I-3) of the U.S. AEC 1969 fire report. These summarized data were verified against the "Results Sheet for On-Site Air Samples" for the month of May, 1969. As will be discussed in detail in the data analysis section, the raw data, in c min^{-1}, are converted to air concentrations by taking into account the analytical and measurement errors, flow rate and sampling time.

Based on our calculations, it would appear that the average air concentrations reported in Appendix I-2 of the U.S. AEC report (1969) are consistent with the raw data with the exception of the two weekend sampling periods. For these periods, one of which was the weekend of the fire, the reported air concentrations appear to be a factor of 3 high. This may be due to the fact that the sampling time was incorrectly assumed to be 1 day instead of 3 days. For the purpose of this analysis, average air concentrations calculated from the raw data sheets for the period of 5/9/92 to 5/12/69 are used instead of those reported in the official fire report.

Details on Sampling Equipment and Analytic Methods

The following discussions provide information that describe the equipment and methods used to produce the air monitoring data.

Sampling flow rates and volumes: There is no indication that the on-site air sampling methodology employed at the time of the 1969 fire was any different than that used during the 1957 fire. The "Health Physics On-Site Site Survey Routine Air Sample Results" raw data sheets from May 1969 confirm that the target sample flow rate was 81.5 $m^3\ d^{-1}$ (2 $ft^3\ min^{-1}$) and that no apparent adjustment to the flow rate was made based on pre- and post-calibration measurements. As a result, the same flow rate uncertainties described previously for the 1957 fire on-site air monitoring results apply to the 1969 fire monitoring data (i.e., triangular distribution: 0.8—1.0—2.0).

Sampling filters and efficiencies: The type of filters used for each individual sample collected during the fire was not identified in the available records. However, there is no indication that the filters used in the on-site samplers at the time of the 1969 fire differed from those used during the 1957 fire. Therefore, it is assumed that either HV-70 or Whatman-41 filters were used and that the uncertainties described previously for collection efficiency and filter burial loss also apply to the 1969 fire air monitoring results. These uncertainties are represented by two uniform distributions, the first ranging from 0.85 to 1.0 (collection efficiency) and the second ranging from 0.86 to 1.14 (burial loss).

Analytic Method: A "Sharene" alpha scintillation counter was used to measure gross alpha radioactivity in filter samples at the time of the 1969 fire. As with the MAC 5 alpha scintillation counters used at the time of the 1957 fire, a correction factor of 30 percent was applied to all sampling results to account for counting efficiency. Daily verifications of this factor were also believed to be accurate to within 10 percent of the standard. Therefore, the same uncertainty used in the 1957 fire analysis is used for the 1969 fire (i.e., a uniform distribution ranging from 0.9 to 1.1).

Overall uncertainty—air monitoring data: The same four sources of uncertainty that were identified for the 1957 fire air monitoring data are applicable to the 1969 air monitoring data. This overall uncertainty is best described by a lognormal distribution with a GM of 1.4 and a GSD of 1.3.

Other Environmental Data

Environmental monitoring for May 1969 is summarized in the Environmental Survey report for January-June, 1969 (Dow Chemical, 1969). Continuous air samples were collected from nine off-site samplers located in Boulder, Broomfield, Coal Creek Canyon, Denver, Golden, Lafayette, Marshall, Wagner "School" site, and Westminster. The average gross alpha concentration for all samplers in May 1969 was 0.003 pCi m^{-3}. The range of average concentrations for the remaining months was 0.0028 pCi m^{-3} (March) to 0.0053 pCi/m^3 (January). Water samples were collected on a monthly basis from Great Western Reservoir, Standley Lake, Baseline Reservoir and Ralston Reservoir. Average gross alpha concentrations ranged from 0.9 pCi L^{-1} (Baseline) to 3.4 pCi L^{-1} (Ralston). Additional samples were collected from Great Western Reservoir and Standley Lake after the fire in May and June 1969. The average concentration of these samples was 1.8 pCi L^{-1}. Average gross alpha radioactivity measured in vegetation samples collected in October 1968 was 90 pCi kg^{-1} for samples collected within 4 miles of the plant and 96 pCi kg^{-1} for samples collected between 4 and 18 miles from the plant. For May 1969, the corresponding average concentrations were 84 pCi kg^{-1} and 77 pCi kg^{-1}. In all cases, the environmental data suggest that plutonium released during the 1969 fire did not reach off-site locations in measurable amounts.

3.4.3.4 1969 Fire Release Estimating Procedure

The approach adopted to estimate the release from the 1969 fire involved the use of an air dispersion model (INPUFF) to estimate release rates that result in predictions of air concentrations at downwind sampler locations that are consistent with the results from these sampling locations. This modeling approach accounted only for the airborne portion of the fire release that had the potential to travel off-site.

Data Analysis

As stated previously, at the time of the 1969 fire, filters were collected from the 12 on-site samplers each weekday and measured for gross alpha radioactivity. Since the fire occurred on a Sunday, the results from samples collected between 8:00 a.m. on 5/9/69 and 8:00 a.m. 5/12/69 form the basis for reconstructing the fire release. A review of the routine sampler data in the months prior to the 1969 fire indicates that there were often measurable levels of gross alpha radioactivity associated with routine operations at the plant. Ideally, any "background"

levels of plutonium would be subtracted from the levels measured in the samplers to estimate the portion that is due to the fire. However background cannot be readily established for data sets having a considerable number of non-detects. Therefore, we have chosen to evaluate the effect of using two different assumptions, either 1) all of the alpha radioactivity collected on the filter is due to the fire or 2) only the portion collected on the filter that is greater than an estimated background value is due to the fire. The following section describes the methods used to estimate background alpha radioactivity levels at each of the on-site samplers.

Determination of background: An "average daily background" level of alpha radioactivity was calculated for each sampler based on the daily sampler results from March 1 to May 9, 1969. For weekend samples, the recorded radioactivity was divided by three and the result was applied to each of the three days. Many of the sample results were reported as 0.21 c min^{-1}, which was considered by the plant to be the minimum alpha radioactivity that could be detected on a filter (Dow Chemical, 1978). Although the actual alpha radioactivity on these filters could have been anywhere between 0 and 0.21 c min^{-1}, a value of 0.21 c min^{-1} was used in the background calculation. In the event that a 72-hour weekend sample was reported as 0.21 c min^{-1}, a value of 0.07 c min^{-1} was applied to each of the three days. This assumption will result in a conservative estimate of daily background for those samplers where the majority of the data were reported as 0.21 c min^{-1}.

The individual data points for the period of 3/1/69 to 5/9/69 for each on-site sampler are presented in Appendix O. The distribution of each data set was evaluated to determine the appropriateness of using the arithmetic mean (normal or Gaussian distribution) or geometric mean (lognormal distribution) to estimate average background concentrations. Since logarithmic transformation of a true lognormal distribution yields a normally distributed data set (Leidel *et al.*, 1977), both the original data sets and the log-transformed data sets were tested for normality using the Kolmogorov-Smirnov (K-S) goodness-of-fit test (Lilliefors, 1967). A data set was considered to pass the test for normality if the calculated test statistic was less than the published value for that number of samples at a probability of 95 percent.

The results of the K-S tests are presented in Appendix O. None of the original or log-transformed data sets passed the test for normality, indicating that the distributions are not normally or lognormally distributed. For the purpose of this analysis, the arithmetic mean is used as the best representation of background alpha radioactivity. A value of three times the calculated daily average background activity, in c min^{-1}, was subtracted from the total gross alpha radioactivity measured at each sampler, also in c min^{-1}, for the weekend sampling period ending 5/12/69 to produce a background-corrected estimate. The total, estimated average daily background and "background"-corrected activities are presented in Table 3-15. The fact that the estimated background activity is greater than the activity measured at the S-8 sampler is likely an artifact of the methods used to estimate average background activity. A review of the

TABLE 3-15

MEASURED AIR CONCENTRATIONS AT ROUTINE SAMPLING LOCATIONS DURING THE 1969 FIRE

Location	Data Not Corrected for Background			Data Corrected for Background			
	Total Activity 5/9-5/12 (c min^{-1})	Estimated Plutonium on Filter (Pu_f)[b] (pCi)	Measured Air Concentration During Fire (C_T)[c] (pCi m^{-3})	Average Daily Background Activity (c min^{-1})	Background-Corrected Total Activity[a] (c min^{-1})	Background-Corrected Estimated Plutonium on Filter (Pu_f)[b] (pCi)	Background-Corrected Measured Air Concentration During Fire (C_T)[c] (pCi m^{-3})
S-1	1.4	3.0	0.050	0.3	0.5	1.1	0.018
S-2	6.3	14	0.23	0.2	5.7	12	0.21
S-3	5.9	13	0.21	0.2	5.3	11	0.19
S-4	5.4	12	0.19	0.2	4.7	10	0.17
S-5	6.1	13	0.22	0.3	5.2	13	0.22
S-6	6.6	14	0.24	0.3	5.7	12	0.21
S-7	6.2	13	0.22	0.6	4.4	9.4	0.16
S-8	11.6	25	0.42	4.0	—	—	—
S-9	6.3	14	0.23	0.2	5.7	12	0.21
S-10	1.1	2.4	0.40	0.2	0.5	1.1	0.018
S-50	4.0	8.6	0.14	0.2	3.4	7.3	0.12
S-51	4.8	10	0.17	0.2	4.2	9.0	0.15

— Estimated background activity higher than total measured activity measured on filter.

a Background-Corrected Total Activity = Total activity - (3 × average daily background activity)

b Pu_f = Total or background-corrected activity / [0.21 (correction factor) × 2.22 dis min^{-1} pCi^{-1}]

c C_T = Pu_f / [Sampling rate 3.4 m^3 hr^{-1}) × Sampling time during fire (17.5 hr)]

0104ALR8

data for the S-8 sampler for the period of 3/1/69 to 5/9/69 indicates that there were several days in which significantly higher levels of gross alpha radioactivity were collected as compared to the other days in this period (Figure 3-25). This is likely due to the fact that the S-8 sampler is downwind of the 903 Pad.

Average air concentrations were calculated from either the total or background-corrected alpha radioactivity using the following equations:

Equation 1:

$$Pu_f = \frac{c \text{ min}^{-1}}{0.21 \times 2.22}$$

where:

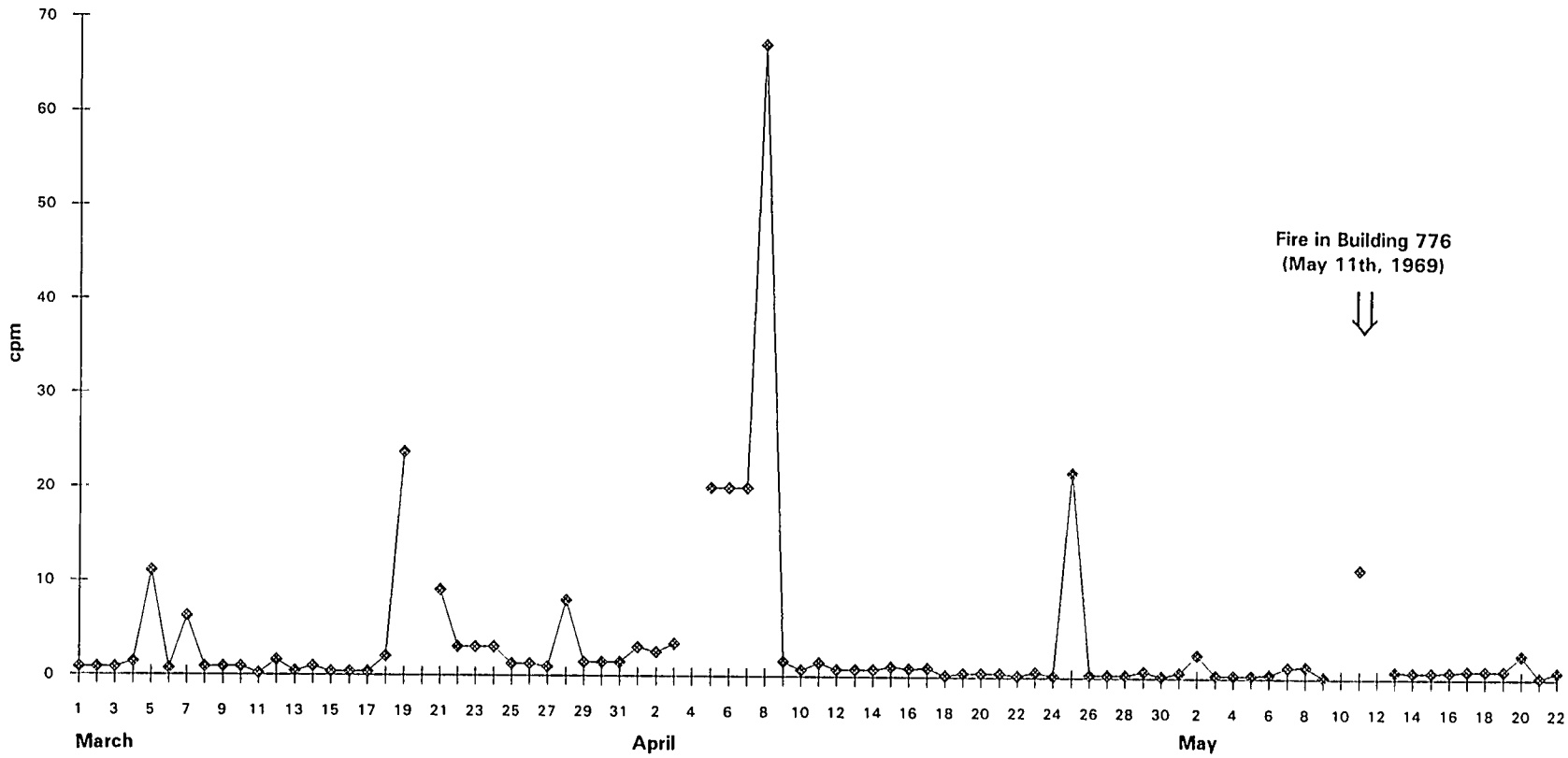
Pu_f	=	Estimated plutonium on filter (pCi)
c min^{-1}	=	Total or background-corrected alpha radioactivity (c min^{-1})
0.21	=	Correction factor, burial loss (0.7) times counter efficiency (0.3)
2.22	=	Conversion factor (dis min^{-1} pCi^{-1})

Equation 2:

$$C_T = \frac{Pu_f}{Rate \times Time}$$

where:

C_T	=	Estimated average air concentration during the fire (pCi m^{-3})
Pu_f	=	Estimated plutonium on filter (pCi)
Rate	=	Sampling flow rate (m^3 hr^{-1})
Time	=	Sampling time during fire (hours)



ChemRisk
A Division of McLaren/Hart

FIGURE 3-25
S-8 SAMPLER ACTIVITY FOR
MARCH, APRIL AND MAY OF 1969

Assuming that the sampling flow rate is equal to 3.4 m^3 hr^{-1} (2 ft^3 min^{-1}) and that the sampling time during the fire is 17.5 hours (2:30 p.m. on 5/11/69 to 8:00 a.m. on 5/12/69 when the filters were removed), values for C_T were calculated from the above equations and are presented in Table 3-15.

The uncertainties associated with these estimates of average air concentrations are those described and quantified previously for the air sampling devices and analytic process used for these air samples. The following section describes the use of the average airborne concentrations of plutonium presented in Table 3-15 in estimating the total plutonium release from the fire.

Emission Rate Estimate

The process of identifying average release rates of plutonium during the 1969 fire that are consistent with the estimated air concentrations based on the environmental data involves the use of the INPUFF computer model, which is run to simulate the dispersion of contaminants during the event. As described previously, the model uses the estimated height of the release, meteorological data and atmospheric stability estimates to predict the movement and dispersion of "puffs" of contaminants released by the fire and to predict average airborne concentrations of contaminants at the locations of the air samplers and any other locations of interest. Eyewitness accounts reported smoke exiting Building 776 from the exhaust vents on the roof of the building. These vents released smoke horizontally or downward onto the roof (inverted J stacks); therefore, a release height of 13 meters, or approximately 1 meter above the roof, was used. The meteorological data are in 5- to 60-minute intervals. INPUFF was used to predict 5-minute average air concentrations throughout the duration of the fire to take advantage of the most detailed data.

The INPUFF model can also account for contaminant removal from the air as a result of deposition to the ground (plume depletion). As with the fine particle release from the 1957 fire, it has been assumed that this removal mechanism plays a very minor role by assuming a settling velocity of zero and a deposition velocity consistent with submicron-size particles of 0.1 cm sec^{-1} (Sehmel, 1984; USEPA, 1979; Sehmel and Hodgson, 1978). However, since the actual particle size distribution is not known, an additional uncertainty factor of 3 (GM 1 of and GSD of 1.7) will be incorporated into the dose calculations in Task 8 to account for the uncertainty in this deposition rate.

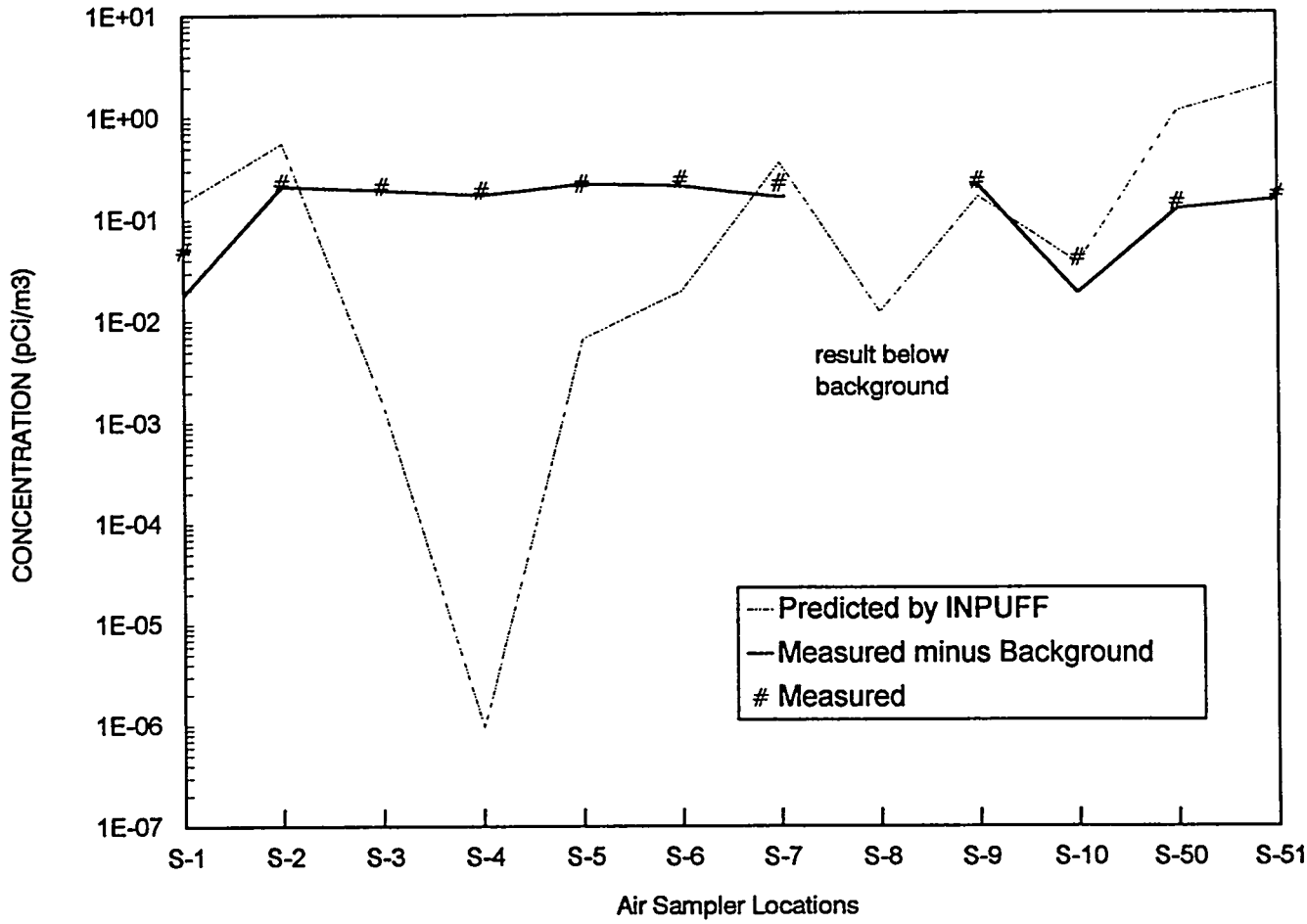
Precipitation scavenging does not have to be taken into account for the 1969 fire, because no precipitation of any kind (i.e., thunderstorm, rain, rain showers, snow pellets, snow showers, sleet, fog or smoke) was recorded at either Stapleton or Jefferson County Airports.

Figure 3-26 presents a comparison of the measured air concentrations calculated from the on-site samplers to the average air concentrations predicted by INPUFF at each of the sampler locations based on a release rate of 0.05 μCi sec^{-1} from 2:30 p.m. to 8:00 p.m. on 5/11/69 and a release rate of 0.02 μCi sec^{-1} from 8:00 p.m. on 5/11/69 to 8:00 a.m. on 5/12/69. These release rates are believed to result in the best fit of the release quantity to the environmental data, regardless of whether or not the data are adjusted for background radioactivity.

The INPUFF predicted air concentrations are within a factor of 12 at 8 of the 12 sampling locations. This is well within the overall uncertainty in our analysis, which is described later in this section. However, INPUFF predicts little or no contamination reaching sampling locations S-3 and S-4, even though these samples had measurable activity, and also substantially underpredicts contamination at samplers S-5 and S-8 (by a factor of over 30). These samplers lie to the northwest (S-3), north (S-4), northeast (S-5), and southeast (S-8) of Building 776. Since the predominant wind direction during the fire was reported from the northeast, followed in the late stages of the fire from the west, of this group of samplers, only S-5 and S-8 would have been downwind during the later stages of the fire. In addition, the majority of the wind observations on which the INPUFF modeling is based were only taken once an hour. It is likely that variations in the wind direction and speed occurred during the hour which are not reflected in the modeling. These variations in the wind direction and speed may have been responsible for carrying contaminants toward these samplers. Significant increases in the release rates that would be necessary to better fit these samplers would result in predicted air concentrations at the remaining on-site sampling locations that greatly exceed the measured values.

The fit of the predicted concentrations is essentially the same for the background-corrected data. As stated previously, the estimated background activity for Sampler S-8 is greater than the total activity measured on the filter for the weekend sampling period ending 5/12/69 due to the inclusion of a few unusually high readings in the background calculation. If the average background activity was calculated without these unusually high samples, the resulting background-corrected value would suggest that the predicted air concentration is actually much closer to the measured value then is indicated by the uncorrected data.

Since the coarse meteorologic data used in the modeling was identified as a potential source of error in estimating the release, efforts were made to compensate for this source of error. As discussed previously, only hourly wind speed and direction data were recorded during most of the 17.5-hour period of the fire. As the wind changed direction during the fire, it is unlikely that it changed abruptly from hour to hour as would be indicated by the data. Instead, it is much more likely that the wind direction changed gradually. To simulate these gradual changes, the hourly data were "smoothed" by assigning an intermediate wind direction for a portion of each hour when the wind shifted between two consecutive hours. For example, if the wind blew



ChemRisk
A Division of McLaren/Hart

TABLE 3-26
MEASURED AND PREDICTED AIRBORNE PLUTONIUM CONCENTRATIONS AFTER THE 1969 FIRE - ORIGINAL METEOROLOGICAL DATA

towards the north during Hour #1 and to the east during Hour #2, the following wind directions would be used:

Hour #1	0-50 minutes	North
	50-60 minutes	Northeast
Hours #2	0-10 minutes	Northeast
	10-60 minutes	East

The wind directions associated with a smoothed meteorological data set are shown in Appendix F. The fire release was remodeled as described previously, using the same release rates for the two periods of the fire, but with the smoothed data set. A comparison of these predicted air concentrations to the measured concentrations is presented in Figure 3-27. As can be seen in the figure, the predicted concentrations at 10 of the 12 sampling locations are within a factor of 12 of the measured values for the uncorrected data. The most significant changes were for Samplers S-5 and S-8, where the difference between the predicted value decreased from a factor of 33 and 35 lower to a factor 2 and 12 lower than the measured values, respectively. The fit of the data remains poor only for S-3 and S-4, which do not fall within the path of the predicted plume at any time during the fire based on the available meteorologic data set. For the background corrected data, the fit to the modeled data is similar to the uncorrected data.

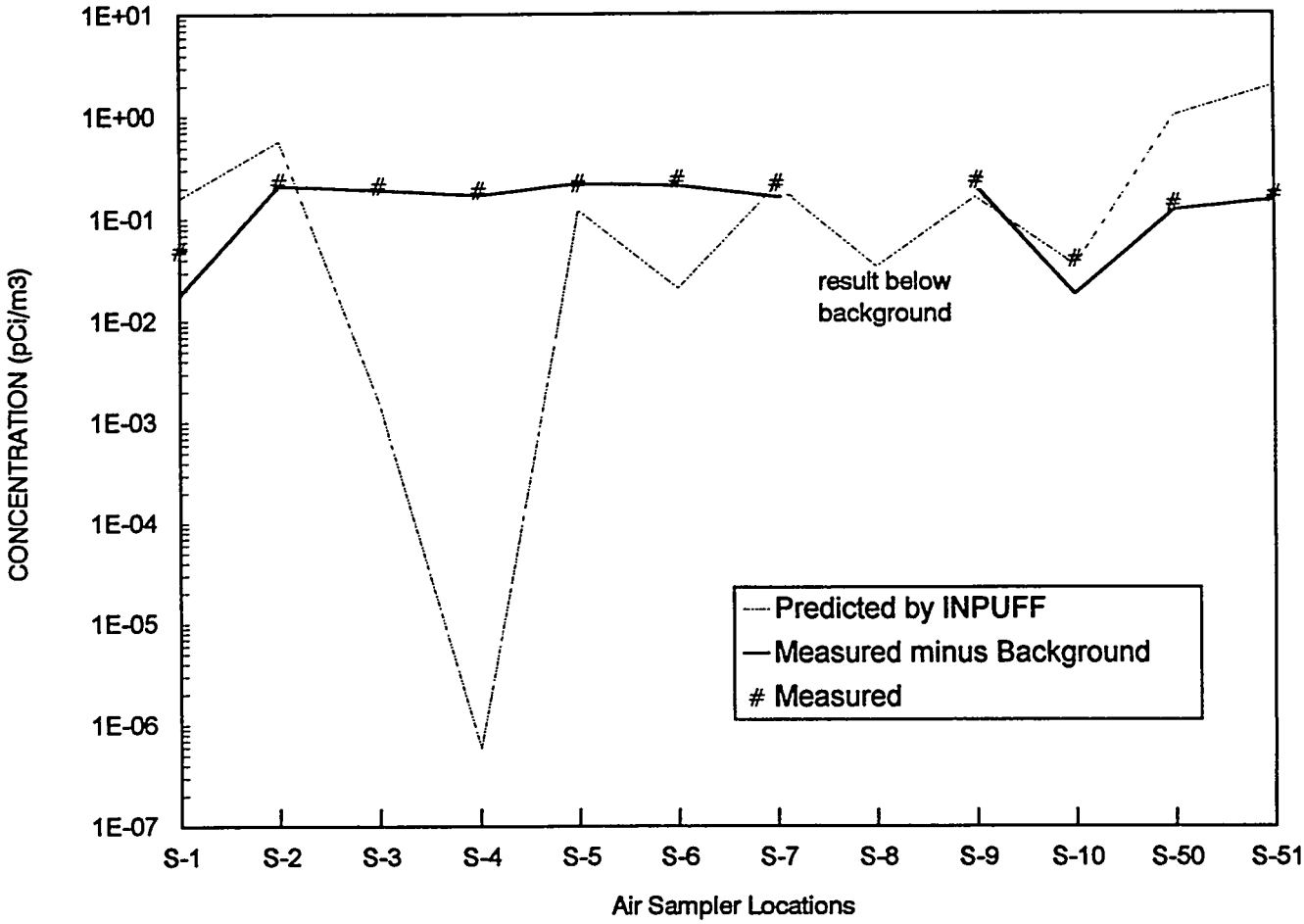
Based on this evaluation, for the same release rates, a slightly better fit to the environmental data is associated with the use of a smoothed meteorological data set. Since these simulated meteorological conditions likely provide a better representation of the actual conditions during the fire, predicted air concentrations based on the smoothed data set will be used in the Task 8 dose calculations.

Air Concentration and Deposition Isopleths

The predicted 17.5-hour average air concentration isopleths based on the "best fit" emission rates and the smoothed meteorological data set are shown in Figure 3-28. The resulting deposition pattern, assuming a deposition velocity of 0.1 cm sec^{-1}, is shown in Figure 3-29. As discussed previously, precipitation scavenging does not apply to the 1969 fire.

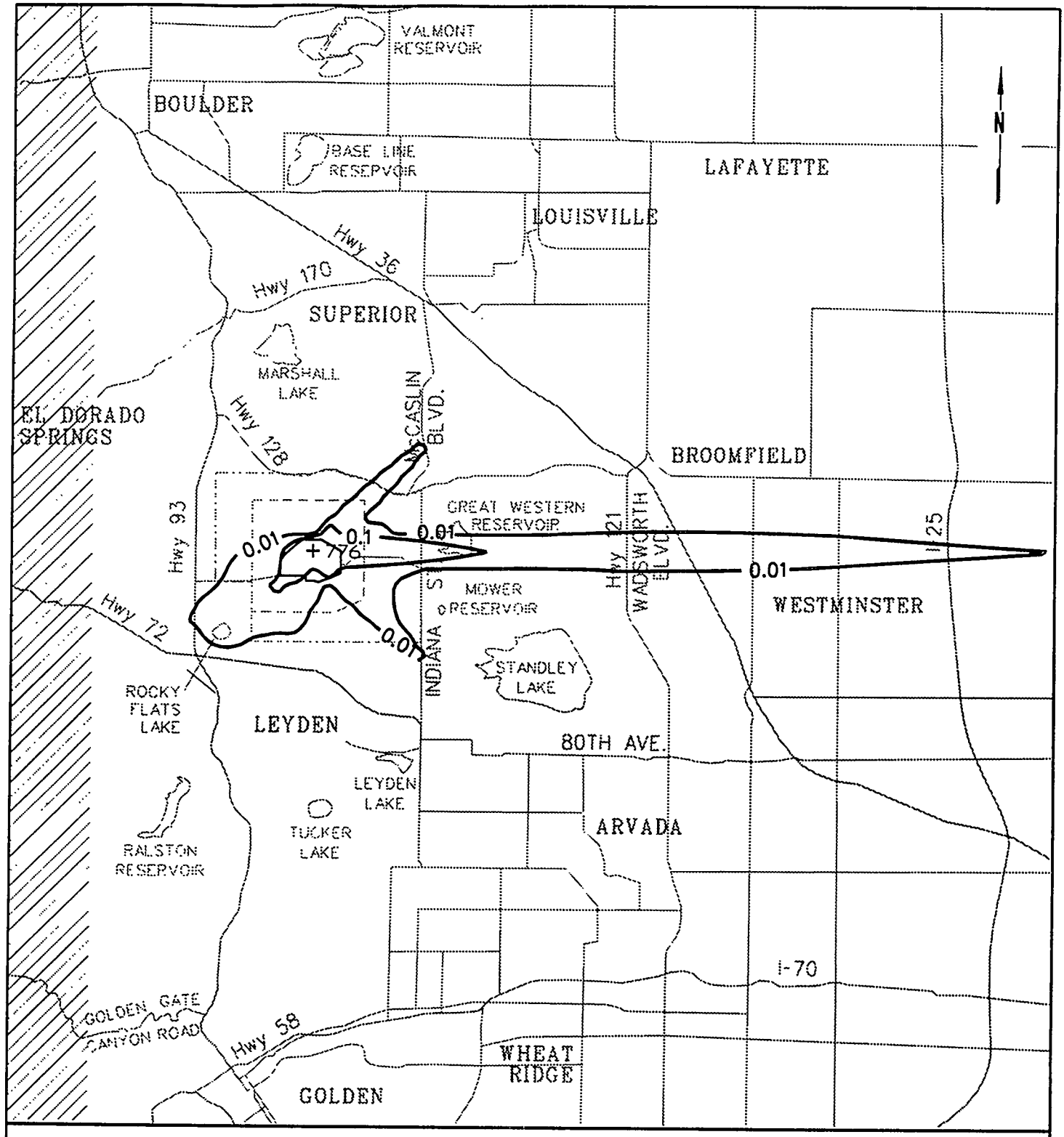
Uncertainty

As with the 1957 fire, the "goodness-of-fit" of the predicted concentrations to the measured concentrations calculated from the sampler information must be evaluated in light of the overall uncertainty associated with this analysis. Three sources of uncertainty were identified as contributing to the overall uncertainty in reconstructing the release from the 1969 fire: air dispersion model, air monitoring data, and time resolution/number of data points. The



ChemRisk
A Division of McLaren/Hart

TABLE 3-27
MEASURED AND PREDICTED
AIRBORNE PLUTONIUM CONCENTRATIONS
AFTER THE 1969 FIRE - SMOOTHED
METEOROLOGICAL DATA



LEGEND

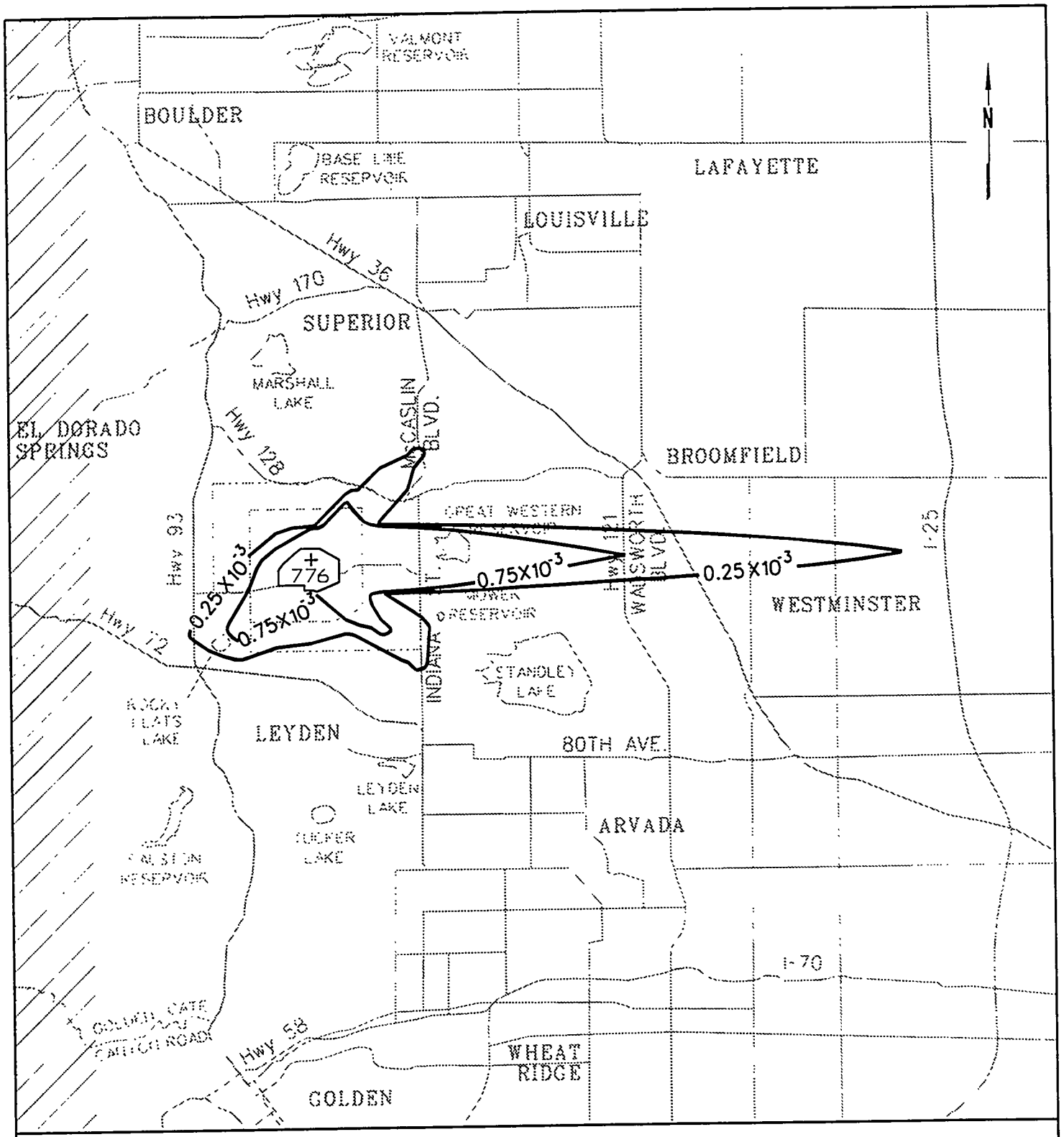
- SECURITY FENCE
- ROCKY FLATS PLANT BOUNDARY 1951-1974
- ROCKY FLATS PLANT BOUNDARY 1974-PRESENT (WITH BUFFER ZONE ADDED)
- FRONT RANGE OF THE ROCKY MOUNTAINS
- + BUILDING 776 STACK
- ISOPLETH CONCENTRATION LINES, pCi m^{-3}
- pCi 10^{-12} CURIE

0' 13,200'
SCALE
SCALE: 1" = 2.5 Miles

ChemRisk
A Division of McLaren/Hart

FIGURE 3-28
PREDICTED 17.5-HOUR AVERAGE AIR CONCENTRATIONS FOR PLUTONIUM RELEASED DURING THE 1969 FIRE (pCi m^{-3})

Rky0194h/3-28.dgn; Rev: 05-20-94



LEGEND

- SECURITY FENCE
- ROCKY FLATS PLANT BOUNDARY 1951-1974
- ROCKY FLATS PLANT BOUNDARY 1974-PRESENT (WITH BUFFER ZONE ADDED)
- FRONT RANGE OF THE ROCKY MOUNTAINS
- + BUILDING 776/STACK
- ISOPLETH CONCENTRATION LINES, mCi km^{-2}
- mCi 10^{-3} CURIE

0' 13,200'
SCALE
SCALE: 1" = 2.5 Miles

FIGURE 3-29
DEPOSTION OF PLUTONIUM FROM THE 1969 FIRE
(mCi km^{-2})

ChemRisk
A Division of McLaren/Hart

Rky0194h/rfh3-29.dgn. Rev: 05-27-94

uncertainties associated with applying the INPUFF model to this type of analysis are represented by a factor of 10 as discussed in Appendix G, and we have assigned a lognormal distribution with a GM of 1 and a GSD of 3.2 to this parameter. The uncertainties associated with the sampling devices and analytic techniques are the same as those defined for the 1957 fire, and were previously combined into a single uncertainty factor represented by a lognormal distribution with a GM of 1.3 and a GSD of 1.3. An uncertainty factor associated with the time resolution and number of data points was also defined for the 1957 fire release. However, in the case of the 1969 fire, there are a few more data points from which to estimate the release rates, and all of the data represented measured values and not upper-bound values based on a limit of detection. For the purpose of this analysis, an uncertainty factor of 5, represented by a log uniform distribution ranging from 0.2 to 5, is included instead of the factor of 10 used in the 1957 fire uncertainty analysis. These individual components were combined into a single, overall uncertainty factor for the 1969 fire using Monte Carlo techniques. This overall uncertainty can be represented by the following equation:

$$U_{Total} = U_{Model} \times U_{Air} \times U_{Data}$$

where:

U_{Total} = Total uncertainty in the 1969 fire release

U_{Model} = Uncertainty in the INPUFF model (lognormal; GM=1.0; GSD=3.4)

U_{Air} = Uncertainty in the air monitoring data (lognormal; GM=1.4; GSD=1.3)

U_{Data} = Uncertainty related to limited time resolution and number of data points (loguniform; -1.6—1.6)

The resulting distribution is best described by a lognormal distribution with a geometric mean of 1.4 and a geometric standard deviation of 4.4. This means that 95 percent of the distribution falls within a factor of approximately 20 of the predicted value.

