

Section 1.0 Introduction

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1.0 Introduction

Rhodia Inc. (Rhodia) has prepared this Resource Conservation and Recovery Act (RCRA) Facility Investigation Report (RFI Report) to fulfill the requirements of Section VIII.E. of the Corrective Action Order on Consent (3008(h) Order) issued to Rhodia pursuant to Section 3008(h) of the Resource Conservation and Recovery Act (“RCRA”) (42 U.S.C. § 6928(h)) by the U.S. Environmental Protection Agency (U.S. EPA) with an effective date of April 29, 2004. This RFI Report describes the investigation activities conducted at the Rhodia Silver Bow Plant (Plant) between 2006 and 2012 in accordance with the Phase 1 RFI Work Plan (Barr, 2009) and October 2012 RFI Work Plan (Barr, 2012a). A number of environmental investigations have been conducted at the Silver Bow Plant since 1988. These investigations have been summarized in previous reports and were compiled in the Current Conditions/Release Assessment Report (CCRA) (Barr, 2006). The RFI Report builds upon the extensive data set that was compiled and documented in the CCRA (Barr 2006). This RFI Report addresses the entire Silver Bow Plant and meets the requirements for an RFI set forth in the 3008(h) Order, the final Corrective Action Plan (CAP) OSWER Directive 9902.3-2A (EPA 520-R-94-004), and the RCRA Corrective Action Advance Notice of Proposed Rulemaking (ANPR), 61 Fed. Reg. 19432 (May 1, 1996).

1.1 Purpose and Scope

The general purpose of an RFI is to evaluate the nature and extent of releases of hazardous waste or hazardous constituents from solid waste management units (SWMUs) or areas of concern (AOCs) at the Silver Bow Site and to gather necessary data to support a Corrective Measures Study (CMS).

The specific objective of the work outlined in this report is to address identified data gaps that were outlined in the U.S. EPA-approved CCRA Report (Barr 2006). The RFI activities include programs to better define site characteristics including groundwater quality, surface water and sediment quality along Sheep Gulch, surface water quality along Silver Bow Creek, SWMU-specific and AOC-specific material and soil quality, background/reference area soil quality and soil gas quality.

1.2 Site Setting, Operations and Current Conditions

Rhodia’s former elemental phosphorus production plant (Silver Bow Plant) occupies approximately 1.25 square miles in Silver Bow County, Montana. The Plant is located at 112° 41' W longitude and 45° 49' N latitude approximately seven miles west of Butte, Montana and one mile south of Ramsay, Montana (Figure 1-1). The property, owned by Rhodia, is located in Sections 23, 24, 25, and 26,

Township 3 North, Range 9 West (Figure 1-2). A figure providing the general Plant area is provided in Figure 1-3.

As shown in Figures 1-2 and 1-3, the Silver Bow Plant is not bound by natural features (e.g., rivers). German Gulch Road abuts the northern boundary of the facility. The remaining property is bounded by industrial and agricultural lands. The Plant is located west of the Continental Divide and northeast of the Pioneer Mountains. The site topography is strongly influenced by proximity to Silver Bow Creek. The site varies in elevation from approximately 5,310 feet above mean sea level (MSL) at Sheep Gulch to 5,480 feet above MSL at the top of the slag pile. The property has flat terrain on the northeast and rising terrain incised with gulches to the south and west. The center of the site is occupied by a tailing basin. Slag piles cover much of the southeast part of the property. Natural slopes at the site generally range between two percent and eight percent, while several of the slag piles presently have slopes as great as 66 percent.

The Plant was constructed in the early 1950s to produce elemental phosphorus using an electric arc furnace method developed by the Tennessee Valley Authority. The Plant produced elemental phosphorus until 1997, when it was shut down for decommissioning and closure. Currently, the approximate boundary of the entire property is fenced to control access to the area.

The CCRA identified the SWMUs and AOCs at the Silver Bow Plant and used the previous environmental investigations to evaluate whether hazardous substances had been released from the SWMUs and AOCs. Figures 1-4, 1-5 and 1-6 show the location of each SWMU and AOC. The CCRA also identified data gaps that need to be addressed in the RFI. The data gaps are as follows:

- Impact of Sheep Gulch discharge to Silver Bow Creek
- Sheep Gulch surface water quality trends
- Sheep Gulch sediment quality
- Groundwater flow characteristics and water quality trends
- Groundwater use north and northwest of the Silver Bow Plant
- Background/Reference Area Soil Quality
- SWMU-specific Soil Quality

A Phase 1 RFI Work Plan was developed to fill the data gaps identified by the CCRA and was approved by U.S. EPA on November 2, 2009. The Final Phase 1 RFI Work Plan is a compilation of

certain investigation activities that were approved by the U.S. EPA and implemented before the Final Phase 1 RFI Work Plan was approved.

The October 2012 RFI Work Plan (Barr, 2012a) was developed to fulfill the data needs identified in the Draft Phase 1 RCRA Facility Investigation Report (Barr, 2012b) submitted to the U.S. EPA in July 2012, the Human Health Risk Assessment Work Plan (Exponent, 2012a), the Baseline Ecological Risk Assessment Work Plan (Exponent, 2012b), and U.S. EPA comments to Rhodia (U.S. EPA, 2011).

1.3 Previous Investigation Reports

This section summarizes the major findings of previous investigations performed at and near the Silver Bow Plant. Comprehensive sampling locations and data from past investigation activities are summarized on figures and tables in this RFI Report. Data qualifiers and footnotes to RFI Report data tables are provided in Table 1-1. Laboratory analytical reports from previous Plant investigations between 2006 and 2012 are included in Appendices 1-A through 1-F respectively.

This data from prior site investigations will reflect the impacts of releases that have occurred. Comments on problematic aspects of data usability are noted in the CCRA (Barr, 2006) and in the data usability assessment included in the Final Phase 1 RFI Work Plan (Barr, 2009), as directed by U.S. EPA. For the CCRA (Barr, 2006), the data was evaluated in order to identify Constituents Of Potential Concern (COPC) categories and parameters above screening levels based on the media sampling data and release information, and provided an evaluation of site conditions based on the major findings of the investigations.

1.3.1 Previous Investigations

A number of environmental investigations were conducted at the Silver Bow Plant. The findings of these investigations are further discussed in detail in Section 5 of this report. The analytical data that resulted from the various investigations was incorporated into a database to further evaluate and summarize the data in a consistent format. The usable data from these investigations is presented in this RFI Report.

1.3.1.1 Site Assessment and Scoring

The U.S. EPA performed a site screening study at the Silver Bow Plant in 1988. The results were presented in a January 1989 report, Analytical Results Report, Stauffer Chemicals Company, Silver Bow, Montana by Ecology & Environment, Inc. (Ecology & Environment, Inc., 1989). The results of

that study were then used in the September 24, 1992 study, Site Inspection Prioritization, Stauffer Chemical Company (URS Consultants, 1992), to assess the Silver Bow Plant site for National Priority List (NPL) status. Based on this U.S. EPA study, the Silver Bow Plant was assigned a score of 12.92 according to the PREscore process. The U.S. EPA and Montana Department of Health and Environmental Sciences concurred in an October 7, 1992 letter declaring the Silver Bow Plant as “Site Evaluation Accomplished”. Due to the low score, the site was not proposed for listing on the NPL.

The site screening study included the installation of three shallow monitoring wells. The study also included collection of groundwater samples, surface water samples from Silver Bow Creek and the Beaver Pond, production well water samples, sediment samples from Silver Bow Creek and soil samples from both onsite and offsite locations. The analytical data from these samples are considered usable for the RFI Report, with the exception of the sediment samples collected from Silver Bow Creek. Silver Bow Creek is a Superfund site not related to the Silver Bow Plant and has been remediated by others. The sediment samples are no longer relevant to the current conditions of Silver Bow Creek. The useable sample results are further discussed and presented in Section 5 of this RFI Report.

1.3.1.2 Transformer Site Investigation Project

Special Resources Management, Inc. (SRM) was retained by Rhône-Poulenc Basic Chemicals to perform a site investigation at the former transformer storage location at the Silver Bow Plant in 1993. The objective of this investigation was to evaluate if polychlorinated biphenyl (PCB) contamination, above the U.S. EPA action level of 25 mg/kg (*see* 40 CFR § 761.61(a)(4)(i)(B)), was present in the soils surrounding the transformer storage area.

The Transformer Site Investigation Project included collection of surface soil samples (10 cm x 10 cm x 1 cm), and field screening using PCB immunoassay analyses. SRM used the field screening results on 35 samples to select five locations for analytical sample collection. The immunoassay analyses did not correlate well with laboratory results, so the field screening results are viewed as general indicators, rather than surrogates for laboratory analysis. These five samples were analyzed for PCBs at an independent laboratory. PCBs were not detected above the U.S. EPA action level of 25 mg/kg.

A soil sample was collected beneath the dismantled and removed PCB transformer storage shed (SWMU 21 on Figure 1-5) in 1994. The Transformer Site Investigation Project, the subsequent

sample from beneath the dismantled PCB storage shed along with the additional samples collected as part of the RFI are further discussed and presented in Section 5.5.21 of this RFI report.

1.3.1.3 Tailing Pond and Groundwater Review

A Silver Bow Plant study, published in an October 1996 report called Silver Bow Facility Tailings Pond and Groundwater Review (Tilman and Nemanic, 1996) addressed the quality of the water supply at the Silver Bow Plant. This review considered quarterly groundwater monitoring data from the Plant production wells that Rhône-Poulenc had collected and reported to Montana Department of Environmental Quality (MDEQ) since 1983. This monitoring and quarterly reporting was a requirement placed on the Plant when the Montana Water Quality Bureau granted the Silver Bow Plant an exemption from groundwater discharge permitting requirements regarding the tailing basin.

Silver Bow Facility Tailings Pond and Groundwater Review (Tilman and Nemanic, 1996) discusses the status of the tailing basin as of the 1996 report date, site geology and hydrogeology, the water discharge to the tailing basin, return water, and production well water quality. The water quality of the water discharged to the Tailing Basin and the quality of the return pond water that was reused in the production process is further discussed in the Groundwater and Tailing Basin and Water Recirculation System (Sections 5.3 and 5.5.1) sections of this report. The production well monitoring program consisted of monthly sampling of production wells RP-W-1, RP-W-4, RP-W-5, RP-W-6 and RP-W-7, and the Plant tap water. The monthly water quality data was averaged for each quarter and reported to the Montana Water Quality Board.

Rhône-Poulenc contracted Hydrometrics to sample the three shallow monitoring wells (installed during the U.S. EPA's site screening study) in September 1994. These sample results were consistent with the laboratory reports (but not the erroneous summary tables) published in the U.S. EPA's 1989 site screening study. The analytical results are further summarized and presented in Section 5 of this RFI report.

1.3.1.4 Voluntary Cleanup Plan

The 1999 draft Voluntary Cleanup Plan (VCP) (Barr, 1999) presented the proposed closure plan of the Rhodia Silver Bow Plant under the Voluntary Cleanup and Redevelopment Act (VCRA) of the State of Montana. The VCP was submitted in draft to MDEQ and was neither commented on nor approved by MDEQ. The VCP addresses required elements of a VCRA voluntary cleanup plan, and included copies or references to previously published studies pertaining to this facility.

From 1997 through 1999, Rhodia conducted investigations at the Silver Bow Plant in preparation for submission of the VCP and final closure of the Plant. In order to develop appropriate closure plans, the objectives of the investigations were to characterize the following: geology; groundwater and surface water flow patterns; quality of shallow and deep groundwater; quality of surface water; potential leaching from site materials; physical characteristics of the tailing; quality of water in the tailing basin; hydrogeologic properties influencing shallow groundwater flow; and aquifer parameters influencing arsenic transport.

The 1997 groundwater and surface water investigation was designed to characterize the shallow groundwater flow patterns, groundwater and surface water quality, and provide environmental characterization information needed to evaluate Plant closure alternatives. The investigation included placement of 12 monitoring wells and six other borings, collection of 14 groundwater and five surface water samples, other testing, and review of past groundwater and surface water sample data from the Silver Bow Plant.

A radiological survey (Appendix 1-G) was performed in 1997 as part of the VCP investigation. Two previous radiation studies pertinent to the Silver Bow Plant, but much more narrowly focused, had also been performed. One study involved sampling at the Silver Bow Plant (Appendix 1-H); the other study looked at the use of slag (such as that produced at the Silver Bow Plant) in street construction (Appendix 1-I). (*see* Section 2.5.2.3.5 regarding slag and Sections 5.4.1 and 5.5 regarding soil and site materials for reviews of the radiological survey findings).

In 1998, water sampling was repeated and expanded to include 15 monitoring wells (the 12 placed in 1997 and the three U.S. EPA wells), five production wells, and eight surface water samples. The results of this investigation were incorporated in the VCP Report. The groundwater data is further discussed and included in Section 5.3 of this RFI report.

A groundwater model was prepared in 1999 in order to integrate surface water and groundwater flow, quality information from the site, and to predict future arsenic groundwater quality for closure scenarios. The groundwater fate and transport model focused on arsenic, the parameter of greatest combined mobility and toxicity. The industry-standard models MODFLOW and MT3DMS were used to model groundwater flow and arsenic transport, respectively. The model represented both the regional and the site groundwater and surface water flow systems, and was calibrated using observed water levels, groundwater discharge estimates, and the observed arsenic distribution. The details of the modeling effort are presented in Appendix 1-J.