The conclusions that can be drawn from this analysis are that the average plutonium release rates of 0.05 μCi sec^{-1} and 0.02 μCi sec^{-1} for the two periods of release during the fire would be consistent with the air sampling and meteorological data that have been reported during the fire (total fire release of 2 mCi over 19.5 hours). Based on these average release rates and the 19.5 hour duration of the fire event (2:30 p.m. on 5/11/69 to 10:00 a.m. on 5/12/69), the total estimated release of plutonium from the fire is 2.8 mCi (2 mCi multiplied by geometric mean of the overall uncertainty distribution of 1.4), the estimates of the upper and lower bounds of

the 95 percent confidence interval about the best estimate are 56 mCi and 0.14 mCi, respectively (Figure 3-30).

Summary—1969 Fire Release

The reconstruction of the 1969 fire was based on limited air sampling and meteorological data collected during the fire. A total release of 2.8 mCi plutonium would be consistent with these data. The uncertainty in this estimate results from the numerous assumptions that have been made and the generally poor quality of the available meteorologic data. The 17.5-hour average air concentrations predicted by the INPUFF computer model previously presented in Figure 3-28 were used in Task 8 to predict off-site exposures from the fire.

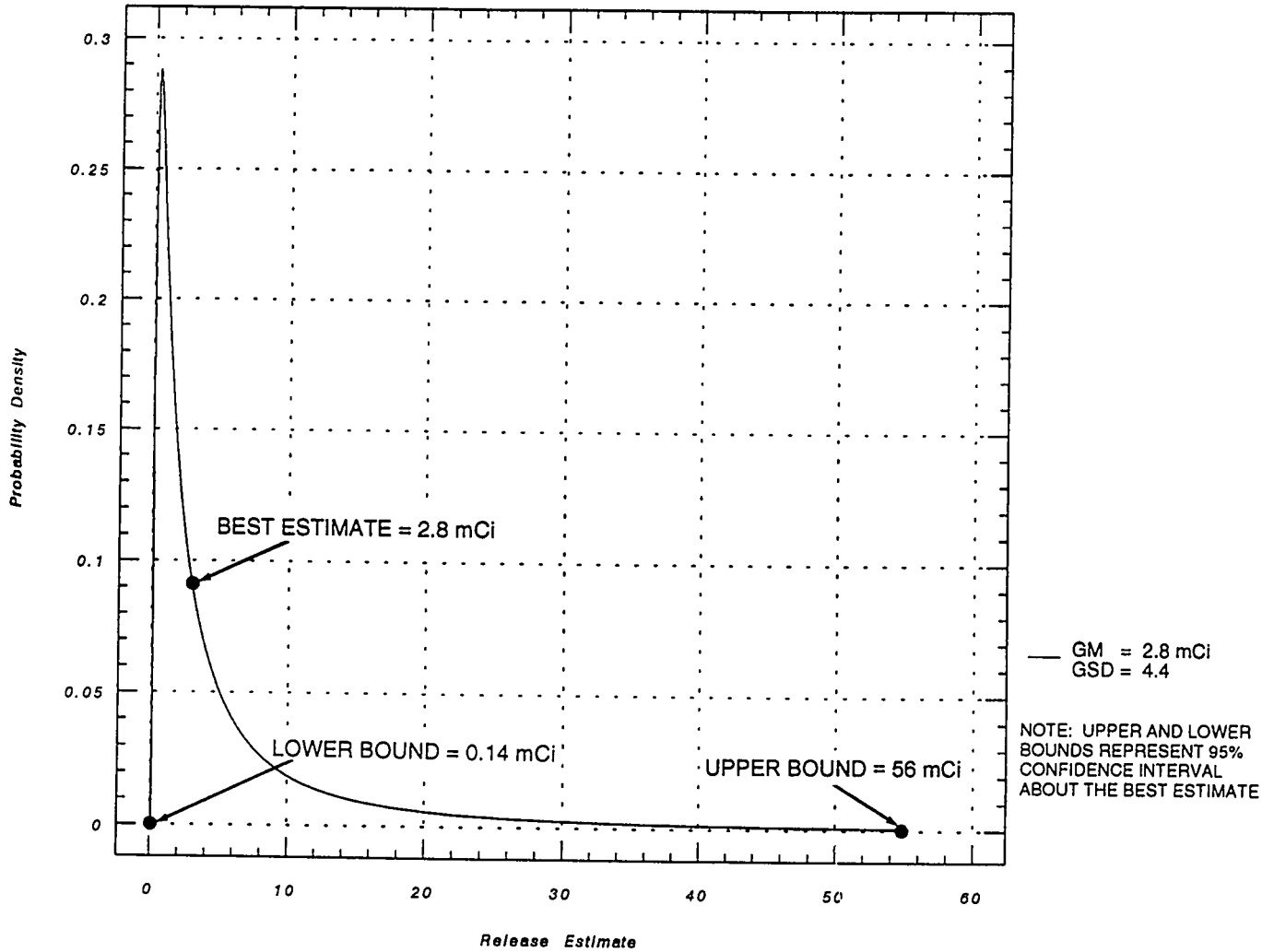
3.4.3.5 Other Estimates of the 1969 Fire Release

No estimate of the amount of plutonium released to the environment is provided in the U.S. AEC 1969 Fire report (USAEC, 1969). In the 1980 Final Environmental Impact Statement (FEIS), a release of 856 μCi plutonium is attributed to the 1969 Fire (USDOE, 1980), although the basis for this release estimate is not provided. Based on our review of the available information, we believe that the value of 856 μCi is based on the sum of the releases for the months of May-August 1969, as shown below:

May	164
June	111
July	392
August	189
	856 μCi

These release estimates were recorded on a handwritten sheet contained in the "Release History" file, which is believed to have provided the basis for the Omnibus and FEIS reports. Using the "Duct Samples—Building 76" recording sheets for these months, we attempted to verify these release estimates, and came up with values that were within 4 percent of those reported in the Release History file. It is unclear why the effluent releases for a four-month period would be attributed to the 1969 fire, although it may have been done to account for higher than usual releases associated with cleanup activities. Nevertheless, using effluent monitoring data alone as the basis for estimating the release from the 1969 fire may not be appropriate, since the stack samplers in the booster systems were disabled approximately 90 minutes after the fire began.

Although no total release estimate was provided in the 1969 fire report, the following measurements of surface contamination on the Building 776 roof and the ground around the building were reported:



ChemRisk
A Division of McLaren/Hart

FIGURE 3-30
1969 FIRE RELEASE ESTIMATE
AND ASSOCIATED UNCERTAINTY

Rky0194h/3-30 Rev 052794

> "...the roof contamination was confined to an area of about 12,000 square feet with a contamination level of 0.02 microcuries per 100 square centimeters with a few spots up to 0.2 microcuries per 100 square centimeters and the ground contamination was confined to an area of 20 feet by 100 feet [2000 square feet], with contamination levels from 0.02 microcuries to 0.2 microcuries per 100 square centimeters."

Based on this information, the following estimate of plutonium on the roof and ground around Building 776 can be calculated:

Roof Contamination:

Total Plutonium = 12,000 $ft^2 \times 0.02\ \mu Ci/100\ cm^2 \times 929\ cm^2\ ft^{-2}$

= 2200 μCi or 2.2 mCi

Ground Contamination:

Total Plutonium = 2,000 $ft^2 \times 0.02\ \mu Ci/100\ cm^2 \times 929\ cm^2\ ft^{-2}$

= 370 μCi or 0.37 mCi

or

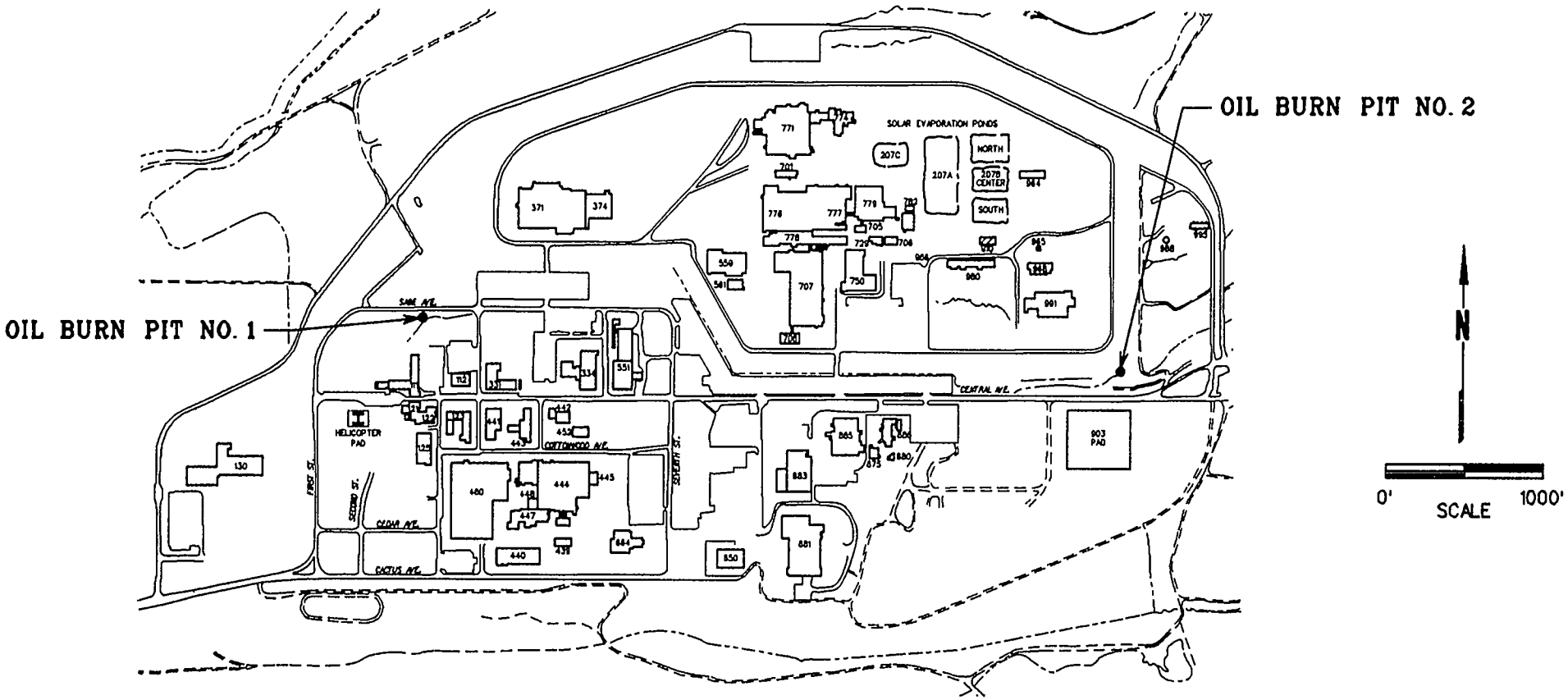
Total Plutonium = 2,000 $ft^2 \times 0.2\ \mu Ci/100\ cm^2 \times 929\ cm^2\ ft^{-2}$

= 3,700 μCi or 3.7 mCi.

These calculations would suggest that approximately 2.6 to 5.9 mCi of plutonium were deposited on or in the vicinity of Building 776 during the 1969 fire. This estimate cannot be directly compared to the estimate derived in this study, since it is based on activity deposited on-site and the approach employed in this study accounts for only the airborne activity that had the potential to travel off-site. It would be more appropriate to add the two estimates together for the purposes of estimating the total fire release.

3.4.4 Burning of Uranium-Contaminated Oil

On a number of occasions from 1956 through 1965, oil contaminated with depleted uranium was burned at Rocky Flats in locations later called Oil Burn Pit #1 and Oil Burn Pit #2. The location of the oil burn pits is shown in Figure 3-31.



ChemRisk
A Division of McLaren/Hart

FIGURE 3-31
OIL BURN PIT LOCATIONS

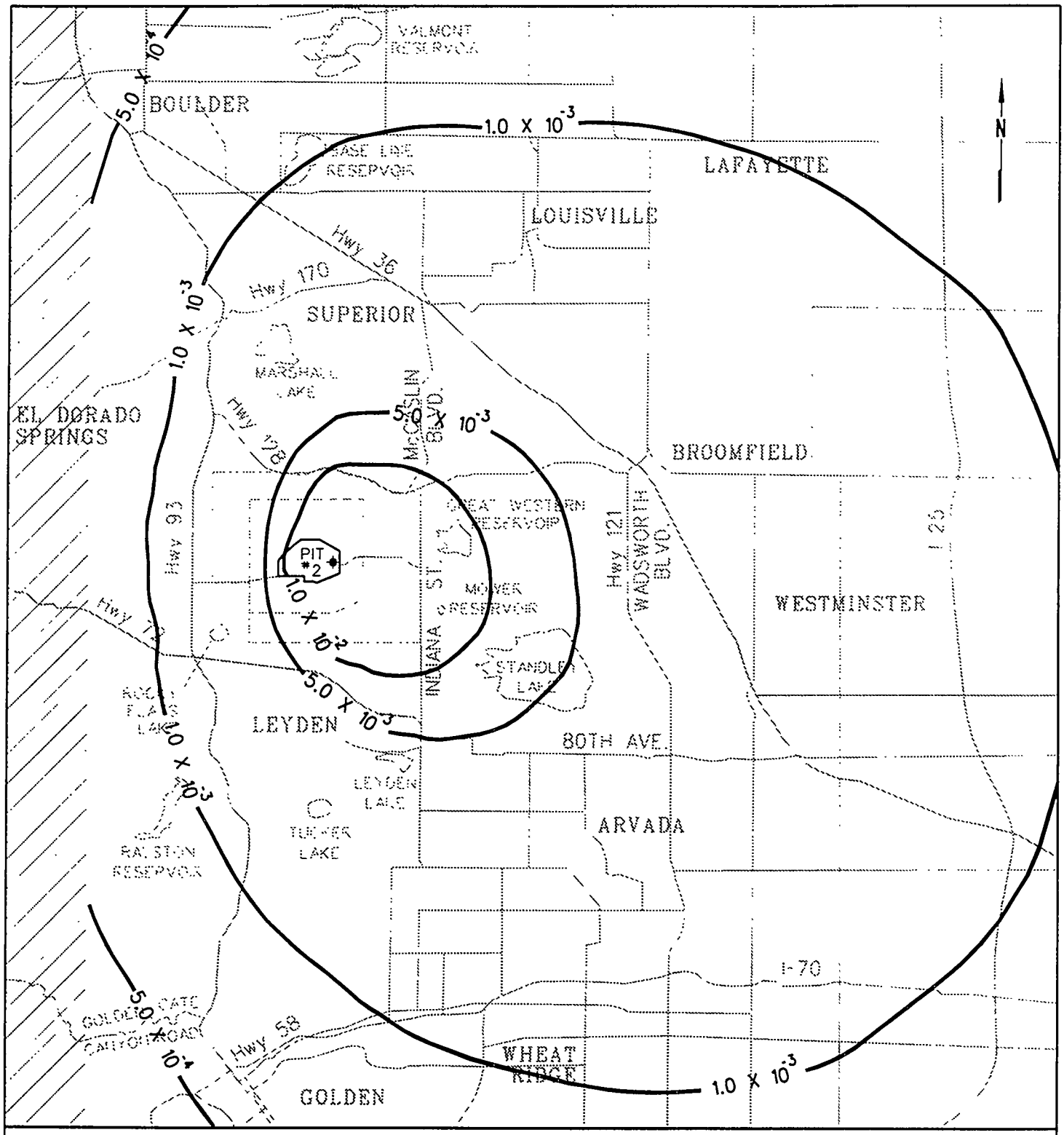
Rky0194h/rfh3-31; Rev: 04-14-94

A test burn took place at Oil Burn Pit #1 on August 18, 1956, and there were 29 more burns at Oil Burn Pit #2 during the period 1957-1965 (USDOE, 1992). Ten drums of oil were burned at Oil Burn Pit #1 (Owen and Steward, 1974), and a total of at least 1354 drums were burned at Oil Burn Pit #2 (USDOE, 1992).

During the test burn at Oil Burn Pit #1, air sampling was conducted in the smoke plume at a location 60 feet south of the burn pit. Total alpha radioactivity concentrations ranged from approximately 0.05 to 13.5 pCi m^{-3}. Air concentrations measured during the burns at Oil Burn Pit #2 were lower than observed at Oil Burn Pit #1, but the measurements were taken at greater (or unknown) distances. Where distances are given for measurements taken near Oil Burn Pit #2, they range between 90 and 300 feet.

Emission parameters for these oil burns are unknown. However, to develop screening-level estimates of potential effects of these releases, a constant, 4-hour ground-level emission of 1 micron uranium particles, released at ambient temperature from a 30 m^2 area source at the location of Oil Burn Pit #2, was modeled using the ISC model. This represents contamination entrained in ground-level airflow. The dimensions of the source area (30 m $\times$ 30 m) used to represent Oil Burn Pit #2 for modeling purposes were estimated based on the size of the burn pit relative to the 903 Pad. The Burn Pit was estimated to be no wider than one-fourth of the width of the 903 Pad, which was approximately 120 m. The indicated values of burn duration, release height, and particle size were selected based on professional judgement after review of available information concerning historical oil burning practices.

The release was modeled using midnight to 6 a.m. meteorological data collected in 1987-1991 to represent meteorological conditions during the nighttime burning periods. The release rate was adjusted to obtain an average air concentration of 13.5 pCi m^{-3}, the maximum concentration measured during the test burn, at 16 points 20 meters (about 60 feet) from the burn pit area in the 16 wind directions for which meteorological data are available. The release rate necessary to obtain an average air concentration of 13.5 pCi m^{-3} at 20 meters from the burn pit is 0.03 μCi sec^{-1}, corresponding to a total release of about 0.01 Ci for 29 four-hour burns. The average air concentration at Indiana Street near the southeast corner of the buffer zone (believed to be the location of the nearest residence) during the burns was then about 0.01 pCi m^{-3}, as shown in Figure 3-32. The relative magnitude of this estimated air concentration is compared to other releases from the plant in a subsequent section of this report (Section 3.6).



LEGEND

- SECURITY FENCE
- ROCKY FLATS PLANT BOUNDARY 1951-1974
- ROCKY FLATS PLANT BOUNDARY 1974-PRESENT (WITH BUFFER ZONE ADDED)
- FRONT RANGE OF THE ROCKY MOUNTAINS
- ISOPLETH CONCENTRATION LINES, pCi m^{-3}
- 10^{-1} SCIENTIFIC NOTATION; 10^{-1} = 0.1 OR 1/10; 10^{-2} = 0.02 OR 1/100; etc.
- pCi 10^{-12} CURIE

0' 13,200'
SCALE
SCALE: 1" = 2.5 Miles

ChemRisk
A Division of McLaren/Hart

FIGURE 3-32
PREDICTED 4-HOUR AVERAGE AIR CONCENTRATIONS FOR URANIUM RELEASE FROM THE OIL BURN PITS (pCi m^{-3})

Rky1293h/rfh3-32.dgn. Rev: 05-23-94

3.5 Resuspension

Both routine and nonroutine airborne releases from the Rocky Flats plant have resulted in deposition of contaminants onto soil in the surrounding communities, although most of the deposited radioactivity is believed to be related to releases from the 903 Pad. Resuspension of contaminated soil near Rocky Flats is therefore a potentially important pathway for human exposure. Healy (1980) discussed three main types of resuspension models (resuspension factor, resuspension rate, and mass loading) and recommended the mass loading approach. Smith *et al.* (1982) reviewed the three types of resuspension models considered by Healy and eleven other more elaborate models. Smith *et al.* indicate that the mass loading and resuspension factor approaches are most commonly used because of the lack of data needed for the other models.

Resuspension Factor

In the resuspension factor approach, the estimated resuspended contaminant concentration is calculated by the following equation:

$$[\mathrm{Air}]_{\mathrm{resusp.}} = f \times R \times [\mathrm{Soil}]_{\mathrm{surface}}$$

Where:

$[\mathrm{Air}]_{\mathrm{resusp.}}$	=	Contaminant concentration associated with resuspended particles in the respirable range (particles with less than 8 μm in aerodynamic equivalent diameter), pCi m^{-3} or pg m^{-3};
f	=	Respirable fraction of airborne contaminant, dimensionless;
R	=	Soil resuspension factor, m^{-1};
$[\mathrm{Soil}]_{\mathrm{surface}}$	=	Surface soil contamination, pCi m^{-2} or pg m^{-2}.

Soil resuspension factors measured in the Rocky Flats area have been reported to vary over several orders of magnitude. Most of these results were derived from field measurements which did not last more than a few days. Measurement of a soil resuspension factor is affected by many parameters, such as mechanical disturbance, humidity, wind direction and velocity, that may change on a hourly or daily basis. This may be one of the reasons why such a wide range of soil resuspension factors were reported in the literature. However, on a monthly or annual basis, variability of soil resuspension at a given site is expected to be much smaller than that indicated by short-term measurements. This is demonstrated in the results of a dust monitoring program conducted at a location about 300 m east of the 903 Pad between July 1981 and June 1982. The device used was a high volume sampler that only sampled airflow with a westerly

component that passed over the pad. Figure 3-33 shows the monthly total dust concentrations registered by the sampler (Hunt and Campbell, 1984). Although the sampling period included January 17, 1982 when wind speeds reached 130 mph and April 2, 1982 with gusts up to 97 mph, the difference between the highest and lowest reported monthly total dust concentrations is only about a factor of 20. Since almost all soil resuspension factors for Rocky Flats have been estimated based on short-term study results, it is difficult to identify an appropriate resuspension factor for use in evaluating long-term health impacts associated with exposure to resuspended soil contaminants. Since the focus of this evaluation is on annual average exposure of the public to contaminants from Rocky Flats, the mass loading approach was selected to model soil resuspension rather than the resuspension factor approach.

Mass Loading

In the mass loading approach, the concentration of airborne respirable contaminants can be estimated by the following equation:

$$[Air]_{resusp.} = A \times M \times F$$

Where:

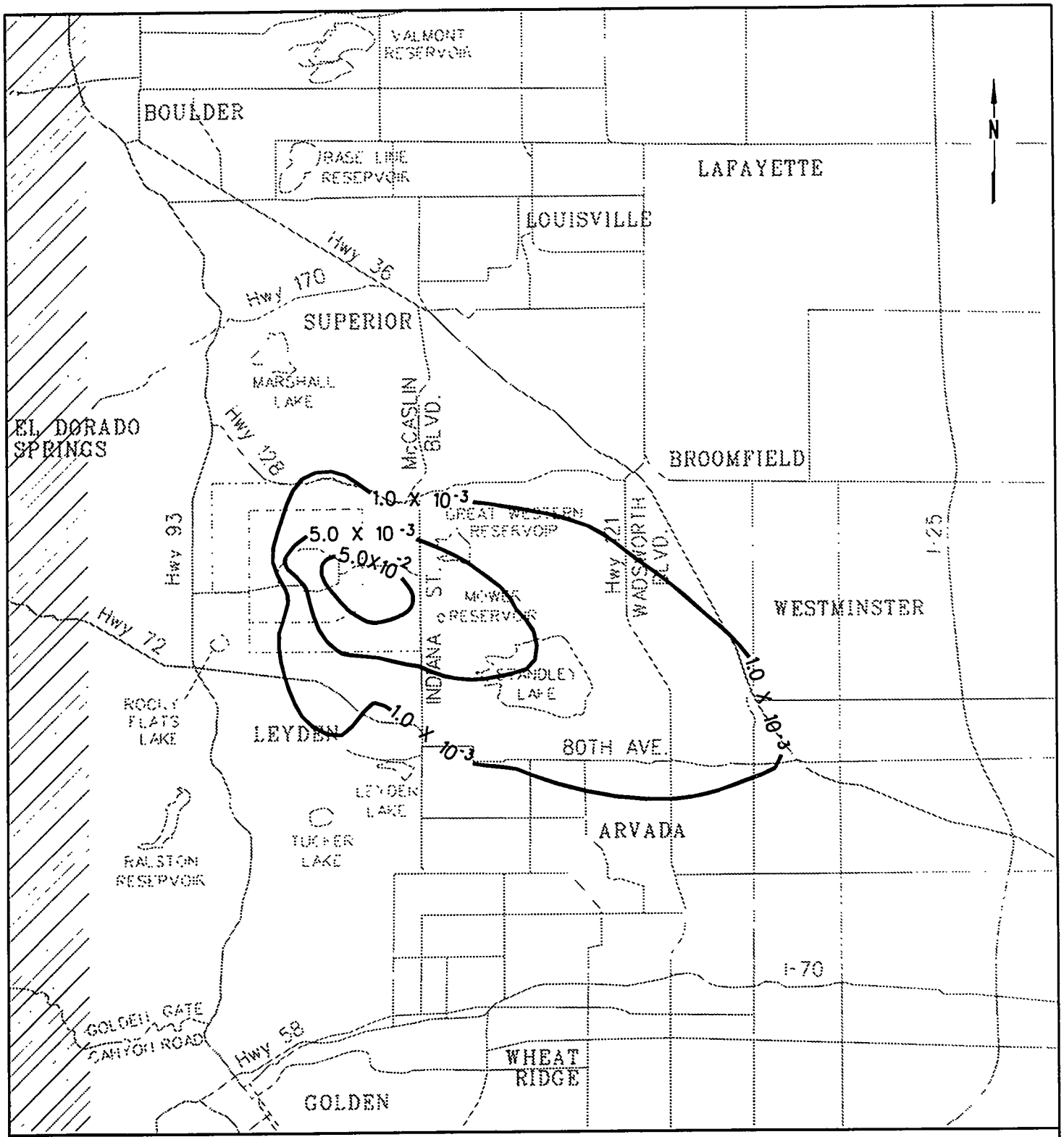
$[Air]_{resusp.}$ = Airborne contaminant concentration associated with resuspended particles in the respirable range (particles with less than 8 μm in aerodynamic equivalent diameter), pCi m^{-3} or pg m^{-3};

A = Contaminant concentration of surface soil, pCi g^{-1} or pg g^{-1};

M = Mass loading factor or concentration of respirable particles in air, g m^{-3}; and

F = Enhancement factor, which is a factor used to account for the nonuniform distribution of contaminant among various soil particle size fractions as well as the non-uniform resuspension of particle sizes, dimensionless.

The accuracy of this model relies on two key parameters: the mass loading factor (M) and the enhancement factor (F). Several studies have been conducted in the vicinity of the 903 Pad to investigate soil resuspension. Some of the results can be used to estimate the values of these two parameters. One of the most detail studies was carried out by Langer (1986) between November 1982 and December 1984. A vertical dust sampling scaffold was placed about 100 m southeast of the Rocky Flats east gate. Dust particle fractions with aerodynamic equivalent diameters less than 3 μm, 3-15 μm, and larger than 15 μm were collected at 1, 3, and 10 m above ground level. Tables 3-16 and 3-17 present the dust sampling results. Samples collected at 1 and 3 m



LEGEND

- ROCKY FLATS PLANT BOUNDARY 1951-1974
- ROCKY FLATS PLANT BOUNDARY 1974-PRESENT
- FRONT RANGE OF THE ROCKY MOUNTAINS
- ISOPLETH CONCENTRATION LINES, fCi m^{-3}
- 10^{-1} SCIENTIFIC NOTATION: 10^{-1} = 0.1 OR 1/10; 10^{-2} = 0.01 OR 1/100; etc.
- fCi 10^{-15} CURIE

0' 13,200'
SCALE
SCALE: 1" = 2.5 Miles

ChemRisk
A Division of McLaren/Hart

FIGURE 3-33
PREDICTED LONG-TERM AVERAGE AIR CONCENTRATIONS OF PLUTONIUM ON RESPIRABLE PARTICLES ASSOCIATED WITH RESUSPENSION FOLLOWING 903 PAD CLOSURE (fCi m^{-3})

Rky0194h/rfh3-33.dgn; Rev: 05-23-94

TABLE 3-16

DUST CONCENTRATIONS SAMPLED ABOUT 100 M SOUTHEAST OF THE ROCKY FLATS EAST GATE

Sampling Period	Dust Concentration ($\mu g\ m^{-3}$)											
	1 m Above Ground Level				3 m Above Ground Level				10 m Above Ground Level			
	<3 μm	3-15 μm	>15 μm	Total	<3 μm	3-15 μm	>15 μm	Total	<3 μm	3-15 μm	>15 μm	Total
1982 Nov-Dec	8.1	7.3	20	35	Results for the 3-meter elevation were not reported for these periods.				6.8	3.8	11	22
1983 Jan-Feb	8.9	7.1	36	52					7.9	5.4	19	32
Mar-Apr	11.0	9.6	22	43					10.0	6.1	14	30
May-June	6.4	8.8	30	45					6.4	8.0	18	32
July-Aug	8.0	10.0	27	45					9.3	9.0	28	46
Sept-Oct	7.4	14.0	24	45					8.4	12.0	23	43
Nov-Dec	9.3	7.0	21	37					7.3	4.5	10	22
1984 Jan-Feb	8.7	11.0	47	67	8.3	10.0	23	41	8.0	7.7	26	42
Mar-Apr	9.0	11.0	27	47	5.7	7.6	19	23	6.3	7.1	15	28
May-June	6.9	12.0	26	45	6.9	11.0	25	43	6.4	9.7	20	36
July-Aug	8.9	15.0	24	48	7.6	12.0	20	40	7.0	10.0	18	35
Sept-Oct	7.3	13.0	21	41	10.0	12.0	21	43	8.1	9.2	14	31
Nov-Dec	6.2	11.0	45	62	6.3	9.7	54	70	5.5	7.6	36	49
Mean ± Standard Deviation	8.2 ± 1.3	11 ± 2.6	28 ± 8.9	47 ± 9.0	7.5 ± 1.5	10 ± 1.7	27 ± 13	43 ± 15	7.5 ± 1.3	7.7 ± 2.3	19 ± 7.3	34 ± 8.5

Reference: Langer, 1986.

0104ALR8

TABLE 3-17

AVERAGE PLUTONIUM-239 CONCENTRATIONS FROM LANGER (1986)
(aCi m^{-3})

Sampling Height (m)	Particle Size		
	< 3 μm	3 - 15 μm	> 15 μm
1	3.9±3.1	18±14	91±85
3	14±19	10±4.4	49±25
10	7.6±9.5	5.5±7.1	25±14

(approximately the breathing height) show that average concentrations of dust particles with aerodynamic equivalent diameters less than 3 μm and 3-15 μm are 7 and 10 $\mu g\ m^{-3}$, respectively. As discussed in Section 3.4.1.2, soil particles with an aerodynamic equivalent diameter of less than 8 μm are considered to be respirable. Using this sampling data and assuming half of the particles measured in the 3-15 μm range are less than 8 μm in diameter, the annual average concentration of respirable particles in the area is estimated to be about 12 $\mu g\ m^{-3}$ (7 $\mu g\ m^{-3}$ + 5 $\mu g\ m^{-3}$).

It should be noted that this estimate is not likely to be significantly affected by high wind events. Langer's sampling included a high wind event in which winds in excess of 90 mph were recorded (between December 21 and December 23, 1984). With the exception of coarse particle fraction, dust concentrations measured during November and December 1984 are not higher than those measured in any other time period.

The Colorado Department of Health has measured mass loading at Rocky Flats for a number of years. The average of the annual mass loading reported as the geometric mean for three years (1980, 1983 and 1984) was 60 $\mu g\ m^{-3}$ (Chick, 1992). This represents the total mass loading of TSP (Total Suspended Particulates, particles less than approximately 30 μm in aerodynamic equivalent diameter) derived from soil as well as other sources (e.g., combustion). As discussed in Section 3.4.1.2, several researchers have estimated that about 10 to 25 percent of the airborne dust around Rocky Flats is respirable. Based on this information, the annual average mass loading of respirable dust is estimated to range from 6 to 15 $\mu g\ m^{-3}$.

Another source of information is airborne particulate monitoring performed throughout the nation by the National Air Surveillance Network. According to an USEPA report (1990), annual mean airborne particle concentrations at 30 nonurban sites range from 5 to 50 $\mu g\ m^{-3}$, and the arithmetic average for 1966 was 38 $\mu g\ m^{-3}$.

Based on the information presented above, the annual mean mass loading of respirable particles (less than 8 μm in aerodynamic equivalent diameter) around Rocky Flats is assumed to have a lognormal distribution with a geometric mean of 12 $\mu g\ m^{-3}$ and a geometric standard deviation of 1.5.

Besides the mass loading factor, another key parameter in the mass loading equation is the enhancement factor, F. It is used to take into consideration the potential for non-uniform distribution of contaminant among different soil particle size fractions, the non-uniform resuspension of particle sizes, and/or the presence of other sources of uncontaminated particulates. Like the mass loading factor, the enhancement factor is affected by many site-specific variables, such as shape, density, size distribution, and cohesiveness of soil particles. If it is assumed that the total contaminant concentrations in air and soil are the same, then the

enhancement factor can be calculated by taking the ratio of the fraction of contaminant contained within a size increment to the fraction of the mass contained within that increment. Information presented in Tables 3-16 and 3-17 was used in Table 3-18 to estimate enhancement factors of plutonium for different particle size fractions. As shown in Table 3-18, enhancement factors calculated for particles less than 15 μm in aerodynamic equivalent diameter vary considerably and range from 0.21 to 1.1. Resuspension of contaminated soil particles is generally highest for a freshly deposited source; several researchers observed that airborne contaminant concentration due to resuspension declines first rapidly and then slowly over a period of 12 to 40 weeks (Anspaugh *et al.*, 1975). It is believed that such a decrease in airborne contaminant concentration with time is not due to an appreciable loss of contaminant from the area, but to a "weathering" process whereby the contaminant becomes less susceptible to erosion. It may be reasoned that the enhancement factor determined for a release event is also likely to decrease with time. Since the air sampling data shown in Tables 3-16 and 3-17 were collected about 14 years after the asphalt covering of the major source of plutonium release (the 903 Pad), enhancement factors calculated in Table 3-18 may not be applied to other time periods.

Other estimates of enhancement factors based on measurements at the Rocky Flats plant were published by Burley (1990). Burley's data are based on four samples taken at Rocky Flats, with sampling and analysis performed by the U.S. Environmental Protection Agency. Each sample was separated into three particle size increments. For each increment, a factor g_i was calculated equal to the ratio of the fraction of the total activity contained within the increment to the fraction of the total mass contained in the increment. The fraction of airborne particle mass contained in each size increment was multiplied by g_i and the result summed across all size increments to yield values of an "enrichment factor" that are equivalent to enhancement factors. The samples yielded enrichment factors that ranged from 1.06 to 2.34, with an average of 1.49.

Measurements by Shinn (1992) at Nevada Test Site locations that are reportedly similar to the environs of the Rocky Flats plant yielded enhancement factors that ranged from 0.87 to 1.04.

The primary advantage of the mass loading approach is that the required input parameters are relatively easy to measure and can be based on site-specific data. The disadvantage is that it assumes a constant level of resuspension, regardless of how long it has been since the contaminant was deposited. As stated above, there is evidence to indicate that resuspension of soil contaminant decreases with the period of time elapsed since the initial deposition of the contaminant.

TABLE 3-18

CALCULATION OF ENHANCEMENT FACTOR FOR RESPIRABLE PARTICLES BASED ON THE INFORMATION PROVIDED IN TABLES 3-16 AND 3-17

	Sampled 1 m Above Ground			Sampled 3 m Above Ground		
	<3μ	3-15 μm	>15 μm	<3μm	3-15 μm	>15 μm
Average Mass Concentration (μg m^3)	8.2 (17%)	11 (23%)	28 (60%)	7.5 (17%)	10 (23%)	27 (63%)
Average Pu-239 Concentration (aCi m^3)	3.9 (3.5%)	18 (16%)	91 (81%)	14 (19%)	10 (14%)	49 (67%)
Enhancement Factor	0.21	0.70	1.4	1.1	0.61	1.1

Based primarily on the Burley (1990) data and the recommendations of Shinn (1994), the enhancement factor was assumed in this analysis to have a triangular distribution with a best estimate of 1.0 and lower and upper bounds of 1.06 and 2.34, respectively. For the purpose of this study, the model uncertainty of the mass loading approach is assumed to have a best estimate of 1.0 and an upper and lower bounds of 0.33 and 3.0, respectively.

3.5.1 Resuspension of 903 Pad Contamination after 1969

Using the equation for the mass loading approach described in the previous section and the soil deposition isopleths for the 903 Pad shown previously in Figure 3-17, the resulting isopleths of resuspended respirable air concentrations are shown in Figure 3-33.

Resuspension from the routine releases and following the 1957 and 1969 fires is not expected to be significant source of exposure, since the particles that were released were very small, resulting in relatively little deposition. However, the dose associated with this route of exposure will also be estimated in Task 8 for these events using the mass loading approach described above.

3.5.2 Resuspension from Contaminated Sediments

As discussed in the Task 5 report, some of the sediment samples taken from Great Western Reservoir (GWR) and Standley Lake contain plutonium in excess of the expected background level of 0.1 pCi g^{-1} from nuclear weapons test fallout (ChemRisk, 1992a). The quality and extent of these sampling data are limited, but they are useful for characterizing the possible magnitude of sediment contamination.

Surface sediments from GWR show contamination ranging between 0.11 and 3.5 pCi g^{-1}, while sediment cores show contamination ranging between 0.24 and 2.7 pCi g^{-1}. Surface sediments from Standley Lake show contamination ranging between 0.04 and 1.3 pCi g^{-1}, and sediment cores show contamination ranging between 0.016 and 0.19 pCi g^{-1} (USDOE, 1991).

Shoreline sediment contamination is particularly important, because people are more likely to be exposed to these sediments, whether in-situ or resuspended, than sediments in deep water areas. Estimation of plutonium concentration in exposed shoreline sediment is complicated by the following factors:

- The area of exposed shoreline sediments varies with time.

- Sediment studies suggest that contaminated sediments may have moved around in the reservoirs. The first extensive bottom sediment sampling by the U.S. EPA in 1970 found the highest concentrations of plutonium in EWR near the mouth of Walnut Creek and in the central section of the reservoir (USEPA, 1971). Sediment sampling by the USEPA in 1973 found the highest concentrations in the deepest parts of the reservoir (USEPA, 1973).

- Plutonium concentrations are five to ten times higher in deeper sediments in core samples taken from GWR (USDOE, 1991). The deeper sediments were probably deposited in the 1960s. No significant variation with sediment depth was observed in Standley Lake core samples (Rockwell, 1984).

Based on the available data, the average plutonium concentration in exposed sediments at GWR is estimated at 0.5 pCi g^{-1}. The data suggest that the sediment contamination varied by approximately a factor at 5 at GWR, suggesting that shoreline sediments could plausibly have ranged from one-fifth to five times this value. The average plutonium concentration in exposed sediments at Standley Lake is estimated at 0.1 pCi g^{-1}. In the case of Standley Lake, the data indicate that the sediment contamination varied by a factor of three.

Figures 3-12 and 3-17 indicate that total deposition near Great Western Reservoir and Standley Lake is about 20 mCi km^{-2}. As discussed previously, surface contamination in the top 1 centimeter (or 0.01 m) of soil is assumed to represent about 20 percent of the total deposition (USEPA, 1977; Anspaugh, 1975). Assuming dry soil bulk density of 1000 kg m^{-3}, the soil contamination would be:

$$C_{soil} = \frac{FC \times [soil]_{surface}}{SD \times BD}$$

where:

C_{soil}	=	Contaminant concentration in soil, pCi g^{-1};
FC	=	Fraction of total contamination in the top 1 cm of soil, dimensionless;
$[soil]_{surface}$	=	Predicted total deposition of contaminant, mCi km^{-2};
SD	=	Depth of surface soil, m; and
BD	=	Dry soil bulk density, kg m^{-3}.

$$C_{soil} = \frac{0.2 \times 20\ mCi\ km^{-2} \times 10^{-6}\ km^2\ m^{-2} \times 10^9\ pCi\ mCi^{-1}}{0.01\ m \times 1000\ kg\ m^{-3} \times 10^3\ g\ kg^{-1}}$$

$$= \mathbf{0.4}\ pCi\ g^{-1}$$

Therefore, the predicted surface activity in the soil around Great Western Reservoir and Standley Lake after the 903 Pad releases ending in 1969 of 0.4 pCi g^{-1} is comparable to the estimated shoreline sediment contamination.

Given the similarity between the plutonium concentrations present in shoreline sediments and the concentrations reported in surface soils, resuspension of contaminated shoreline sediments should not result in doses that exceed those estimated for the resuspension of contaminated soils. The only difference is that such exposures to contaminants in sediments may have initially occurred for a small number of individuals residing close to the reservoirs during the 1950s and early 1960s, whereas resuspension of contaminants in area soils only became a concern after the releases from the 903 Pad in the late 1960s. However, the limited sediment data that do exist suggest that much of the contamination present was released as a result of pond reconstruction activities in the early 1970s and that sediment contamination would have been limited in the 1950s and 1960s.

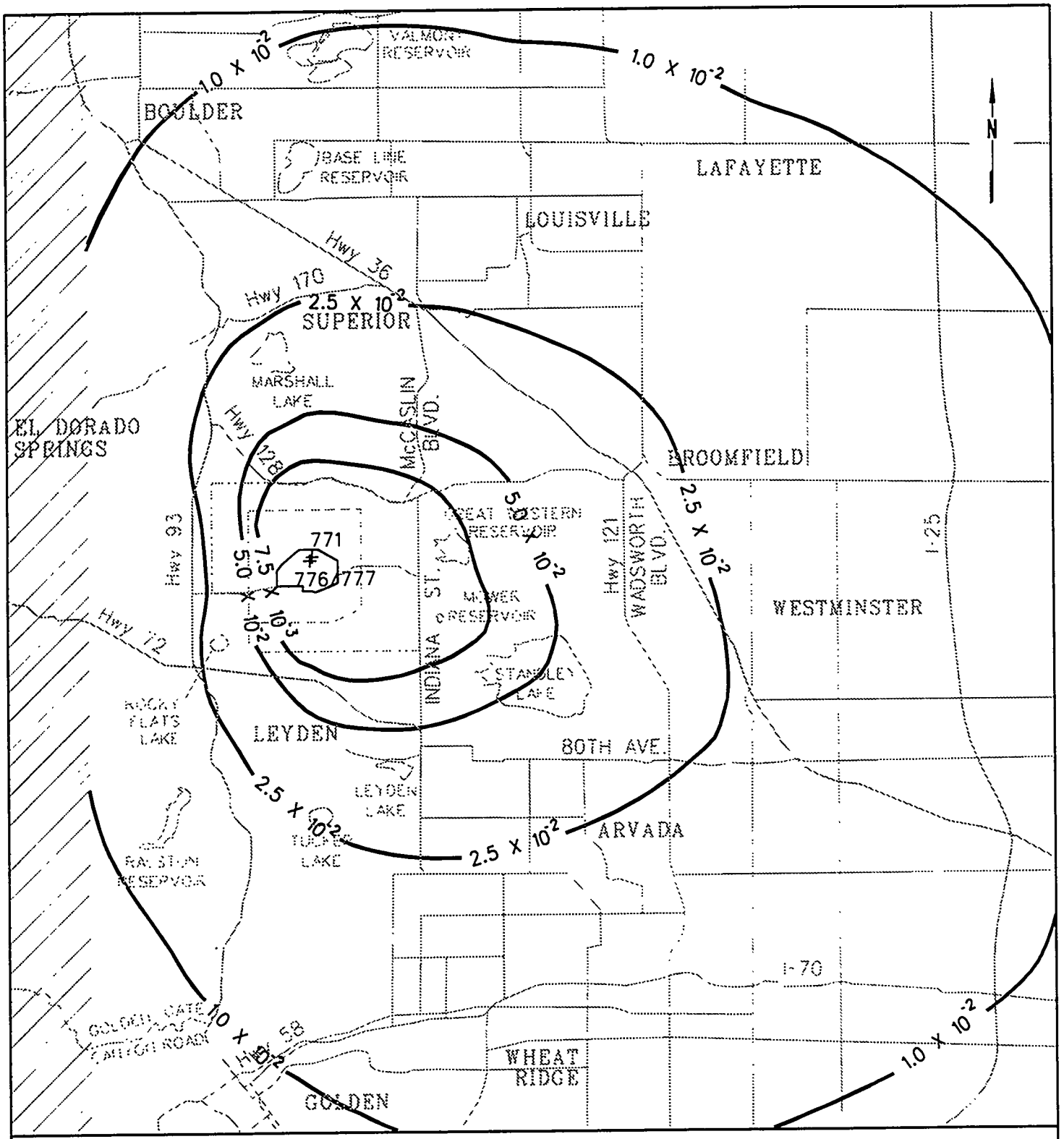
In summary, the limited information available for evaluating exposures to contaminants in resuspended shoreline sediments suggests that these exposures were unlikely to have contributed any additional incremental exposure compared to exposures to contaminants in resuspended soils in the vicinity of the reservoirs. Therefore, further, separate evaluation of exposure to resuspended sediments is not warranted based on currently available data.

3.6 Relative Importance of Releases

The releases that are evaluated in this report occurred over varying lengths of time and were of differing magnitude. In the interest of beginning to put the magnitude of these events and their relative potential to cause harm to human health into perspective, each of the various releases is summarized in this section in terms of a time-integrated air concentration. The term time-integrated air concentration refers to the average air concentration during a contaminant release multiplied by the duration of the release. This is a measure of the total contamination to which an individual could be exposed during a particular release, which can then be compared directly to the time-integrated air concentrations for other releases of the same material. This comparison can provide an indication of the relative importance of each type of release to an individual residing near the plant continuously from 1953 through 1989. Comparisons should

not be made between different materials, since the time-integrated concentrations are reported in terms of activity and do not take into consideration the dosimetry of the materials. The resulting dose to individuals, which depends on breathing rate, uptake and clearance factors, were calculated in Task 8.

Time-integrated air concentration isopleths are obtained by multiplying the air concentration isopleths developed in earlier sections of this report by the estimated total release (routine releases only) and the time over which the release occurred. The time-integrated concentration isopleths from routine releases of plutonium are shown in Figure 3-34 as an example. The time-integrated air concentrations at Indiana Street near the southeast corner of the buffer zone are presented in Table 3-19. As can be seen in the table, the most significant release of plutonium is related to the 903 Pad before it was covered in 1969. For enriched uranium, the screening estimate of time-integrated concentration associated with the single day release on January 24, 1956 is actually higher than the estimated value for all routine emissions of enriched uranium over the 37-year period. This is likely an artifact of assuming worst-case meteorological conditions in the absence of site-specific information. As a result, the time-integrated concentration for this single-day release may be overestimated by one or more orders of magnitude. Finally, the release of depleted uranium from the oil pit burning is insignificant compared to routine release of this material.



LEGEND

- SECURITY FENCE
- ROCKY FLATS PLANT BOUNDARY 1951-1974
- ROCKY FLATS PLANT BOUNDARY 1974-PRESENT (WITH BUFFER ZONE ADDED)
- FRONT RANGE OF THE ROCKY MOUNTAINS
- + BUILDING 771 STACK
- + BUILDING 776/777 STACK
- ISOPLETH CONCENTRATION LINES, μCi sec m^{-3}
- 10^{-1} SCIENTIFIC NOTATION: 10^{-1} = 0.1 OR 1/10; 10^{-2} = 0.01 OR 1/100; etc.
- μCi 10^{-6} CURIE

0' 13,200'
SCALE
SCALE: 1" = 2.5 Miles

ChemRisk
A Division of McLaren/Hart

FIGURE 3-34
PREDICTED TIME-INTEGRATED AIR CONCENTRATIONS FOR A 30 mCi RELEASE OF PLUTONIUM OVER 37 YEARS (μCi sec m^{-3})

Rky0194h/rfh3-34.dgn: Rev 05-27-94

TABLE 3-19

TIME-INTEGRATED AIR CONCENTRATIONS FOR RELEASES FROM THE ROCKY FLATS PLANT AT NEAREST RECEPTOR[a,b]
($nCi\ sec\ m^{-3}$)

	Plutonium	Enriched Uranium	Depleted Uranium
Routine Releases	89	49	106
January 24, 1956		83[c]	
903 Pad Direct Release (65-69) Soil Resuspension (70-89)	240 6.3		
1957 Fire	4.1		
1969 Fire	0.56		
Oil Burning			6.1

[a] Southwest corner of buffer zone at Indiana Street, except for the January 24, 1956 enriched uranium release, when the wind was presumed to have come from the north. The nearest receptor for this release event is directly south of the plant, along Highway 72.

[b] Comparisons should not be made between materials, since the time-integrated concentrations are reported in terms of activity and do not take into consideration the dosimetry for the materials.

[c] This estimate is based on worst-case assumptions of wind speed, wind direction, and atmospheric stability, and may be overestimated by one or more orders of magnitude.

REFERENCES

Anderson, B. V. (1964). "Plutonium Aerosol Particle Size Distributions." *Health Physics*, 10:897, 1964, as cited in Kathren (1974).

Angell, O. H. (1955). "Monthly Progress Report—Site Survey—November, 1955." Rocky Flats internal report to E.A. Putzier, December 7, 1955. Repository Document AC-1053.

Angell, O. H. (1956). "Monthly Progress Report—Site Survey—December 1955." Rocky Flats internal report to E.A. Putzier, January 5, 1956. Repository Document AC-1053.

ANSI (1969). "American National Standard Guide to Sampling Airborne Radioactive Materials in Nuclear Facilities." American National Standards Institute, New York, New York. ANSI N13.1-1969

Anspaugh *et al.* (1975). "Resuspension and Redistribution of Plutonium in Soils." *Health Physics*, 29:571-582. Repository Document MO-398.

Barrick C. W. (1981). "Past Accidental Releases of Radioactivity from the Rocky Flats Plant." Rocky Flats Environmental Sciences Department, January 14, 1981. Repository Document IN-449.

Beck, H. L. (1966). *Health Physics*, 12:313.

Burley (1990). Burley, G. "Transuranium Elements. Volume II, Technical Basis for Remedial Actions." Office of Radiation Programs. USEPA, Washington, DC. Report EPA 520/1-90-016. June.

CDH (1978). Colorado Department of Health. "Radioactive Soil Contamination (Cesium 137 and Plutonium) in the Environment near the Rocky Flats Nuclear Plant." September 1977, revised April 1978. Repository Document AC-632.

Chapman, T. (1960). Rocky Flats letter to Dr. N. Woodruff, USAEC Washington, 2/17/60. Repository Document EN-1243.

ChemRisk (1992). "Reconstruction of Historical Rocky Flats Operation and Identification of Release Points." Project Tasks 3 and 4. Final Draft Report. August. Repository Document TA-1202.

ChemRisk (1994). "Estimating Historical Emissions from Rocky Flats." Project Task 5 Report. March. Repository Document TA-1240.

Chick, N. D. (1992). Personal communication. Colorado Department of Health, Air Pollution Control Division. June 19, 1992.

Crow, L. (1974). "Characteristic Airflow Patterns Near Rocky Flats Plant and Their Relationship to Metropolitan Denver." LWC #143. December 16, 1974.

Dow Chemical (1953-1971). Site Survey Locations and Analyses. Repository Document AC-1057.

Dow Chemical (1957). "Report of Investigation of Serious Incident in Building 71 on September 11, 1957 (unclassified version)," Dow Chemical, October 7, 1957, and "Supplementary Report on Fire in Building 71, September 11, 1957," Dow Chemical, December 10, 1957. Repository Document IN-426.

Dow Chemical (1964-1970). Result and Calculation Sheet for On-Site Air Samples (1964-1970). Repository Document AC-1204.

Dow Chemical (1969). Environmental Survey — January-June 1969 and July-December 1969. Dow Chemical Co., Rocky Flats Division, Golden, Colorado. Repository Document AC-159.

Dow Chemical (1970a). A Letter from the Dow Chemical Company to Roy L. Cleere, Colorado Department of Health, March 20, 1970. Repository Document IN-386.

Dow Chemical (1970b). Environmental Survey—January-June 1970. Dow Chemical Co., Rocky Flats Division, Golden, Colorado. Repository Document AC-160.

Dow Chemical (1974). Annual Environmental Monitoring Report—Rocky Flats Plant—January-December 1973. Dow Chemical Co., Rocky Flats Division, Golden, Colorado. Repository Document AC-260.

Dow Chemical (1978). Result Calculation Sheets for On-Site Air Samples and Off-Site Air Samples, 1964-1978. Repository Document AC-1204.

Ettinger, H. J., W. D. Moss, and H. Busey (1967). "Characteristics of the Aerosol Produced from Burning Sodium and Plutonium". *Nuclear Science and Engineering*, 30:1.

Fairfield and Woods (1978). "Pre-Trial Statement." Civil Action Nos. 75-M-1111, 75-M-1162, and 75-M-1296. Repository Document IP-1157.

Fields, D. (1983). "Computation of Radionuclide Particulate Finite Area Fugitive Source Strengths," *Health Physics*, 44:653-655. Repository Document MO-1230.

Geiger, E. L. (1959). "Radioassay of Uranium and Plutonium in Vegetation, Soil and Water." *Health Physics*, 1:405-408.

Hagan P. G., and F.J. Miner (1970). "Water Soluble Plutonium on Plenum Filters." Chemistry Research and Development, Process Engineering. The Dow Chemical Company, Rocky Flats Division. CRDL 950355-4. November 11, 1970. Repository Document MO-759.

Hammond, S. E. (1957a). "Monthly Progress Report—Site Survey—September 1975." Rocky Flats internal report to T. S. Chapman, October 8, 1957. Repository Document AC-1053.

Hammond, S. E. (1957b). "Monthly Progress Report—Site Survey—October 1957." Rocky Flats internal report to C. W. Piltingsrud, November 6, 1957. Repository Document AC-1053.

Hammond, S. E. (1957c). "Monthly Progress Report—Site Survey—November 1957." Rocky Flats internal report to C. W. Piltingsrud, November 6, 1957. Repository Document AC-1053.

Hammond, S. E. (1958a). "Determination of Contamination from Rocky Flats Plant in the Environs—Interim Report", Rough Draft, March 13, 1958. Repository Document IN-1076.

Hammond, S. E. (1958b). "Monthly Progress Report—Site Survey—December 1957." Rocky Flats internal report to T.S. Chapman, January 8, 1958. Repository Document AC-1053.

Hammond, S. E. (1971). "Industrial-Type Operations as a Source of Environmental Plutonium," LA 4576, Proceedings of Environmental Plutonium Symposium held at Los Alamos Scientific Laboratory, August 4-5, 1971. Repository Document RE-721.

Hayden, J. (1974). Rocky Flats Environmental Master File item 00006416, Dow Chemical Rocky Flats Division, Letter from J. Hayden to P. Krey of USAEC Health and Safety Laboratory, September 24, 1974.

Hayden, J. (1977). RFP-2705, Rocky Flats Environmental Sciences report approved on 8/18/77 alternately titled "Effects of Size Fractionation Methods on Plutonium Distribution in Soil," or "Size Fractionation Methods: Measuring Plutonium in Respirable Dust." Repository Document AC-516.

Healy, J. W. (1980). "Review of Resuspension Models" In *Transuranic Elements in the Environment*, W.C. Hanson, ed., DOE/TIC 22800, Technical Information Center, U.S. Department of Energy. Repository Document EN-121.

Higley, K. A. (1992). "Progress Report on Radioecological Investigations at Rocky Flats: Assessment of a Model to Describe the Environmental Transport and Fate of ^{241}Am and ^{239,240}Pu." A report to EG&G Rocky Flats, Inc. from the Department of Radiological Health Sciences, Colorado State University, Fort Collins, Colorado. February 1992.

Hill, J. E. (1957). "Monthly Progress Report — Site Survey — September, 1957," Rocky Flats internal report to E.A. Putzier, October 1, 1957. Repository Document AC-1053.

Hill, J. E. (1993a) Personal communication with Mr. John E. Hill on January 28, 1993.

Hill, J. E. (1993b). Personal communication with Mr. John E. Hill on February 10, 1993.

Hill, J. E. (1993c). Personal communication with Mr. John E. Hill on February 13, 1993.

Hinds, W. (1982). *Aerosol Technology — Properties, Behavior and Measurement of Airborne Particles*, John Wiley & Sons, New York.

Horst, T. (1982). "The Estimation of Airborne and Surface Contamination Resulting from the Deposition-Resuspension Process. *Health Physics*, 43:269-272.

Hunt and Campbell (1984). Hunt, D. and G. Campbell. "HS&E Environmental Sciences Semiannual Progress Report for 1982, January through July." June 25, 1984, Rockwell International, RFP-3650.

Hurley, J. (1980). "High Volume Sampler Evaluation." RFP 2866, Environmental Studies Group Annual Report for 1978.

Jacoe, P. W. (1976). A letter written by Mr. P. W. Jacoe to an unknown person, dated June 9, 1970. Colorado Department of Health, Denver, Colorado. 10 pages.

Kathren, R. L. (1974). "Towards Interim Report BNWL-SA-1510." Appendix A of A Historical Summation of Environmental Incidents Affecting Soils at or Near the USAEC Rocky Flats Plant by J. B. Owen and L. M. Steward. Repository Document RE-318.

Kirchner, R. A. (1966). "A Plutonium Particle Size in Production Areas at Rocky Flats." *Am. Ind. Hygiene J.*, 27:396. Repository Document CH-478.

Kittinger, W. D. (1953a). "Monthly Progress Report for February." Rocky Flats internal report to O.M. Wisdahl, March 5, 1953. Repository Document AC-1053.

Kittinger, W. D. (1953b). "Monthly Progress Report for March." Rocky Flats internal report to O.M. Wisdahl, April 7, 1953. Repository Document AC-1053.

Kittinger, W. D. (1953c). "Monthly Progress Report for April." Rocky Flats internal report to O.M. Wisdahl, May 11, 1953. Repository Document AC-1053.

Kittinger, W. D. (1953d). "Monthly Progress Report for May." Rocky Flats internal report to O.M. Wisdahl, June 5, 1953. Repository Document AC-1053.

Kittinger, W. D. (1953e). "Monthly Progress Report for June." Rocky Flats internal report to O.M. Wisdahl, July 3, 1953. Repository Document AC-1053.

Kittinger, W. D. (1953f). "Monthly Progress Report for July." Rocky Flats internal report to O.M. Wisdahl, August 5, 1953. Repository Document AC-1053.

Kittinger, W. D. (1953g). "Monthly Progress Report for August." Rocky Flats internal report to O.M. Wisdahl, September 2, 1953. Repository Document AC-1053.

Kittinger, W. D. (1954a). "Site Survey Monthly Progress Report for January 1954." Rocky Flats internal report to O.M. Wisdahl, February 1, 1954. Repository Document AC-1053.

Kittinger, W. D. (1954b). "Site Survey Monthly Progress Report for February 1954." Rocky Flats internal report to O.M. Wisdahl, March, 1954. Repository Document AC-1053.

Kittinger, W. D. (1992). Personal communication with Mr. W.D. Kittinger on May 1, 1992.

Krey, P. W. (1974). "Plutonium-239 contamination in the Denver Area." Letters to the Editor reply to "Plutonium-239 contamination in the Denver Area." *Health Physics*, 26:117-220. Repository Document AC-190.

Krey P, R. Knuth, T. Tamura, and L. Toonkel (1974). "Interrelation of Surface Air Concentrations and Soil Characteristics at Rocky Flats," page 744 in "Atmospheric-Surface Exchange of Particulate and Gaseous Pollutants (1974)," Proceedings of a Symposium held at Richland, Washington, September 4-6, 1974. Repository Document AC-706.

Krey, P. W. (1976). "Remote Plutonium Contamination and Total Inventories from Rocky Flats." *Health Physics*, 30:209-214. Repository Document AC-728.

Krey, P., E. Hardy, H. Volchok, L. Toonkel, R. Knuth, M. Coppes, and T. Tamura (1976). "Plutonium and Americium Contamination in Rocky Flats Soil — 1973,". Health and Safety Laboratory Report HASL-304. Repository Document AC-192.

Krey, P., and E. Hardy (1970). "Plutonium in Soil Around the Rocky Flats Plant." Health and Safety Laboratory Report HASL-235. Repository Document AC-193.

Langer, G. (undated). RFP-3461, "Activity, Sizes, and Flux of Resuspended Particles from Rocky Flats Soil." Repository Document MO-202.

Langer (1974). "Wind Resuspension of Trace Amounts of Plutonium Particles from Soil in a Semi-Arid Climate." RFP-3633, 1973. Repository Document AC-467.

Langer, G. (1979). "Draft Report - Plutonium and Beryllium Plenum Filter Loading Estimates for Accidental Stack Release Calculations." Rocky Flats Environmental Studies Group, November 1979. Repository Document RE-776.

Langer, G. (1980). "Fugitive Dust Measurement and Modeling." RFP 2866 Environmental Sciences Group Annual Report for 1978. Edited by D. C. and J. D. Hurley, Rockwell International, Energy Systems Group, Rocky Flats Plan, Golden, Colorado. August 21, 1980. RFP-2866. Repository Document EN-1238.

Langer, G. (1985a). "Dust Transport — Wind Blown and Mechanical Resuspension," Rocky Flats Internal Progress Report, July - December 1985. Repository Document MO-96.

Langer, G. (1985b). "Wind Resuspension of Trace Amounts of Plutonium Particles from Soil in a Semi-Arid Climate." Internal Rocky Flats Report (RFP-3633), Rockwell International, Golden, Colorado. Repository Number AC-467.

Langer (1986). Langer, G. "Dust Transport - Wind Blown and Mechanical Resuspension." September 20, 1986, Rockwell International, RFP-3914.

Langer, G. (1989). "Resuspension of Soil Particles from Rocky Flats Containing Plutonium Particles — A Review." Rockwell International Rocky Flats, December 1989. Repository Document RE-766.

Lee *et al* (1982). Lee S. Y., E. A. Bondietti, and T. Tamura. "Dissolution Characteristics of Pu-Contaminated Soils and Sediments in Lung Serum Stimulant Solution." *Health Physics*, 43(5):663-668.

Leidel, N., K. Busch, and J. Lynch (1977). *Occupational Exposure Sampling Strategy Manual*, Technical Appendix K (NIOSH 77-173).

Lilliefors, H. W. (1967). "On the Kolmogorov-Smirnov Test for Normality with Mean and Variance Unknown." *J. Am. Stat. Ass.*, p. 399-402.

Lindeken, C. L. (1961). "Use of Natural Airborne Radioactivity to Evaluate Filters for Alpha Air Sampling." *Am. Ind. Hyg. Ass. J.*, 22(4):232-237.

Lindeken, C. L., R. L. Morgan and K. F. Petrock (1963). "Collection Efficiency of Whatman 41 Filter Pater for Submicron Aerosols." *Health Physics*, 9:305-308.

Linkenheil, D. G. (1990). "An Estimation of the Risk From Plutonium in Soil at Guideline Levels of the Colorado Department of Health and the Environmental Protection Agency." Masters Thesis, Colorado State University. March 1, 1990.

Litaor, M. I. (1993). "Spatial Analysis of Plutonium Activity in Soils East of Rocky Flats Plant." Proceedings of the Twenty-Sixth Mid-Year Topical Meeting of the Health Physics Society, January 24-28, 1993.

Little, C. A. (1976). "Plutonium in a Grassland Ecosystem." Dissertation, Colorado State University. Repository Document EN-198.

Little, C. A., and F. Whicker (1978). "Plutonium Distribution in Rocky Flats Soil." *Health Physics*, 34:451, 1978.

Little, C. A. (1980). "Plutonium in a Grassland Ecosystem: In: *Transuranic Elements in the Environment*. W. C. Hanson ed. pp. 420–440. DOE/TIC-22800. U.S. DOE Oak Ridge, TN.

Loser, R., and R. Tibbals (1972). "Soil sampling East of Indiana Street." RFP report #317-72-186, prepared for J. Willing, dated Nov 29, 1972. Given as Appendix D-3 of: Final Past Remedy Report, Operable Unit No. 3 — IHSS 199, May 1991. Repository Document RE-95.

Loser, R. (1971). Plutonium in Soil Surrounding the Rocky Flats Plant, RFP #482-71-4, prepared for J. Seed, dated April 26, 1971. Product Research and Development Service Report. Repository Document RE-763.

Martell, E. (1975). "Actinides in the Environment and Their Uptake by Man." National Center for Atmospheric Research Technical Note NCAR-TN/STR-110. May 1975. Repository Document IP-807.

Moore, R. E., C. F. Baes, III, L. M. McDowell-Boyer, A. P. Watson, F. O. Hoffman, J. C. Pleasant and C. W. Miller (1979). "*AIRDOS-EPA: A Computerized Methodology for Estimating Environmental Concentrations and Dose to Man form Airborne Releases of Radionuclides.*" EPA 520/1-79-009.

Morris, D., and A. Johnson (1967). "Summary of Hydrologic and Physical Properties of Rock and Soil Materials as Analyzed by the Hydrologic Laboratory of the U.S. Geological Survey — 1948-1960," USGS Water Supply Paper 1839-D.

NBS (1984). National Bureau of Standards. *Estimating a Lower Limit of Detection for Radiological Effluent and Environmental Measurements.* 1984.

NCRP (1985). National Council on Radiation Protection and Measurements. "Radiological Assessment: Predicting the Transport Bioaccumulation and Uptake by Man of Radionuclides Released to the Environment." Report 76. Bethesda, MD, pg. 69.

Owen, J., and L. Steward (1974). "Environmental Inventory: A Historical Summation of Environmental Incidents Affecting Soil at or near the USAEC Rocky Flats Plant" January 1974. Repository Document RE-318.

Peterson, W. B. (1986). "A Demonstration of INPUFF with the MATS Data Base." *Atmospheric Env.*, 20(7):1341-1346.

Peterson, H. T. (1983). "Terrestrial and Aquatic Food Chain Pathways." In: *Radiological Assessment: A Textbook on Environmental Dose Analysis.* Edited by J. E. Till and H. R. Meyer. U.S. Government Printing Office, Washington D.C.

Poet, S., and E. Martell (1972). "Plutonium-239 and Americium-241 Contamination in the Denver Area." *Health Physics*, 23:537-548. Repository Document AC-641.

Randerson, D (1984). "Power Production and the Atmosphere." In: *Atmospheric Science and Power Production.* Edited by Darryl Randerson. Technical Information Center, Office of Scientific and Technical Information, U.S. Department of Energy. 1984.

Rao, K. S. (1981). "*Analytical Solutions of A Gradient-Transfer Model for Plume Deposition and Sedimentation.*" National Oceanic and Atmospheric Administration, Silver Springs, Maryland. September 1981. PB82-2151153

Rimberg, D. (1969). "Penetration of IPC 1478, Whatman 41, and Type 5G Filter Pater as a Function of Particle Size and Velocity." *Am. Ind. Hyg. Ass. J*, 30(4):394-401.

Rockwell International. (1971). "Rocky Flats Plant and Surrounding Area Contours, Drawing #18789-2, Issue B, Sheet 2 of 3." It is also called: "Soil Sampler Locations," #PRD 482-71-4. ChemRisk document #92CR021, Item 1 A45702.

Rockwell International (1984). "Standley Lake Sample Collection Summary, August, 1984."

Rockwell Technical Report (1985). "Airflow Patterns near the Rocky Flats Plant" Technical Report 1985-02, February 1985. United States Department of Energy Administration Contract DE-AC04-76DP03533.

Schwendiman *et al.* (1968). Schwendiman L.C., J. Mishima, and C.A. Radasch. "Airborne Release of Particles in Overheating Incidents Involving Plutonium Metal and Compounds. Pacific Northwest Laboratory, Battelle Memorial Institute. Richland, Washington. Repository Document RE-1251.

Seed, J., K. Calkins, C. Illsley, F. Miner, and J. Owen (1971). "Committee Evaluation of Plutonium Levels in Soil Within and Surrounding USAEC Installation at Rocky Flats, Colorado." Dow Chemical Rocky Flats Division Report RFP-INV-10. Repository Document AC-726.

Sehmel, G. (1976). "Airborne Pu-238 and Pu-239 Associated with Larger Than Respirable Resuspended Particles at Rocky Flats during July 1973," Battelle Pacific Northwest Laboratories. BNWL-2119, Repository Document RE-832.

Sehmel, G. (1980). "Particle Resuspension: A Review." *Environment International*, 4:107-127. Repository Document RE-831.

Sehmel, G. (1982a). "Resuspension Rates from Aged Inert-Tracer Sources," pg. 1072, Vol. 2 in *Precipitation Scavenging, Dry Deposition, and Resuspension — Proceedings of 4th International Conference*, Pruppacher *et al.*, editors, Elsevier. Repository Document MO-1207.

Sehmel, G. (1982b). "Resuspension Factors for Aged Plutonium Sources." pg. 36 in Part 3, Pacific Northwest Laboratory Annual Report for 1981 to the DOE Office of Energy Research.

Sehmel, G. A. (1984). "Deposition and Resuspension." In: *Atmospheric Science and Power Production*, edited by D. Randerson. Technical Information Center, Office of Scientific and Technical Information, U.S. Department of Energy. DOE/TIC-27601 (DE84005177).

Sehmel, G., and W. Hodgson (1978). "A Model for Predicting Dry Deposition of Particles and Gases to Environmental Surfaces." PNL-SA-6721, Battelle Pacific Northwest Laboratories.

Setter, L. R. and G. I. Coats (1961). "The Determination of Airborne Radioactivity." *Am. Ind. Hyg. Ass. J.*, 22(1)64-69.

Shinn, J. (1991). "Enhancement Factors for Resuspended Aerosol Radioactivity: Effects of Topsoil Disturbance." Fifth Annual Conference on Precipitation Scavenging and Atmosphere-Surface Exchange Processes, July 15 - 19, 1991, Richland, Washington.

Shinn (1994). Shinn, J. H. Personal communication with Joseph H. Shinn of Lawrence Livermore National Laboratory. April, 1994.

Shinn (1992). Shinn, J.H. "Enhancement Factors for Resuspended Aerosol Radioactivity: Effects of Topsoil Disturbance." In: *Precipitation Scavenging and Atmosphere-Surface Exchange Volume 3 — The Summers Volume: Applications and Appraisals*. Proceedings of the Fifth International Conference on Precipitation Scavenging and Atmosphere-Surface Exchange Processes, Richland, WA, July 15-19, 1991. Hemisphere Publishing Corporation.

Shinn, J., *et al.* (1982). "Plutonium Aerosol Fluxes and Pulmonary Exposure Rates During Resuspension from Bare Soils near a Chemical Separation Facility," pg. 1131, Vol. 2 in *Precipitation Scavenging, Dry Deposition, and Resuspension — Proceedings of 4th International Conference*. Pruppacher *et al.*, editors, Elsevier. Repository Document MO-1155.

Slinn, W.G.N. (1984). "Precipitation Scavenging." In: *Atmospheric Science and Power Production*. Edited by Darryl Randerson. Technical Information Center, Office of Scientific and Technical Information, U.S. Department of Energy.

Smith, W., F. Whicker, and H. Meyer (1982). "Review and Categorization of Saltation, Suspension and Resuspension Models." *Nuclear Safety*, 23(6):685. Repository Document MO-396.

Stewart, K. (1963). *Progress in Nuclear Energy*. (Series V) 5:535, 1963, as cited in Kathren (1974).

Stewart, K. (1965). "Proceedings of the International Symposium on Radioactive Pollution of Gaseous Media." Vol. II, Presses Universitaires de France, Paris 1965, pp. 327-366, as cited in Kathren (1974).

USAEC (1969). "Report on Investigation of Fire, Building 776-777, Rocky Flats Plant, Golden, Colorado, May 11, 1969." U.S. Atomic Energy Commission, August 1969. Repository Document IN-775.

USDOE (1980). "Final Environmental Impact Statement, Rocky Flats Plant Site, Golden, Jefferson County, Colorado." Volume 1. U.S. Department of Energy, April 1980, DOE/EIS-0064. Repository Document EN-1.

USDOE (1991). "Final Past Remedy Report — Operable Unit No. 3 — IHSS 199," May 1991. Repository Document RE-95.

USDOE (1992). "Historical Release Draft Report for the Rocky Flats Plant — Volumes I and II." U.S. Department of Energy, January 1992. Repository Document RE-1139.

USEPA (1970). *Workbook of Atmospheric Dispersion Estimates*. D.B. Turner, EPA Office of Air Programs.

USEPA (1971). "Radioactivity Levels in the Environs of the Rocky Flats Plutonium Plant, Golden, Colorado, 1970." April 1971. USEPA.

USEPA (1973). "Radioactivity Levels in the Environs of the Rocky Flats Plutonium Plant, Golden, Colorado, 1970. Part II. December 1973, USEPA.

USEPA (1977). "Rocky Flats Facility/Technical Assessment Document." Repository Document EN-730.

USEPA (1979). "AIRDOS-EPA: A Computerized Methodology for Estimating Environmental Concentrations and Dose to Man from Airborne Releases of Radionuclides." December 1979, U.S. Department of Commerce NTIS PB80-147838.

USEPA (1990). "Transuranium Elements. Volume 1, Elements of Radiation Protection." Office of Radiation Programs. USEPA, Washington, DC. Report EPA 520/1-90-015.

Volchok, H. L., R. H. Knuth, and M. T. Kleinman (1972). "The Respirable Fraction of Plutonium at Rocky Flats." *Health Physics*, 23:395. Repository Document RE-639.

Winges, K. D. and F. J. Gombar (1990a). "Fugitive Dust Model (FDM)—First Validation Study." Appendix A-1 of *User's Guide for the Fugitive Dust Model (FDM) (Revised)* May 1992.

Winges, K. D. and F. J. Gombar (1990b). "Fugitive Dust Model (FDM)—Second Validation Study." Appendix A-2 of *User's Guide for the Fugitive Dust Model (FDM) (Revised)* May 1992.

Woodard, R. W. (1971). "Plutonium Particulate Studies on Booster System No. 3 (Building 771) Filter Plenum." Chemistry Research and Development, Process Engineering. The Dow Chemical Company, Rocky Flats Division. CRDL 940610-1. January 27, 1971. Repository Document RE-687.

APPENDIX A

TRITIUM EXPOSURE MODELING

APPENDIX A

TRITIUM EXPOSURE MODELING

Tritium is known to have been released from the Rocky Flats Plant into the environment. The approaches to evaluating the environmental fate and transport of tritium differ from the other materials of concern. Since tritium released as tritiated water or hydrogen readily mixes with its stable counterparts in nature, specific exposure pathways are not identified. Instead, numerous alternative methodologies have been proposed for evaluating exposure to tritium. In 1969, Evans proposed what is referred to as the specific activity method (Till, 1983), which assumes that the concentrations of tritium in the atmosphere, water, biota and humans are equal at a given location. Since this is a very unlikely assumption, the National Council on Radiation Protection and Measurement (NCRP) proposed a variation of this method that can be used when the tritium concentrations in air, water and food products are known or can be estimated (NCRP, 1979). The NCRP model assumes the dose of tritium through various exposure pathways depends on the relative contribution to the total water intake of a reference individual. The annual dose per unit concentration for 3 liters per day water intake can be described by the following equation:

$$D = \frac{1.22\ C_W + 1.27\ C_{f1} + 0.22\ C_{f2} + 0.22 C_a}{3.0} \times DRF$$

where:

D	=	annual dose (mrem),
C_w	=	concentration of tritium in drinking water (pCi L^{-1}),
C_{f1}	=	concentration of tritium in water in food (pCi L^{-1}),
C_{f2}	=	concentration of tritium oxidized to water upon metabolism of food (pCi L^{-1})
C_a	=	concentration of tritium in atmospheric water (pCi L^{-1}), and
DRF	=	dose rate factor (mrem yr^{-1} per pCi L^{-1}). The dose rate factor used by the NCRP is 95×10^{-6} mrem yr^{-1} per pCi L^{-1} .

The concentration of tritium in atmospheric water is determined by the following equation:

$$C_a = \frac{C_{air}}{AH}$$

where:

C_a = concentration of tritium in atmospheric water (pCi L^{-1})

C_{air} = concentration of tritium in the atmosphere (pCi m^{-3}), and

AH = atmospheric humidity (g_{water} m^{-3}_{air} or ml_{water} m^{-3}_{air}).

Historical measurements of concentrations of tritium in food products around the Rocky Flats plant are not available. Consistent with the recommendation of NCRP (1979), it is assumed in this evaluation that tritium concentration in food is equal to that in air, i.e., $C_f = C_a$. The U. S. Nuclear Regulatory Commission (USNRC, 1977) suggests a value of 50 percent of that in the air based upon a model published by Anspaugh *et al.* (1972). However, more recent studies indicate that tritium concentration in vegetation rapidly approaches that in air after a release event (Murphy and Pendergast, 1979; Murphy *et al.*, 1982).

Monitoring data of tritium in the drinking water of several cities around the plant from 1970 through 1989 are available and will be used in the evaluation of tritium exposure through drinking water pathway. A majority of the contamination is believed to be associated with liquid effluent releases (ChemRisk, 1994). Contribution of airborne tritium releases to tritium concentration in drinking water is expected to be relatively small. NCRP (1979) suggests concentration of tritium in drinking water can be assumed to be equal to 1 percent of that in the air. As exposure to tritium in drinking water will be evaluated by a different approach, this pathway is not included in the specific activity method, i.e., $C_w = 0$.

Values of other parameters used in calculation of radiation dose as a result of tritium exposure are provided in Table A-1.

TABLE A-1
PARAMETERS RELEVANT TO TRITIUM DOSE ASSESSMENT

Parameter	Units	Distribution	Mean/Mode	Range	Reference
F_f	dimensionless	Triangular	0.4	0.1 - 0.7	Professional Judgement
F_a	dimensionless	Uniform	NA	0.5 - 1.0	Professional Judgement
AH	g m^{-3}	Triangular	4.7	3.5 - 5.5	Etnier, 1980

REFERENCES

Anspaugh *et al.* (1972). Anspaugh, L.R., J.J. Korando, W.L. Robertson, and J.R. Martin. "Dose to Man Via the Food-Chain Transfer Resulting from Exposure to Tritiated Water Vapor." UCRL-73195, Rev. 1, Lawrence Livermore Laboratory, Livermore, CA.

ChemRisk (1994). ChemRisk Division, McLaren/Hart Environmental Engineering. "Estimating Historical Emissions from Rocky Flats." Task 5 Report, Rocky Flats Phase I Health Studies.

Etnier (1980). Etnier, E.L. "Regional and Site-Specific Absolute Humidity Data for Use in Tritium Dose Calculations." *Health Physics* 39(2):318-320.

Murphy and Pendergast (1979). Murphy, C.E., Jr., and M.M. Pendergast. "Environmental Transport and Cycling of Tritium in the Vicinity of Atmospheric Releases." In: *Symposium on the Behavior of Tritium in the Environment*, S. Freeman, ed., International Atomic Energy Agency, Vienna.

Murphy *et al.* (1982). Murphy, C.E., Jr., C.W. Sweet, and R.D. Fallon. "Tritium Transport Around Nuclear Facilities." *Nuclear Safety* 23(6), 677-85.

NCRP (1979). National Council on Radiation Protection and Measurements. "Tritium in the Environment." NCRP Report No. 62, Washington D.C.

Till (1983). Till, J.E. "Models for Special-Case Radionuclides." In: *Radiological Assessment, a Textbook on Environmental Dose Analysis*. J.E. Till and H. R. Meyer, eds. United States Nuclear Regulatory Commission, Washington D.C.

USNRC (1977). U.S. Nuclear Regulatory Commission. "Calculation of Annual Doses to Man from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR Part 50, Appendix I." Regulatory Guide 1.109. Office of Standards and Development. Washington, D.C.

APPENDIX B

RATIONALE FOR SELECTING COMPLETE EXPOSURE PATHWAYS

APPENDIX B
RATIONALE FOR SELECTING COMPLETE EXPOSURE PATHWAYS

B.1 Air

The rationale for selecting the complete exposure pathways for materials released to the atmosphere is detailed below.

Air - Humans (Inhalation/Immersion)

Both solvent vapors and metal particulates released from the plant are likely to have reached off-site locations. For vapors, direct inhalation exposure is a complete pathway. Whether inhalation is a complete pathway for particulates depends on the size of the particulates. According to the American Conference of Governmental Industrial Hygienists (ACGIH) and the U.S. Atomic Energy Commission (USAEC), respirable particulates have aerodynamic diameters less than 10 μm. Table B-1 shows the relationship between particle size and percent of particles considered respirable (Hinds, 1982). Metals released from the Rocky Flats Plant during routine operations were predominately submicron-sized (i.e., < 1 μm) particles. Additionally, some of the particles released from the 1957 fire and the 903 pad are believed to have been less than 5 μm in diameter. Inhalation exposure is therefore considered a complete pathway for the metals released from routine and nonroutine operations.