The 1999 investigation was designed to provide site-specific data for groundwater flow characterization along the buried channel of Sheep Gulch and in the vicinity of the tailing basin, and to assess the site-specific arsenic sorption properties of the soils beneath the tailing basin in order to better understand fate and transport of arsenic in the aquifer. The 1999 investigation included placement of two pumping wells, two piezometers, and 13 soil borings. Two groundwater samples were collected from each pumping well. Samples were also collected from three other monitoring wells and one surface water station. The investigation included pump tests at the two pumping wells and specific capacity/recovery rate tests at four monitoring wells.

In addition, Silver Bow Creek stream flow measurements were made, which show gains in stream flow from groundwater inflow. Other testing included tailing and soil sample leach tests and total analysis for selected parameters. Finally, surface water and groundwater samples collected from seven locations were analyzed for elemental phosphorus. Most of this information was collected in support of the groundwater modeling process, and the 1999 study results as well as the groundwater model were published with the draft VCP report.

The radiological study results and pertinent sample locations are presented in Section 5. The analytical data resulting from samples collected during the VCP investigations are summarized along with data from the other reports in the data summary tables provided in Section 5 of this RFI report.

1.3.1.5 Pre-closure Groundwater Monitoring Report

Rhodia implemented a pre-closure groundwater monitoring program to characterize the shallow groundwater quality in the immediate vicinity of the clarifier and the used carbon brick and furnace liner pile for the purpose of determining whether releases have occurred. Groundwater quality was characterized through an iterative monitoring program consisting of three successive rounds of monitoring well installation and groundwater sampling: October 2001, January 2002, and September 2002. Rhodia prepared a cumulative report after each sampling event and submitted the report to the Agencies (U.S. EPA and MDEQ) for comments. Rhodia responded to each comment and obtained U.S. EPA approval prior to conducting subsequent pre-closure groundwater monitoring activities.

A U.S. EPA contractor (Tetra Tech) collected split samples during the January 2002 sampling event and analyzed each sample at U.S. EPA's independent laboratory. This analytical data was incorporated into the subsequent Pre-closure Groundwater Monitoring Report (Barr, 2002).

The pre-closure monitoring work and associated data were most recently summarized in a December 2002 report (Barr, 2002). Groundwater quality was characterized through an iterative monitoring

program consisting of three separate sampling events including placement of eight new monitoring wells (MW-01-1, MW-01-2, MW-01-3, MW-01-4, MW-01-5, MW-01-6, MW-02-1, and MW-02-2) and sample collection at two previously constructed monitoring wells (MW-97-5 and MW-97-7). The analytical data for this investigation are further discussed and included in Section 5 of this RFI report. The analytical data for the split samples collected by Tetra Tech are consistent with the original analysis (Tetra Tech, 2002).

1.3.1.6 Additional Groundwater and Surface Water Data Collection

Additional groundwater and surface water samples were collected by Rhodia in 2002, 2004, and 2005. The 2002 data were reported to the MDEQ and the U.S. EPA in a letter dated February 3, 2003. Two new monitoring wells, MW-02-3 and MW-02-4, were placed in the northwest portion of the Silver Bow Plant property in 2002. The purposes of the well installation was to better understand the groundwater elevation and quality in this area, and to evaluate whether the domestic wells, northwest and potentially downgradient of the site, were being adversely affected by groundwater from the Silver Blow Plant site. The wells were sampled on October 9, 2002. The groundwater sample data is included in Section 5.3 of this RFI report.

Sampling was performed at two surface water stations on September 9, 2002: SW-6 on Sheep Gulch and SW-5 at the Beaver Pond. No other Sheep Gulch surface water samples were collected because there was no flow at the other Sheep Gulch surface water stations (SW-4, SW-3, and SW-1) or at the Sheep Gulch tributary surface water station, SW-2. The purpose of this sampling was to obtain additional data at these surface water locations under conditions of no surface flow in much of Sheep Gulch. The September 2002 surface water sample data are included in Section 5.1 of this RFI report.

The two northwest monitoring wells, MW-02-3 and MW-02-4, were sampled again on October 22, 2004, as proposed in the August 27, 2004 draft CCRA. The sample data were reported to the U.S. EPA and MDEQ in an e-mail dated November 18 and a conference call on November 23, 2004. The two monitoring wells and five other site monitoring wells were sampled on January 10 and 11, 2005. Monitoring wells MW-02-3, MW-02-4, MW-97-3, MW-97-4, and PW-99-1 were sampled on January 10, 2005 and MW-97-10 and MW-97-11 were sampled on January 11, 2005. The results of the sampling were transmitted to U.S. EPA and MDEQ in an e-mail dated March 4, 2005. The groundwater sample data is included in Section 5.3 of this RFI report.

The two northwest monitoring wells, MW-02-3 and MW-02-4, were sampled again on April 12, 2005, and October 30, 2005. The results of these sampling events were transmitted to U.S. EPA and MDEQ in

letters dated June 27, 2005 and January 3, 2006. The groundwater sample data is included in Section 5.3 of this RFI report.

1.3.1.7 Expanded Site Investigation

U.S. EPA Region 8 authorized Booz Allen Hamilton (Booz Allen) to conduct an Expanded Site Investigation (ESI) at the Silver Bow Plant in 2003. The purpose of the ESI was to gather new data and update existing data for re-evaluating the Rhodia site with respect to U.S. EPA's Hazard Ranking System criteria (Booz Allen Hamilton 2004).

Booz Allen conducted a field program to collect samples of onsite wastes, onsite and offsite groundwater, surface water and sediment, and surface soils. The field work was conducted from July 15 to July 24, 2003. The field program consisted of collection of thirteen groundwater samples, eight surface water/sediment sample pairs, one onsite surface water sample, seven surface soil samples from offsite communities, six sediment samples in the tailing basin, five waste-pile samples, four background/reference soil samples, one clarifier solids sample, and one clarifier water sample. The ESI reported results for a sample called ESI MW-02-3, but that sample was a duplicate of the ESI MW-01-2 sample, and was not a sample from the monitoring well MW-02-3. Sample results from the ESI are included and discussed in Section 5 of this RFI report.