TABLE B-1
CRITERIA FOR RESPIRABLE DUST[a]

Aerodynamic Diameter (μm)	Percent Respirable per USAEC	Percent Passing Selector per ACGIH
<2	100	90
2.5	75	75
3.5	50	50
5.0	25	25
10	0	0

a Hinds, 1982

In addition to direct inhalation, individuals may be exposed to certain airborne radionuclides by immersion. Immersion exposure occurs when the atmosphere around an individual contains gamma emitting radionuclides. Isotopes of three of the four radionuclides of concern, i.e., americium, plutonium, and uranium, produce both alpha and gamma radiation. When these radioactive elements are ingested or inhaled, internal exposure due to alpha radiation is the main health concern. However, if these elements are outside the body, alpha radiation is not a health

concern, and immersion becomes a relevant route of exposure. Since these radionuclides produce gamma radiation, immersion is also considered a complete exposure pathway.

Air - Livestock - Humans (Ingestion) Air - Vegetation - Humans (Ingestion) Air - Vegetation - Livestock - Humans (Ingestion)

Airborne contaminants can be inhaled by farm animals and reach humans through the food chain, and contaminants deposited on fruits or vegetables can be taken up by humans through ingestion. Additionally, contaminants deposited on pasture can be taken up by grazing cattle, and, subsequently, by humans through meat and milk ingestion. Based on information collected for Task 7 (ChemRisk, 1994a), vegetable gardens, beef cattle, and, to a limited extent, dairy cattle were raised in the immediate vicinity of Rocky Flats in the past. Therefore, indirect exposures to the materials of concern through the ingestion of vegetables, beef, and milk are all considered complete pathways.

No large sheep, pig, or chicken raising operations were identified in the immediate vicinity of the plant. Exposure pathways related specifically to these animals are not evaluated further.

B.2 Surface Water

The rationale for selecting complete exposure pathways for materials released to surface water is detailed below.

Water - Humans (Ingestion)

As described in the Task 5 report, Great Western Reservoir has been the municipal water supply for Broomfield since 1955, and Standley Lake has provided water to Westminster, Northglenn and Thornton since 1966 (ChemRisk, 1994b). As a result, ingestion of drinking water is a complete exposure pathway for the areas serviced by Great Western Reservoir and Standley Lake.

Water - Humans (Dermal contact) Water - Humans (Immersion) Water - Fish - Humans (Ingestion)

As described in the Task 7 report (ChemRisk, 1994a), Standley Lake is open to the public for recreational uses. For this reason, fish ingestion, and dermal contact with and immersion in contaminated water are complete pathways for nonvolatile materials of concern. In contrast, these pathways are not considered complete for Great Western Reservoir as it is closed to the public.

Water - Livestock - Humans (Ingestion) Water - Vegetation - Humans (Ingestion) Water - Vegetation - Livestock - Humans (Ingestion)

Water from Great Western Reservoir has been used for irrigation in the past; however, this practice was stopped in 1955 (ChemRisk, 1994b). Since 1914, water from Standley Lake has been used for irrigation; some of the water is transported through ditches to irrigate agricultural areas northeast of the lake. As vegetable gardens and cattle were raised in the immediate vicinity of Rocky Flats in the past, these indirect food-chain pathways related to the surface waters of Great Western Reservoir and Standley Lake are considered complete.

B.3 Soil and Sediment

The rationale for selecting complete pathways for materials released to soil and sediment is detailed below.

Soil/sediment - Humans (Ingestion) Soil/sediment - Humans (Dermal Contact) Soil/sediment - Humans (Ground Exposure)

Contaminants in surface soils, including sediment, can be taken up by humans through ingestion or dermal contact. Additionally, humans may be exposed to certain radionuclides in surface soil through ground exposure. Ground exposure occurs when an individual is exposed to gamma radiation emitted from radionuclides deposited on the ground surface. Although contaminants in surface soil can be carried to deeper soil through percolation of rain water, this is a very slow process for nonvolatile materials due to their low water solubilities. Soil ingestion, dermal contact, and ground exposure are therefore considered complete exposure pathways at Rocky Flats. Since Standley Lake is open to the public, these pathways are also considered complete for exposed shoreline sediments.

Soil/sediment - Air - Humans (Inhalation/Immersion)

As discussed above, soil contaminants can, under certain conditions, be resuspended into the atmosphere. When an individual is near contaminated topsoil, inhalation of and immersion in the resuspended soil particulates can take place. Since contaminants were detected in many off-site soil samples and in some sediment samples taken from Standley Lake, inhalation of and immersion in resuspended soil particles are considered complete pathways.

Soil - Livestock - Humans (Ingestion
Soil - Vegetation - Humans (Ingestion)
Soil - Vegetation - Livestock - Humans (Ingestion)

Besides direct exposures, contaminants in soil can migrate through the food chain and reach humans. Beef and milk can be contaminated in two ways:

1) contaminants in soil can be absorbed by pasture through the root system or deposited onto pasture following resuspension and then ingested by grazing cattle, or

2) contaminants in soil can be taken up by cattle through soil ingestion.

If vegetables and food crops are grown on contaminated soil, they are also likely to be contaminated through root absorption or deposition. Vegetable gardens, beef cattle and, to a limited extent, dairy cattle were raised in an area with soil contamination; therefore, these indirect pathways are considered complete for the metals of concern.

REFERENCES

ChemRisk (1994a). "Demographic and Land Use Reconstruction of the Area Surrounding Rocky Flats Plant." Project Task 7 Report. April. Repository Document RE-214.

ChemRisk (1994b). "Estimating Historical Emissions from Rocky Flats." Project Task 5 Report. March. Repository Document TA-1240.

Hinds (1982). Hinds, W. *Aerosol Technology—Properties, Behavior and Measurement of Airborne Particles*. John Wiley & Sons, New York.

APPENDIX C

GROUNDWATER EVALUATION

APPENDIX C
GROUNDWATER EVALUATION

C.1 Groundwater Systems at Rocky Flats

This section provides a brief overview of the hydrogeology of the Rocky Flats area reported in the Rocky Flats Plant Site, Final Environmental Impact Statement (USDOE, 1980) in relation to groundwater as a transport medium. This appendix presents the results of an initial evaluation performed in early 1992, as well as an early 1993 re-evaluation in the form of an addendum based on new site data and information that revised our understanding of the geology of the site.

The surficial material at the plant property is the Rocky Flats Alluvium. It is comprised of clay, sand, gravel and cobbles. The shallow groundwater system in the Rocky Flats Alluvium is under unconfined conditions. Beneath the alluvium is the bedrock, comprised of the Arapahoe and Laramie Formations. The majority of the groundwater movement in the Arapahoe Formation occurs in sandstone lenses, including a recently-identified basal conglomeratic sandstone. This medium-grained to conglomeratic sandstone marker bed located at the bottom of the Arapahoe Formation was interpreted to represent a meandering channel deposit beneath the Rocky Flats plant and as a braided river downslope of the Rocky Flats plant. Groundwater in the sandstone lenses and the alluvium are now believed to be hydraulically-connected. Flow direction in these two groundwater systems is easterly to an area of discharge near Fort Lupton, Colorado. The Laramie Formation can be separated into two geological units. The Upper Laramie consists mainly of relatively impermeable claystone with thin sandstone lenses. The Lower Laramie is more permeable as it is comprised of sandstones and siltstones. Due to recent revisions to the hydrogeologic model beneath the site, investigators believe that some of the uppermost sandy units in the upper Laramie Formation may be hydraulically connected to the alluvium and Arapahoe transmissive units. However, due to the thickness of the predominantly clayey Upper Laramie (300-350 ft, EG&G, 1992), the Lower Laramie would be hydraulically distinct from the shallow water-bearing units.

The groundwater pathway review for the purposes of this project is based on an evaluation of the following sources:

- Hydrogeologic reports, including:

  Phase II Geologic Characterization Data Acquisition Final Report, prepared for EG&G Rocky Flats, Inc. by Ebasco Services, Inc. (EG&G, 1992); and

  Section 3.4 (Groundwater Monitoring) of a 1991 Site Environmental Report for the site (EG&G, 1991a);

- 1989-1991 analytical data from monitoring wells located at the Rocky Flats Plant;

- A residential well inventory for areas down-gradient of the Rocky Flats plant; and

- Discussions with Colorado State, federal, and EG&G personnel.

This evaluation focuses on the following:

- Potential exposure pathways for down-gradient populations;
- Potential routes of transport;
- Potential for and evidence of historical off-site contaminant migration from the Rocky Flats plant within the groundwater pathways; and
- Uncertainties.

These points are discussed in the following sections.

C.2 Exposure Pathways for Down-gradient Populations

Three potential groundwater-related exposure pathways are identified for the populations located down-gradient of the Rocky Flats plant. These pathways include contact with municipal well water, private well water, and surface waters contaminated by groundwater.

Out of the three potential exposure pathways, contact with contaminated municipal well water would potentially affect the largest area and population. The municipal wells for the cities located east or down-gradient of the Rocky Flats plant draw water from the Laramie aquifer, at approximately 1000 ft below ground surface (Nachtrieb and Schnoor, 1991). These depths indicate that the municipal wells would actually be screened in the Lower Laramie Formation. This aquifer is recharged up-gradient of the Rocky Flats plant and is separated vertically from the Rocky Flats plant by a thick layer of fairly impermeable claystone and shale (Hurr, 1976). As a result, contaminants in the topsoil on the plant property are unlikely to have reached the lower Laramie aquifer and contaminated municipal well water. It is unlikely that the municipal wells represent a potential exposure pathway for down-gradient populations.

Based on the geology of the site, the only plausible groundwater exposure pathways would be:

(1) contact with groundwater that reaches individuals through private residential or agricultural wells (which draw water from various permeable zones or shallow aquifers) located down-gradient of the Rocky Flats plant; and

(2) contact with surface waters contaminated by groundwater.

C.3 Routes of Transport

Based on the hydrogeologic characteristics of the Rocky Flats plant area, five potential contaminant transport routes have been identified that could lead to possible down-gradient exposure. These potential routes consist of:

(1) Contaminants infiltrating through the alluvium directly into the permeable sandbeds of the Arapahoe and Upper Laramie Formations and moving down-gradient toward individual wells that happen to be screened in the same permeable zones.

(2) Contaminants infiltrating into the alluvium, moving down-gradient along the alluvial/bedrock interface to individual wells that happen to be screened in the same permeable alluvial zones.

(3) Contaminants moving down-gradient along the alluvial/bedrock interface for some distance, further infiltrating into the Arapahoe Formation, and traveling toward the wells of concern.

(4) Contaminants moving down-gradient along the alluvial/bedrock interface, eventually emerging at a seep or spring where the water table meets a sloping ground surface. These seeps and springs in turn would carry any potential contaminants to surface water bodies such as stream channels or lakes.

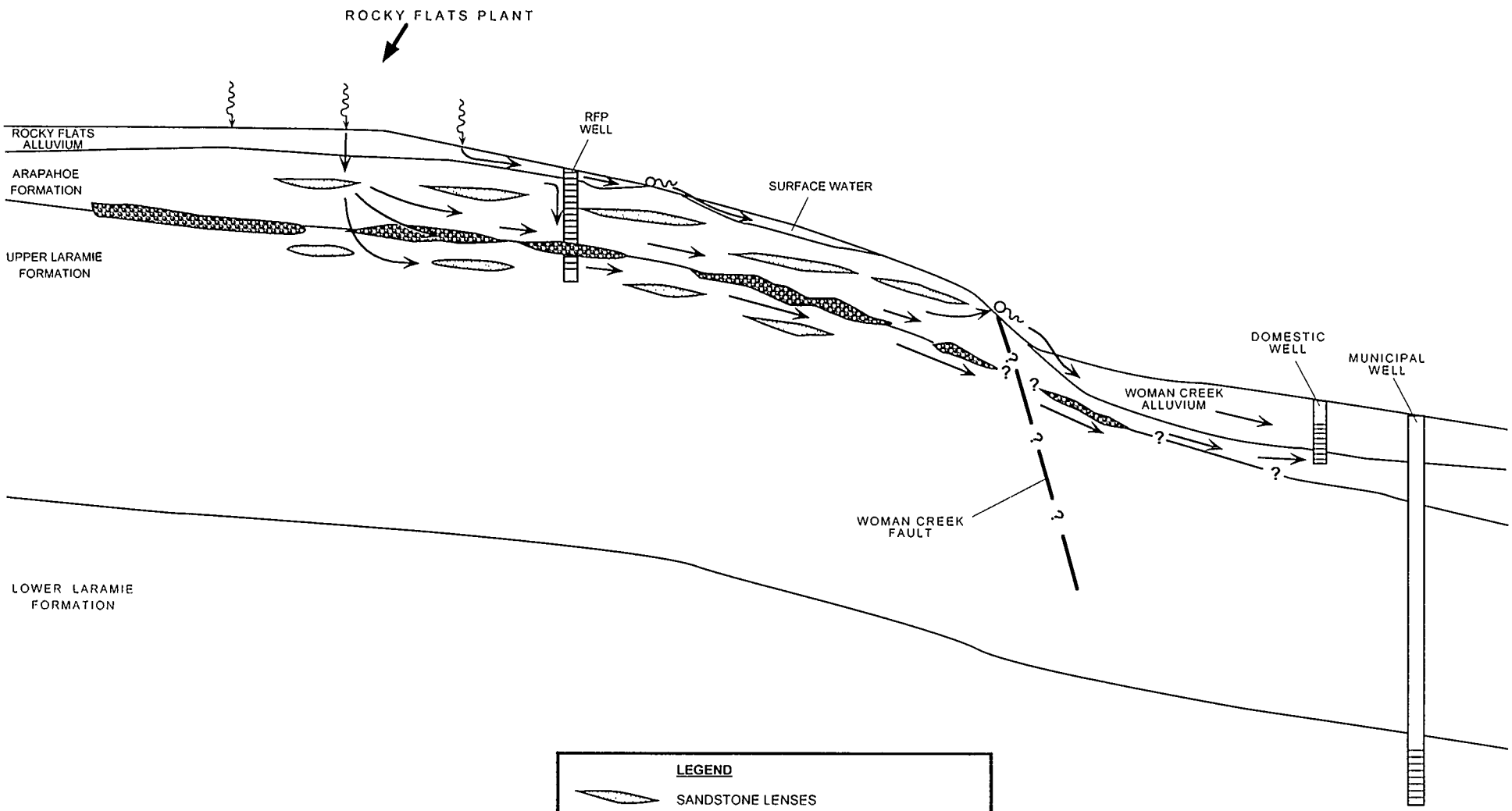
(5) Contaminants in surface water infiltrating into the alluvium or down into the Arapahoe Formation and moving to wells of concern.

Figure C-1 is a graphic representation of the identified potential groundwater transport routes. The relative importance of potential groundwater transport routes are discussed below with respect to the relevant geologic framework, the hydrologic characteristics, and monitoring well data. For each potential transport route, concluding remarks as to the level of concern that should be placed on contaminants moving along that route are also given.

C.3.1 Alluvium/Bedrock Pathways

This pathway involves contaminants infiltrating through the Rocky Flats Alluvium directly into the underlying bedrock units. The time that it takes for water to infiltrate through the alluvium is considered to be negligible for the study of this pathway. Migration along this pathway would be within the hydraulically connected alluvium, Arapahoe Formational and sandstones within the upper portions of the Upper Laramie Formation.

The Rocky Flats alluvium varies between 10 and 20 feet (ft) thick beneath the RFP (EG&G, 1992). The Arapahoe Formation is composed primarily of sandstones and claystones with a distinctive medium-grained conglomeratic sandstone marker bed located at the contact with the Laramie Formation. The Arapahoe Formation varies between 15 and 25 ft thick beneath the RFP (EG&G, 1992). The upper portion of the Laramie Formation is approximately 300 to 350 ft



LEGEND

- SANDSTONE LENSES
- CONGLOMERATIC SANDSTONE MARKER BED
- POTENTIAL GROUNDWATER FLOWPATHS DISCUSSED IN TEXT
- SPRINGS
- INFILTRATING WATER

THIS FIGURE IS NOT TO SCALE

ChemRisk
A Division of McLaren/Hart

FIGURE C-1
POTENTIAL GROUNDWATER
TRANSPORT ROUTES OF CONCERN
ROCKY FLATS PLANT
CONCEPTUAL MODEL

thick and is composed primarily of claystones with beds of very fine to medium-grained sandstone (EG&G, 1992). The sandstone beds of the upper Laramie and Arapahoe Formations and the marker bed were formed in moderate to high energy environments with moderate to high deposition rates.

The marker bed as described in the Ebasco report is fairly continuous throughout the RFP area, based on the evaluation of surface exposures and well log information. Sandstone beds reclassified to the Arapahoe and upper Laramie Formations are assumed to be lenticular and laterally discontinuous at the RFP Site (EG&G, 1992). All RFP wells appear to be screened in the Arapahoe and upper Laramie Formations. However, reclassification based on reinterpretation of sub-surface geology may be required for the RFP wells and other wells downgradient of the RFP.

The hydraulic connection described between the alluvium and the permeable beds in the Arapahoe and upper Laramie Formation (EG&G, 1991a), reportedly represents an upper, unconfined aquifer in these geologic units. This unconfined aquifer represents a potential combined groundwater pathway for contaminant migration within the alluvium, Arapahoe and upper Laramie Formations. Assuming that the Alluvium/Bedrock pathway from the RFP area exists, the exposure points for potentially-contaminated water would be domestic or agricultural wells screened in the alluvium, Arapahoe or upper Laramie Formations. There are no registered wells within the first mile downgradient of Indiana Street (the property boundary), while at least 15 registered wells are located within the second mile downgradient of the RFP property boundary. Of these 15 wells, seven are screened between 50 ft and 200 ft below ground surface, which are depths that the sandstone beds and marker bed would be found if their regional dip, known to be approximately 1-2 degrees to the east beneath the RFP, is extended two miles east of the site. Two of the 15 wells, are screened approximately 10 ft below ground surface in alluvial deposits.

It has not been established whether the sandstone beds in the Arapahoe and upper Laramie Formation found at the RFP extend further east than Indiana Avenue; therefore it may not be appropriate to assume that the individual wells found two miles east of the site are screened in the same sandstone beds as the RFP wells. In addition, information is not available on whether the alluvium, Arapahoe and upper Laramie Formations are in hydraulic connection east of the RFP site. However, the marker bed is documented in many RFP wells logs and has been found south of RFP in the Golden area and east of RFP in surface exposures near Standley Lake. For the purposes of assessing potential contaminant transport along the Alluvium/Bedrock pathway from the center of RFP to wells located two miles east of the site, potential travel times for contaminant transport within the alluvium and marker bed have been estimated. These travel times represent a "worst-case" estimation of the shortest conceivable time for contaminated groundwater to migrate from the RFP to downgradient wells. The actual travel times are likely to be longer.

Hydraulic conductivities within the Arapahoe sandstones are documented as varying between 10^{-3} cm sec^{-1} to 10^{-8} cm sec^{-1} with most values occurring between 10^{-4} and 10^{-6} cm sec^{-1} (Pottorff, 1993). The alluvium has hydraulic conductivity values ranging from 10^{-5} cm sec^{-1} to 10^{-3} cm sec^{-1}

Pottorff, 1993). Hydraulic conductivity data was not available for the medium-grained conglomeratic sandstone marker bed. A reasonable assumption would be that it contains an average conductivity value equivalent to the upper range for the sandstone beds, from 10^{-5} cm sec^{-1} to 10^{-3} cm sec^{-1}. These values are similar to the range of conductivity values calculated for the alluvium, and with published values of approximately 1×10^{-5} to 5×10^{-4} cm sec^{-1} (Freeze and Cherry, 1979). Effective porosity of the sandstones and alluvium reportedly varies between 0.1 and 0.25 and the slope of the dipping Arapahoe Formation ranges between one and two degrees beneath the RFP. Since similar data specific to the marker bed is unavailable, travel time through the marker bed is calculated using the alluvium and sandstone values and a conservative estimate of hydraulic conductivity ranging from 1×10^{-4} cm sec^{-1} to 1×10^{-3} cm sec^{-1}.

Use of these hydraulic values results in an estimated time of 30-300 years for groundwater to move two miles from beneath the center of the site to the downgradient receptor wells. These travel times are conservatively low, particularly with respect to contaminant migration, due to the following important assumptions:

- The marker bed found at the site extends for at least two miles to the east and is hydraulically connected from the RFP to downgradient receptor wells. Downgradient receptor wells are screened within the marker bed and not within other permeable sandstone beds. As mentioned earlier, a surface exposure of the marker bed was identified at Standley Lake. However, the lateral extent of the marker bed was not documented in other areas downgradient of the RFP site.

- Due to the thinness of the Arapahoe Formation, there is a possibility that the marker bed may pinch out prior to it reaching the downgradient receptors. If this is the case then the continuity of the unit to the potential exposure points is questionable.

- Hydraulic connection between the alluvium and the permeable beds in the Arapahoe and upper Laramie Formations may not exist downgradient of the RFP site. Additional investigations are necessary to characterize hydraulic conditions east of the RFP.

- Calculations assume constant recharge throughout the year with no evapotranspiration which would inhibit downward contaminant movement. Most recharge at the site occurs during the spring to late summer (EG&G, 1991a) with high evapotranspiration occurring throughout the summer (Hurr, 1976). Snow cover during the winter months and a partially paved ground surface at the site also inhibits downward infiltration.

- All of the contaminants of concern act as tracers and are not retarded in any way during migration. However, radionuclides and metals have high retardation rates due to sorption processes.

- Presence of a potential fault zone in the Walnut Creek area downgradient of the RFP site may inhibit or enhance the potential migration of contaminants to downgradient receptors. Additional investigations are necessary to determine the effect the potential fault zone may have on contaminant migration.

Because of the long travel time estimated for this route compared with the years of operation of the plant, these transport pathway is not likely to be a concern.

C.3.2 Alluvium-Only-Pathway

The geologic framework for this pathway involves the Rocky Flats alluvium or topmost formation, a clayey and sandy gravel formation with varying amounts of caliche. It is generally coarser grained west of the Rocky Flats plant and becomes finer grained toward the east. Its estimated thickness was recently revised to between 10 and 20 ft.

In this potential pathway, contaminants would infiltrate the alluvium down to the alluvium/bedrock interface. The change in formation conductivity at this transition would cause the groundwater to flow subhorizontally along the interface, potentially to a domestic well or a point of surface discharge. Such discharge occurs all around the Rocky Flats plant in springs where the contact between the alluvium and bedrock intersects with the eastward sloping land surface.

Travel time calculations for contaminant movement within the alluvium are presented below. It is assumed in the calculation that a complete pathway within the alluvium exists to the first down-gradient receptor wells two miles from the Rocky Flats plant. However, the Rocky Flats alluvium may pinch out before it reaches other alluvium bodies which could complete this pathway. Hydraulic conductivity for the alluvium has been documented as varying between 10^{-2} and 10^{-8} cm sec^{-1}, with most values falling between 10^{-3} and 10^{-5} cm sec^{-1} (Pottorff, 1991; USDOE, 1991, and EG&G, 1991c). Effective porosity of the sandstones varies between 0.1 and 0.25 and the slope of the dipping contact ranges between one degree and two degrees beneath the Rocky Flats plant. Travel time through the alluvium was calculated using these ranges for gradient and effective porosity and using a conservative hydraulic conductivity of 1×10^{-3} cm sec^{-1}.

Ignoring several limiting factors that would increase the travel time, a worst-case calculation indicated that the shortest conceivable time for groundwater to arrive at domestic wells two miles down-gradient of the center of the site is in the 30-300 year time frame. These travel times are conservative due to the following assumptions:

- As previously mentioned, the continuity of this potential pathway from the RFP to downgradient receptors is questionable. The alluvial units beneath the Plant may likely pinch out before reaching other alluvial bodies (e.g. Women Creek alluvium) which could maintain the continuity of the pathway. However, the potential pathway is maintained to provide worst-case estimation and illustrate other, more feasible, pathways (e.g. alluvium-surface water-reinfiltration).

- It is assumed in the calculation that there is constant recharge throughout the year with no evapotranspiration, which would inhibit downward contaminant movement. Most recharge at the site actually occurs during the spring and early summer with high evapotranspiration occurring throughout the summer. Snow cover during the winter months and a partially paved ground surface at the site also inhibit downward infiltration.

- All contaminant transport is assumed to occur vertically to the Arapahoe sandstone/alluvial contact. However, lateral movement occurs during infiltration of water into heterogeneous media. Infiltration through the alluvium will cause an undetermined amount of lateral movement, preventing all of the infiltration from reaching the contact. In addition, some of the infiltrating water will reach the Arapahoe Formation and infiltrate into that unit (as discussed in the first potential groundwater pathway).

- All of the contaminants of concern are assumed to act as tracers and are not retarded in any way during movement through the soils or aquifer. It is known that radionuclides and metals of concern are generally retarded due to sorption processes.

- The potential presence of the "Women Creek Fault" downgradient of the RFP may inhibit or enhance the potential migration of contaminants to downgradient receptors in this potential pathway as well.

The operational history of the facility is slightly longer than 30 years. However, due to the conservative assumptions used in deriving the travel time, the "Rocky Flats Alluvium aquifer only" transport pathway is not likely to be a significant groundwater pathway.

C.3.3 Rocky-Flats-Alluvium-to-Arapahoe-Formation Pathway

This pathway is similar to the Alluvium/Bedrock and Alluvium Only Pathways. This potential pathway incorporates the possibility that the alluvium and bedrock units may have been unintentionally connected downgradient of the RFP by poorly-constructed wells. Therefore, it is possible for contaminants to infiltrate into the Rocky Flats Alluvium, move down-gradient along the alluvial/bedrock interface and infiltrate into the Arapahoe/Upper Laramie Formations further away from the plant site. Contaminants carried by this potential pathway would be expected to have worst-case travel time estimates within the ranges calculated for the "Alluvium Only" pathway and "Alluvium/Bedrock" pathways (30-300 years). This pathway is not likely to be a concern, for reasons discussed above.

C.3.4 Rocky-Flats-Alluvium-to-Surface-Water Pathway

In many areas around the Rocky Flats plant, springs occur where the contact between the alluvium and bedrock intersects the eastward sloping land surface. It is likely that these springs then lead to streams. Therefore, it is possible that the contaminated groundwater in the alluvium

has impacted the surface water. Great Western Reservoir and Standley Lake, located downgradient of the plant, are most likely to be impacted by this route of transport.

C.3.5 Alluvium/Bedrock to Surface Water Reinfiltrating into Alluvium and Bedrock Pathway

The Alluvium to Surface Water and Reinfiltrating Into Alluvium and/or Bedrock Pathway, as originally defined in the initial investigation, included contaminants infiltrating into the Rocky Flats alluvium, migrating downgradient prior to emerging at seeps and springs. Contaminants would subsequently reinfiltrate into alluvium or bedrock downgradient of the RFP site. Due to the recent revisions in the site conceptual model, this potential pathway would involve transport through the alluvium and permeable beds of the Arapahoe and near-surface Upper Laramie formations prior to emerging at seeps and springs. Contaminants could then be transported along surface water bodies and subsequently reinfiltrate into alluvium or bedrock downgradient of the RFP site.

The geologic framework for the bedrock is described above in the Alluvium/Bedrock Only Pathway, while the geologic framework for the alluvium is discussed as part of the Alluvium to Surface Water Pathway in the initial report. The travel time calculations for groundwater movement within the alluvium and bedrock, 30 to 300 years, calculated for the Alluvium/Bedrock Only Pathway, apply to this pathway as well. It is assumed that travel time along surface water bodies is negligible. The travel time calculated for the Alluvium/Bedrock to Surface Water and Reinfiltrating into Alluvium and/or Bedrock is conservative based on the same assumptions described above for the Alluvium/Bedrock Only Pathway.

This potential transport pathway is not likely to be important for the metals and radionuclides of concern in this study. The chemicals are either of low water solubility or strongly adsorbed by soil matter, so they are not likely to migrate from surface water to the groundwater in the alluvium or Arapahoe Formation without retardation. This potential transport pathway is also of limited importance for the volatile solvents. This is because the volatile halogenated hydrocarbons are more likely to evaporate into the atmosphere than stay in the surface water. Based solely on the hydrogeology of the region, this pathway may have the highest potential for carrying contaminants to off-site domestic wells. However, due to the physical properties of the compounds of concern as discussed above, it is believed that this pathway is only of limited importance. This conclusion is based on the known properties of the two aquifer systems.

However, if there is a direct conduit, like a poorly constructed well connecting the surface water and downgradient Alluvium or bedrock, then contaminants might have entered these two aquifer units via such a conduit.

C.4 Evidence of Contaminant Migration

Upon reviewing the 1989-1991 analytical results from selected bedrock wells at the Rocky Flats plant, there are indications of some contaminant movement within the Arapahoe Formation, as well as the Rocky Flats Alluvium. Based on EG&G's 1992 revision to the site conceptual model,

wells previously referred to as screened in the Arapahoe Formation may actually be screened in the Upper Laramie, Arapahoe, or both formations. The evidence for some contaminant movement within the Rocky Flats Alluvium is based on analytical data that show that the higher contaminant concentrations follow the two stream drainages at the site (Dodge, 1991). Levels of gross alpha, gross beta, uranium-233/234, and uranium-238 exceeding background concentrations were found in the Indiana Street bedrock wells being evaluated as well as some wells screened in the Rocky Flats Alluvium. No elevated levels of plutonium or americium were found. Background concentrations are considered to be those found in up-gradient bedrock wells. Natural uranium is not known to be found in the bedrock formations beneath the site, though it is indigenous to some of the alluvial formations in the area.

Higher than background levels of nitrate were detected in some wells screened in the "Arapahoe" Formation (Table C-1). However, the highest level detected among the selected well samples was less than 3,000 ppb, and the potential source of this chemical is not clear.

As shown in Table C-1, the 1989-1991 analytical data do not present evidence of contaminants in down-gradient wells for other metals or organics in the "Arapahoe" aquifer. Levels of cadmium, chromium, mercury, lead, nickel, acetone, and methylene chloride detected in wells located near Indiana Street are slightly higher or the same as the background. Contaminant movement into and within the "Arapahoe" Formation may partially result from the substantial number of wells improperly installed at the Rocky Flats plant. Four of the 50 wells reviewed during this study showed poor well construction with screened intervals covering alluvium and some bedrock. Such well construction could potentially lead to a contaminated bedrock aquifer or more rapid transfer of contaminants from the surface to the bedrock.

TABLE C-1

COMPARISON OF LEVELS OF METALS, ORGANICS, AND NITRATE DETECTED IN ARAPAHOE AQUIFER NEAR INDIANA STREET AND THE BACKGROUND

Chemicals	Levels Detected in the Background (ppb)[a,b]	Levels Detected Near Indiana Street (ppb)[b]
Cadmium	2-5	2-5
Chromium	3-10	10-17.8
Mercury	0.2	0.2
Lead	1-3	1-5
Nickel	31-40	32-65.4
Methylene Chloride	7	16
Acetone	21-22	14-52
Nitrate	20-100	600-2,800

a Levels of contaminant detected in three up-gradient wells are assumed to be the background.
b Based on a selected number of monitoring well data analyzed between 1989 and early 1991.

Nickel and 1,1,1 TCA were found at higher than background concentrations in the Rocky Flats Alluvium at Indiana Street, indicating that there may have been some contaminant transport within the alluvium. Other than 1,1,1 TCA, no other volatile organic compounds were detected in the alluvial wells. It is believed that most of the volatile organic compounds would volatilize during surface emergence of groundwater. Levels of cadmium, chromium, mercury, and lead detected in the Rocky Flats Alluvium at wells located near Indiana Street are slightly higher or the same as the background (Table C-2).

TABLE C-2

COMPARISON OF LEVELS OF METALS AND DETECTED IN ROCKY FLATS ALLUVIUM NEAR INDIANA STREET AND THE BACKGROUND

Chemicals	Levels Detected in the Background (ppb)[a,b]	Levels Detected Near Indiana Avenue (ppb)[b]
Cadmium	2-5	2-5
Chromium	3-10	10-20
Mercury	0.2	0.2-0.22
Lead	1	1-5
Nickel	4	6.6-131
Nitrate	300-7,000	50-300

a Levels of contaminant detected in three up-gradient wells are assumed to be the background.
b Based on a selected number of monitoring well data analyzed between 1989 and early 1991.

C.5 Uncertainties

There are three main areas of uncertainty associated with this review of transportation of contaminants by groundwater. They include uncertainties associated with the analytical data, the geologic units wells are screened within, and geologic structure of the Rocky Flats plant site. These uncertainties affect our level of confidence in predicting possible contaminant transport routes and groundwater travel times.

Uncertainties Associated with the Analytical Data

A number of observations during the original evaluation in early 1992 suggested poor quality or limited use of some analytical data. The observations included:

- The presence of some repetition of the same analytic results for different wells.
- The presentation of different values for the same contaminant, sampled on the same day within one well.
- The presentation of dissolved and/or total concentrations for metals and radionuclides and therefore comparisons could only be made where both values were presented.

Although a large number of wells are located on the site and many years of sampling results have been complied, only analyses from 1989-1991 were selected from approximately 50 wells on the Rocky Flats plant property for this review. Analytical data were selected for wells that were located on the site, up-gradient of the site, and down-gradient of the site. Four of the fifty well logs examined showed well construction diagrams that indicated a potential for cross-contamination of different aquifers (Dodge, 1991). These well logs showed screened intervals within the alluvium and open boreholes into the top part of the bedrock. These well logs were an indication that there may have been more rapid movement of contaminants from the alluvium to the bedrock aquifer due to poor well construction. Finally, there was much variation in the hydraulic conductivity values documented for the various aquifers. The variations resulted from the wide variety of aquifer test procedures employed by different parties. The values used were conservative as well as based on the frequency of values encountered for each aquifer.

After the conclusion of this review, certain analytical errors listed above were reportedly corrected by the plant. These changes are likely to affect the values presented in Table C-1 and C-2 and some aspects of the assessment.

Uncertainties Associated with the Geologic Units Screened Within Wells

Recent revisions to the site conceptual model included the hydraulic-connectiveness of the alluvium, Arapahoe and Upper Laramie Formations as well as the presence of a distinctive conglomeratic marker bed at the base of the Arapahoe Formation. As a result, reclassification of the lithologic units in which the Rocky Flats plant monitoring wells and downgradient receptor wells are screened in may be required. Such a reclassification would allow for a more quantifiable interpretation of whether the marker bed at the base of the Arapahoe Formation is a likely contaminant pathway by identifying whether the subject wells were screened in the Arapahoe Formation, the marker bed, Upper Laramie or elsewhere.

Uncertainties Associated with Geologic Structure of the Rocky Flats Plant Site

There are known fault zones in the vicinity of Walnut Creek and the eastern boundary of the Rocky Flats plant. Their presence may affect potential contaminant migration from the site to downgradient populations. The fault zone apparently trends northeast from Woman Creek to Walnut Creek with the southeastern face of the fault stratigraphically lower than the northwestern face. Information is not yet available as to the potential effect the fault may have on local hydrogeology or potential contaminant migration. Therefore, additional investigation of the geologic structure and the potential impact on groundwater levels and flow directions in the area of the Walnut Creek fault is necessary.

The characterization of the fault's attitude and groundwater contours in the vicinity of the fault zone may indicate whether groundwater flow and potential contaminant migration to downgradient receptors is retarded or enhanced by the fault, thereby refining the worst-case travel time estimates for each identified potential groundwater pathway. While much remains to be identified about the fault's impact on groundwater movement, its currently-believed orientation (northeastward) would be disruptive to continuous flow across the fault trace, thereby

hindering groundwater movement. However, if the fault dips towards the potential receptor wells, and the fault plane is of high permeability, travel time to those wells could be reduced significantly.

C.6 Conclusions

The scenarios evaluated for potential off-site contaminant transport via groundwater from Rocky Flats plant activities include transport to municipal well water, private well water, and surface water. The municipal well water exposure route is the least likely due to the depth and recharge locations for the formations screened by the municipal wells down-gradient of the site. Surface water contamination could result from alluvial aquifer contamination discharging through springs into surface water bodies such as the Woman Creek and Walnut Creek drainages. Potential human exposure via this route is discussed under surface water exposure in Section 3.4.

There are several potential routes that might have carried contaminants from the Rocky Flats plant to alluvial or bedrock wells near Indiana Street. However, based on the hydrogeology of the site and physical properties of the compounds of concern, these routes are not likely to be of significance.

Elevated levels of gross alpha, gross beta, and uranium isotopes were detected in alluvial and bedrock wells near Indiana Street. This may have been due to the natural occurrence of uranium in the area's alluvial formations or cross-contamination between different aquifer systems as a result of improper well construction. Higher than background levels of nickel and 1,1,1-trichloroethane were also detected in some alluvial well water samples. However, 1,1,1-trichloroethane was detected at a concentration of only 9 ppb and elevated levels of nickel may be attributed to the past mining activities in the region.

Based on the evaluation presented above, it is not likely that contaminants from the Rocky Flats plant have migrated in groundwater significantly beyond Indiana Street between 1953 and 1989 and impacted domestic wells. In the absence of additional groundwater monitoring data that is planned for collection in the coming years as part of the Superfund investigations, the existence of contaminants in domestic wells located beyond Indiana Street cannot be further evaluated.

REFERENCES

Dodge (1991). Dodge, C. EG&G, Rocky Flats. Personal Communication with C. Dodge, November 1991.

EG&G (1991a). EG&G Rocky Flats, Inc. "Site Environmental Report for 1991." Chapter 3, Environmental Monitoring Programs, Section 3.4, Groundwater Monitoring.

EG&G (1991b). EG&G Rocky Flats, Inc. "Draft Geologic Characterization." July 31, 1991.

EG&G (1991c). EG&G Rocky Flats, Inc. "Draft Final Groundwater Protection and Monitoring Plan." June 13, 1991. Repository Document EN-699.

EG&G (1992). EG&G Rocky Flats, Inc. "Phase II Geologic Characterization Data Acquisition, Surface Geologic Mapping of the Rocky Flats Plant and Vicinity, Jefferson and Boulder Counties, Colorado." Final Report. March, 1992.

Freeze and Cherry (1979). Freeze, R.A., and J. Cherry *Groundwater*, Prentice-Hall, Inc.

Hurr (1976). Hurr, R. T. "Hydrology of a Nuclear-Processing Plant Site, Rocky Flats, Jefferson County, Colorado." U.S. Geological Survey Open File Report 76-268. Repository Document EN-481.

Nachtrieb and Schnoor (1991). Personal communications with S. Nachtrieb and K. Schnoor, City of Westminster and City of Broomfield.

Pottorff (1991). Personal communication with E. Pottorff, Colorado Department of Health Services. December, 1991.

Romero and Bainebridge (1990). Romero, J. C., and H. C. Bainebridge. "Groundwater. Resources of the Bedrock Aquifers of the Denver Basin, Colorado." Office of the State Engineer, Division of Water Resources.

USDOE (1980). "Final Environmental Impact Statement, Rocky Flats Plant Site, Golden, Jefferson County, Colorado." Volume 1. U.S. Department of Energy, April 1980, DOE/EIS-0064. Repository Document EN-1.

USDOE (1991). "Phase 1 RFI/RI Work Plan, Operable Unit 6." U.S. Department of Energy, Rocky Flats Plant, Golden, Colorado, September 1991. Repository Document RF-940.

APPENDIX D

RELATIVE COMPARISON OF PATHWAYS FOR VOLATILE COMPOUNDS

APPENDIX D

RELATIVE COMPARISON OF PATHWAYS FOR VOLATILE COMPOUNDS

A screening method developed by McKone and Daniels (1991) is employed to compare the doses due to direct inhalation, vegetable, milk, and meat ingestion for volatile compounds.

The calculation of doses resulting from different exposure pathways is shown in the Tables D-1 and D-2. The result indicates that for the volatile compounds shown in the tables, the dose resulting from inhalation is over 1,000 times greater than the dose received through vegetable, milk, and meat ingestion. Therefore, for these compounds, inhalation exposure clearly dominates over the ingestion exposure pathways.

The following equations are obtained from McKone, T. E., and J. I. Daniels' (1991) "Estimating Human Exposure through Multiple Pathways from Air, Water and Soil," *Regulatory Toxicology and Pharmacology* 13:36-61.