1.3.2 Other Data Sources

1.3.2.1 SSTOU

The Streamside Tailings Operable Unit (SSTOU) of the Silver Bow Creek/Butte Area Superfund Site lies just north of the Plant's northern boundary, across German Gulch Road. The SSTOU contains wastes from past mining and milling activities in the area. MDEQ has assumed the responsibility for this Superfund Remedial Action. The wastes were deposited along Silver Bow Creek, which flows approximately parallel to the Facility's northern boundary. Remediation activities for the SSTOU were driven by the Comprehensive Environmental Responsibility, Compensation and Liability Act (CERCLA). Completed activities at the SSTOU include removal of streamside tailings and stream channel reconstruction (U.S. EPA, 2005). The objective of the work was to remove contaminated tailings, impacted soils and sediment until the order-of-magnitude criteria decrease in contaminant concentration is met. This order-of-magnitude criteria is generally intended to achieve the following metals levels, according to the State's project manager (Chavez, 2004):

- Arsenic generally less than 200 mg/kg.
- Cadmium generally less than 20 mg/kg.
- Copper, lead, and zinc generally less than 1000 mg/kg.
- Mercury generally less than 10 mg/kg.

The remaining tailings were covered with clean fill materials and vegetated.

There have been extensive investigations over an extended period of time for the SSTOU Superfund Site. The U.S. EPA has collected media samples to establish and characterize hazardous constituent concentrations in background/reference areas for the SSTOU. A number of soil, sediment, groundwater, and surface water samples were collected, including a number of samples in the reach of Silver Bow Creek north of the Rhodia Silver Bow Plant. These samples were not analyzed for elemental phosphorus.

The 1993 SSTOU background/reference area sampling included collection of 34 surface soil samples and 21 groundwater samples collected from domestic wells located outside the influence of the SSTOU.

The SSTOU investigation included sampling Silver Bow Creek and its tributaries under a variety of flow conditions over several years.

The SSTOU investigation included placement of monitoring wells astride Silver Bow Creek north of the Silver Bow Plant (Titan 1994). Data and figures for this sampling are further discussed in Section 5 of this RFI report.

1.3.2.2 REC Plant MPDES Permit

The REC Advanced Silicon Materials, Inc. (REC Plant, former ASiMI plant), performed an investigation to obtain groundwater quantity and quality information from their property located adjacent to the south side of the Silver Bow Plant. Water quality information for shallow groundwater monitoring wells was provided by the REC Plant to Rhodia and is discussed in Section 5 of this RFI report. REC also obtained a Montana Pollutant Discharge Elimination System (MPDES) permit for discharge to Sheep Gulch (the water is discharged to a tributary, which joins Sheep Gulch south of the Rhodia property). The REC Plant water quality discharge limits are relevant as to acceptable water quality in that drainage way and evaluation of conditions at the Silver Bow Plant.

In February 1998, the REC Plant placed two monitoring wells along a tributary to Sheep Gulch; the wells are located upstream and, for groundwater, upgradient of the Silver Bow Plant. These wells were placed in fluvial valley deposits beneath Sheep Gulch, as evidenced by the 5 to 20 feet of sand, gravel, and silt reported to be present at the ground surface in the boring logs for the wells. The REC Plant monitoring wells are further discussed in Section 5 of this RFI report. Similar fluvial deposits were encountered in the historical location of Sheep Gulch beneath the tailing basin at the Silver Bow Plant.

The REC Plant obtained an MPDES permit from the State of Montana to discharge treated process wastewater and storm water to Sheep Gulch. The allowable discharge concentrations (30 day averages) and allocated average loading under the final limits, applicable after November 2000 are as follows (based on a 1.5 million gallon per day discharge): arsenic, 0.018 mg/L (77 g/day loading), cadmium, 0.0034 mg/L (15 g/day loading), and fluoride, 4.0 mg/L (17,700 g/day loading).

The MPDES permit also requires submittal of monthly discharge monitoring reports. The data are entered into U.S. EPA's Permit Compliance System (PCS) database. Additional discussion about the REC plant wastewater discharge and groundwater quality is provided in Section 5.3.2.

1.4 Report Organization

This report is organized into seven sections, including this introduction.

- Section 2 summarizes site background information including: facility operations; plant demolition; land use and surrounding area; regulatory history and environmental compliance; waste streams, SWMUs and AOCs.
- Section 3 provides the site conceptual model and includes a discussion of the geology, hydrogeology and hydrology of the site at both a regional and site level.
- Section 4 provides an evaluation of the background data collected for surface water, sediment, soil and groundwater.
- Section 5 summarizes RFI results and includes a discussion of remedial investigation activities conducted at the site between and an evaluation the collected site data
- Section 6 contains a discussion of recommendations.

References are provided within each individual section.

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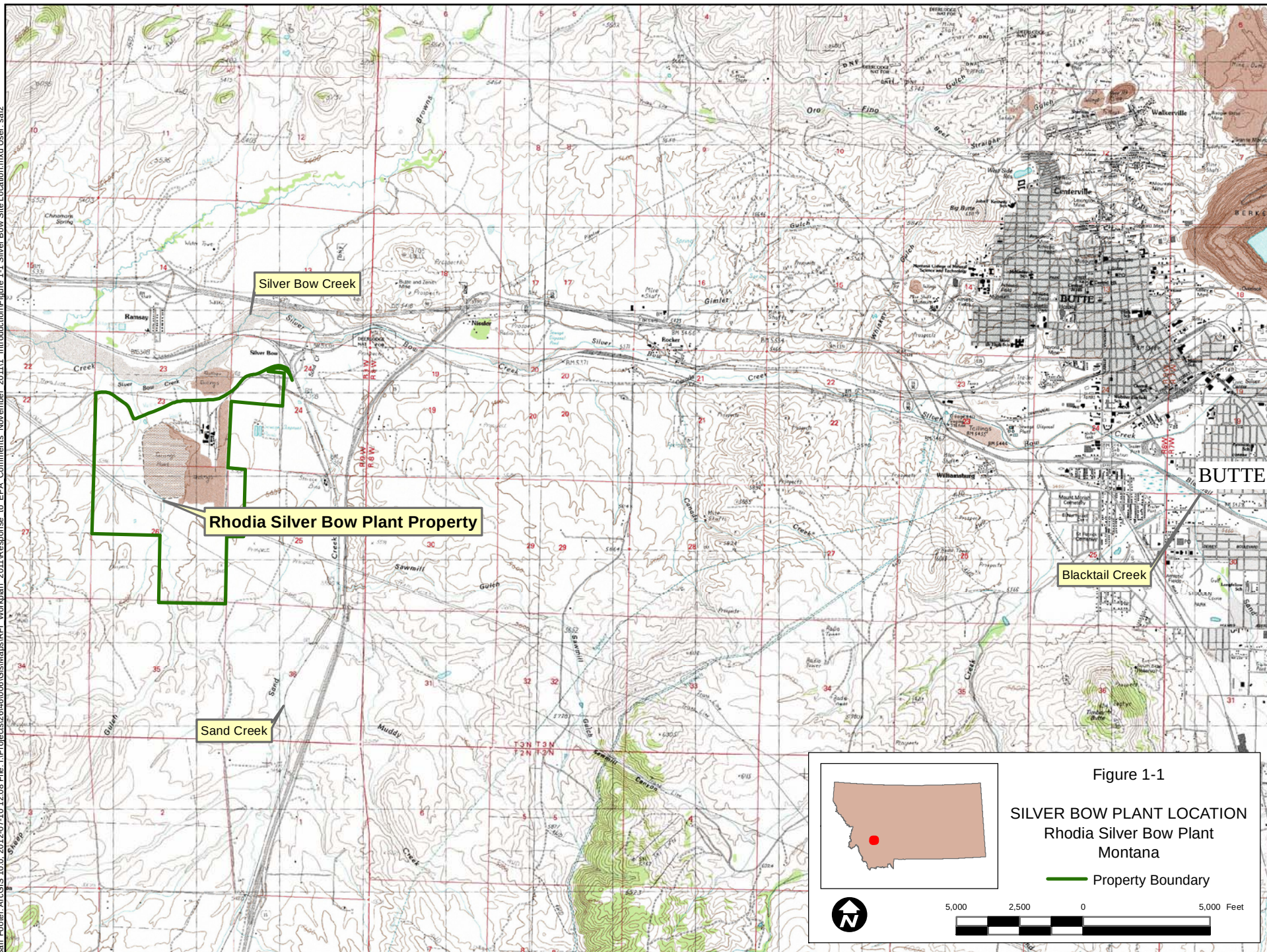
Tables

Table 1-1
RFI Report Data Qualifiers and Footnotes
RFI Report 2012
Rhodia Silver Bow Plant

N	Normal sample																																													
FD	Field duplicate																																													
SPLIT	Sample separated and sent to additional laboratory for duplicate analysis																																													
MCL	Maximum contaminant level																																													
MDL	Method detection limit																																													
MMDL	Maximum method detection limit																																													
RDL	Reporting detection limit																																													
UCL	Upper Confidence Limit of the mean of combined 2010 background/reference area data and ESI background data set. Used ProUCL selected UCL.																																													
B	Potential false positive value based on blank data validation procedures.																																													
b	Potential false positive value based on blank data validation procedures.																																													
C	Coeluting compound																																													
E	Estimated value. Exceeded the instrument calibration range.																																													
h	EPA recommended sample preservation, extraction or analysis holding time was exceeded.																																													
J	The analyte was positively identified and the associated numerical value is the approximate concentration of the analyte in the sample (due to either the quality of the data generated because certain quality control criteria were not met, or the concentration of the analyte was below the CRQL)																																													
R	The sample results are unusable due to the quality of the data generated because certain criteria were not met. The analyte may or may not be present in the sample.																																													
S	Potential false positive based on statistical analysis of blank sample data.																																													
BQD	Equipment malfunction																																													
BQQ	Some aspect of QA/QC was not met.																																													
BQU	Historical qualifier - definition is unknown.																																													
xx	The historical result had no available laboratory reporting limit but the result was non-detect.																																													
--	Not analyzed/not available.																																													
<	Parameter was not detected at the RDL. If the parameter was not detected at the RDL, the RDL was selected as the maximum concentration. See summary table for additional information, including parameter-specific RDL.																																													
*	Estimated value. QA/QC criteria not met.																																													
(1)	There are only 5 detected values in this data. It should be noted that even though bootstrap may be performed on this data set, the resulting calculations may not be reliable enough to draw conclusions.																																													
(12)	MT DEQ-7 Aquatic Life Standards, Acute and Chronic, or these metals are expressed as a function of total hardness (mg/l, CaCO3). The values displayed in the chart correspond to a total hardness of 25 mg/l. The hardness relationships are: <table><tr><td></td><td colspan="2">Acute= exp.{ma[ln(hardness)]+ba}</td><td colspan="2">Chronic= exp.{mc[ln(hardness)]+bc}</td></tr><tr><td></td><td>ma</td><td>ba</td><td>mc</td><td>Bc</td></tr><tr><td>Cadmium</td><td>1.0166</td><td>-3.924</td><td>0.7409</td><td>-4.719</td></tr><tr><td>Copper</td><td>0.9422</td><td>-1.7</td><td>0.8545</td><td>-1.702</td></tr><tr><td>Chromium III</td><td>0.819</td><td>3.7256</td><td>0.819</td><td>0.6848</td></tr><tr><td>Lead</td><td>1.273</td><td>-1.46</td><td>1.273</td><td>-4.705</td></tr><tr><td>Nickel</td><td>0.846</td><td>2.255</td><td>0.846</td><td>0.0584</td></tr><tr><td>Silver</td><td>1.72</td><td>-6.52</td><td>-----</td><td>-----</td></tr><tr><td>Zinc</td><td>0.8473</td><td>0.884</td><td>0.8473</td><td>0.884</td></tr></table> Note: If the hardness is <25mg/L as CaCO3, the number 25 must be used in the calculation. If the hardness is greater than or equal to 400 mg/L as CaCO3, 400 mg/L must be used in the calculation.		Acute= exp.{ma[ln(hardness)]+ba}		Chronic= exp.{mc[ln(hardness)]+bc}			ma	ba	mc	Bc	Cadmium	1.0166	-3.924	0.7409	-4.719	Copper	0.9422	-1.7	0.8545	-1.702	Chromium III	0.819	3.7256	0.819	0.6848	Lead	1.273	-1.46	1.273	-4.705	Nickel	0.846	2.255	0.846	0.0584	Silver	1.72	-6.52	-----	-----	Zinc	0.8473	0.884	0.8473	0.884
	Acute= exp.{ma[ln(hardness)]+ba}		Chronic= exp.{mc[ln(hardness)]+bc}																																											
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Silver	1.72	-6.52	-----	-----																																										
Zinc	0.8473	0.884	0.8473	0.884																																										
(14)	MT DEQ-7 Aquatic Life Standards, Acute and Chronic, for pentachlorophenol is dependent on pH. Values displayed in the chart correspond to a pH of 6.5 and are calculated as follows: <table><tr><td>Acute = exp[1.005(pH) - 4.869]</td><td>Chronic = exp[1.005(pH) - 5.134]</td></tr></table>	Acute = exp[1.005(pH) - 4.869]	Chronic = exp[1.005(pH) - 5.134]																																											
Acute = exp[1.005(pH) - 4.869]	Chronic = exp[1.005(pH) - 5.134]																																													
(23)	MT DEQ-7 Human Health Standards. The concentration of iron must not reach values that interfere with the uses specified in the surface and ground water standards (17.30.601 et seq. and 17.30.1001 et seq.) The Secondary Maximum Contaminant Level of 300 micrograms per liter which is based on aesthetic properties such as taste, odor, and staining may be considered as guidance to determine the levels that will interfere with the specified uses.																																													
(24)	MT DEQ-7 Human Health Standards. The concentration of manganese must not reach values that interfere with the uses specified in the surface and ground water standards (17.30.601 et seq. and 17.30.1001 et seq.). The Secondary Maximum Contaminant Level of 50 micrograms per liter which is based on aesthetic properties such as taste, odor, and staining may be considered as guidance to determine the levels that will interfere with the specified uses.																																													
(36)	MT DEQ-7 Human Health Standards. The human health criteria for arsenic is the more restrictive of the risk based level of 1 in 1000 [1x10-3], or the MCL.																																													