The airborne concentration ($C_{(air)}$) for all chemicals is assumed to be unity, 1 $\mu g\ m^{-3}$;

Dose due to inhalation: $F_{ah} = 0.39$

Dose due to vegetable ingestion: $F_{av} = 2.5\times10^{-6}\ (R \times T/H) \times (0.9+0.1 \times K_{ow})$

Dose due to milk ingestion: $F_{ak} = [0.68 + 1.2\times10^{-3}\ (R \times T/H) \times (0.9+0.1\times K_{ow})] \times B_k$

Dose due to meat ingestion: $F_{at} = [0.38 + 3.8\times10^{-4}\ (R \times T/H) \times (0.9 + 0.1 \times K_{ow})] \times B_t$

where:

R	=	Gas constant, 62.4 torr-l(air)/mol-K
T	=	Ambient temperature, 293° K
H	=	Henry's Law constant, torr-l/mol, which is converted from the more common units f atm-m^3/mol
K_{ow}	=	Partition coefficient between octanol and water, unitless
B_k	=	Biotransfer factor from cattle intake to milk concentration, (mg L^{-1} per mg d^{-1})
B_t	=	Biotransfer factor from cattle intake to meat concentration, (mg kg^{-1} per mg d^{-1})

TABLE D-1

PHYSICAL CONSTANTS

Chemicals	C_{air} ($\mu g\ m^{-3}$)	H (atm m^{-3} mol^{-1})	H (torr L mol^{-1})	K_{ow}	B_k (d L^{-1})	B_t (d/kg)
Carbon tetrachloride	1	2.40×10^{-2}	18,240	437	3.50×10^{-6}	1.10×10^{-5}
Chloroform	1	2.90×10^{-3}	2,204	93	7.40×10^{-7}	2.30×10^{-6}
Methylene chloride	1	2.00×10^{-3}	1,520	20	1.40×10^{-7}	4.50×10^{-7}
Tetrachloroethylene	1	2.60×10^{-2}	19,760	398	3.20×10^{-6}	1.00×10^{-5}
1,1,1-Trichloroethane	1	1.40×10^{-2}	10,640	316	2.50×10^{-6}	7.90×10^{-6}
Trichloroethylene	1	9.10×10^{-3}	6,916	240	1.90×10^{-6}	6.00×10^{-6}

TABLE D-2

COMPARISON OF DOSES FROM VEGETABLES, MEAT AND MILK INGESTION FOR VOLATILE ORGANICS

Chemicals	Inhalation F_{ah}	Vegetables Ingestion F_{av}	Milk Ingestion F_{ak}	Meat Ingestion F_{at}	F_{ah}/ $[F_{av} + F_{ak} + F_{at}]$
Carbon tetrachloride	0.39	1.12×10^{-4}	2.57×10^{-6}	4.37×10^{-6}	$3.49 \times 10^{+3}$
Chloroform	0.39	2.12×10^{-4}	5.78×10^{-7}	9.48×10^{-7}	$1.84 \times 10^{+3}$
Methylene chloride	0.39	8.72×10^{-5}	1.01×10^{-7}	1.77×10^{-7}	$4.47 \times 10^{+3}$
Tetrachloroethylene	0.39	9.41×10^{-5}	2.32×10^{-6}	3.94×10^{-6}	$4.14 \times 10^{+3}$
1,1,1-Trichloroethane	0.39	1.40×10^{-4}	1.87×10^{-6}	3.17×10^{-6}	$2.79 \times 10^{+3}$
Trichloroethylene	0.39	1.65×10^{-4}	1.44×10^{-6}	2.43×10^{-6}	$2.37 \times 10^{+3}$

APPENDIX E

AIR DISPERSION COMPUTER MODELS

APPENDIX E
AIR DISPERSION COMPUTER MODELS

After a review of available air pollution dispersion models, the following models were selected for use:

1. ISC (Industrial Source Complex) model (Wackter and Foster, 1986) is used for long-term releases and releases where event-specific meteorological data were not available.

   The Industrial Source Complex Long Term (ISCLT) model is the version of ISC used for long-term (i.e., seasonal and annual) modeling. ISCLT is a steady-state Gaussian plume model that can account for multiple point, area, and volume sources; building downwash effects; limited terrain adjustment; and settling and dry deposition of particulates. ISCLT is appropriate for flat or rolling terrain, with ground level receptors lower than the point source stack heights. This is typical of the situation at Rocky Flats.

   Complex terrain models are not appropriate for the Rocky Flats area in the present analysis. Complex terrain is defined by modelers as terrain exceeding the height of the stack being modeled. Complex terrain models can predict concentrations on downwind terrain higher than the emitting stack height, but they are only valid for predicting concentrations on terrain above stack height.

   The complex wind patterns in the Rocky Flats area, because of its proximity to the Rocky Mountains and local topographic influences, were considered in the selection of the ISC model. Ideally, to simulate these conditions, a model that could process meteorological data from many stations located over the area of interest and create a three-dimensional wind field describing the flow pattern should be used. However, such as approach becomes important only when the area of concern extends beyond a radius of approximately 25 miles. Initial dose reconstruction efforts are focussing on the areas immediately adjacent to Rocky Flats. If an expansion of the area is then deemed appropriate, other models may need to be considered.

2. INPUFF (Integrated PUFF model) (Peterson, 1986) is used for short-term accidental releases, such as the 1957 and 1969 fires, where event-specific meteorological data were available.

   INPUFF is a Gaussian integrated puff model designed to simulate dispersion from semi-instantaneous or continuous point sources over a spatially and temporally variable wind field. Gaussian-puff algorithms treat source emissions as a series of puffs emitted into the atmosphere. INPUFF assumes each puff remains circular during transport so that $\sigma_x = \sigma_y$. Each puff is free to move in response to changing wind speed and direction rather than being constrained to a single centerline. The contribution of all puffs is summed at each receptor location.

The algorithms incorporated in INPUFF to account for particle deposition and settling were presented by Rao (1982) as the mathematical formulation of the Gradient-Transfer or K-Theory for non-reacting pollutant dispersion and deposition from an elevated continuous point source. As presented by Rao, and used in INPUFF, the solutions are expressed as extensions of the Gaussian plume algorithms (without deposition) currently used in U.S. EPA models. According to Rao, the vertical diffusion field alone is modified by loss due to deposition. For values of V_d [deposition velocity] on the order of a few centimeters per second, the shape of the vertical concentration profile is changed only slightly.

The model was modified slightly to allow for a larger number of receptor locations and shorter intervals between puff releases.

3. FDM (Fugitive Dust Model) (Winges, 1990) is used to simulate airborne dispersion processes that transported contaminated soil away from the 903 pad and created the off-site soil contamination pattern observed in late 1969 and the early 1970s.

The Fugitive Dust Model is a computerized air quality model specifically designed for computing concentration and deposition impacts from fugitive dust sources. The model is generally based on the well-known Gaussian plume formulation for computing concentrations, but the model has been specifically adapted to incorporate an improved gradient-transfer deposition algorithm. Emissions for each source are apportioned by the user into a series of particle size classes. A gravitational setting velocity and a deposition velocity are calculated by FDM for each class. The model incorporates a detailed deposition routine based on Ermak's (1977) analytical solution of the atmospheric diffusion equation.

The theoretical results are similar to those used in INPUFF. FDM has the ability to treat both turbulent and gravitational removal mechanisms for particles through the deposition velocity and gravitational settling velocity parameters, respectively. Again as with INPUFF, the Gradient-Transfer theory is used to account for plume depletion due to particle deposition/settling. Error in predicted concentration is introduced due to inconsistent assumptions made (regarding the behavior of the eddy diffusivity, K) in the development of the theory. A correction term is calculated to ensure that mass is conserved. This correction is not attempted by INPUFF.

FDM treats an area source by dividing it into a default of 5 line sources perpendicular to wind direction. The option is available to iteratively divide the source into increasingly more lines until the difference between successive iterations is sufficiently small. The model then computes the concentration/deposition at each receptor (considering only the upwind portions of the area source). Calculations made for each independent time interval assume uniform conditions during that interval.

Originally written to model transport of particles less than 30 μm in size, FDM was extended for this project by the program's author, K. Winges, to model transport of particles up to 150 μm in size.

It was originally planned to make extensive use of the TRAC model, under development at Rocky Flats, for historical inhalation exposure modeling. Considerable effort was expended on accommodating the TRAC model to the purposes of the dose reconstruction project, but the model was eventually abandoned for the following reasons:

- The TRAC model has not been verified because it is still evolving. Several inconsistencies and inaccuracies were discovered in TRAC model runs conducted for the project.

- The TRAC model is designed to use an extensive base of meteorological data to predict effects of present-day accidents at Rocky Flats on the metropolitan Denver area. It offers no special advantages over simpler, validated, and EPA-approved air models when used in conjunction with more limited meteorological data available for estimating effects of historical releases.

- It became clear that it would be expensive and time-consuming to run the TRAC model at Rocky Flats on the computers it was designed for, or to convert the program to run on other computers. Furthermore, as explained above, there were no benefits expected from using TRAC that would justify the added time and expense.

REFERENCES

Ermak (1977). Ermak, D. L. "An Analytical Model for Air Pollutant Transport and Deposition from a Point Source," *Atmospheric Environment*, vol. 11, pp. 231-237.

Peterson (1986). Peterson, W. B. "INPUFF 2.0 - A Multiple Source Gaussian Puff Dispersion Algorithm, User's Guide," Atmospheric Sciences Research Laboratory Office of Research and Development, USEPA (updated January, 1988)

Rao (1982). Rao, K. S. "Analytical Solutions of a Gradient-Transfer Model for Plume Deposition and Sedimentation," NOAA Technical Memorandum ERL ARL-109.

Wackter and Foster (1986). Wackter, D. J., and J. A. Foster. "Industrial Source Complex (ISC) Dispersion Model User's Guide - Second Edition -- Volume I." EPA-450/4-86-005a. June.

Winges (1990). Winges, K.D. "User's Guide for the Fugitive Dust Model (FDM)," Revised. September, 1992, EPA-910/9-88-202R.

APPENDIX F

METEOROLOGICAL DATA

APPENDIX F
METEOROLOGICAL DATA

Air pollution dispersion models use appropriate meteorological data to calculate estimated air concentrations of contaminants in the vicinity of a source. Therefore, meteorological data are a key input to the modeling process.

On-site meteorological data of varying quality have been recorded since the plant began operating. Generally speaking, high-quality meteorological data suitable for detailed modeling of events at Rocky Flats is not available for periods before 1987. Validated meteorological data are available for the years 1987-1991 and were used for the modeling of long-term events. Five years of data include most major weather patterns, and the U. S. EPA considers a five-year database standard for adequate long-term assessment of air quality impacts at a given site.

The five years of meteorological data underwent quality assurance confirmation and auditing by the Rocky Flats meteorologist. Data were collected on-site at a 61-meter tower in the west buffer zone. The data include: wind speed and direction (flow vector, or direction toward which the wind is blowing), Pasquill-Gifford atmospheric stability category, ambient temperature, and mixing height.

Wind speed and direction data pertinent to the 1957 (Table F-1) and 1969 (Table F-2) fires were provided in a Dow Chemical letter to Dr. Roy Cleare, Executive Director of the Colorado Department of Health, dated March 20, 1970. As described in the 1969 fire discussion, a "smoothed" wind direction data set was generated for the purposes of the release analysis. This smoothed data set is presented in Table F-3.

The Rocky Flats meteorologist also provided hourly observation data from 1968 through mid-1973 and for the last half of 1975. Additional hourly observation data could not be located.

TABLE F-1

1957 FIRE WIND DATA

Date	Time	Wind Direction	Wind Speed (m sec^{-1})	Wind Speed (mph)	Inferred Atmospheric Stability Classes
9/11/57	10:00 pm	160°	1.79	4	F
	10:15 pm	160°	0.45	1	F
	10:30 pm	75°	0.45	1	F
	10:45 pm	30°	1.34	3	F
	11:00 pm	315°	3.13	7	E
	11:15 pm	315°	3.13	7	E
	11:30 pm	315°	3.13	7	E
	11:45 pm	330°	4.47	10	E
9/12/57	12:00 am	290°	4.47	10	E
	12:15 am	285°	4.92	11	E
	12:30 am	285°	6.26	14	D
	12:45 am	285°	4.02	9	E
	1:00 am	280°	3.58	8	E
	1:15 am	290°	2.68	6	F
	1:30 am	285°	3.13	7	E
	1:45 am	285°	2.68	6	F
	2:00 am	285°	2.68	6	F
	2:15 am	285°	4.02	9	E
	2:30 am	285°	4.47	10	E
	2:45 am	275°	4.47	10	E
	3:00 am	275°	5.81	13	D
	3:15 am	275°	6.71	15	D
	3:30 am	270°	5.36	12	D
	3:45 am	270°	4.92	11	E
	4:00 am	275°	5.36	12	D
	4:15 am	290°	2.24	5	F
	4:30 am	350°	1.34	3	F

TABLE F-1

1957 FIRE WIND DATA

Date	Time	Wind Direction	Wind Speed (m sec^{-1})	Wind Speed (mph)	Inferred Atmospheric Stability Classes
	4:45 am	120°	3.13	7	E
	5:00 am	180°	3.13	7	E
	5:15 am	150°	2.68	6	F
	5:30 am	120°	2.68	6	F
	5:45 am	95°	0.89	2	F
	6:00 am	75°	0.89	2	F
	6:15 am	315°	0.45	1	F
	6:30 am	315°	2.24	5	F
	6:45 am	315°	3.13	7	E
	7:00 am	330°	3.58	8	B
	7:15 am	310°	2.24	5	B
	7:30 am	345°	1.79	4	B
	7:45 am	350°	0.45	1	A
	8:00 am	30°	0.45	1	A
	8:15 am	60°	1.34	3	B
	8:30 am	75°	0.89	2	A
	8:45 am	40°	1.79	4	A
	9:00 am	30°	1.79	4	A
	9:15 am	40°	1.34	3	A
	9:30 am	25°	1.79	4	A
	9:45 am	35°	2.24	5	A
	10:00 am	30°	2.68	6	B

Source: Letter to Dr. Roy Cleere, Executive Director of Colorado Department of Health, March 20, 1970. Repository Document IN-386.

TABLE F-2

1969 FIRE WIND DATA

Date	Time	Wind Direction	Wind Speed (m sec^{-1})	Wind Speed (mph)	Inferred Atmospheric Stability Classes
5/11/69	2:30 pm - 2:35 pm	N	1.7	4	B
	2:35 pm - 2:40 pm	E	1.8	4	B
	2:40 pm - 2:45 pm	E	2.7	6	B
	2:45 pm - 2:50 pm	NE	2.7	6	B
	2:50 pm - 2:55 pm	NE	1.8	4	B
	2:55 pm - 3:00 pm	NE	1.8	4	B
	3:00 pm - 3:05 pm	SE	0.9	2	B
	3:05 pm - 3:10 pm	E	1.8	4	B
	3:10 pm - 3:15 pm	NE	1.8	4	B
	3:15 pm - 3:20 pm	E	1.8	4	B
	3:20 pm - 3:25 pm	"Variable"	1.8	4	B
	3:25 pm - 3:30 pm	"Variable"	0.9	2	B
	3:30 pm - 4:00 pm	N	1.3	3	B
	4:00 pm - 5:00 pm	NE	1.3	3	B
	5:00 pm - 6:00 pm	NE	1.3	3	B
	6:00 pm - 7:00 pm	NE	0.9	2	B
	7:00 pm - 8:00 pm	E	0.9	2	B
	8:00 pm - 9:00 pm	NE	0.9	2	E
	9:00 pm - 10:00 pm	W	1.3	3	F
	10:00 pm - 11:00 pm	W	4.023	9	E
	11:00 pm - 12:00 pm	W	1.341	3	F
	12:00 pm - 1:00 am	W	3.129	7	E
	1:00 am - 2:00 am	W	3.123	7	E
	2:00 am - 3:00 am	W	2.235	5	F
	3:00 am - 4:00 am	W	1.788	4	F
	4:00 am - 5:00 am	SW	2.235	5	F
	5:00 am - 6:00 am	"Variable"	1.788	4	F

TABLE F-2

1969 FIRE WIND DATA

Date	Time	Wind Direction	Wind Speed (m sec^{-1})	Wind Speed (mph)	Inferred Atmospheric Stability Classes
	6:00 am - 7:00 am	NW	2.235	5	F
	7:00 am - 8:00 am	W	5.812	13	D

Source: Letter to Dr. Roy Cleere, Executive Director of the Colorado Department of Health, March 20, 1970. Repository Document IN-386.

TABLE F-3

SMOOTHING ADJUSTMENTS TO WIND DIRECTION DATA FOR THE 1969 FIRE

Meteorological Interval	Original Data	Smoothed Data
2:30 pm - 4:00 pm	NO CHANGES MADE to short-interval data	
4:00 pm - 5:00 pm	NE	NE
5:00 pm - 6:00 pm	NE	NE
6:00 pm - 6:50 pm	NE	NE
6:50 pm - 7:10 pm	NE	ENE
7:00 pm - 7:10 pm	E	ENE
7:10 pm - 7:50 pm	E	E
7:50 pm - 8:00 pm	E	ENE
8:00 pm - 8:10 pm	NE	ENE
8:00 pm - 8:50 pm	NE	NE
8:50 pm - 9:00 pm	W	W
9:00 am - 3:00 am 6-Hour Period	W	W
3:00 am - 3:50 am	W	W
3:50 am - 4:00 am	W	WSW
4:00 am - 4:10 am	SW	WSW
4:10 am - 5:00 am	SW	SW
5:00 am - 5:20 am	SW	WSW
5:20 am - 5:40 am	W	W
5:40 am - 6:00 am	NW	WNW
6:00 am - 6:50 am	NW	NW
6:50 am - 7:00 am	NW	WNW
7:00 am - 7:10 am	W	WNW
7:10 am - 8:00 am	W	W

= inferred wind direction

APPENDIX G

UNCERTAINTY ANALYSIS

APPENDIX G
UNCERTAINTY ANALYSIS

The Rocky Flats dose reconstruction project focuses on past exposures. Because of the necessity of using incomplete past environmental monitoring and release information, imperfect models, and estimates of transfer and uptake factors, uncertainty is associated with the dose estimates.

Uncertainty analysis assesses the confidence level in the predicted result by incorporating the state of knowledge about environmental transport and exposure phenomena and the quality of model parameters in the dose determination process. In the following sections, the source and nature of uncertainties in the dose estimation process are discussed.

G.1 Sources of Uncertainty

The sources of uncertainty can be separated into three categories: model uncertainty, lack of knowledge, and variability. Each of them is discussed briefly below.

G.1.1 Model Uncertainty

Models are used when there is insufficient or no measurement data for a location of interest. Models are simplified and idealized representations of complex environmental transport, food chain bioaccumulation, and human uptake processes. Model uncertainty arises from our incomplete knowledge or oversimplification of the processes under investigation.

Estimates of model uncertainty have been developed for the air dispersion models used for this report. The basis for the estimated uncertainty in the application of the three air dispersion models used in this project is described in this section.

<u>Uncertainty Associated with the Application of the ISC Model to Filter Plenum Releases</u>

Routine emissions from filter plenum exhaust were modeled using ISCLT, a Gaussian plume atmospheric dispersion model, to predict long-term average air concentrations. Little and Miller (1979), in their review of Gaussian plume atmospheric models, estimate that for a highly instrumented flat-field site, ground-level centerline concentration predictions within 10 kilometers of a continuous point-source are accurate within a factor of 1.2. Predictions of annual average concentrations for a *specific point* on flat terrain and within 10 kilometers of the release point are accurate within a factor of 2. Miller and Hively's more recent review article (1987) of Gaussian plume model estimation of airborne radionuclide exposures reiterates the earlier estimates.

In our application of the ISC model to filter plenum releases, the input meteorologic data are not derived from a highly instrumented site. However, the model is used to predict annual average concentrations over a sector rather than point-specific concentrations. The studies described above suggest that uncertainties in these model predictions would range from a factor of 1.2

to 2. We have chosen a factor of 3 to represent the uncertainty in predictions made with the ISC model. The uncertainty factor to be applied to the results of the analysis is represented by a lognormal distribution having a geometric mean of 1 and a geometric standard deviation of 1.4 (95% of the distribution is within a factor of 2 of the geometric mean).

Uncertainty Associated with the Application of the FDM to 903 Pad Releases

Emissions from the 903 pad were modeled using FDM, which is based on a Gaussian plume formulation that has been specifically adapted to incorporate an improved gradient-transfer deposition algorithm. Validation studies that have been performed for the model (Winges, 1992; Appendices A(1) & A(2)) suggest that model predictions are generally accurate within a factor of 2 for particles in the TSP size range (approximately <30 μm). However, the conditions under which the model was validated are significantly different than those for this application. The validation studies examined predictions for particle sizes in the TSP size range using good quality meteorological data for the actual release. The application of the model to the 903 pad release involved the evaluation of particles up to 150 μm in size, used a surrogate long-term meteorological data set, and placed increased importance on short-term events (high wind-speed events). The model developer has suggested that this application could have uncertainties as large as a factor of 10. The uncertainty factor to be applied to the results of the analysis is represented by a lognormal distribution having a geometric mean of 1 and a geometric standard deviation of 3.2 (95% of the distribution is within a factor of 10 of the geometric mean).

Uncertainty Associated with the Application of INPUFF Model to 1957 and 1969 Fire Releases

Emissions from the 1957 and 1969 fires were modeled using INPUFF, a Gaussian puff atmospheric dispersion model, to predict average air concentrations during the course of the fire. Peterson (1986) compared INPUFF-predicted peak concentrations with data from a 1983 tracer study and found that the greatest discrepancy between experimental and observed peak concentrations is about a factor of three. Peterson concludes that "INPUFF slightly overestimates highest peak concentrations...". The experimental data upon which Peterson based this comparison represented highly instrumented meteorological data which should allow for more accurate modeling than does the relatively poor quality meteorological information available for the 1957 and 1969 fires. The uncertainty associated with the application of the INPUFF model to the fire release predictions would be expected to exceed a factor of 3.

Miller and Hively (1987) estimate an uncertainty factor of 10 for Gaussian plume predictions for a specific hour and receptor point, flat terrain and steady meteorological conditions. Gaussian plume and puff models are based on a similar mathematical formulation, the most important difference being that INPUFF can handle changing meteorological conditions. Since the INPUFF application in this study involves the calculation of average concentrations at discrete sampling locations for estimating the release, a factor of 10 is believed to be an appropriate value for uncertainty. Therefore, the uncertainty factor to be applied to the results of the analysis is represented by a lognormal distribution having a geometric mean of 1 and a geometric standard deviation of 3.2 (95 percent of the distribution is within a factor of 10 of the geometric mean).

G.1.2 Incomplete Knowledge

Model parameters are the inputs to models. They are usually either directly measured or extrapolated from other measured quantities. One type of model input parameter is the emission rate or source term (which is described in the Task 5 report; ChemRisk, 1992) as an input to the air dispersion models. In many cases, model inputs have some uncertainty associated with the measurement or are derived from published experiments designed for other purposes. The site conditions in the experiment, like soil moisture content, soil pH, annual precipitation level, and local vegetation, may be different from those of the situation being modeled. Using measurement data that have uncertainty or published model parameters that do not accurately represent the situation being modeled results in uncertainty in the model prediction. Therefore, even with a perfect model, uncertainty in the model parameters produces uncertainty in the model prediction. In this study, we have attempted to identify and quantify those uncertainties in the model inputs that are likely to contribute to the overall uncertainties in the model results.

G.1.3 Variability

Variability occurs when the value of a model parameter depends on time, space or some individual characteristic. For example, beef consumption rates are different among individuals in an exposed population. In order to estimate the doses received by individuals in population through the beef ingestion pathway, it is important to include the variability of this parameter.

G.2 Monte Carlo Simulation

This section discusses the use of Monte Carlo simulation to propagate the uncertainties associated with the models and parameters into an overall uncertainty in the final dose estimates. Exposure to a contaminant through inhalation exposure is used as an example to illustrate how Monte Carlo simulation works. The contaminant received by an adult through inhalation can be represented by the following equation:

$$I_{air} = \frac{ER \times DF \times U_{air}}{BW}$$

where:

I_{air} = Daily intake of contaminant per unit body weight due to inhalation, pCi kg^{-1} d^{-1}

ER = Emission rate, Ci y^{-1}

DF = Dilution factor predicted by an air dispersion model, pCi m^{-3} per Ci y^{-1}

U_{air} = Inhalation rate of an adult, m^3 d^{-1}

BW = Average body weight of an age group, kg

In this example, uncertainties in the four terms, ER, DF, U_{air}, and BW are mainly due to incomplete knowledge, model uncertainty, variability and variability, respectively. Based on the estimated uncertainties associated with ER, DF, U_{air}, and BW, a frequency distribution function is assigned to each term. Monte Carlo simulation is used to propagate the uncertainties in the terms and determine the uncertainty associated with I_{air}. A computer software program such as "Crystal Ball®" (Decisioneering Corp., 1990) can be used to carry out the simulation, which involves the following steps:

1. A value is randomly chosen for each term based on its probability distribution function. This is done in such a way that, using a normal distribution as an example, a value close to the mean is much more likely to be chosen than a value close to the lower or upper bound.

2. Using the chosen values, intake is calculated according the equation shown above.

3. Steps 1 and 2 are repeated many times. For example, the computer program may repeat the process 3,000 times. As a result, 3,000 estimates are obtained that can be combined to generate a frequency distribution for the estimated intake. The characteristics of the frequency distribution can be determined (e.g., lognormal) and descriptors of the distribution, the geometric mean (GM) and geometric standard deviation (GSD), can also be obtained from the "Crystal Ball" output.

From the estimated distribution and distribution descriptions (e.g., geometric mean and geometric standard deviation), it is possible to determine the best estimate and the confidence interval about this estimate. For example, if the median is chosen to represent the best estimate, then the 95 percent confidence interval about this estimate is the geometric mean multiplied by the square of the geometric standard deviation (upper bound) and by the inverse of the square of the geometric standard deviation (lower bound).

G.3 Conclusion

Evaluation of the nature and estimate magnitude of uncertainties associated with various models and model parameters is an important element of dose reconstruction. Uncertainties associated with the air dispersion models and the exposure model can arise from several sources, including the models themselves, exposure assumptions and incomplete site-specific information. Quantitative uncertainty analysis is used to combine these uncertainties and estimate the overall uncertainty in the final dose estimate.

REFERENCES

ChemRisk (1994). "Estimating Historical Emissions from Rocky Flats." Project Task 5 Report. March. Repository Document TA-1240.

Decisioneering Corp. (1990). "Crystal Ball, a Forecasting and Risk Management Program for Macintosh, Version 2.0." Decisioneering Corporation, Denver, Colorado.

Little and Miller (1979). Little, C. A. and C. W. Miller. "The Uncertainty Associated with Selected Environmental Transport Models." ORNL-5528.

Miller and Hively (1987). Miller, C. W., and L. M. Hively. "A Review of Validation Studies for the Gaussian Plume Atmospheric Dispersion Model." *Nuclear Safety* Vol. 28, No. 4. October-December 1987. pp. 522-531.

Peterson (1986). Peterson, W. B. "A Demonstration of INPUFF with the MATS Data Base." *Atmospheric Environment* Vol. 20, No. 7. pp. 1341-1346. 1986.

USEPA (1989). U.S. Environmental Protection Agency. "Risk Assessment Methodology, Environmental Impact Statement, NESHAPS for Radionuclides, Background Information Document—Volume 1." Office of Radiation Programs. September. EPA/510/1-89-005.

Winges (1992). Winges, K.D. "User's Guide for the Fugitive Dust Model (FDM) (revised), Volume I: User's Instructions." May. EPA-910/9-88-202R.

APPENDIX H

INFORMATION SUPPORTING
903 PAD RELEASE DURING 1968 AND 1969

APPENDIX H

INFORMATION SUPPORTING 903 PAD RELEASE DURING 1968 AND 1969

Historical Data on 903 Pad Releases

Data from the S-8 air sampler indicate that releases from the 903 pad were highest from November 1968 through April 1969 (Figure 3-1 from the Seed *et al.*, (1971) report is reproduced in this appendix as Figure H-1.).

The chronology on page 5 of Seed *et al.* (1971) says that:

- Removal of drums began in January 1967.
- The last drums were shipped to Building 774 in June 1968, when high winds spread some contamination.
- The first coat of fill material was applied to the pad area in July 1969.

Also:

- Barrick (1981) says the drums were gone by June 5, 1968, and that vegetation analysis indicated that maximum releases were between May and October 1968.
- Weeds and vegetation were burned off the drum storage area in October 1968 (Seed, 1970).
- Grading was started for applying an asphalt cap over the area in November 1968. On July 23, 1969, the first course of fill was applied to the 903 pad as a base for installation of an asphalt cap (Freiberg, 1970).
- Barrick (1991) claimed that winds in the 80 mph range are needed to resuspend significant amounts of plutonium contaminated soil; 80 mph winds occurred about three times during the year that the 903 pad was uncovered. Barrick said that a damaged war surplus grader was used to prepare the 903 pad area for paving and that the grader was running at about 20 mph because the low gear was not operable. During two of the days that the grading work was done, there were strong winds that carried the dust kicked up by the grader downwind.

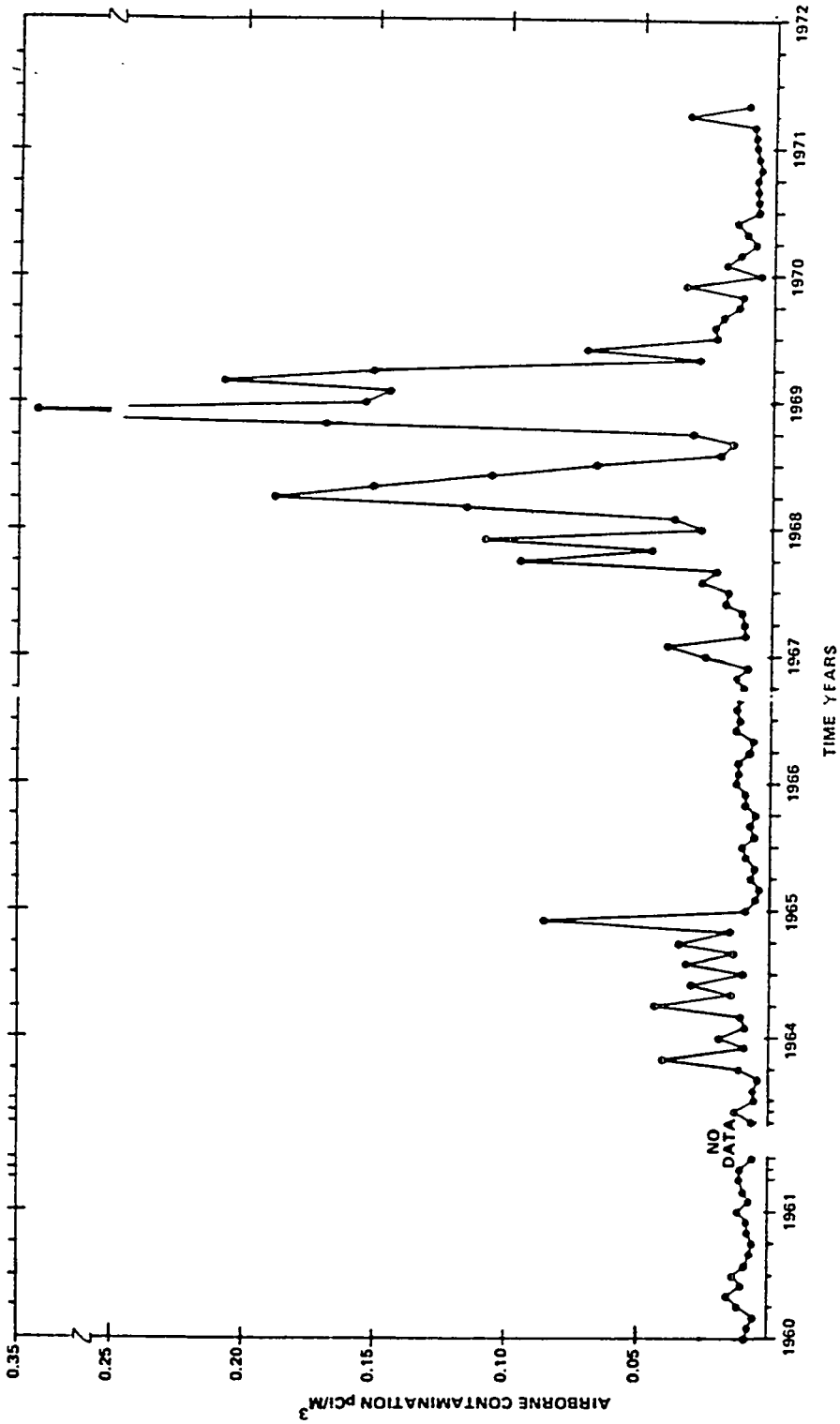


Figure 3-1. Monthly Averages of Daily Airborne Contamination Values from Air Sampler S-8 Located just East of the Drum Storage Area.

FIGURE H-1
REPRODUCTION OF FIGURE 3-1
SEED et al; 1971

Lake Sediment Data for the Time of 903 Pad Releases

Hardy *et al.* (1978) reported an analysis of two sediment cores collected on August 25, 1976 in Standley Lake. They found a peak in the concentrations of Pu-238, Pu-239, and Pu-240, and Am-241 in the sediment layer at core depths between 24 and 26 cm.

Making assumptions about sedimentation rates, it is possible to use the sediment core data to date the time of occurrence of the peak deposition. Hardy *et al.* assume that:

- The middle of the 42-44 cm section of their cores corresponds to the end of 1963, six months after the maximum fallout concentrations from intensive nuclear testing by the U.S. and the Soviet Union in 1961 and 1962; and

- The middle of the 32-34 cm section of their cores corresponds to the end of 1966, six months after the first appearance of increased Pu-238 in Northern Hemisphere fallout from failure of the Pu-238 powered SNAP 9-A satellite over the Southern Hemisphere in 1964.

From this information, Hardy *et al.* derive an average sedimentation rate of 3.4 cm y^{-1} and date the maximum concentration in the 24-26 cm section of the cores as corresponding to late 1969.

According to the S-8 air sampler data, releases from the 903 pad were highest from November 1968 through April 1969. Thus, Hardy *et al.* date the maximum sediment concentration of transuranic radionuclides in Standley Lake as occurring about six months after the maximum airborne particulate concentrations of these radionuclides were observed downwind of the 903 pad in the first quarter of 1969. This is consistent with the release of particulates from the 903 pad in late 1968 and early 1969 if it is assumed that it takes about six months for airborne particulates or particulates transported by stream flow from the 903 pad to be incorporated in the sediments at the bottom of Standley Lake.

If aerial deposition on the surface of Standley Lake is more rapidly incorporated into sediments, the sediment data are still consistent with the main release of contamination from the 903 pad occurring in late 1968 and early 1969. The imprecision associated with the Hardy *et al.* assumption of a six-month lag between maximum airborne contamination concentrations and the incorporation of the radionuclides into sediment at the bottom of Standley Lake could move their timeline back by up to six months if aerial deposition is rapidly incorporated in the sediment.

REFERENCES

Barrick (1981). Barrick, C. W. "Past Accidental Releases of Radioactivity from the Rocky Flats Plant." Rocky Flats Environmental Sciences Department, January 14, 1981. Repository Document IN-449.

Barrick (1991). Barrick, C. W. Personal communication with C. W. Barrick, 1991.

Freiberg (1970). Freiberg, K. J. "903 Oil Drum Storage Area." April 14, 1970. Repository Document RE-735.

Hardy *et al.* (1978). Hardy, E. P., H. D. Livingston, J. C. Burke, and H. L. Volchok. "Time Pattern of Off-Site Plutonium Contamination from Rocky Flats Plant by Lake Sediment Analysis." EML-342, July 1978. Repository Document AC-642.

Seed (1970). Seed, J.R. "Status Report of Committee on Plutonium in Soil." Document Code L00047. 1970. Repository Document IN-560.

Seed *et al.* (1971). Seed, J. R., K. W. Calkins, C. T. Illsley, F. J. Miner, and J. B. Owen. "Committee Evaluation of Plutonium Levels in Soil Within and Surrounding USAEC Installation at Rocky Flats, Colorado." Dow Chemical, Rocky Flats Division Report RFP-INV-10 1971. Repository Document AC-726.

APPENDIX I

SOIL AND AIR SAMPLING INFORMATION RELATED TO THE 903 PAD

APPENDIX I

SOIL AND AIR SAMPLING INFORMATION RELATED TO THE 903 PAD

This appendix contains a summary of information and data on soil and air sampling used to support the analysis of releases from the 903 Pad. Table I-1 identifies the soil surveys and provides a summary of some of their relevant aspects. Table I-2 provides a summary of the sampling data for each of the identified sampling points in the soil surveys. Table I-3 provides a summary of the locations of the ambient air samplers and reference locations for the 903 Pad and Building 771.

TABLE I-1

SUMMARY OF PU-239 SOIL SURVEYS BETWEEN 1969 AND 1973

Author & Map Identifiers	Dates of Sample Collection	Measured or Assumed Soil Density ($g\ cm^{-3}$)	Number of Sampling Sites	Reference
Hammond, 1970 5-162 to 5-324	Aug 1969	1.0	8	a,l
Rockwell International, 1971 B1 to B83	Aug 1969-June 1970	1.0	83	c,t
Poet and Martell, 1972 A to Z	Sept 1969-Jan 1970	1.0	28	b,t
Rockwell International, 1971 G1 to G38	Jan-June 1970	1.0	33	c,t
Krey and Hardy, 1970 R1 to R33	Feb 1970	1.2 (1-15 cm) 2.4 (15-20 cm)	33	c,f,g,t
Rockwell International, 1971 B101 to B138	Dec 1970	1.0	38	c,t
Krey *et al.*, 1976 H1 to H26	July 1973	1.0	26	d

Note: Surveys include those for which sampling site locations could be determined. There are a total of 249 sites. No data are available for 12 of the sites, so there are 237 sites with soil data.

References: See Table I-3.

TABLE I-2

SUMMARY OF PLUTONIUM SOIL SAMPLES TAKEN NEAR THE ROCKY FLATS PLANT BETWEEN 1969-1973

X Coord UTM Easting (m)	Y Coord UTM Northing (m)	Measured Soil ^{239}Pu (mCi km^{-2})	Sample Depth (cm)	Site Codes	Corrected Soil ^{239}Pu (mCi km^{-2})	Radius from 903 Pad (m)	Soil Value Ref	Site Ref
479420	4415510	2.4	20	R1	0.7	3,985	c,e,f,g,t	e,f
481060	4415550	3.1	20	R2	1.4	2,352	c,e,f,g,t	e,f
481070	4414030	4.2	20	R3	2.5	2,658	c,e,f,g,t	e,f
484150	4417860	11.0	20	R4	9.3	2,658	c,e,f,g,t	e,f
484170	4416170	15.0	15	R5	13.3	1,154	c,e,f,g,t	e,f
484130	4415290	1950.0	20	R6	1948.3	730	c,e,f,g,t	e,f
483540	4414950	480.0	20	R7	478.3	386	c,e,f,g,t	e,f
484130	4414870	630.0	20	R8	628.3	852	c,e,f,g,t	e,f
484120	4413150	2.6	20	R9	0.9	2,277	c,e,f,g,t	e,f
485730	4419310	2.2	20	R10	0.5	4,629	f,g	f
486080	4417750	5.4	20	R11	3.7	3,624	c,e,f,g,t	e,f
486460	4416100	47.0	20	R12	45.3	3,160	c,e,f,g,t	e,f
485800	4414670	50.0	20	R13	48.3	2,484	c,e,f,g,t	e,f
485400	4413300	17.0	20	R14	15.3	2,836	c,e,f,g,t	e,f
487080	4413280	18.0	20	R15	16.3	4,203	c,e,f,g,t	e,f
486780	4410470	19.0	20	R16	17.3	5,903	e,f,g	e,f
489080	4415690	14.0	20	R17	12.3	5,693	c,e,f,g,t	e,f
492250	4420190	2.0	20	R18	0.3	10,106	c,f,g,t	f

TABLE I-2
(Continued)

SUMMARY OF PLUTONIUM SOIL SAMPLES TAKEN NEAR THE ROCKY FLATS PLANT BETWEEN 1969-1973

X Coord UTM Easting (m)	Y Coord UTM Northing (m)	Measured Soil ^{239}Pu (mCi km^{-2})	Sample Depth (cm)	Site Codes	Corrected Soil ^{239}Pu (mCi km^{-2})	Radius from 903 Pad (m)	Soil Value Ref	Site Ref
491870	4411600	8.0	20	R19	6.3	9,247	c,e,f,g,t	e,f
493620	4417300	2.6	20	R20	0.9	10,412	f,g	f
495660	4416350	2.7	20	R21	1.0	12,304	c,e,f,g,t	e,f
493910	4406720	2.2	20	R22	0.5	13,574	f,g	f
501310	4426440	3.0	20	R23	1.3	21,087	f,g	f
501330	4418100	2.6	20	R24	0.9	18,146	f,g	f
500440	4409400	2.4	20	R25	0.7	18,036	f,g	f
502160	4398230	2.3	20	R26	0.6	25,371	f,g	f
505430	4399110	2.0	20	R27	0.3	27,345	f,g	f
518740	4416490	2.5	20	R28	0.8	35,360	f,g	f
553160	4404090	2.0	20	R29	0.3	70,657	f,g	f
518800	4436670	2.8	20	R30	1.1	41,345	f,g	f
516950	4450760	2.1	20	R31	0.4	48,809	f,g	f
528210	4465230	2.7	20	R32	1.0	67,082	f,g	f
496200	4471050	1.8	20	R33	0.1	57,191	f,g	f
483780	4415390	6430.0	5	H1	10045.2	388	d	d
483830	4415340	3990.0	5	H2	6232.7	431	d	d
483830	4415560	322.0	5	H3	501.4	497	d	d
483830	4415230	1440.0	5	H4	2248.3	437	d	d

TABLE I-2
(Continued)

SUMMARY OF PLUTONIUM SOIL SAMPLES TAKEN NEAR THE ROCKY FLATS PLANT BETWEEN 1969-1973

X Coord UTM Easting (m)	Y Coord UTM Northing (m)	Measured Soil ^{239}Pu (mCi km^{-2})	Sample Depth (cm)	Site Codes	Corrected Soil ^{239}Pu (mCi km^{-2})	Radius from 903 Pad (m)	Soil Value Ref	Site Ref
484280	4415380	1947.0	5	H5	3040.5	883	d	d
484140	4415360	107.0	5	H6	165.5	742	d	d
484070	4415350	1370.0	5	H7	2138.9	671	d	d
484200	4415170	1730.0	5	H8	2701.4	812	d	d
484200	4414910	456.0	5	H9	710.8	894	d	d
484200	4415700	165.0	5	H10	256.1	890	d	d
484590	4415720	81.1	5	H11	125.0	1,259	d	d
484590	4415400	593.0	5	H12	924.9	1,193	d	d
484590	4415090	428.0	5	H13	667.0	1,210	d	d
484590	4414710	266.0	5	H14	413.9	1,333	d	d
485010	4415390	354.0	5	H15	551.4	1,612	d	d
484740	4416020	29.6	5	H16	44.5	1,516	d	d
485080	4415850	26.1	5	H17	39.1	1,765	d	d
484980	4415070	140.0	5	H18	217.1	1,598	d	d
484980	4414580	77.3	5	H19	119.1	1,740	d	d
485910	4416200	32.0	5	H20	48.3	2,663	d	d
485910	4415090	101.0	5	H21	156.1	2,520	d	d
485910	4414120	42.4	5	H22	64.6	2,778	d	d

TABLE I-2
(Continued)

SUMMARY OF PLUTONIUM SOIL SAMPLES TAKEN NEAR THE ROCKY FLATS PLANT BETWEEN 1969-1973

X Coord UTM Easting (m)	Y Coord UTM Northing (m)	Measured Soil ^{239}Pu (mCi km^{-2})	Sample Depth (cm)	Site Codes	Corrected Soil ^{239}Pu (mCi km^{-2})	Radius from 903 Pad (m)	Soil Value Ref	Site Ref
483540	4415330	1480.0	5	H23	2310.8	141	d	d
483630	4415340	33,400.0	5	H24	52,185.8	232	d	d
483490	4415230	150,000.0	5	H25	234,373.3	120	d	d
483510	4415220	28,400.0	5	H26	44,373.3	142	d	d
485910	4417180	5.8	1	A	27.3	3,130	b,c,e,i,t	b,e,i
485800	4414100	60.8	1	B	302.3	2,688	b,c,e,i,t	b,e,i
485080	4417470	0.4	1	C	0.3	2,736	b,c,e,i,t	b,e,i
479460	4408960	0.6	1	D	1.3	7,473	b,c,e,i,t	b,e,i
479710	4408770	1.3	1	E	4.8	7,509	b,c,e,i,t	b,e,i
480150	4408570	1.3	1	F	4.8	7,483	b,c,e,i,t	b,e,i
479880	4419730	1.4	1	G	5.3	5,650	b,c,e,i,t	b,e,i
482440	4417930	0.6	1	H	1.3	2,790	b,c,e,i,t	b,e,i
489200	4417750	7.7	1	I	36.8	6,292	b,c,e,i,t	b,e,i
487590	4415860	5.2	1	J	24.3	4,226	b,c,e,i,t	b,e,i
487860	4416130	4.0	1	K	18.3	4,535	b,c,e,i,t	b,e,i
488940	4415030	0.5	1	L	0.8	5,547	b,c,e,i,t	b,e,i
488960	4414180	1.7	1	M	6.8	5,674	b,c,e,i,t	b,e,i
487320	4413780	6.1	1	N	28.8	4,208	b,i	b,i
481860	4425970	0.3	1	O	0.0	10,771	b	b,i

TABLE I-2
(Continued)

SUMMARY OF PLUTONIUM SOIL SAMPLES TAKEN NEAR THE ROCKY FLATS PLANT BETWEEN 1969-1973

X Coord UTM Easting (m)	Y Coord UTM Northing (m)	Measured Soil ^{239}Pu (mCi km^{-2})	Sample Depth (cm)	Site Codes	Corrected Soil ^{239}Pu (mCi km^{-2})	Radius from 903 Pad (m)	Soil Value Ref	Site Ref
485730	4425950	0.5	1	P	0.8	10,892	b	b,i
487750	4422540	0.2	1	Q	0.0	8,438	b	b,i
492160	4422700	0.4	1	R	0.3	11,461	b	b,i
492150	4420210	0.5	1	S	0.8	10,029	b	b,i
495640	4417520	0.8	1	T	2.3	12,438	b	b,i
495130	4411840	1.5	1	U	5.8	12,232	b,c,e,t	b,e,i
491360	4410110	2.4	1	V	10.3	9,508	b,c,e,t	b,e,i
487060	4410290	0.2	1	W	0.0	6,213	b,c,e,t	b,e,i
485020	4410810	0.8	1	X	2.3	4,783	b,c,e,t	b,e,i
482410	4412280	1.9	1	Y	7.8	3,188	b,c,e,t	b,e,i
478290	4414230	0.5	1	Z1	0.8	5,223	b	b
478300	4415830	1.1	1	Z2	3.8	5,126	b	b
474670	4425650	1.4	1	Z3	5.3	13,532	b	b,i
479210	4417830	3.8	5	B1/2-324	4.2	4,889	a,c,e,l,t	a,e
479320	4417580	1.1	5	B2/2-306	0.0	4,669	a,c,e,l,t	a,e
479300	4416750	4.5	5	B3/2-288	5.3	4346	a,c,e,l,t	a,e
479400	4414900	4.3	5	B4/2-252	5.0	4,021	a,c,e,l,t	a,e
479400	4414350	7.0	5	B5	9.2	4,114	j	e
479400	4412620	2.3	5	B6	1.9	4,820	c,e,t	e

TABLE I-2
(Continued)

SUMMARY OF PLUTONIUM SOIL SAMPLES TAKEN NEAR THE ROCKY FLATS PLANT BETWEEN 1969-1973

X Coord UTM Easting (m)	Y Coord UTM Northing (m)	Measured Soil ^{239}Pu (mCi km^{-2})	Sample Depth (cm)	Site Codes	Corrected Soil ^{239}Pu (mCi km^{-2})	Radius from 903 Pad (m)	Soil Value Ref	Site Ref
480260	4419670	4.1	5	B7/2-342	4.7	5,373	a,c,e,l,t	a,e
479420	4417240	0.5	5	B8	0.0	4,423	c,e,t	e
479420	4415770	5.0	5	B9/2-270	6.1	4,006	a,c,e,l,t	a,e
479420	4413470	1.8	5	B10	1.1	4,385	c,e,t	e
479880	4413540	7.0	5	B11/2-234	9.2	3,940	a,j	a,e,j
480280	4412670	9.0	5	B12/2-216	12.4	4,087	a,c,e,t	a,e
479730	4411930	1.8	5	B13	1.1	4,989	c,e,t	e
479780	4411400	0.5	5	B14	0.0	5,328	c,e,t	e
479660	4410360	11.7	5	B15	16.6	6,204	c,e,t	e
479320	4409390	4.3	5	B16	5.0	7,190	c,e,t	e
482300	4418050	27.9	5	B17/2-360	41.9	2,953	a,c,e,t	a,e
481070	4417170	6.3	5	B18/1-324	8.1	2,981	a,c,e,l,t	a,e
482020	4417170	6.3	5	B19/1-342	8.1	2,316	a,c,e,l,t	a,e
481070	4416700	10.4	5	B20/1-288	14.5	2,713	a,c,e,l,t	a,e
481420	4416710	1.3	5	B21	0.3	2,425	c,e,t	e
481070	4415680	6.3	5	B22/1-270	8.1	2,359	a,c,e,l,t	a,e
481070	4415330	6.8	5	B23/1-252	8.9	2,330	a,c,e,l,t	a,e
481070	4414970	6.8	5	B24/1-234	8.9	2,355	a,c,e,l,t	a,e
481070	4412530	2.3	5	B25/2-198	1.9	3,627	a,c,e,l,t	a,e

TABLE I-2
(Continued)

SUMMARY OF PLUTONIUM SOIL SAMPLES TAKEN NEAR THE ROCKY FLATS PLANT BETWEEN 1969-1973

X Coord UTM Easting (m)	Y Coord UTM Northing (m)	Measured Soil ^{239}Pu (mCi km^{-2})	Sample Depth (cm)	Site Codes	Corrected Soil ^{239}Pu (mCi km^{-2})	Radius from 903 Pad (m)	Soil Value Ref	Site Ref
481600	4412390	9.5	5	B26	13.1	3,430	c,e,t	e
481450	4410580	11.3	5	B27	16.0	5,116	c,e,t	e
482210	4410500	5.4	5	B28	6.7	4,955	c,e,t	e
483600	4418230	5.0	5	B29/2-018	6.1	2,927	a,c,e,t	a,e
482820	4417170	5.4	5	B30/1-360	6.7	1,948	a,c,e,l,t	a,e
483480	4417170	9.0	5	B31/1-018	12.4	1,862	a,e,t	a,e
484170	4417170	5.4	5	B32/1-036	6.7	2,013	a,c,e,l,t	a,e
483660	4414570	69.8	5	B33	107.4	784	c,e,t	e
482790	4414190	16.7	5	B34	24.4	1,275	c,e,t	e
482540	4412280	2.3	5	B35/2-180	1.9	3,150	a,c,e,l,t	a,e
483200	4412020	0.5	5	B36	0.0	3,296	c,e,t	e
483950	4411460	3.2	5	B37/2-162	3.3	3,889	a,c,e,l,t	a,e
483210	4410440	3.6	5	B38	3.9	4,874	c,e,t	e
483970	4410460	8.1	5	B39	11.0	4,883	c,e,t	e
484290	4418010	3.6	5	B40/2-036	3.9	2,843	a,c,e,t	a,e
485800	4415870	0.5	5	B41	0.0	2,464	c,e,t	e
485800	4415610	4.1	5	B42/2-090	4.7	2,419	a,c,e,t	a,e
484950	4415480	9.9	5	B43	13.8	1,559	c,e,t	e

TABLE I-2
(Continued)

SUMMARY OF PLUTONIUM SOIL SAMPLES TAKEN NEAR THE ROCKY FLATS PLANT BETWEEN 1969-1973

X Coord UTM Easting (m)	Y Coord UTM Northing (m)	Measured Soil ^{239}Pu (mCi km^{-2})	Sample Depth (cm)	Site Codes	Corrected Soil ^{239}Pu (mCi km^{-2})	Radius from 903 Pad (m)	Soil Value Ref	Site Ref
485800	4414910	2.7	5	B44	2.5	2,433	c,e,t	e
485800	4414350	121.5	5	B45	188.1	2,585	c,e,j,t	e,j
484250	4411370	0.5	5	B46	0.0	4,031	c,e,t	e
485330	4411090	5.4	5	B47	6.7	4,640	c,e,t	e
485840	4410350	3.6	5	B48	3.9	5,528	c,e,t	e
484960	4410190	5.9	5	B49	7.5	5,352	c,e,t	e
485940	4417520	3.6	5	B50/2-054	3.9	3,367	a,c,e,t	a,e
485940	4416680	9.5	5	B51/2-072	13.1	2,886	a,c,e,t	a,e
486150	4415230	17.6	5	B52	25.8	2,751	c,e,t	e
486200	4414100	6.3	5	B53/2-108	8.1	3,050	a,c,e,t	a,e
487300	4413960	3.2	5	B54	3.3	4,127	a,c,e,t	a,e
487300	4413540	3.6	5	B55/2-126	3.9	4,283	a,c,e,t	a,e
486770	4413260	37.8	5	B56	57.4	3,945	a,c,e,t	a,e
485950	4412800	4.1	5	B57/2-144	4.7	3,578	a,c,e,t	a,e
486370	4410150	20.7	5	B58	30.6	5,954	c,e,t	e
488930	4414890	3.6	5	B59	3.9	5,546	a,c,e,t	a,e
488070	4414070	5.0	5	B60	6.1	4,832	a,c,e,t	a,e
488930	4414070	9.0	5	B61	12.4	5,667	c,e,t	e
488830	4410460	20.7	5	B62/5-126	30.6	7,281	a,c,e,l,t	a,e

TABLE I-2
(Continued)

SUMMARY OF PLUTONIUM SOIL SAMPLES TAKEN NEAR THE ROCKY FLATS PLANT BETWEEN 1969-1973

X Coord UTM Easting (m)	Y Coord UTM Northing (m)	Measured Soil ^{239}Pu (mCi km^{-2})	Sample Depth (cm)	Site Codes	Corrected Soil ^{239}Pu (mCi km^{-2})	Radius from 903 Pad (m)	Soil Value Ref	Site Ref
487350	4408520	3.6	5	B63/5-144	3.9	7,855	a,l	a,e
489140	4417420	14.9	5	B64	21.6	6,116	a,c,e,t	a,e
489090	4416560	5.0	5	B65	6.1	5,826	a,c,e,t	a,e
489110	4415380	5.9	5	B66	7.5	5,710	a,c,e,t	a,e
489070	4414030	6.8	5	B67	8.9	5,813	c,e,t	e
490520	4412960	6.3	5	B68/5-108	8.1	7,498	a,c,e,l,t	a,e
488960	4410090	NA	NA	B69	NA	7,626		e
490000	4410050	NA	NA	B70	NA	8,440		e
491470	4417800	4.1	5	B71/5-072	4.7	8,445	a,c,e,t	a,e
491840	4417530	NA	NA	B72	NA	8,727		e
492070	4416380	NA	NA	B73	NA	8,736		e
492180	4415850	NA	NA	B74	NA	8,797		e
491090	4415440	NA	NA	B75	NA	7,691		e
491230	4410030	NA	NA	B76	NA	9,444		e
490640	4408460	NA	NA	B77	NA	9,967		e
492950	4415160	3.6	5	B78/5-090	3.9	9,551	a,l	a,e
493190	4414680	0.9	5	B79	0.0	9,810	c,e,t	e
493140	4414000	NA	NA	B80	NA	9,828		e
493140	4413160	NA	NA	B81	NA	9,974		e

TABLE I-2
(Continued)

SUMMARY OF PLUTONIUM SOIL SAMPLES TAKEN NEAR THE ROCKY FLATS PLANT BETWEEN 1969-1973

X Coord UTM Easting (m)	Y Coord UTM Northing (m)	Measured Soil ^{239}Pu (mCi km^{-2})	Sample Depth (cm)	Site Codes	Corrected Soil ^{239}Pu (mCi km^{-2})	Radius from 903 Pad (m)	Soil Value Ref	Site Ref
493130	4411760	NA	NA	B82	NA	10,357		e
493130	4410650	NA	NA	B83	NA	10,788		e
484170	4416430	3.2	1	B101	14.3	1,359	c,e,t	e
484170	4416320	7.2	1	B102	34.3	1,270	c,e,j,t	e
484040	4416210	5.8	1	B103	27.3	1,104	c,t	e
484290	4415900	73.8	1	B104	367.3	1,068	c,e,t	e
484300	4415630	262.4	1	B105	1310.3	955	c,e,t	e
484170	4415560	212.0	1	B106	1058.3	810	c,e,t	e
484280	4415400	1397.2	1	B107	6984.3	885	c,e,t	e
484190	4415180	369.4	1	B108	1845.3	801	c,e,t	e
484280	4415040	324.4	1	B109	1620.3	920	c,e,t	e
484280	4414950	414.4	1	B110	2070.3	951	c,e,t	e
484410	4415980	26.1	1	B111	128.8	1,212	c,e,t	e
484450	4415620	54.9	1	B112	272.8	1,095	c,e,t	e
484430	4415530	127.8	1	B113	637.3	1,053	c,e,t	e
484480	4415370	76.0	1	B114	378.3	1,082	c,e,t	e
484430	4415430	772.2	1	B115	3859.3	1,037	c,e,t	e
484480	4415180	564.8	1	B116	2822.3	1,088	c,e,t	e
484450	4415000	252.9	1	B117	1262.8	1,095	c,e,t	e

TABLE I-2
(Continued)

SUMMARY OF PLUTONIUM SOIL SAMPLES TAKEN NEAR THE ROCKY FLATS PLANT BETWEEN 1969-1973

X Coord UTM Easting (m)	Y Coord UTM Northing (m)	Measured Soil ^{239}Pu (mCi km^{-2})	Sample Depth (cm)	Site Codes	Corrected Soil ^{239}Pu (mCi km^{-2})	Radius from 903 Pad (m)	Soil Value Ref	Site Ref
484450	4414820	112.0	1	B118	558.3	1,159	c,e,t	e
484920	4415820	7.6	1	B119	36.3	1,603	c,e,t	e
485110	4415130	55.8	1	B120	277.3	1,719	c,e,t	e
485060	4414840	103.0	1	B121	513.3	1,725	c,e,t	e
485470	4415970	3.6	1	B122	16.3	2,173	c,e,t	e
485260	4415890	8.6	1	B123	41.3	1,948	c,e,t	e
485420	4415440	49.0	1	B124	243.3	2,024	c,e,t	e
485390	4415520	56.7	1	B125	281.8	2,001	c,e,t	e
485360	4415150	199.4	1	B126	995.3	1,967	c,e,t	e
485340	4415020	45.0	1	B127	223.3	1,962	c,e,t	e
485390	4415090	32.8	1	B128	162.3	2,002	c,e,t	e
485390	4414810	21.6	1	B129	106.3	2,052	c,e,t	e
486040	4416170	11.7	1	B130	56.8	2,777	c,e,t	e
485930	4416100	11.4	1	B131	55.3	2,650	c,e,t	e
485900	4416110	11.1	1	B132	53.8	2,625	c,e,t	e
485960	4415640	11.0	1	B133	53.3	2,581	c,e,t	e
485930	4415550	10.8	1	B134	52.3	2,541	c,e,t	e
485900	4415230	10.7	1	B135	51.8	2,501	c,e,t	e
485900	4415120	10.8	1	B136	52.3	2,507	c,e,t	e

TABLE I-2
(Continued)

SUMMARY OF PLUTONIUM SOIL SAMPLES TAKEN NEAR THE ROCKY FLATS PLANT BETWEEN 1969-1973

X Coord UTM Easting (m)	Y Coord UTM Northing (m)	Measured Soil ^{239}Pu (mCi km^{-2})	Sample Depth (cm)	Site Codes	Corrected Soil ^{239}Pu (mCi km^{-2})	Radius from 903 Pad (m)	Soil Value Ref	Site Ref
485900	4415020	10.8	1	B137	52.3	2,517	c,e,t	e
485900	4414590	10.9	1	B138	52.8	2,602	c,e,t	e
483090	4416250	20.7	5	G1	30.6	990	c,e,t	e
483590	4416320	33.3	5	G2	50.3	1,028	c,e,t	e
483620	4416430	2.7	5	G3	2.5	1,141	c,e,t	e
484110	4416270	13.1	5	G4	18.8	1,194	c,e,t	e
484140	4416350	17.6	5	G5/1-054	25.8	1,276	a,c,e,l,t	a,e
483150	4416040	270.9	5	G6	421.6	772	c,e,t	e
483530	4416150	9.0	5	G7	12.4	850	c,e,t	e
484000	4416060	2.7	5	G9	2.5	960	c,e,t	e
484060	4416120	18.0	5	G10	26.4	1,045	c,e,t	e
483650	4415670	9.5	5	G11	13.1	438	c,e,t	e
483970	4415690	5.0	5	G12	6.1	685	c,e,t	e
484160	4415820	14.9	5	G13/1-072	21.6	915	a,c,e,l,t	a,e
483560	4415460	373.5	5	G14	581.9	219	c,e,t	e
483820	4415430	2128.5	5	G15	3324.1	437	c,e,t	e
482760	4414770	5.4	5	G18	6.7	837	c,e,t	e
483030	4414850	35.1	5	G19	53.1	590	c,e,t	e
483610	4415030	1377.0	5	G20	2149.9	350	c,e,t	e

TABLE I-2
(Continued)

SUMMARY OF PLUTONIUM SOIL SAMPLES TAKEN NEAR THE ROCKY FLATS PLANT BETWEEN 1969-1973

X Coord UTM Easting (m)	Y Coord UTM Northing (m)	Measured Soil ^{239}Pu (mCi km^{-2})	Sample Depth (cm)	Site Codes	Corrected Soil ^{239}Pu (mCi km^{-2})	Radius from 903 Pad (m)	Soil Value Ref	Site Ref
484050	4415210	1431.0	5	G22	2234.2	658	c,e,t	e
484120	4414790	48.6	5	G23	74.2	888	c,e,t	e
484250	4414950	396.0	5	G25	617.0	923	c,e,t	e
484020	4414680	6.3	5	G26	8.1	884	c,e,t	e
483000	4414640	8.1	5	G27	11.0	780	c,e,t	e
483540	4414470	39.6	5	G28	60.2	852	c,e,t	e
483940	4414390	117.0	5	G29	181.1	1,067	c,e,t	e
482420	4414430	7.2	5	G30	9.5	1,317	c,t	e
482870	4414350	8.6	5	G31	11.7	1,097	c,e,t	e
483580	4414290	26.1	5	G32	39.1	1,036	c,e,t	e
484120	4414390	10.8	5	G33	15.2	1,168	c,e,t	e
482290	4414270	9.0	5	G34	12.4	1,521	c,e,t	e
482790	4414350	9.0	5	G35	12.4	1,137	c,e,t	e
483420	4414110	5.9	5	G36	7.5	1,200	c,e,t	e
482730	4414050	3.2	5	G37	3.3	1,427	c,e,t	e
483030	4414080	0.9	5	G38	0.0	1,284	c,e,t	e
485910	4407630	14.8	5	5-162	21.4	8,080	a,l	a,l
482670	4406710	5.4	5	5-180	6.7	8,631	a,l	a,l

TABLE I-2
(Continued)

SUMMARY OF PLUTONIUM SOIL SAMPLES TAKEN NEAR THE ROCKY FLATS PLANT BETWEEN 1969-1973

X Coord UTM Easting (m)	Y Coord UTM Northing (m)	Measured Soil ^{239}Pu (mCi km^{-2})	Sample Depth (cm)	Site Codes	Corrected Soil ^{239}Pu (mCi km^{-2})	Radius from 903 Pad (m)	Soil Value Ref	Site Ref
479130	4409310	4.5	5	5-216	5.3	7,364	a,l	a,l
476410	4411530	2.7	5	5-234	2.5	7,947	a,l	a,l
476510	4413940	4.1	5	5-252	4.7	7,025	a,l	a,l
476410	4415630	6.3	5	5-270	8.1	6,997	a,l	a,l
476940	4420060	4.5	5	5-306	5.3	8,018	a,l	a,l
478360	4421100	3.6	5	5-324	3.9	7,676	a,l	a,l

Note: Coordinate locations are expressed in terms of the Universal Transverse Mercator (UTM), Zone 13 system. The origin of the UTM coordinates is the southwest corner of Building 707 of the Plant (i.e., 482774E, 4415537N; EG&G, 1991). However, since Building 707 is not shown on all of the maps containing soil data, the Building 707 coordinates were used to establish the coordinates of the Building 771 stack, which were then used as the basis for establishing the location of the soil samples. Sample depth refers to the depth to which soil was excavated. Note that no soil samples were taken at 12 of the sites (B69-70, B72-77, and B80-83) and that sites R23 through R33 are more than 10 miles away from the plant. Soil samples denoted 5-xxx refer to 1969 samples taken at a 5 mile radius and at various angles with respect to the center of the Rocky Flats Plant, e.g., 5-162 is located 162 degrees from true north. Some sites have both an alphabetic code and a distance-angle code, such as B1/2-374. Loser's 1970 map shows only alphabetical codes, but many of the 1969 survey samples were first given distance-angle code names, such as in Rocky Flats Plant (1969). Corrected soil concentrations are computed by first adjusting the measured value for depth, as described in the text, and then subtracting the background value of 1.7 mCi km^{-2} (Krey, 1974 and 1976). The radius of each sampling location is computed from the center of the 903 Pad, at UTM coordinates (483400E, 4415310N). The first 87 sites were sampled by the Colorado Committee on Environmental Information or the USAEC Health and Safety Laboratory. The last 150 sites (with designations beginning with B or G) were sampled by Rocky Flats personnel.

References: See Table I-3.

TABLE I-3

LOCATION COORDINATES OF THE AMBIENT AIR NETWORK AT ROCKY FLATS PLANT AND OTHER POINTS OF INTEREST

X Coord UTM Easting (m)	Y Coord UTM Northing (m)	Pre-1974 Site Code	Post-1974 Site Code	Site Description	Site Ref
482160	4415320	S-1	NA	On-site, W of Bldg 441	h,m
482470	4415520	S-2	NA	On-site, N of Bldg 551	h,m
482470	4416060	S-3	NA	On-site, near Gate 14, inside N Perimeter Rd	h,m,q
482860	4416080	S-4	NA	On-site, near Gate 13, inside N Perimeter Rd	h,m
483270	4415930	S-5	NA	On-site, NE of solar pond 207B, inside NE Perimeter Rd	h,m
483250	4415400	S-6	NA	On-site, NW of the 903 Pad on Central Ave	h,m
483310	4415250	S-7	NA	On-site, SW of the 903 Pad	h,m,q
483590	4415370	S-8	S-07	On-site, S of East Gate guard shack, inside SE Perimeter Rd	d,h,m,n
482790	4415390	S-9	NA	On-site, S of Bldg 708	h,m
482570	4415150	S-10	S-12	On-site, NE corner of Cedar Ave & 7th St	h,m,n
476500	4414300	S-11	S-44	Coal Creek	m,n
481000	4422750	S-13	S-51	Marshall	m,n,q
477000	4426700	S-15	S-54	Boulder	m,n
492700	4426400	S-16	S-55	Lafayette	m,n
492500	4418150	S-17	S-56	Broomfield	m,n
487500	4413100	S-18	S-58	Former Wagner School 96th & Alkire	k,m,n
485090	4401580	S-20	S-62	Golden N edge of town	m,n
501000	4395000	S-23	S-61	Denver Roof, 20th & Stout	m,n
497150	4408500	S-25	S-60	Westminster	m,n

TABLE I-3

LOCATION COORDINATES OF THE AMBIENT AIR NETWORK AT ROCKY FLATS PLANT AND OTHER POINTS OF INTEREST

X Coord UTM Easting (m)	Y Coord UTM Northing (m)	Pre-1974 Site Code	Post-1974 Site Code	Site Description	Site Ref
483600	4415730	S-50	S-06	On-site, E of Bldg 995, inside NE Perimeter Rd	
483350	4415750	S-51	S-05	On-site, E of solar pond 207B, off Spruce Ave	h,m,n
483400	4415310	P903	P903	Approx Center of the 903 Pad	h,m
482870	4415870	P771	P771	Bldg 771 stack	h,m

Notes: The origin of the UTM coordinates is the southwest corner of Building 707 of the plant (i.e., 482774E, 4415537N; EG&G, 1992). Locations S1 to S51 refer to both on-site and off-site air sampler locations before 1974. All air samplers were replaced with high-volume samplers and renumbered in 1975. P903 refers to the approximate center of the fenced area surrounding the 903 Pad in 1968 and P771 refers to the Building 771 stack.

REFERENCES

a Rocky Flats Plant (1969). EMF Catalog #60-13880-RR-008(p), #00006536. "Site Survey Locations and Analysis: 1969, Off-Site Soil Sampling Locations, Rocky Flats Plant." Repository Document AC-1057.

b Poet, S., and E. Martell (1972). "Plutonium-239 and Americium-241 contamination in the Denver area." *Health Physics*, Vol. 23, pp. 537-548. Repository Document AC-641.

c Seed, J., K. Calkins, C. Illsley, F. Miner, and J. Owen (1971). "Committee evaluation of plutonium levels in soil within and surrounding USEAC installation at Rocky Flats, Colorado." Prepared by Dow Chemical Co., Golden, Colorado, Report #RFP-INV-10. Repository Document AC-726.

d Krey, P., E. Hardy, H. Volchok, L. Toonkel, R. Knuth, M. Coppes, and T. Tamura (1976). "Plutonium and americium contamination in Rocky Flats Soil — 1973." Prepared by the U.S. Energy Research and Development Administration, New York, Health and Safety Laboratory Report #HASL-304. Repository Document AC-192.

e Rockwell International (1971). "Rocky Flats Plant and surrounding area contours, Drawing #18789-2, Issue B, Sheet 2 of 3." It is also called: "Soil Sampler Locations," #PRD 482-71-4. ChemRisk document #92CR021, Item 1 A 45702.

f Krey, P., and E. Hardy (1970). "Plutonium in soil around the Rocky Flats Plant." Prepared by the U.S. Atomic Energy Commission, Health and Safety Laboratory, New York, Report #HASL-235. Repository Document AC-193.

g Krey, P., and B. Krajewski (Undated). "Plutonium isotopic ratios at Rocky Flats." Source unknown. Repository Document AC-737. pp. I-67, I-94.

h Hammond, S. (Undated). "Industrial-type operations as a source of environmental plutonium." Source unknown. Repository Document RE-721, pp. 25-35.

i Martell, E. (1970). A letter addressed to Glenn Seaborg, U.S. Atomic Energy Commission, Washington, D.C., dated Jan 13, 1970. Repository Document IP-222, 14 pp.

j Owen, J., and L. Steward (1974). "A historical summation of environmental incidents affecting soils at or near the US AEC Rocky Flats Plant." Prepared January 29, 1974 by the Rocky Flats Division of Dow Chemical. Repository Document RE-318.

k Volchok, H., R. Knuth, and M. Kleinman (Undated). "Plutonium in the neighborhood of Rocky Flats, Colorado: Airborne respirable particles." HASL #246. Repository Document AC-575.

l Hammond, S. E. (1970). "Soil sampling report — week ending April 17, 1970, Plutonium Strontium-90 Results." Report is addressed to W. H. Lee. Repository Document EN-1016.

m Unknown (1969). "Decontamination and body counting." Draft report of the May 11, 1969 fire, with an apparent date of 6/3/1969. ChemRisk Document: 92CR038, Item 1 A, pp. 33782-33806.

n EG&G (1992). "Air surveillance network siting study, Rocky Flats Plant, Appendix B: RAAMP Sampler Locations." Internal document written by EG&G, Rocky Flats, Inc., Jan. 1992, pp. B-1 -B-4.

o Krey, P. W. (1976). "Remote plutonium contamination and total inventories from Rocky Flats." *Health Physics*, Vol. 30, pp. 209-214. Repository Document AC-728.

p Jacoe, P. W. (1976). A letter written by Mr. Jacoe to an unknown person, dated June 9, 1970. Colorado Dept. of Health, Denver, Colorado. 10 pages.

q Rocky Flats Plant (1967). Rocky Flats Plant aerial photos, negative #12579-02 and #12579-08, taken 11/15/1967.

r EG&G (1991). Digitized base map surrounding the Rocky Flats Plant. Repository Document PO-1158.

s Loser, R., and R. Tibbals (1972). "Soil sampling east of Indiana Street." RFP report #317-72-186 prepared for J. Willing, dated Nov 29, 1972. Given as Appendix D-3 of Final Past Remedy Report, Operable Unit No. 3—IHSS 199, May 1991. Repository Document RE-95.

t Loser, R. (1971). "Plutonium in soil surrounding the Rocky Flats Plant." RFP #482-71-4, prepared for J. Seed, dated April 26, 1971. Repository Document RE-763.

u Love, C., W. Kittinger, T. Barry, F. Linck, C. Bogard, L. Matheson, S. Hammond, R. Woodard, and D. Irwin (1970). "Report of the Task Force on potential off-site contamination." Dow Chemical Co., Rocky Flats Division, Golden, Col. Repository Document RE-1104.

v Dow Chemical (1969). "Environmental Survey — January-June 1969." Dow Chemical Co., Rocky Flats Division, Golden, Colorado. Repository Document AC-159.

w Krey, P. W. (1974). "Plutonium-239 contamination in the Denver area." Letters to the editor reply to "Plutonium-239 contamination in the Denver Area." *Health Physics*, Vol. 26, pp.117-220. Repository Document AC-190.

x Anspaugh, L., J. Shinn, J. Phelps, and N. Kennedy (1975). "Resuspension and redistribution of plutonium in soils." *Health Physics*, Vol. 29, pp. 571-582. Repository Document MO-398.

y EPA (1977). Rocky Flats Facility/Technical Assessment Document.

APPENDIX J

CREATING A SITE MAP OF SOIL CONTAMINATION DATA

APPENDIX J
CREATING A SITE MAP
OF SOIL CONTAMINATION DATA

To create a computerized map of the soil contamination data presented in Appendix I, Table I-2, data consistency was checked by plotting coordinates of all soil locations on a large-scale digitized map and using the Surfer plotting/viewing program (Golden Software, Ver. 4.15) to verify the results. The digitized map was obtained from EG&G (1991) as a series of files based on U. S. Geological Survey (USGS) DLG (digital line graph) data format. EG&G originally obtained map data from USGS in a 1:24,000 scale as six quadrangle maps surrounding Rocky Flats: Eldorado Springs, Arvada, Louisville, Lafayette, Ralston Buttes, and Golden. EG&G then edge-matched the six quads into one coverage and converted it to DXF format in state planar coordinates. The map files contain data on streams, lakes, railways, fence lines, and roads. The files were loaded into AutoCad (Autodesk Inc., Version 10) and printed as 36-inch maps. An electronic digitizer was used to trace map features, such as fences, roads, and lakes. While tracing site features, points were electronically recorded whenever there was a change in direction of a road or lake shore. Anywhere between 13 to 116 coordinates were recorded for each feature, with an estimated accuracy of 5 meters at recorded locations. State planar coordinates were then converted to UTM coordinates using Tralaine (Mentor Software, Inc., Version 2.10). Tralaine converts x,y locations from Central Colorado State planar coordinates to UTM-Zone 13 coordinates. This conversion is accurate to less than a meter. All plotting, contouring, and verification of soil sampling locations were done using digitized site features in the UTM coordinate system.

Soil sampling locations were read into the plotting/viewing program of Surfer and MicroStation (Version 3.5.1). Screen drawings with a scale as small as 1 meter per millimeter were used to view relative locations of soil sites to fence lines, road intersections, etc. Sample locations were adjusted to make them consistent with Loser's map.

Soil sampling sites within or near the plant perimeter or security fence should be accurate to within 10-50 meters. Soil sites inside the cattle fence around RFP should be consistent with Loser's map to within 50-100 meters, and sites from 1 mile to 5 miles should be consistent within 100-1000 meters. The exceptions are the 23 air sampler locations in Appendix I, Table I-3, which should be accurate to within 10 meters.

REFERENCES

EG&G (1991). Digitized base map surrounding the Rocky Flats Plant. Repository Document PO-1158.

APPENDIX K

DATA RELATIVE TO SOIL PARTICLE SIZE DISTRIBUTION FOR 903 PAD EVALUATION

APPENDIX K

DATA RELATIVE TO SOIL PARTICLE SIZE DISTRIBUTION FOR 903 PAD EVALUATION

The particle size distribution of the material transported away from the 903 Pad by the wind is needed to establish the transport characteristics of the soil and the fraction of particles of respirable size. The respirable fraction largely determines the inhalation dose resulting from the 903 Pad releases. A particle size distribution giving a larger fraction of respirable particles will result in a greater inhalation dose.

The soil particle size distribution is an input to the computer models used to determine the downwind concentration and deposition of soil particles transported from the 903 Pad. The starting point for estimating the size distribution of the contaminated soil transported off of the 903 Pad is an estimate of the potentially resuspendable soil particle size distribution.

Krey *et al.* (1974) collected six surface soil samples near Rocky Flats with portable vacuum cleaners, to represent soil that could be resuspended. Krey *et al.* separated their soil samples into particle size fractions ranging from > 840 microns to < 0.2 micron. Wet sieving was used for the fractions above 53 microns, and sedimentation was used to separate smaller size particles. Krey *et al.* (1974) state:

> "The mass and activity distributions of the 6 surface soil samples generally followed a log-normal distribution. [P]lutonium activity is not uniformly distributed with the soil mass. The activity median diameter of 5 soils from the Rocky Flats area averaged about 50 microns (range 6-100 microns) as compared to about 200 microns (range 100-360 microns) for the mass median diameter. These averages omitted the soil sample taken immediately east of the asphalt (903) pad because this soil was fill brought in to cover the initially contaminated surface.
>
> "[O]nly 3.8 and 13% (respectively) of the mass and plutonium activity in surface soil are in the respirable range.
>
> "The respirable fraction of surface soil is defined here as all particles below 7 [microns] which are separated by gravitational settling methods. It refers to soil particles which settle in water at rates equivalent to the rates of spherical particles with diameters [less than or equal to 7 microns] and with densities of 2.6 grams per cubic centimeter. This is not the conventional definition of respirable fraction applied to aerosols.... [T]his definition in surface soil is on the conservative side, exhibiting a greater respirable fraction than could exist."

The percentage of soil particles found in small size fractions depends strongly on sample preparation techniques (Hayden, 1977). Hayden collected soil samples at two places at Rocky Flats using the procedure specified by Dr. Carl Johnson and his colleagues (1976). Hayden then used four different soil fractionation procedures in his soil sampling:

A. dry sifting;

B. sedimentation with minimal agitation;

C. ultrasound agitation and sedimentation; and

D. hydrogen peroxide digestion, ultrasound agitation, and sedimentation, as used by Johnson *et al.* (1976).

Hayden first separated his two soil samples into fractions greater and less than 2 mm in size. One sample had 30 percent by weight > 2 mm and 70 percent < 2 mm, and the other had 48 percent by weight > 2 mm and 52 percent < 2 mm. Then he studied the soil particles less than 2 mm in size, and found increasing amounts of soil mass and plutonium activity in the < 10 micron fraction of soil resulting from soil fractionation procedures A through D. In analyzing the two soil sample fractions less than 2 mm in size, method A indicated 1 percent or less of the soil sample weight for each sample was in the < 10 micron subgroup, method B showed about 5.5 percent of the soil sample weight for each sample in the < 10 micron subgroup, and method D indicated about 23 percent and 39 percent of soil sample weights for the respective samples in the < 10 micron subgroup (see Table K-1).

Hayden's results using method D are in general agreement with work done by the Colorado Department of Health (CDH, 1978) on soil samples from Rocky Flats, which found 40 percent of one soil sample in the < 5 micron size fraction and 29 percent of another soil sample in the < 5 micron size fraction, using Johnson's fractionation method (Hayden's method D).

TABLE K-1

WEIGHT PERCENT IN THE < 10 MICRONS SIZE FRACTION USING FRACTIONATION METHOD

Method	Sample 1 Weight Percent	Sample 2 Weight Percent
A	0.5	1.0
B	5.5	5.4
C	31.0	14.3*
D	38.8	22.7

* Repeat analysis gave 15.0%.