Figures

Barr Footer ArcGIS 10.0 2012-07-10 12:08 File: I:\Projects\2046\06\GistMaps\REL Workplan 2011\Response to EPA Comments November 2011\ Introduction\Figure 1-1 Silver Bow Site Location.mxd User: sal2



Source: Ramsay, Buxton, Butte North, and Butte South USGS 7.5 minute quadrangles

Barr Footer: ArcGIS 10.0, 2012-07-10 12:08 File: I:\Projects\26146006\GIS\Maps\RFI Workplan_2011\Response to EPA Comments November 2011\Introduction\Figure 1-2 Property Boundary Ownership.mxd User: sgl2

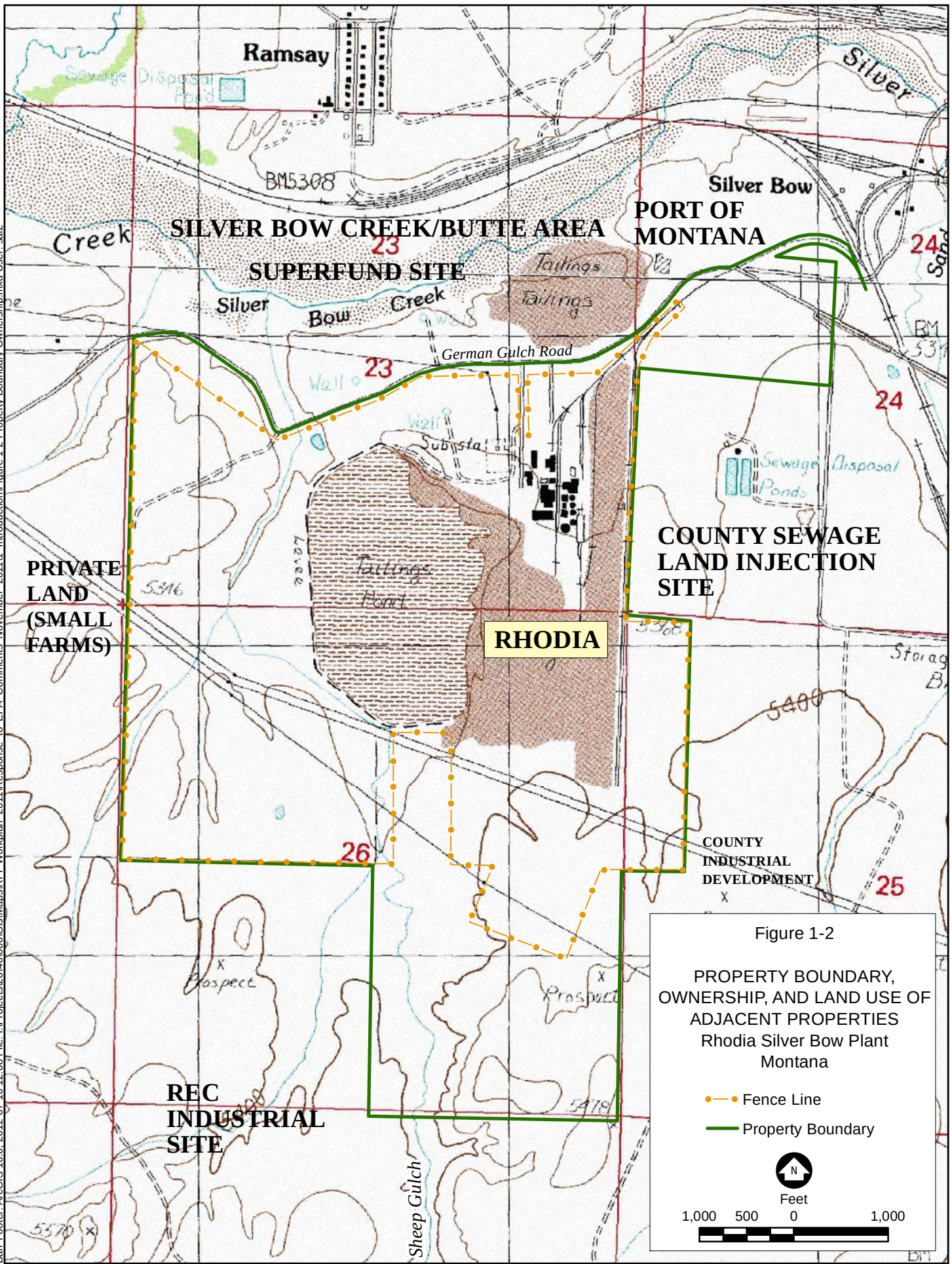
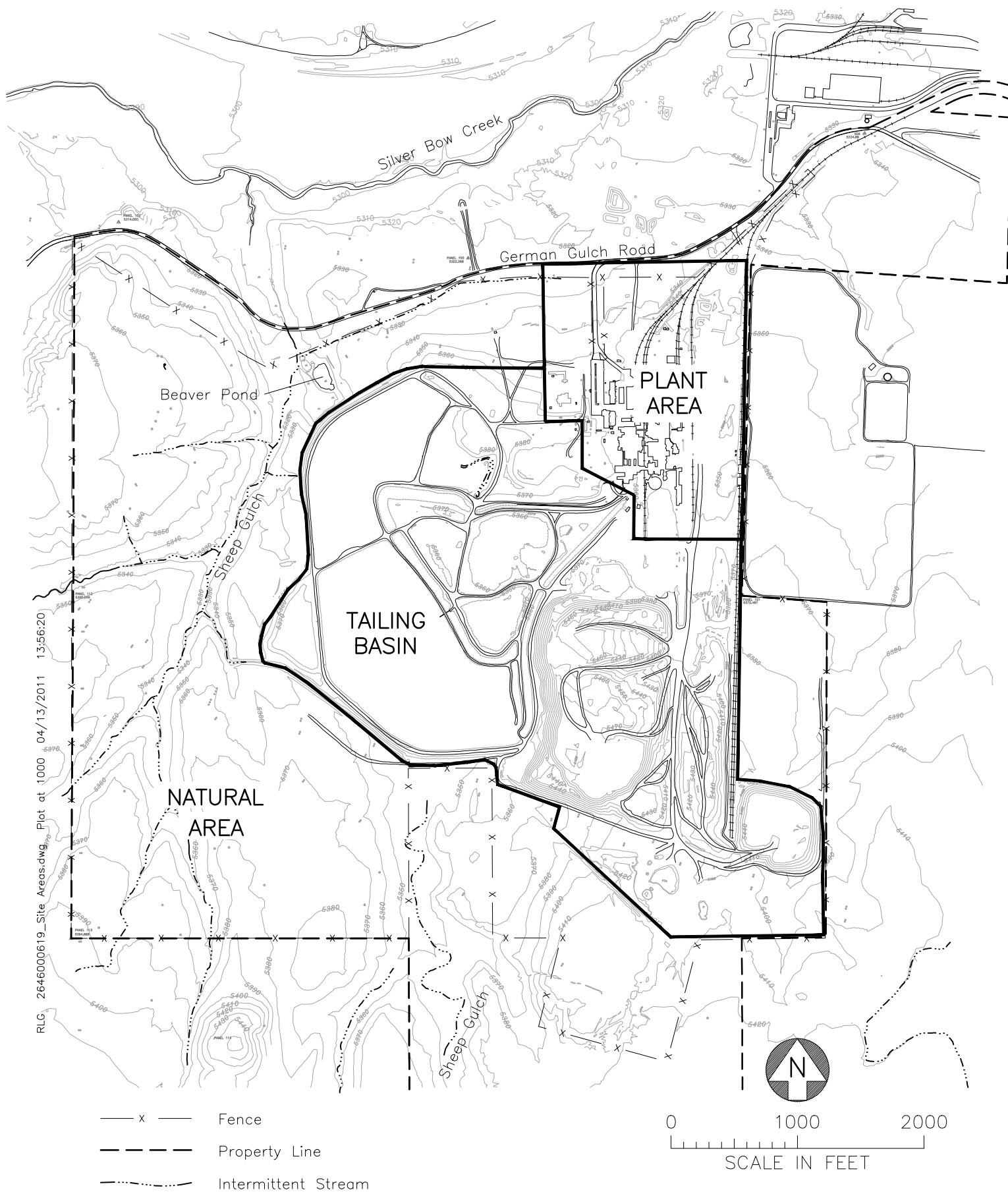