Hayden's method B found 7 to 8 percent of the plutonium activity in the < 10 micron soil fraction, while method D found 75 percent and 84 percent of the plutonium activity in the < 10 micron soil fraction. This is the result of increasing disruption of in-situ particle associations. Hayden concluded that strongly disruptive soil fractionation procedures yield results that do not represent the actual size distributions occurring in the field, and stated his belief that method B "provides the most realistic data for evaluating an environmental inhalation hazard."

Hayden's soil particle size distribution data from Rocky Flats soil samples fractionated with his method B can be summarized as follows:

	Sample 1	Sample 2
weight percent in fraction > 2 mm	30.5	48.4
weight percent in fraction < 2 mm	69.5	51.6
weight percent in fraction < 10 microns	5.5	5.4
percent of plutonium contamination on fraction < 10 microns	8	7

The agglomerating effect of cutting oil, which has the consistency of light motor oil (Little and Whicker, 1978), would be expected to reduce the fraction of respirable particles in the soil, however this effect has not been quantified.

Based on the material presented above, the following assumptions were made about the potentially resuspendable soil particle size distribution at Rocky Flats:

1. The soil particle size distribution is log-normal with a mass medium diameter of 200 μm [Krey *et al.*, 1974].

2. 5 percent of the soil mass is in the particle size fraction with diameter < 10 μm [Hayden, 1977].

A log normal soil particle size distribution with mass median diameter 200 μm and geometric standard deviation 6.18 has 5 percent of the soil mass in the size fraction < 10 μm in diameter. This soil size distribution is used in modeling the transport or contaminated soil away from the 903 Pad.

Airborne Mass Loading of Respirable Particles

The Colorado Department of Health has measured mass loading at Rocky Flats for a number of years. The average of the annual mass loading reported as the geometric mean for three years (1980, 1983, and 1984) was 60 $\mu g\ m^{-3}$ (Chick, 1992). This represents the total mass loading of TSP (approximately < 30 μm in equivalent aerodynamic diameter) derived from soil as well as other sources (e.g. combustion).

Langer (1985) found an average airborne mass loading of particles less than 3 microns in diameter at Rocky Flats of 8.5 $\mu g\ m^{-3}$, based on measurements taken from November 1982 to February 1984. Langer defines these particles as respirable and states that:

> "...respirable particles (at Rocky Flats) are mostly combustion pollutants from the metropolitan area and vehicle exhausts. This size fraction is deep black in color, while the other fractions are the color of the local soil (light brown)."

If only 50 percent of Langer's 8.5 $\mu g\ m^{-3}$ mass loading of particulates < 3 microns was from soil particles, the remaining 50 percent of combustion products would probably be sufficient to create the black color of the 3-micron-size fraction, and the resulting mass loading of airborne

soil particles < 3 microns in diameter would be 4.25 $\mu g\ m^{-3}$. If approximately half of the <3 μm particles Langer measured (4.25 $\mu g\ m^{-3}$) were derived from soil, then 7 percent (4.25/60) of the airborne soil particles at Rocky Flats would be <3 μm. This is in agreement with the estimated 7 percent of particles <3 microns in the TSP fraction (< 30 microns in diameter) of the assumed Rocky Flats soil size distribution.

Since the TSP fraction of the assumed Rocky Flats soil size distribution has about 7 percent of the particles < 3 microns in size and about 13 percent of the particles < 5 microns in size; 8 $\mu g\ m^{-3}$ ($8 \times 10^{-6}\ g\ m^{-3}$) is believed to be a reasonable estimate of long-term average mass loading of respirable (< 5 microns) resuspended soil-derived airborne particulates near Rocky Flats. Further, if the measured mass loading of TSP of 60 $\mu g\ m^{-3}$ at Rocky Flats were all soil derived, 13 percent of the TSP or 7.8 $\mu g\ m^{-3}$ should be respirable, based on the assumed Rocky Flats soil size distribution.

For the purposes of this study we have assumed that the best estimate of the mass loading of respirable particles is 8 $\mu g/m^3$. Based on the limited information located regarding this value, the uncertainty in this value will be represented by a lognormal distribution with a geometric mean of 1 and a geometric standard deviation of 1.2 such that 95 percent of the distribution lies within a factor of 1.5 of the best estimate.

REFERENCES

CDH (1978). Colorado Department of Health. "Radioactive Soil Contamination (Cesium-137 and Plutonium) in the Environment Near the Rocky Flats Nuclear Plant." September 1977, revised April 1978. Repository Document AC-632.

Chick, N. D. (1992). Personal communication. Colorado Department of Health, Air Pollution Control Division. June 19, 1992.

Hayden, J. A. (1977). "Effects of Size Fractionation Methods on Plutonium Distribution in Soil or Size Fractionation Methods: Measuring Plutonium in Respirable Dust." RFP-2705. Repository Document AC-516.

Johnson, C. J., R. R. Tidball, and R. C. Severson (1976). "Plutonium Hazard in Respirable Dust on the Surface of Soil." *Science*, 193: 488, 1976. Repository Document IP-459.

Krey, P. W., R. Knuth, T. Tamura, and L. Toonkel (1974). "Interrelations of Surface Air Concentrations and Soil Characteristics at Rocky Flats." p. 744 in *Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants* (1974). Proceedings of a Symposium held at Richland, Washington, September 4-6, 1974. Repository Document EN-706.

Langer, G. (1985). "Wind Resuspension of Plutonium Particles from Soil in a Semi-Arid Climate." RFP-3633/DE85 003910.

Little, C. A., and F. W. Whicker (1978). "Plutonium Distribution in Rocky Flats Soil." *Health Physics*, 34: 451, 1978.

APPENDIX L

STUDIES OF PLUTONIUM CONCENTRATION AS A FUNCTION OF SOIL PARTICLE SIZE FOR 903 PAD EVALUATION

APPENDIX L

STUDIES OF PLUTONIUM CONCENTRATION AS A FUNCTION OF SOIL PARTICLE SIZE FOR 903 PAD EVALUATION

A key issue in the evaluation of the 903 Pad releases is the relationship between plutonium concentration and soil particle size. No direct measurements of this relationship are available for the actual release. However, studies of contaminated soils around the plant and airborne dust after the pad was covered have been reviewed. These studies provide some support for the assumption of a direct relationship between plutonium contamination and soil particle mass.

Surface Soil

Langer (1974) reported data collected on the plutonium concentration of soil removed from the surface with a small, portable wind tunnel. The particles were separated into six size fractions in the 0.5 to 90 micron range by a cascade impactor. Langer said:

> "Pu-239 activity varied from 2 to 2000 pCi/g (4.4 to 4400 dpm/g), with the highest activity carried by the largest soil particles."

USEPA (1977) obtained data on the distribution of plutonium as a function of soil particle size in the vicinity of Rocky Flats. USEPA found (Table V, page 38) that the < 10 micron fraction was 20 percent by weight in all samples, and that this fraction carried about half of the plutonium activity.

Little and Whicker (1978) looked at larger-sized soil particles, with a minimum fraction size of 45 microns and less. They collected soil samples at locations from about 200 to 800 meters downwind (east southeast to southeast) of the 903 Pad to determine the plutonium concentration of various particle size fractions in soil contaminated by releases from the 903 Pad. They air-dried their soil samples and separated them into fractions by dry sieving. Little and Whicker found that the plutonium concentration in their soil samples was higher in the surface layer. Plutonium concentrations were also higher in the finer soil fractions. The different trends of plutonium concentration with particle size found by Langer (1974) and Little and Whicker (1978) may result in part from the different amount of disaggregation of soil particles caused by their respective sampling methods as well as from the different particle size ranges investigated.

CDH (1978) soil sampling techniques also result in higher plutonium concentrations in the finer soil fractions. CDH samples indicate that the plutonium concentration was 1.5 to 2.5 times greater in the particle size fraction < 5 microns (as obtained by Johnson's separation method) than in the particle size fraction < 2 mm.

Of these studies of observed soil contamination with plutonium, only the Langer study would seem to support the relationship between plutonium contamination and soil particle size. The observation of higher plutonium contamination being associated with the finer soil fractions in soils located off the 903 Pad would seem to contradict this relationship. However, only the finer fraction of plutonium bearing soil particulates released from the 903 Pad would be transported

off the pad to any significant extent. Therefore, off-pad soils should contain contamination that is largely associated with the finer soil fraction.

Airborne Dust

Langer's data (Langer, 1974) on airborne soil particles near the 903 Pad indicate plutonium-239 activity increasing with particle size from about 0.8 pCi g^{-1} (1.76 dis min^{-1} g^{-1}) for 0.5 micron particles to about 6 pCi g^{-1} (13.2 dis min^{-1} g^{-1}) for 90 micron particles.

Langer (Undated) has also reported the following 1982 data on increasing plutonium concentrations in larger-size fractions of suspended dust:

Size Fraction (microns)	Concentration (Bq g^{-1})	Concentration (dis min^{-1} g^{-1})
< 3	0.12	7.2
3 - 10	no data	---
10 - 15	0.48	29
> 15	1.5	90

Langer (1989, page 14) mentions that wet sieving of > 10 micron aerodynamic equivalent diameter airborne dust samples into 44 and 74 micron sieve fractions showed that the plutonium distribution is roughly proportional to dust particle mass. Freon was used as the suspension medium to minimize de-agglomeration.

These airborne dust studies suggest that the assumption of a direct relationship between plutonium contamination and particle mass is reasonable.

REFERENCES

CDH (1978). Colorado Department of Health. "Radioactive Soil Contamination (Cesium-137 and Plutonium) in the Environment Near the Rocky Flats Nuclear Plant." September 1977, revised April 1978. Repository Document AC-632.

Langer, G. (Undated). "Activity, Size, and Flux of Resuspended Particles from Rocky Flats Soil." RFP-3461. Repository Document MO-202.

Langer, G. (1974). "Wind Resuspension of Trace Amounts of Plutonium Particles from Soil in a Semi-Arid Climate." RFP-3633, 1973. Repository Document AC-467.

Langer, G. (1989). "Resuspension of Soil Particles from Rocky Flats Containing Plutonium Particles — A Review." Rockwell International Rocky Flats, December 1989. Repository Document RE-766.

Little, C. A., and F. W. Whicker (1978). "Plutonium Distribution in Rocky Flats Soil." *Health Physics* 34: 451, 1978.

USEPA (1977). U.S. Environmental Protection Agency. "Rocky Flats Facility Technical Assessment Document." Repository Document EN-730.

APPENDIX M

HIGH READINGS IN THE S-8 AIR SAMPLER
NOVEMBER 1968 - JANUARY 1969

APPENDIX M
HIGH READINGS IN THE S-8 AIR SAMPLER
NOVEMBER 1968 - JANUARY 1969

Hammond (1971) and Seed *et al.* (1971) report monthly air sampler data for the S-8 sampler east of the 903 Pad. High monthly average air concentrations of alpha particle activity were observed in the S-8 sampler from November 1968 through April 1969. Both Hammond and Seed *et al.* reported the maximum on-site air sampler reading as 0.34 pCi m^{-3} in the S-8 sampler for the month of December 1968. However, the actual maximum monthly average is 1.53 pCi m^{-3} at the S-8 sampler in January 1969. The error is apparently due to a data transcription error in the monthly on-site survey sheets, where a value of 0.153 was entered for January 1969. Only the February 11, 1969 Health Physics Status Report (Putzier, 1969) correctly reported the true maximum on-site air concentration for January 1969. All other reports give the incorrect value of 0.153 pCi m^{-3} for this month instead of the correct value of 1.53 pCi m^{-3}. Daily readings of long-lived alpha activity from sampler S-8 are given in Tables M-1 through M-3 for the months of November 1968, December 1968, and January 1969. The monthly average air concentrations were calculated from the daily long-lived alpha activity measurements using the following equation:

$$[\text{Air}]_{\text{average}} = \frac{\text{Total c min}^{-1}}{0.21 \times 2.22 \times \text{Rate} \times \text{Time}}$$

where:

$[\text{Air}]_{\text{average}}$	=	Average air concentration (pC m^{-3})
Total c min^{-1}	=	Total long-lived alpha activity measured during averaging period
0.21	=	Correction factor = filter burial loss (0.7) times counter efficiency (0.3)
2.22	=	Conversion factor (dis min^{-1} pCi^{-1})
Rate	=	Sampling flow rate (81.5 m^3 d^{-1})
Time	=	Total sampling time during averaging period (days)

The calculated monthly average air concentrations from November and December 1968 and January 1969 are also shown in Tables M-1 through M-3. The highest daily activity ever recorded at S-8 occurred on January 30-31, 1969, with a reading of approximately 650 c min^{-1} or a 24-hour average concentration of approximately 17 pCi m^{-3}.

It should be noted that these calculations were performed in part as a verification of the methods used by the plant site. As such, the number of days used in the above equation is equal to the number of days in the corresponding calendar month and not the number of days in the sampling period, as indicated in the "Result Sheet for On-Site Air Samples" during this period. The magnitude of the error introduced by this methodology depends on the magnitude of the difference between the number of days in the calendar month and the actual number of days in the sampling period. For these three months, there is a difference of three days for the November and December 1968 results and no difference for the January 1969 results. The re-calculated the monthly average concentrations for November and December 1968 are 0.19 pCi m^{-3} and 0.31 pCi m^{-3}, respectively, approximately 10 percent higher or lower than the concentrations reported by the plant.

REFERENCES

Hammond, S. E. (1971). "Industrial-Type Operations as a Source of Environmental Plutonium." LA 4576, Proceedings of Environmental Plutonium Symposium held at Los Alamos Scientific Laboratory, August 4-5, 1971. Repository Document RE-721.

Putzier, E. (1969). "Health Physics Status report for Buildings 444, 881, 883, 886, 991, Site Survey, Equipment Decontamination, and Construction — January 1969." The Dow Chemical Co., Rocky Flats Division, February 11, 1969. Repository Document RE-375.

Seed, J., K. Calkins, C. Illsley, F. Miner, and J. Owen (1971). "Committee Evaluation of Plutonium Levels in Soil Within and Surrounding USAEC Installation at Rocky Flats, Colorado." Dow Chemical Rocky Flats Division Report RFP-INV-10. Repository Document AC-726.

TABLE M-1

ON-SITE S-8 AIR SAMPLER LONG-LIVED ALPHA ACTIVITY RESULTS FOR NOVEMBER 1968

(Winds 30 mph or higher and count rates 10 c min^{-1} or higher are bolded)

Sampling Period	Sample Count Rate (c min^{-1})	Peak Wind (mph) with Direction
10/31-11/01	4.8	8 NW
11/01-11/04	1.2	14 W
11/04-11/05	1.5	14 W
11/05-11/06	0.21[a]	10 W & SE
11/06-11/07	0.21[a]	9 N
11/07-11/08	0.21[a]	15 W
11/08-11/11	5.0	**30 W**
11/11-11/12	2.6	**30 W**
11/12-11/13	0.7	15 W & S
11/13-11/14	0.21[a]	15 S
11/14-11/15	0.21[a]	15 W
11/15-11/18	2.1	15 W, SW, N, NW
11/18-11/19	1.1	15 NW
11/19-11/20	0.21[a]	13 W
11/20-11/21	0.7	13 W & SE
11/21-11/22	0.5	**30 W & SW**
11/22-11/25	**134.5**	**30 W & SW**
11/25-11/26	**35.1**	**30 W**
11/26-11/27	0.4	10 N
Total (c min^{-1})	190	
Number of Days	30	
Air Conc[b] (pCi m^{-3})	0.17	

a MDA - below detection

b Monthly Average Air Conc. = Total c min^{-1} / 0.21 × 2.22 × 81.5 m^3 d^{-1} × # of days

Source: Data from site survey sheets found in Federal Records Center (FRC) Boxes #217293 (labeled "Health Physics On Site, Off Site Survey Routine Air Sample Results"), and FRC #SB215089 and #51566 (labeled "Result Sheet for On Site Air Samples").

TABLE M-2

ON-SITE S-8 AIR SAMPLER LONG-LIVED ALPHA ACTIVITY RESULTS FOR DECEMBER 1968

(Winds 30 mph or higher and count rates 10 c min^{-1} or higher are bolded)

Sampling Period	Sample Count Rate (c min^{-1})	Peak Wind (mph) with Direction
11/27-12/02	6.7	20 W
12/02-12/03	2.5	**40 W**
12/03-12/04	**23.6**	**40 W**
12/04-12/05	6.2	**35 W**
12/05-12/06	**261.5**	**35 W**
12/06-12/09	**14.4**	**30 W**
12/09-12/10	2.5	15 NW & W
12/10-12/11	1.7	**30 W**
12/11-12/12	**35.7**	**30 W & NW**
12/12-12/13	8.6	**30 W & NW**
12/13-12/16	2.1	25 W
12/16-12/17	1.6	13 SW
12/17-12/18	4.3	28 W
12/18-12/19	3.8	28 W
12/19-12/20	0.21[a]	11 N
12/20-12/23	**11.6**	**30 W**
12/23-12/24	1.9	23 W
12/24-12/26	1.0	15 W
12/26-12/27	0.21[a]	25 W
12/27-12/30	5.1	25 W
12/30-12/31	9.2	20 W
Total (c min^{-1})	400	
Number of Days	31	
Air Conc[b] (pCi m^{-3})	0.34	

a MDA - below detection

b Monthly Average Air Conc. = Total c min^{-1} / 0.21 × 2.22 × 81.5 m^3 d^{-1} × # of days

Source: Data from site survey sheets found in Federal Records Center (FRC) Boxes #217293 (labeled "Health Physics On Site, Off Site Survey Routine Air Sample Results"), and FRC #SB215089 and #51566 (labeled "Result Sheet for On Site Air Samples").

TABLE M-3

ON-SITE S-8 AIR SAMPLER LONG-LIVED ALPHA
ACTIVITY RESULTS FOR JANUARY 1969
(Winds 30 mph or higher and count rates 10 c min^{-1} or higher are bolded)

Sampling Period	Sample Count Rate (c min^{-1})	Peak Wind (mph) with Direction
12/31/68-1/02	**44.3**	20 W
1/02-1/03	**36.7**	20 SW
1/03-1/06	**116.3**	**35 W**
1/06-1/07	**215.0**	**50 E**
1/07-1/08	**422.2**	**50 E**
1/08-1/09	2.9	25 W
1/09-1/10	**24.0**	15 W
1/10-1/13	**41.9**	25 W
1/13-1/14	9.6	20 W
1/14-1/15	2.9	20 W
1/15-1/16	**19.1**	17 W
1/16-1/17	4.7	16 N
1/17-1/20	**45.1**	**30 W & SW**
1/20-1/21	3.1	20 W
1/21-1/22	**15.3**	15 W & SW
1/22-1/23	4.3	13 W, NW, N
1/23-1/24	**11.0**	15 W
1/24-1/27	**68.2**	**40 SW**
1/27-1/28	3.4	25 S
1/28-1/29	1.3	**35 W**
1/29-1/30	**55.6**	**35 W**
1/30-1/31	**654.3**	**45 W**
Total (c min^{-1})	1800	
Number of Days	31	
Air Conc[b] (pCi m^{-3})	15	

a MDA - below detection
b Monthly Average Air Conc. = Total c min^{-1} / 0.21 × 2.22 × 81.5 m^3 d^{-1} × # of days

Source: Data from site survey sheets found in Federal Records Center (FRC) Boxes #217293 (labeled "Health Physics On Site, Off Site Survey Routine Air Sample Results"), and FRC #SB215089 and #51566 (labeled "Result Sheet for On Site Air Samples").

APPENDIX N

PLUME RISE SENSITIVITY ANALYSIS

APPENDIX N
PLUME RISE SENSITIVITY ANALYSIS

Plume rise has been identified as an area of concern with regard to characterizing releases from the 1957 fire. Plume rise is the distance that heated stack emissions rise above the top of the stack before cooling to ambient temperature. Since information is not available regarding ambient temperature or temperature of the Building 771 stack emissions for the night of the fire, a plume rise could not be calculated. A plume rise of 100 feet is assumed in the analysis of the fire for the initial period based on eye-witness testimony and information on events of the fire. A plume rise of zero is assumed after 2:00 a.m. on 9/12/57, when the filter plenum fire was reported out.

Summary of Modeling Results

A detailed discussion of the modeling approach and the results appears is Section 3.4.2.4, and Table 3-11 summarizes air-sampler data and INPUFF model predictions. Air concentrations were predicted for two periods, depending on when the filters were changed during the early morning hours of 9/12/57 and when the tail end of the emissions passed beyond the samplers. Air concentration measurements for the first period were below the limit of detection for all of the on-site samplers and the sampler at the Wagner "School" site. For the second period, the measured air concentration was above the detection limit at one or more of the on-site samplers and at the Wagner "School" site.

The estimated release rate result in predicted air concentrations during the first period that are substantially below the estimated upper-bound concentration at all on-site samplers, while the predicted concentration at the Wagner "School" sampler matches the estimated upper-bound concentration. Therefore, changes in the predicted air concentrations as a result of different plume rise assumptions would be most important from the standpoint of the fit of the data at the Wagner "School" site. For the second period, the on-site sampler data drive the best-fit of the release estimate, since there is a very poor fit with the Wagner "School" measurement.

Analysis of Sensitivity

Several INPUFF runs were designed to investigate the sensitivity of the 1957 fire modeling results to changes in the assumed plume rise of plutonium-contaminated emissions. Contaminant plume heights considered for the initial period of the fire from 10:40 p.m. on 9/11/57 until 2:00 a.m. on 9/12/57 (while the filter plenum was burning) are 50, 100, 150 and 250 feet *above* the Building 771 stack tip (plume rise). Plume rises considered for the period after the filter plenum fire was reported out at 2:00 a.m. on 9/12/57, are 0, 50, 100 and 150 feet.

Initial Hours

For the initial period of the fire, increasing the plume rise from 100 to 150-foot or greater results in predicted concentrations essentially equal to zero at on-site sampler locations. This

is due to the stable meteorological conditions that were assumed during the night of the fire. Stable meteorological conditions are characterized by low dispersion and minimal downwashing (transport towards the ground) of the contaminant plume. Decreasing the plume rise from 100 feet to 50 feet during the initial period of the fire increases predicted air concentrations at on-site receptors by over a factor of 30. None of these changes would be inconsistent with the environmental monitoring data for the on-site samplers.

Adjusting the plume rise during the initial period of the fire has significantly less effect on predicted concentrations at the off-site Wagner "School" sampler. Increasing the plume rise from 100 feet to 150 feet lowers the predicted air concentrations at Wagner School by less than a factor of 2. Increasing the plume rise to 250 feet, corresponding to a release height of 395 (stack height of 145 feet) decreases the concentration predicted at the Wagner "School" location by less than a factor of 3 (compared to the run with 100-foot plume rise). If these higher plume rises in fact occurred, our best fit release estimate would be a factor of 2 to 3 high, which is well within the overall uncertainty that we have described for this analysis.

Early Morning Hours

Based on the meteorological conditions that have been inferred for the early morning hours of the fire, increasing the plume rise from 0 to 150 feet decreases the predicted concentrations at on-site receptors by less than a factor of 3 (while the predicted concentration at the Wagner "School" sampler decreases by a factor of 6.5). This would actually provide a better fit to the environmental data for the on-site samplers for the release rate that was selected in our analysis.

Conclusion

The sensitivity analysis of model results to different assumptions of plume rise of emissions from the 1957 fire suggest that the largest increase in release estimates that would still be consistent with predicted air concentrations at the on-site and off-site samplers would be a factor of 3. This is well within the range of overall uncertainties that have been applied to the estimate of the release from the fire.

APPENDIX O

BACKGROUND DATA ON THE 1969 FIRE

APPENDIX O

BACKGROUND DATA ON THE 1969 FIRE

This appendix contains a summary of the on-site air monitoring data reported during the two months prior to the 1969 fire. The sources of these data are "Results Sheets for On- and Off-Site Air Samples" (Dow Chemical records from 1964, 1965, 1966, 1969, 1970, 1971, and 1978. Repository Document AC-1204). These data were used to evaluate typical levels of airborne activity (background) at the time of the fire. The weekly sampling routine involved collection of four daily (24-hour) samples and one three-day (72 hour) weekend sample. The results from the three-day samples have been divided by 3 and this average daily concentration is reported for each of day for weekend samples.

Also included in this appendix are the results of the Kolmogorov-Smirnov (K-S) goodness-of-fit test (Lilliefors, 1967). The distribution of each data set was evaluated to determine the appropriateness of using the arithmetic mean (normal or Gaussian distribution) or population mean (lognormal distribution) to estimate average background concentrations. Since logarithmic transformation of a true lognormal distribution yields a normally distributed data set (Leidel *et al.*, 1977), both the original data sets and the log-transformed data sets were tested for normality using the K-S goodness-of-fit test. A data set was considered to pass the test for normality if the calculated test statistic was less than the published value for that number of samples at a probability of 95 percent. None of the original or log-transformed data sets passed the test for normality, indicating that the distributions are not normally or lognormally distributed. For the purpose of this analysis, the arithmetic mean is used as the best representation of background alpha radioactivity.

REFERENCES

Leidel, N., K. Busch, and J. Lynch (1977). "Occupational Exposure Sampling Strategy Manual." Technical Appendix K (NIOSH 77-173).

Lilliefors, H. W. (1967). "On the Kolmogorov-Smirnov Test for Normality with Mean and Variance Unknown." *J. Am. Stat. Ass.*, p. 399-402.

APPENDIX O

ON-SITE AIR SAMPLING DATA FOR MARCH 1—MAY 9, 1969
GROSS ALPHA RADIOACTIVITY (COUNTS PER MINUTE)

Date of Collection	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-50	S-51
03/01/69	0.2	0.07	0.07	0.2	0.3	0.07	0.13	0.83	NS	0.07	0.07	0.13
03/02/69	0.2	0.07	0.07	0.2	0.3	0.07	0.13	0.83	NS	0.07	0.07	0.13
03/03/69	0.2	0.07	0.07	0.2	0.3	0.07	0.13	0.83	NS	0.07	0.07	0.13
03/04/69	0.21	0.21	0.21	0.5	0.21	0.21	0.21	1.4	NS	0.21	0.21	0.21
03/05/69	0.5	0.21	0.21	0.21	0.21	0.21	0.6	11.1	NS	0.5	0.21	0.21
03/06/69	0.21	0.21	0.21	0.5	0.5	0.21	0.21	0.7	NS	0.21	0.21	0.21
03/07/69	0.21	0.21	0.04	1	0.21	0.21	1.2	6.3	NS	0.21	0.21	0.21
03/08/69	0.07	0.07	0.1	0.07	0.07	0.23	0.07	0.9	NS	0.07	0.27	0.07
03/09/69	0.07	0.07	0.1	0.07	0.07	0.23	0.07	0.9	NS	0.07	0.27	0.07
03/10/69	0.07	0.07	0.1	0.07	0.07	0.23	0.07	0.9	NS	0.07	0.27	0.07
03/11/69	0.21	0.4	0.21	0.3	0.21	0.21	0.21	0.21	NS	0.21	0.21	0.21
03/12/69	0.3	0.21	0.4	0.21	0.21	0.21	0.21	1.6	NS	0.21	0.21	0.21
03/13/69	0.21	0.21	0.21	0.21	0.4	0.3	0.21	0.5	NS	0.21	0.21	0.21
03/14/69	0.6	0.4	0.21	0.21	0.21	0.21	0.21	1	NS	0.21	0.3	0.21
03/15/69	0.13	0.07	0.07	0.07	0.13	0.07	0.07	0.4	NS	0.17	0.27	0.07
03/16/69	0.13	0.07	0.07	0.07	0.13	0.07	0.07	0.4	NS	0.17	0.27	0.07
03/17/69	0.13	0.07	0.07	0.07	0.13	0.07	0.07	0.4	NS	0.17	0.27	0.07

APPENDIX O

ON-SITE AIR SAMPLING DATA FOR MARCH 1—MAY 9, 1969
GROSS ALPHA RADIOACTIVITY (COUNTS PER MINUTE)

Date of Collection	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-50	S-51
03/18/69	0.7	0.21	0.21	0.21	0.21	0.8	0.3	2.1	NS	0.21	0.21	0.21
03/19/69	0.7	0.21	0.21	0.21	0.21	0.21	0.21	23.7	NS	0.21	0.21	0.7
03/20/69	1.2	0.3	0.21	0.7	0.4	0.21	0.4	R	NS	0.21	0.5	0.21
03/21/69	0.6	0.6	0.21	0.5	0.21	0.21	0.21	9.1	NS	0.3	0.21	0.21
03/22/69	0.07	0.07	0.13	0.07	0.07	0.07	0.23	3.1	NS	0.07	0.17	0.07
03/23/69	0.07	0.07	0.13	0.07	0.07	0.07	0.23	3.1	NS	0.07	0.17	0.07
03/24/69	0.07	0.07	0.13	0.07	0.07	0.07	0.23	3.1	NS	0.07	0.17	0.07
03/25/69	0.21	0.21	0.21	0.21	0.21	0.21	0.4	1.3	NS	0.21	0.21	0.3
03/26/69	0.3	0.21	0.3	0.3	0.21	0.21	0.21	1.3	NS	0.21	0.21	0.21
03/27/69	0.5	0.7	0.21	0.21	0.3	0.21	0.21	1	NS	0.3	0.21	0.21
03/28/69	0.4	0.4	0.21	0.21	0.21	0.21	0.5	8	NS	0.3	0.9	0.21
03/29/69	0.13	0.3	0.07	0.2	0.3	0.07	0.07	1.47	NS	0.13	0.13	0.27
03/30/69	0.13	0.3	0.07	0.2	0.3	0.07	0.07	1.47	NS	0.13	0.13	0.27
03/31/69	0.13	0.3	0.07	0.2	0.3	0.07	0.07	1.47	NS	0.13	0.13	0.27
04/01/69	0.21	0.21	0.4	0.3	0.21	0.21	0.4	3.1	NS	0.21	0.21	0.21
04/02/69	0.21	0.5	0.3	0.21	0.4	0.21	0.4	2.6	NS	0.21	0.21	0.5
04/03/69	0.7	0.21	0.21	0.8	0.5	0.21	0.21	3.5	NS	0.21	0.5	0.5

APPENDIX O

ON-SITE AIR SAMPLING DATA FOR MARCH 1—MAY 9, 1969
GROSS ALPHA RADIOACTIVITY (COUNTS PER MINUTE)

Date of Collection	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-50	S-51
04/04/69	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
04/05/69	0.1	0.13	0.17	0.1	0.13	0.17	0.1	20	0.2	0.27	0.6	0.27
04/06/69	0.1	0.13	0.17	0.1	0.13	0.17	0.1	20	0.2	0.27	0.6	0.27
04/07/69	0.1	0.13	0.17	0.1	0.13	0.17	0.1	20	0.2	0.27	0.6	0.27
04/08/69	0.21	0.21	0.21	0.21	0.21	0.21	0.4	67.2	0.3	0.4	0.21	0.21
04/09/69	0.21	0.21	0.3	0.21	0.21	0.21	1.7	1.6	0.5	0.21	0.4	0.21
04/10/69	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.7	0.21	0.4	0.21	0.21
04/11/69	0.4	0.21	0.21	0.21	0.32	1.1	18.2	1.5	0.6	0.6	0.4	0.3
04/12/69	0.43	0.13	0.37	0.07	0.43	0.1	0.33	0.77	0.17	0.23	0.13	0.7
04/13/69	0.43	0.13	0.37	0.07	0.43	0.1	0.33	0.77	0.17	0.23	0.13	0.7
04/14/69	0.43	0.13	0.37	0.07	0.43	0.1	0.33	0.77	0.17	0.23	0.13	0.7
04/15/69	0.21	0.4	0.21	0.21	0.21	0.21	0.21	1.1	0.21	0.21	0.21	0.21
04/16/69	0.6	0.21	0.3	0.3	0.21	0.21	0.21	0.9	0.21	0.21	0.4	0.21
04/17/69	0.21	0.21	0.21	0.21	0.5	0.3	0.21	1	0.3	0.3	0.21	0.21
04/18/69	0.4	0.21	0.21	0.6	0.3	0.3	0.3	0.21	0.21	0.21	0.21	0.5

APPENDIX O

ON-SITE AIR SAMPLING DATA FOR MARCH 1—MAY 9, 1969
GROSS ALPHA RADIOACTIVITY (COUNTS PER MINUTE)

Date of Collection	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-50	S-51
04/19/69	0.2	0.07	0.13	0.07	0.17	0.07	0.17	0.47	0.07	0.1	0.07	0.13
04/20/69	0.2	0.07	0.13	0.07	0.17	0.07	0.17	0.47	0.07	0.1	0.07	0.13
04/21/69	0.2	0.07	0.13	0.07	0.17	0.07	0.17	0.47	0.07	0.1	0.07	0.13
04/22/69	0.21	0.21	0.3	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
04/23/69	0.21	0.5	0.4	0.3	0.4	0.21	0.6	0.6	0.5	0.3	0.21	0.21
04/24/69	0.4	0.21	0.3	0.21	0.8	0.3	0.21	0.21	0.21	0.21	0.21	0.21
04/25/69	0.6	0.21	NS	NS	0.21	0.21	0.21	21.7	0.21	0.21	NS	0.3
04/26/69	0.13	0.07	0.1	0.13	0.07	0.07	0.13	0.33	0.1	0.07	0.07	0.07
04/27/69	0.13	0.07	0.1	0.13	0.07	0.07	0.13	0.33	0.1	0.07	0.07	0.07
04/28/69	0.13	0.07	0.1	0.13	0.07	0.07	0.13	0.33	0.1	0.07	0.07	0.07
04/29/69	0.8	0.21	0.21	0.21	0.6	0.21	0.21	0.7	0.3	0.21	0.21	0.21
04/30/69	0.21	0.4	0.3	0.21	0.6	0.21	0.3	0.21	0.3	0.21	0.21	0.21
05/01/69	1.2	0.21	0.6	0.21	0.21	0.21	0.7	0.6	0.21	0.4	0.3	0.5
05/02/69	0.21	0.21	0.3	0.21	0.21	0.8	2.2	2.5	0.21	0.21	0.6	0.21
05/03/69	0.07	0.07	0.07	0.07	0.07	0.07	0.37	0.37	0.1	0.27	0.1	0.07
05/04/69	0.07	0.07	0.07	0.07	0.07	0.07	0.37	0.37	0.1	0.27	0.1	0.07
05/05/69	0.07	0.07	0.07	0.07	0.07	0.07	0.37	0.37	0.1	0.27	0.1	0.07

APPENDIX O

ON-SITE AIR SAMPLING DATA FOR MARCH 1—MAY 9, 1969
GROSS ALPHA RADIOACTIVITY (COUNTS PER MINUTE)

Date of Collection	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-50	S-51
05/06/69	0.21	0.21	0.3	0.21	0.21	0.3	0.21	0.5	0.21	0.3	0.21	0.21
05/07/69	0.21	0.21	0.4	0.21	0.21	0.6	1.8	1.2	0.7	0.21	0.5	0.21
05/08/69	0.3	0.3	0.3	0.21	0.4	0.21	0.21	1.3	0.21	1	0.21	0.21
5/09/69	0.21	0.21	0.4	0.21	0.4	3.2	0.21	0.21	0.21	0.21	0.21	0.21

R = Sample removed from evaluation because it is an outlier (154.6 c min^{-1}).
NS = No Sample.
ND = No data were located for this sampling period.
[ ] = 72-hour sample. Recorded value divided by 3.

APPENDIX P

COMMENTS AND RESPONSES CONCERNING THE DRAFT PHASE I TASK 6 REPORT "EXPOSURE PATHWAY IDENTIFICATION AND TRANSPORT MODELING"

APPENDIX P

COMMENTS AND RESPONSES CONCERNING THE DRAFT PHASE I TASK 6 REPORT "EXPOSURE PATHWAY IDENTIFICATION AND TRANSPORT MODELING"

Comment 1. Page 13. End of paragraph 3. In the report it is stated that "the actual quantities were no more than 35 times higher or less than 1/35 of the estimate. However, in this case, the estimate may be somewhat biased on the high side, because..." These two statements are inconsistent. If the estimate is biased on the high side it would lie closer to the upper bound estimate than the lower bound estimate.

Response 1. *The text was changed to "The overall uncertainty in the predictions for the 1957 fire are very large due to the very limited and poor quality data available to evaluate the event. The uncertainties associated with the 1957 fire predictions are on the order of a factor of 35".*

Comment 2. Table 2-2. Sediment is usually considered a component of the surface water system. Since it is to be considered together with the soil in this report a footnote or similar needs to be provided with the table to let the reader know this is where it is being treated.

Response 2. *A footnote was added to Table 2-2 indicating sediment was considered together with soil.*

Comment 3. Page 27. Final paragraph. The term B_{milk} is not defined.

Response 3. *B_{milk} was changed to F_m, which is defined on page 28.*

Comment 4. Page 31. It is not clear why the monitoring results are explained by the *relatively low bioconcentration factors.* The factors are all significantly above one indicating that these materials can bioaccumulate in fish. Rather, it would appear that the monitoring results indicate that the concentrations of the radionuclides and metals of concern in the lake water are extremely low.

Response 4. *The text has been revised to acknowledge that the fact that CDH did not detect beryllium or radionuclides of concern in fish collected from Standley Lake may be due to two factors: (a) extremely low concentration of beryllium and radionuclides of concern in Standley Lake water and (b) relatively low bioconcentration factors. Bioconcentration factors of radionuclides and metals of concern range from less than 1 (plutonium) to 19. In contrast, bioconcentration of some organics can be as high as 1000.*

Comment 5. Figure 3-2. As noted in the HAP meeting (May 1993) the presentation of this and subsequent figures could be greatly improved: more appropriate landmarks should be selected; consistent scales used; results presented using the same units, where possible to facilitate comparison; the full extent of Highway 93 indicated.

Comment 5. *The figures in this report have been improved.*

Comment 6. Section 4.3.1 903 Pad Release. Reference should be made to the earlier Phase I reports produced by ChemRisk which provide considerable background information about the 903 Pad and the associated contaminant releases.

Response 6. *Reference is now made to the Task 3/4 and Task 5 reports.*

Comment 7. Page 47. The uncertainty of a factor of two for the ISC model predictions of routine releases is not well supported for the Rocky Flats terrain. This uncertainty should be verified by comparison to air monitoring data or by some other means.

Response 7. *The literature addressing uncertainty in dispersion models was re-evaluated. In order to account for the potential effects of Rocky Flats terrain and the limited availability of local meteorological data, the uncertainty factor for the ISC model predictions has been changed from a factor of 2 to a factor of 3. Model uncertainty verification studies were not possible during Phase I.*

Comment 8. Page 48. Indicate whether the 0.1 cm/sec deposition velocity for <1 m particles is physical diameter or aerodynamic diameter. Since Pu is a heavy element, these two quantities are considerably different.

Response 8. *The text has been modified from "less than 1 micron in diameter" to "less than 1 micron in equivalent aerodynamic diameter".*

Comment 9. Page 49. The fact that predicted deposition from normal releases is much less than actual measurements could mean several things: 1) normal releases are not important relative to accidents (implied conclusion) or 2) normal source terms are underestimated or 3) the dispersion/deposition model is inadequate. The study should "close the loop' by demonstrating good agreement between reconstructed accident deposition and measurements. Don't expect the reader to accept "alternative 1" (above), when others are also plausible.

Response 9. *Reference has been made to Section 3.4.1, which discusses some of the information supporting the conclusion that the 903 Pad is the source of the majority of the deposited contamination.*

Comment 10. Page 54. The last paragraph is a good, straightforward explanation. This type of communication would be appropriate for a public meeting as wells as this report.

Response 10. *No response necessary. The referenced text is now on page 56.*

Comment 11. Page 57. The data in Figure H-1 are very useful. Were the original data located or is this a direct representation of the figure from Seed et al. 1971? If you did locate the data and do a quality check or any adjustments to the data, give yourselves credit and say so. We feel that the data from the other onsite samplers should be examined as well. If not done in Phase I, we will plan to do this in Phase II. Regardless, the original data should be located, if possible.

Response 11. *The figure shown in Appendix H is a direct representation of the figure from Seed et al., 1971. However, original air sampling data cards were located at the Federal Records Center during the Phase I investigation and were reviewed as part of the evaluation of release incidents. Copies of some of these records are included in repository document RE-1111.*

Comment 12. Page 61. Does the 25% uncertainty of measurements reported by Krey and Hardy (1970) mean one standard deviation, as ChemRisk has assumed, or two S.D.? Or some other interval.

Response 12. *In their 1970 report, Krey and Hardy estimated that the "analytical precision of aliquoting the sample and analysis" of plutonium in soil was about ± 20%. Their confidence level is not clearly stated in the report. Based on this study and soil data reported by Krey et al. (1976) and Poet and Martell (1972), the analytic uncertainty factor associated with the 903 Pad soil data has been represented by a normal distribution with a mean of 1.0 and a standard deviation of 0.1. In this distribution, the 95 percent confidence interval about the best estimate ranges from approximately 0.8 to 1.2. The report was accordingly modified.*

Comment 13. Page 62. It is not convincing not to include some uncertainty in the soil bulk density factor. If this uncertainty is similar to the analytical uncertainty, and that is included, then it seems that this parameter uncertainty should be also. It is hard to believe that the CSU recent data are the only ones available for the bulk density of Rocky Flats soils.

Response 13. *In the revised report, uncertainty associated with the soil bulk density is included in the overall uncertainty.*

Comment 14. Page 73. Last sentence of paragraph 2. It does not make sense to conclude that "5% of the soil mass has particle diameters less than 10 microns, which is in agreement with Hayden's (1977) results," because Hayden's data were used to make this assumption in the first place.

Response 14. *The sentence (now on page 75) was changed to "With this soil size distribution, 5 percent of the soil mass has particle diameters less than 10 microns".*

Comment 15. Page 75. 3rd paragraph. Appendix M does not allow one to deduce that high daily S-8 air sampler readings occurred only on days when there were observations of wind from the west at 30 mph or greater.

Response 15. *Meteorological data have been added to Appendix M to make such evaluations possible. Tables M-1 through M-3 now present S-8 sampler results for November and December 1968 and January 1969. The results are presented with indications of the peak wind speed recorded for each sampling period and the wind direction(s) that were associated with peak winds.*

Comment 16. Page 79. The analysis summarized in Table 3-2 illustrates good use of the air monitoring record to support an appropriate model (power of wind speed).

Response 16. *No response necessary.*

Comment 17. Page 80. Paragraph 3, line. TSP is not defined. This is also the case in Appendix K, page 3, last line of penultimate paragraph.

Response 17. *In the evaluation of 903 Pad releases, TSP (Total Suspended Particulates) is defined as particles with aerodynamic diameters less than 30 μm. This definition has been added to the two text locations noted.*

Comment 18. Page 81. The discussion regarding the comparison of predicted and measured plutonium concentrations in air at S-8, S-6, and S-7 is an important one. This would be an appropriate place to reiterate what the plutonium particle size distribution is predicted to be at the point of the samplers. Then, see if the sampler collection efficiency, as a function of particle size, could account for some of the bias noted.

Response 18. *We are unable to present an evaluation of the type described without significant further investigation.*

Comment 19. Page 84. Change title and column headings to clarify that the 1969-1973 data are soil and what the units are (mCi ^{239}Pu per square km).

Response 19. *The suggested changes were made to Table 3-3.*

Comment 20. Page 90. Last paragraph. It is good to indicate that these release estimates will be the subject of further detailed investigation in Phase II, perhaps including different approaches to estimating the release.

Response 20. *The report has been revised as suggested (page 93).*

Comment 21. Page 94. Line 3. *Verticle* is misspelled and should be corrected to *vertical*.

Response 21. *The misspelled word was corrected (page 96).*

Comment 22. Figure 3-19. It is not clear what the numbers adjacent to the soil sample locations refer to.

Response 22. *The numbers adjacent to the soil sample locations refer to the contamination of vegetation by plutonium (in dis min^{-1} kg^{-1}) released from the 1957 fire. The figure labels have been improved.*

Comment 23. Page 97. The source of information for the routine air monitoring data during the 1957 fire was the monthly (September) site survey report. Were more original sources (e.g., analytical data sheets) searched for and/or located? The uncertainty about which and how many on-site samplers collected measurable levels of activity (page 96, last sentence) could have been cleared up by locating original data sources. If they were searched for and not located, perhaps this should be stated here.

Response 23. *Records relating to sampling during or after the 1957 fire were identified in listings of holdings of the Federal Records Center in Denver. However, the boxes identified as likely relevant were retrieved to the Rocky Flats Plant according to FRC records. Rocky Flats personnel were not able to locate these missing records at the plant during the Phase I investigation. This information has been added to the Section 3 text.*

Comment 24. Page 101. 2nd paragraph, final sentence. This does not read properly, it would appear that "divided by <u>the</u> account" should be changed to "divided by <u>to</u> account".

Response 24. *The identified typographical error was changed as suggested (page 103).*

Comment 25. Page 104. Figure 3-19 should be captioned to indicate whether values represent plutonium or gross alpha activity.

Response 25. *The Figure 3-19 caption was revised to indicate that the values represent plutonium radioactivity. As stated in the text (page 105), vegetation samples were routinely analyzed for total alpha radioactivity. However, in the months after the 1957 fire, most vegetation samples were also analyzed by pulse height analysis to determine the portion of total alpha radioactivity that was attributable to plutonium.*

Comment 26. Page 106. The fact that most of the ambient air samplers registered no long-lived alpha activity during the 1957 fire means that using the air monitoring data to estimate the release has limited usefulness. Other methods of estimating the potential release should be investigated. This is planned in Phase II, which is pointed out on page 134.

Response 26. *No response necessary.*

Comment 27. Page 108. It is stated that the raw analytical data sheets for the 1957 fire were not found in the documentation reviewed. Do you have a clue as to where they might be?

Response 27. *See response to Comment 23.*

Comment 28. Page 109. Third line from bottom. "2.26" should be "2.22".

Response 28. *The identified typographical error was changed as suggested.*

Comment 29. Page 109. Last sentence. Did they routinely count the ambient air filters for 60 minutes?

Response 29. *We were unable to clearly establish count times for ambient air filters even after considerable review of documents and personnel interviews. The 60-minute count time assumed in the referenced text was based on practices for airborne effluent particle samples.*

Comment 30. Page 114. 2nd paragraph. The reference to EPA, 1979 should be changed to USEPA, 1979.

Response 30. *The text was changed as suggested.*

Comment 31. Page 123. See main text for possible alternative scenarios for analysis.

Response 31. *The text of the report discusses the possibility of alternative scenarios. It is anticipated that alternative scenarios will be explored during the Phase II investigations.*

Comment 32. Page 125. Line 1. Is there any information about what vegetation was sampled? This might allow more site-specific mass interception factors to be defined.

Response 32. *The type of vegetation sampled was not identified in site survey reports.*

Comment 33. Page 125. 2nd paragraph. The term coarse particles is not defined quantitatively.

Response 33. *No data on the particle size distribution of the coarse particle release are available. Section 3.4.2.4 was revised to include a discussion of how modeling was used to obtain an estimate of the average deposition velocity that best fits available environmental monitoring data. The resulting deposition velocity for the coarse particle release was 18 cm sec^{-1}.*

Comment 34. Page 132. Items 3 and 4. These two documents do not appear to be in the reference section.

Response 34. *Item 3 is listed in reference section under Hammond (1971), since Barrick attributes this report to him (see text). The text has been revised to reflect this. As stated in page 135 of the report, item 4 was not located. It is probably a hand-written note referred to by Barrick in his 1981 summary report.*

Comment 35. Page 143. 3rd paragraph. It is not clear why it is appropriate to assume the arithmetic mean is the best representation of background alpha radioactivity when the data sets are not normally or lognormally distributed.

Response 35. *We agree that the arithmetic mean may not be ideally suited to summarizing the background alpha radioactivity when the data sets are not normally or lognormally distributed. However, other approaches such as excluding extreme values from the data sets or using the median instead of the mean also have their limitations. There are other ways to carry out background correction, and the results are likely to be similar to the background corrected air concentrations presented in the draft report. As demonstrated in the report, results obtained by using this approach are not very much different from that obtained by using uncorrected data.*

Comment 36. Figure 3-25. It would be helpful to include the month names alongside the dates on the x-axis, and to indicate the period when the 1969 fire took place.

Response 36. *Figure 3-25 was changed as suggested.*

Comment 37. Tables 3-16 and 3-17. The information contained in these two tables could be compared more easily if it were presented graphically.

Response 37. *The data in the referenced tables have been transformed into graphs (Figures 3-26 and 3-27).*

Comment 38. Page 159. 2nd paragraph. What were the criteria for selecting the parameter values (i.e., constant release, 4-hour ground-level emission, 1 μm particles, 30 m^2 source area) for the screening-level estimate?

Response 38. *The dimensions of the source area (30 m × 30 m) used to represent Oil Burn Pit #2 for modeling purposes were estimated based on the size of the burn pit relative to the 903 Pad. The Burn Pit was estimated to be no wider than one-fourth of the width of the 903 Pad, which was approximately 120 m. The indicated values of burn duration, release height, and particle size were selected based on professional judgement after review of available information concerning historical oil burning practices.*

Comment 39. Page 163. Line 11. It is not stated what the enhancement factor represents.

Response 39. *The Section 3.5 discussion of resuspension has been revised extensively.*

The proposed revision to Section 3.5 was submitted to Joseph H. Shinn of Lawrence Livermore National Laboratory for review. Mr. Shinn stated that the section was well written, but offered some additional references and suggested revision of the stated range for values of the enhancement factor based on work by Gordon Burley. These changes suggested by Mr. Shinn have been incorporated into the Task 6 report.

Comment 40. Page 163. Final sentence of the paragraph after the bullet items. This sentence is confusing. It is not being suggested that the uncertainties in the deposited activity concentration in soil, calculated using the FDM model, will be used as input for the resuspension calculations?

Response 40. *The sentence in question has been removed from the text.*

Comments 41. Page 166. 2nd paragraph. It is not clear why the uncertainties associated with using the resuspension factor approach have to be incorporated into the uncertainty estimate for resuspension calculated using the mass loading approach. It doesn't make sense to mix the two if the mass loading approach is to be used to quantify resuspension, as it states in the report.

Response 41. *The revision of Section 3.5 included clarification of the uncertainties associated with application of the mass loading approach.*

Comment 42. Page 179. The title of the work by Little and Whicker has been omitted.

Response 42. *The omitted title has been added.*

Comment 43. Page 181. The reference Sehmel, G. (1979b) should read (1976).

Response 43. *This identified reference has been corrected.*

Comment 44. Appendix C. The contents of the addendum to Appendix C which updates the original assessment need to be incorporated into Appendix C. It is very confusing in its present format. A figure presenting the different geologic formations and indicating the alternative groundwater pathways would be most helpful.

Response 44. *The information contained in the draft addendum has been incorporated into the revised Appendix C. A figure illustrating potential groundwater pathways has been added.*

Comment 45. Appendix D. The units of F_{ah}, F_{av}, F_{ak} and F_{at} should be indicated.

Response 45. *The units of F_{ah}, F_{av}, F_{ak} and F_{at} have been added to the appendix.*

Comment 46. Appendix E. Page 3, second bullet point. It is not obvious why EPA-approved air models are considered suitable for this assessment.

Response 46. *Reference to USEPA - approved air models is made only to acknowledge that they have gone through evaluation and validation processes conducted by professionals in this field.*

Comment 47. Appendix F. Paragraph 3. Provide an example of the data comprising the five year dataset so that it can be compared with that available for the 1957 and 1969 fires.

Response 47. *An example of the five-year meteorological data set is included in Appendix F.*

Comment 48. Appendix O. If the data sets are neither normally or lognormally distributed, why is the arithmetic mean used as the best representation of background alpha radioactivity? The source of the data is this table should be given.

Response 48. *Refer to Response 35. The data were obtained from the following source, which is now identified in the appendix: "Results Sheet for On- and Off-site Air Samples." Dow Chemical. 1964, 1965, 1966, 1969, 1970, 1971, 1978. Repository Document AC-1204.*

Comment 49. ChemRisk® has used a mass-loading approach in estimating average air concentrations. To be consistent with their calculation of resuspension from the 903-pad itself, they need to account for the contribution of high wind speed events. It is not clear to me from their language that they are going to do this. If they simply use Figure 3-32 to calculate doses, they will be making an error.

Response 49. *The revised Section 3.5 discussion of resuspension includes a discussion of impacts of high wind events.*

Comment 50. ChemRisk® has underestimated the uncertainty. As discussed on pages 164 and 165 of the May draft, an alternate approach is possible to the mass-loading approach (Resuspension-factor method). ChemRisk suggests that the two approaches give consistent values. They fail to mention that the resuspension factors measured for Rocky Flats vary over 8 orders of magnitude. It is beyond me how they can then conclude that there is only a three orders of magnitude range about the 95% confidence interval.

Response 50. *The revised Section 3.5 discussion of resuspension is based primarily on the mass loading approach, for reasons outlined in the text. Measurement of soil resuspension factors is affected by many parameters, including mechanical disturbance, humidity, wind direction, and wind velocity that can vary greatly over short time periods. However, on a monthly or annual basis, variability of soil resuspension for a given site is expected to be much smaller than that indicated by short-term measurements. Uncertainties of the mass loading approach are discussed in Section 3.5.*

Comment 51. In calculating the resuspension factor on page 165, they make use of a formula (developed by Anspaugh) designed for use when site-specific data is absent and ignore the specific Rocky Flats data. In so doing, they are in effect double counting the reduction of resuspension of deep samples. Their logic in this section is tortured. The whole business looks to me like a sign of out-and-out bias.

Response 51. *The discussion of resuspension has been revised to make our approach clearer. The resuspension factor approach is no longer used in the Task 6 resuspension evaluation.*

Comment 52. Page 1. Summary of Findings - Third Bullet. The term "Relocation" is a poorly chosen word. The sandstones were not relocated or physically moved as the term implies. Rather they were reclassified as Upper Laramie from the Arapahoe. Replace "Relocation" with "Reclassification".

Response 52. *We agree that "reclassification" is an appropriate word to describe the new interpretation, as the reviewer suggested, and actually used the word several times during the discussion in question. While we do not necessarily agree with the reviewer's opinion that relocation cannot be used in this context, we have revised the referenced discussion in the Task 6 report.*

Comment 53. Page 2. First Paragraph, Third Sentence. It incorrectly stated that the basal marker sandstone is believed to be continuous and the Surface Geologic Mapping Report (EG&G, 1992) is misquoted. The Surface Mapping Report clearly and unequivocally states that the basal sandstone, while easily recognizable and readily mapped due to its microscopic and macroscopic properties, is a discontinuous unit. The discontinuous nature of the Arapahoe Fm basal sandstone marker is discussed extensively and documented with field data on six pages - pages 95, 97, 100, 102, 104, and 136. Also, the recognized thickness of the Arapahoe Fm at RFP has been reduced. The combination of reduced thickness and sandstone discontinuity indicate a <u>lower</u> probability for contaminant transport via groundwater migration in this pathway. Revise the Addendum to acknowledge these facts.

Response 53. *The reviewers of our Addendum apparently misinterpreted the intent and scope of our Addendum (and original evaluation). They apparently believe that the rationale for revising our worst-case estimates of travel times was based on the continuity of the conglomeratic and/or sandy stream channel marker bed at the base of the Arapahoe Formation (fm).*

We recognize that the marker bed is not always detected in borings beneath and downgradient of the RFP. In fact, we discussed that aspect within the text of the Addendum, and cautioned that the estimated travel times are overly conservative, due in part to the discontinuity of the marker bed. As discussed below, revision of theoretical travel times was not based on continuity of the marker bed, but instead on hydraulic parameters inherent to the geologic unit itself.

The purpose of the travel time estimates was to provide a worst-case estimate of the time it would take for contaminated groundwater beneath the RFP to reach potential downgradient receptors, using site-specific and relevant published data to identify potential migration pathways. The data required to calculate realistic travel times is not available, and such collection would probably be cost-prohibitive, labor-intensive, and time-consuming. Fortuitously, "worst-case estimates" of potential travel times can be made using several assumptions which over-state the possibility and rate of such migration (see original evaluation and Addendum). Actual travel times (if any) will actually be much longer than the worst-case estimates. The intent of these worst-case estimates is to provide a relative basis and comfort level for risk management decisions.

The continuity of the geologic unit in which the contaminated ground water could theoretically migrate was only one of those assumptions. Other equally important and conservative assumptions included constant recharge; no retardation; uniform hydraulic conductivity, range in porosity and slope of the formation; a straight path to the potential receptor; and lack of lateral movement during infiltration. In reality, each of these assumptions overstate the possibility and implied rate of ground water migration. Given that, travel times estimated using the assumptions result in an "earliest possible" arrival time, which is actually much shorter than what could really occur or should be expected. Therefore, the 30-300 years (or the original 60-600 years) calculated for ground water migration within the Arapahoe does not indicate when we expect the chemicals to arrive at the potential exposure point. Ignoring all the limiting factors, the earliest conceivable time that the chemicals could show up at the exposure point would be within this timeframe. Therefore, if the RFP has been in operation for less than this time period, it would be very unlikely that contamination from the plant has reached the potential receptors.

Several factors considered during the compilation of the Addendum are noteworthy. First is that the marker bed was noted as traceable for one mile and 0.5 miles in the general vicinity of the RFP, and was known to be present as far away as Golden. This implies that the unit is relatively extensive in its occurrence, despite its lack of presence in some soil borings. Secondly, the marker bed was interpreted to represent a meandering channel deposit beneath the RFP and as a braided river downslope of the RFP. Therefore, downslope of the plant, one would expect to encounter numerous interchannel deposits of finer-grained material, without loss of the continuity of the unit. Thirdly, the contact between the Arapahoe and Laramie has been interpreted as an erosional surface, with the Arapahoe cutting into the Laramie. This indicates the possibility of a permeability contrast between the two geologic units, adding to the base of the Arapahoe Formation's ability to hold and/or transmit ground water. For these reasons, the Addendum considered the marker bed to be relatively continuous. This meant that one of the basic assumptions did not appear to be as unlikely as previously assumed, and additional caution may therefore be warranted.

The travel time calculations are sensitive to the hydraulic conductivity of the system being modeled. The original travel time estimates used an average value based on conductivities obtained from various pump tests performed in the various sandy units previously interpreted to be within the Arapahoe Formation. The new geologic information indicated that: 1) many of these units may belong instead to the Laramie Formation, and 2) conductivity of the conglomeratic marker bed was poorly understood. Therefore, published conductivity values typical of conglomerates (Freeze and Cherry, 1979) were used in the recalculations of travel time within the Arapahoe, resulting in the reduced range presented in the Addendum. Again, we do not expect that the

actual travel times are within the new range (30-300 years), but that the new evidence calls for additional conservatism to insure that the intent of the estimation (risk management support) was still valid. For the reasons outlined above, we believed that the methodology used and the conclusion reached in the Addendum is appropriate.

Comment 54. Page 3. Paragraph 4. See Specific Comment above. The sandstones in the lower part of the Arapahoe Fm and the Upper Laramie Fm are discontinuous channel deposits. They are in hydraulic contact with the alluvium only in localized occurrences. Thus, the surficial alluvium and near surface bedrock units are a discontinuous groundwater flow pathway that is unlikely to facilitate transport to downgradient receptors. Revise the addendum to acknowledge this fact.

Response 54. *See Response 53 and the revised Appendix C.*

Comment 55. Page 3. Paragraph 2. The finding of discontinuity of the Arapahoe Fm basal sandstone gives little justification or rationale to reduce the estimated travel times. Travel times are appropriate as originally estimated. Revise the Addendum to acknowledge this fact.

Response 55. *See Response 53 and the revised Appendix C.*

Comment 56. Glossary. The glossary is among the most important elements of this report; it should facilitate understanding of the terms and results of the report by the public and it indicates the level of competency of the investigators. This report's glossary contains numerous basic scientific errors and misleading definitions to the point of questioning the understanding of the subject by the authors.

Response 56. *The definitions of a number of the terms in the report glossary have been revised. The difficulty with glossaries in reports of public studies is to pick the appropriate level of detail and technical rigor for definitions. While we don't disagree with any of the statements included in the suggested definitions presented by the Council, many of the terms they contain (e.g., specific ionization, atomic mass units, transmutation) are beyond the vocabulary of many potential report readers and would likely be understood by only those who are very familiar with the term being defined in the first place. The glossary could be expanded to include all of the terms included in these definitions, but would in that case go beyond the level of information that is necessary to understand the report and could detract from communication of the primary messages from this study.*

Comment 57. Text. Examples of industrial accuracy for weights of supplies and chemicals, i.e., the difference between shipping weights and actual quantities received, should be given to show that a mass balance of the chemicals is not possible and DOE is not hiding information.

Response 57. *The information that is available to characterize historical inventories of materials of concern is extremely limited. In cases where inventory data are available, they are in terms of quantities on hand at a point in time, and are not accompanied by sufficient documentation of quantities shipped and/or received that would support further characterization of this potential source of uncertainty.*

Comment 58. Page 11.1. Strongly question the accuracy of line 3 "the hazard posed by plutonium in the oil is many times greater than the depleted uranium and therefore is the focus of the evaluation." Ruling out risks from uranium will not pay well with the public without facts to support the decision.

Response 58. *The Task 6 assessment of 903 pad releases focused on plutonium as the primary contributor to off-site exposures from dispersal of contaminated soil. Many more drums contained plutonium than contained uranium, plutonium has a much higher specific activity than uranium, and dose conversion factors for plutonium isotopes are higher than those for uranium isotopes. A discussion of these factors have been added to the Task 6 report. The Task 8 dose assessment process has included selection of uncertainty bounds in a manner such that it is highly unlikely that off-site doses from exposure to alpha-emitting activity (from both plutonium and uranium) released from the 903 pad fall outside of the specified confidence range.*

Comment 59. Throughout the report chemical concentrations are assumed to be bioavailable, this is not the case and will cause overestimation of risks.

Response 59. *Bioavailability of contaminants is addressed in several manners in the dose assessment portions of this study. For each radionuclide, published values describing the time period of clearance from the lung and the fractional uptake from the small intestine to the blood have been used as described in the Task 8 report.*

Methodologies for reflection of biological uptake fractions for chemicals are not as advanced as for radionuclides. In the draft Task 8 report we discussed some limited data on absorption of volatile organic chemicals and beryllium. We have indicated that, because of the paucity of human data about absorption of contaminants at low concentrations, we assumed that 100 percent of inhaled material was absorbed. While this assumption may have led to overestimation of volatile organic chemical doses by at most a factor of

2 or 3 and beryllium doses by a factor of 10 (inhalation) or 100 (ingestion), incorporation of these uncertainties would not significantly impact any conclusions presented in the draft Task 8 report.

Revisions to the draft Task 8 report will incorporate these identified absorption uncertainties into the calculations of chemical doses.

Comment 60. It was stated in this task report that the area in interest was flat so a complex terrain models was not necessary. Less than 5 miles to the west of the Rocky Flats Plant (R.F.P.) the terrain is 2400 feet higher than R.F.P. Just 3 1/2 miles south-east of R.F.P. is Wagner School and the elevation has already dropped 500-600 feet below the stack. Terrain differences like this have a significant impact on wind patterns and was the primary reason for developing the TRAC model. While the area is called Rocky Flats it certainly is not level and should not be modeled as such.

Response 60. *The report does not make the indicated statement. The populations of concern are located principally in the gently rolling terrain surrounding Rocky Flats, and the models chosen for the study have been shown to perform well in such settings. More complex models that employ wind field information obtained from a considerable number of meteorological stations in the vicinity of Rocky Flats may perform better. However, only very crude meteorologic data, and in some cases, no meteorologic data for the actual period of interest are available for evaluating release events with such complex models. It is unlikely that the TRAC model would provide better results with the limited data available for early release events. Phase II investigations will re-examine the need to employ a wind-field model.*

Comment 61. It was stated in Appendix E. "Complex terrain models can predict concentrations on downwind terrain higher than the emitting height, but they are only valid for predicting concentration on terrain above stack height." I do not know where this idea originated but this is not the case.

Response 61. *It appears that the reviewer was confusing complex terrain with complex models or wind field models. Using the term complex terrain as we have defined it, we believe that the referenced statement is accurate.*

Comment 62. It becomes more obvious that the models used to determine the source term of the 1957 release were not adequate when the wind speeds recorded at R.F.P. during the accident were reduced from 3 m.p.h. to 1 m.p.h. in order to match the observed readings at the Wagner School. In order to match the observed readings at the variables such as vertical exit velocity, temperature of the release, etc. or the model itself need to be changed, not observed data.

Response 62. *Meteorological observations were not altered for the analysis in question. Section 3.4.2.4 was revised to include a discussion of how available meteorological data were interpreted to support the evaluation of 1957 fire emissions.*

Comment 63. I also question the plume height used to model this release. The height of 100 feet was obtained by a visual night time observation near the source. The temperature of the release would have to be very low to only gain 100 feet before reaching equilibrium. I suggest that more work is needed in determining the vertical exit velocity caused by the fans and the fire and a temperature great enough to partially melt the led cap on top of the stack which is still visible today. These two variables are very important in performing 3-D modeling.

Response 63. *A sensitivity analysis of plume rise parameters on the 1957 fire analysis was performed as described in Appendix N. Plume rises of 0, 50, 100, and 150 feet above the top of the 145-foot Building 771 stack were evaluated. The sensitivity analysis of model results to different assumptions of plume rise suggests that the largest increase in release estimates that would still be consistent with predicted air concentrations at the on-site and off-site samplers would be a factor of three. This is well within the range of overall uncertainties that have been applied to the estimate of 1957 fire releases.*

Comment 64. During the public meeting on May 26, 1993 the statement was made that the TRAC model needed a large number of weather stations to run. I have not performed a sensitivity analysis on the number of stations needed to run accurately, however, I believe a complex terrain model with one weather station is more accurate than a non-terrain model with one weather station. This is not the case for the 1957 fire. Weather data is available from Stapleton Airport, Lowery Air Force Base and possibly weather data from Fort Collins. Additional weather data such as air temperature should be available from local newspapers. A Boulder newspaper might also supply additional weather data. Upper air weather data may be available from Stapleton and Lowery from balloon soundings. This additional weather data would increase the accuracy of the TRAC model and could also be used to search archived weather data to find similar weather patterns for the time of year that the 1957 fire occurred. Because the 1957 fire occurred during an International Geophysical Year additional meteorological data should be available for this area.

Response 64. *It has not been demonstrated that a more complex (e.g., wind field or 3-D) model would provide better results with the limited data available for early release events. Additional sources of meteorological data are very limited and were not determined to be useful during the Phase I study. The Phase II study will re-examine the need to employ a more complex terrain model.*

Comment 65. Figure 3-2. Word. Wagner School is meaningless.

Response 65. *The report has been revised to refer to the site of the <u>former</u> Wagner School.*

Comment 66. Map incorrect on residences and roads-Highway 93.

Response 66. *The Task 6 figures have been revised in accordance with comments received.*

Comment 67. Need to show Mower Reservoir

Response 67. *Mower Reservoir has been added to the Task 6 figures.*

Comment 68. Scale should list miles, feet, as well as meters

Response 68. *The revised Task 6 figures have scales of feet and miles indicated. The unit conversion table provided facilitates conversion to meters or kilometers if desired.*

Comment 69. Scales should be consistent (Figures 3-2, 3-3 differ).

Response 69. *The Task 6 figures have been revised in accordance with comments received.*

Comment 70. Maps should name Roads, Streets, bodies of water and streams i.e., Woman Creek, Walnut Creek, Big Dry Creek.

Response 70. *The Task 6 figures have been revised in accordance with comments received.*

Comment 71. Page 49. Last Paragraph. Says Building 910 rather than 881.

Response 71. *The referenced text has been revised to refer to Building 881 rather than Building 910.*

UNIT CONVERSION TABLE

METRIC FRACTIONS

Multiple	Decimal Equivalent	Prefix	Symbol
10^6	1,000,000	mega-	M
10^3	1,000	kilo-	k
10^2	100	hecto-	h
10	10	deka-	da
10^{-1}	0.1	deci-	d
10^{-2}	0.01	centi-	c
10^{-3}	0.001	milli-	m
10^{-6}	0.000001	micro-	μ
10^{-9}	0.000000001	nano-	n
10^{-12}	0.000000000001	pico-	p
10^{-15}	0.000000000000001	femto-	f
10^{-18}	0.000000000000000001	atto-	a

METRIC CONVERSION TABLE

Multiply	By	Equals	Multiply	By	Equals
in.	2.54	cm	cm	0.394	in.
ft	0.305	m	m	3.28	ft
ac	0.404	ha	ha	2.47	ac
mi	1.61	km	km	0.621	mi
lb	0.4536	kg	kg	2.205	lb
liq. qt.-U.S.	0.946	L	L	1.057	liq. qt.-U.S.
ft^2	0.093	m^2	m^2	10.764	ft^2
mi^2	2.59	km^2	km^2	0.386	mi^2
ft^3	0.028	m^3	m^3	35.31	ft^3
d/m	0.450	pCi	pCi	2.22	d/m
pCi/L(water)	10^{-9}	μCi/mL(water)	μCi/mL(water)	10^9	pCi/L(water)
pCi/m^3(air)	10^{-12}	μCi/cc(air)	μCi/cc(air)	10^{12}	pCi/m^3(air

TRADITIONAL AND INTERNATIONAL SYSTEMS OF RADIOLOGICAL UNITS

(Traditional units are in parentheses.)

Quantity	Name	Symbol	Expression in Terms of Other Units
absorbed dose	Gray	Gy	J/Kg^{-1}
	(rad)	rad	10^{-2} Gy
activity	Becquerel	Bq	1 dps
	(curie)	Ci	3.7×12^{10} Bq
dose equivalent	Sievert	Sv	J/Kg^{-1}
	(rem)	rem	10^{-2} Sv
exposure	Coulomb per kilogram		C/Kg^{-1}
	(roentgen)	R	2.58×10^{-4} C/Kg^{-1}

0104ALR2

GLOSSARY

absorb	To take up and make part of an existing whole.
adsorb	The adhesion of extremely thin layers of molecules to solid bodies or liquids.
AEC	Atomic Energy Commission.
aerodynamic diameter	The diameter of a particle that takes into account both density and atmospheric drag.
aerosol	A suspension of fine solid or liquid particles in gas.
agglomeration	The process of collecting in a ball, mass, or cluster.
airborne effluent	Any contaminant emerging from a pipe or similar outlet into the air; waste products from industrial plants as stack gases.
air dispersion model	A mathematical model that predicts the movement of airborne materials in the atmosphere.
alpha emitter	A radioactive material that releases energy in the form of alpha particles.
alpha particle	A positively charged nuclear particle that consists of two protons and two neutrons and is ejected at high speed in certain radioactive transformations.
alpha pulse-height analysis	A method for identifying and quantifying alpha-emitting radionuclides by recording the frequency of emission of alpha particles of specific energies.
alpha spectrometry	A method of identifying and quantifying alpha emitting radionuclides.
atmospheric stability	The amount of turbulent energy that is present in the atmosphere.
alveolar region	The region of the lung containing the alveoli, which are microscopic air sacs where oxygen diffuses into the bloodstream.

back-calculation	A technique used to work back from a known or given result of a calculation to determine an unknown input value to the calculation.
"background" radioactivity	Radioactivity normally present in the natural environment, or not attributable to a particular known source of interest.
beta emitter	A radioactive material that releases energy in the form of beta particles.
beta particle	An electron or positron ejected from the nucleus of an atom during radioactive decay.
beta radiation	Beta particles emitted by certain radionuclides. Beta radiation penetrates paper and is stopped by thin plastics and has significantly less health impact than alpha particles. Sources include plutonium, uranium, tritium.
bioaccumulation	The net accumulation of a chemical by an organism as a result of uptake from all exposure routes.
burial loss	The retaining of radioactive particles in a filter medium such that their energy is not detected by radiation measurement systems.
cascade impactor	An instrument that can be used to determine the size distributions of airborne particles.
cfm	Cubic feet per minute — a volumetric rate unit.
Church litigation	Civil actions brought against the corporations that operated the Rocky Flats Plant and the U.S. Government during the 1970s by neighboring landowners.
computer modeling	A series of mathematical calculations used to predict the effect of such things as physical, chemical or environmental processes that are performed with the aid of a computer.
curie (Ci)	The conventional unit of activity equal to 3.7×10^{10} nuclear transformations per minute.
cutting oil	A liquid applied to a cutting tool to assist in the machining operation by washing away chips or serving as a lubricant or coolant.

decay product	Element formed from the spontaneous disintegration of an unstable atomic nucleus.
degrease	To remove grease from.
depleted uranium	Metallic element number 92 from which most of the U-235 isotope has been removed (leaving principally U-238).
deposition	The removal of mass from the atmosphere via transport to an environmental surface.
deposition velocity	The rate at which particulates are removed from the air.
disintegrations per minute (dis min^{-1} or dpm)	The rate of nuclear transformations exhibited by a radionuclide. Nuclear transformations are the events that lead to emission of radiations as the atom changes to a more stable form.
dose coefficient	A constant used to convert from a quantity of radioactivity to which a person is exposed to some measure of the resulting dose.
dosimetry	The theory and application of the principles and techniques involved in the measuring and recording of radiation doses.
dry deposition	Removal of material from the atmosphere without the aid of precipitation.
effluent	Any material emerging from a pipe or similar outlet; waste products from industrial plants as stack gases or liquid mixtures.
emission point	Location of release of waste products.
enriched uranium	Metallic element number 92 in which the content of the fissionable 235 isotope has been increased above the 0.7 percent found in nature.
entrain	To draw in and transport (as solid particles or gases).
environmental transport	The movement of a material through environmental media (e.g., air, surface water or groundwater).

exposure pathway	A route through which a radionuclide or chemical released from a source reaches an individual.
evapotranspiration	A combination of evaporation from open bodies of water, evaporation from soil surfaces, and transpiration from the soil by plants.
filter plenum	The portion of a building air exhaust or ventilation system that contains media to collect or separate out matter carried by the air.
fission	The splitting of a heavy atomic nucleus into approximately equal parts, accompanied by release of a large amount of energy.
fission product	A nuclide formed as a result of fission.
gamma emitter	A radioactive element that emits photons, which are identical in form to X rays.
gamma radiation	A non-particulate photon ray capable of penetrating paper and plastics. Lead provides an effective shield against gamma radiation; health effects are identical to X-rays of the same energy.
global fallout	Radionuclides in the environment resulting from world-wide testing of nuclear devices.
glove box	A sealed, protectively lined compartment having holes to which are attached gloves for use in handling dangerous materials inside the compartment.
gram	A metric unit of mass, equal to one-thousandth of a kilogram and nearly equal to one cubic centimeter of water at its maximum density.
gross alpha activity	Radioactivity measured in terms of alpha particles emitted, with no determination of their energy or the identity of the specific radionuclides from which they were emitted.
groundwater	Water within the earth that supplies wells and springs.
half-life	The time required for an unstable element or nuclide to lose one-half of its radioactive intensity in the form of alpha, beta, and gamma radiation.

halogen	Any of the five elements fluorine, chlorine, bromine, iodine, and astatine that form part of the group VII A of the periodic table of elements.
Henry's Law Constant	Describes the propensity of a chemical to volatilize from environmental media into the atmosphere.
HEPA filter	High efficiency particulate air filter.
hydraulic conductivity	The capacity of a rock to transmit water
hydrogeology	The study of groundwater.
in situ	In place.
intercept	To stop, seize, or interrupt in progress or course or before arrival.
immersion	A route of exposure to beta or gamma emitting radionuclides present in the atmosphere.
isokinetic sampling	Refers to the removal of a sample from an air stream where the velocity of the air entering the sampling device is the same as the velocity of the air in the duct at the sampling point.
isotopes	Nuclides having the same atomic number but different atomic weights; they have similar chemical properties but different physical properties.
isopleth	A line on a map connecting points at which a given variable has a specified constant value.
iteration	The process of repeating.
kilogram	The basic metric unit of mass nearly equal to 1,000 cubic centimeters of water at the temperature of its maximum density.
liquid scintillation counter	An instrument which measures radioactivity by placement of a sample in a liquid "cocktail" that emits light which can be related to the quantity of radioactivity present.
lognormal	A distribution in which values are positively skewed (i.e., most values

distribution	occur near the minimum value).
long-lived alpha activity	Alpha-emitting radioactivity from which short-lived radionuclides have been allowed to decay away or have been subtracted using an algorithm designed to quantify only those radionuclides with long half-lives.
mass loading	The amount of particulate matter suspended in the atmosphere.
mass median diameter	The median diameter of a particle size distribution in relation to mass.
median	A value in an ordered set of values below and above which there is an equal number of values or which is the arithmetic mean of the two middle values if there is no one middle number.
Monte Carlo	The traditional method of sampling random variables in simulation modeling.
MPL	Maximum permissible exposure level. Typically defined by regulatory agencies to control exposure to radiation.
normal distribution	A distribution in which values are equally likely to be below or above the most likely value (i.e., a "bell-shaped" curve).
octanol-water partition coefficient	A parameter that describes the relative partitioning of a material between a polar medium (i.e., water) and non-polar media.
organic solvents	Non-polar, carbon containing substances (hydrocarbons) capable of dissolving another substance.
particle size distribution	Frequency of occurrence of particles by size as measured by diameter.
particulate	Of or relating to minute separate particles.
percolation	The movement of a liquid through a permeable substance.
planimetry	A method for determining the area of a plane by tracing its boundary line.

porosity	The voids or openings in a material expressed as a ratio of the volume of openings to the total volume.
precipitation scavenging	The removal of any material from the atmosphere to the surface of the earth by various types of precipitation (e.g., rain or snow).
probability density function	A range of values where the likelihood that the parameter is actually equal to any particular value within the range is defined.
radioactive daughter	A radionuclide that is the product of the radioactive decay of a given element.
radionuclide	A radioactive form of an element distinguished by its atomic number, atomic weight, and energy state.
recharge	The entry of water into the saturated zone at the water table surface.
respirable fraction	The fraction of airborne particles that are considered respirable.
respirable particles	Particles that can reach the alveolar region of the lungs, generally considered to be particles with aerodynamic diameters less than 8 microns.
resuspension	The transport of material from an environmental surface to the atmosphere.
resuspension factor	The ratio of the contaminant concentration deposited on the ground (amount per square area) and in the air (amount per cubic area).
retardation	The inhibition of flow through an aquifer due to the transfer of contaminant mass from the pore water to the solid part of the porous medium.
risk	A dangerous element or factor.
runoff	Water that has drained off a surface.
sampling train	All the components or devices used to collect a sample.
scintillation counter	A device for detecting ionizing radiation by the scintillation light produced by certain materials, such as crystals.

shielding factor	A term used in calculating radiation dose that accounts for any material or obstruction that absorbs radiation.
source term	Information relating the quantity and characteristics of a contaminant release.
specific activity	The total activity of a given radionuclide per gram of a compound, element, or radioactive nuclide.
spectrophotometry	A technique of instrumental analysis involving measurement of the absorption of radiant energy by a substance as a function of the energy incident upon it.
spectroscopy	A branch of analytical chemistry devoted to identification of elements and elucidation of atomic and molecular structure by measurement of the radiant energy absorbed or emitted by a substance.
spontaneous fissioning	The property of certain materials which undergo splitting without the external application of neutrons.
stability class	A description of the amount of turbulent energy that is present in the atmosphere.
stratigraphy	Geology that deals with the origin, composition, distribution and succession of strata.
surface water	Water present on the earth's surface, e.g. rivers, streams and lakes.
triangular distribution	A distribution specified by minimum, maximum and most likely values.
tritiated water	Water in which one or more hydrogen atoms have been replaced with tritium, the radioactive form of hydrogen.
tritium	The radioactive isotope of hydrogen, containing one proton and two neutrons. Chemically identical to natural hydrogen, tritium can easily be taken into the body by any inhalation, ingestion, or absorption paths. Decays by beta emissions; radioactive half-life is about 12.3 years.
uncertainty	A description of the lack of knowledge or variability of some value.

unconfined	Not isolated by an impermeable layer.
uniform distribution	A distribution in which all values between the minimum and maximum are equally likely to occur.
UTM	Universal Transverse Mercator coordinate system.
variance	A measure of how widely dispersed the values are in a distribution.
volatile solvents	A class of non-polar carbon containing substances (hydrocarbons) with Henry's Law constants greater than 10^{-3}.
wastewater	Liquids deemed to have no economical value.
weapons grade plutonium	Plutonium that is approximately 94 percent Pu-239 by mass, with about 5.8 percent Pu-240 and small amounts of Pu-238, Pu-241, Am-241, and Pu-242.
wet deposition	Removal of material from the atmosphere as a result of precipitation scavenging.

Colorado Department of Health
Health Studies on Rocky Flats, A-3
4300 Cherry Creek Drive South
Denver, CO 80220
(303) 692-2640 or 692-2700