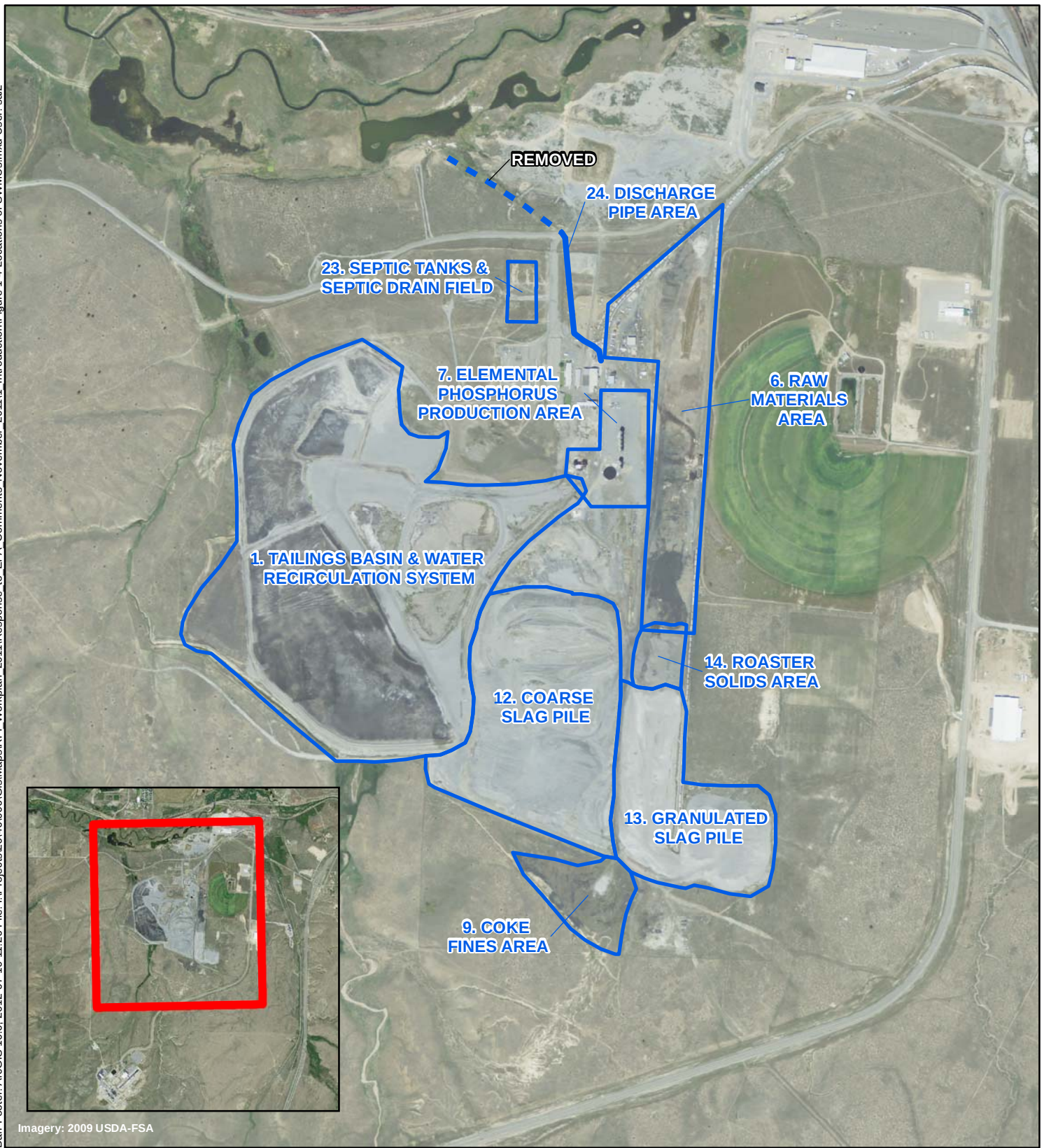
Figure 1-2
PROPERTY BOUNDARY, OWNERSHIP, AND LAND USE OF ADJACENT PROPERTIES
Rhodia Silver Bow Plant
Montana

● Fence Line
— Property Boundary

Feet
1,000 500 0 1,000

Source: Buxton and Ramsay, Montana USGS 7.5 minute quadrangles





 Solid Waste Management Unit

Notes:
SWMU 1 is inclusive of SWMUs 19 & 15.
SWMU 6 is inclusive of SWMU 26.
SWMU 7 is inclusive of SWMUs 2, 11 & 18.

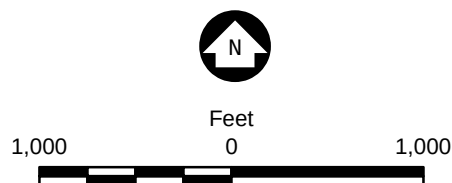


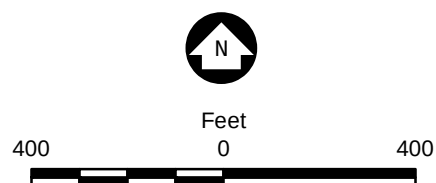
Figure 1-4
LOCATION OF SWMUs
1, 6, 7, 9, 12, 13, 14, 23 & 24
Rhodia Silver Bow Plant
Montana



 Solid Waste Management Unit

Figure 1-5

LOCATION OF SWMUs
2-5, 8, 10, 15-22, & 25-27
Rhodia Silver Bow Plant
Montana



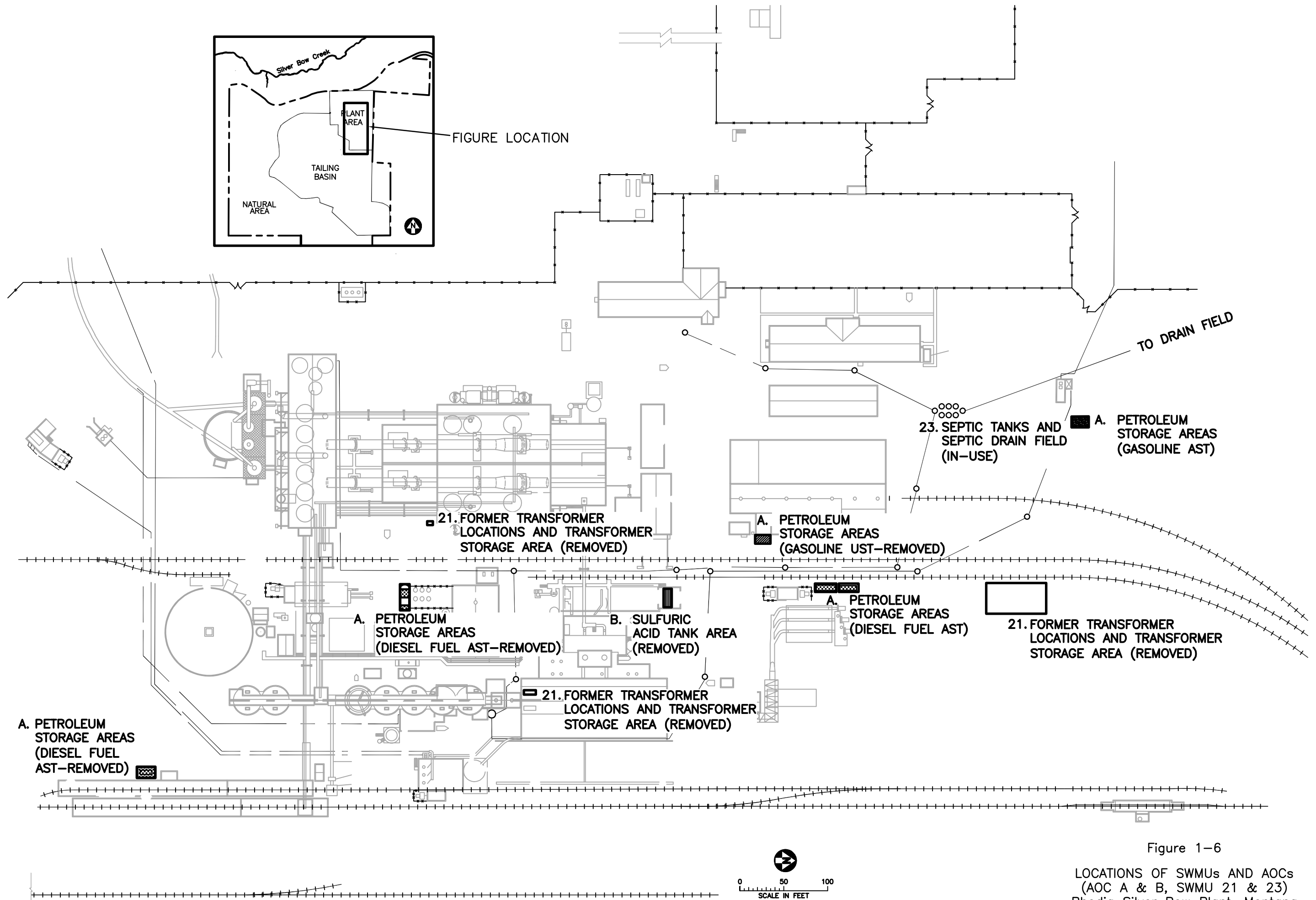


Figure 1-6
LOCATIONS OF SWMUs AND AOCs
(AOC A & B, SWMU 21 & 23)
Rhodia Silver Bow Plant, Montana

Appendices

Appendices 1A – 1E

2006 – 2010 Laboratory Data (*on compact disc*)

Appendix 1-F
2012 Laboratory Data (*on compact disc*)

Appendix 1-G

Radiological Survey

January 21, 1999

Mr. Jim Langseth
Project Manager
Barr Engineering Company
8300 Norman Center Drive
Minneapolis, MN 55437-1026

**Radiological Assessment
Rhone-Poulenc Silver Bow Plant**

Dear Jim:

This letter report presents the results of a Radiological Assessment at the Rhone-Poulenc Basic Chemicals Company Silver Bow Plant. TREC Inc. (TREC) is incorporating comments and finalizing the radiological assessment document originally prepared by *SECOR* International Incorporated. As outlined by Barr's request for proposal, dated October 30, 1997, the two primary objectives for the site radiation survey are: (1) to provide data that may be used to determine if protection is required for workers on site during site closure; and (2) to provide data to determine potential exposure levels at the site for potential recreational users following closure.

Four main tasks were performed for this radiological assessment including:

- Review of existing data;
- Additional site survey and sampling;
- Determination of background radiation in the area surrounding the facility; and
- Summary of data results identifying sources of radiation and the corresponding radiation levels.

These tasks and associated calculations and results are discussed in greater detail in the following sections.

Our evaluation of the site indicates that the current dominant source of gamma radiation exposure at the site is slag. There are no regulations that directly apply to emissions of naturally occurring radioactive materials (NORM) (gamma radiation and radon) from an elemental phosphorous facility. However, EPA Region X, in conjunction with a Technical Work Group comprised of other state and federal agencies and representatives of industry, local communities and Indian tribes, has developed guidelines applicable to radiation levels from phosphorous slag. These guidelines require no protective actions for individual doses of less than 100 mrem/year. Modeling indicates that the dose from existing site source materials at the Silver Bow Plant is approximately 28 mrem/year above background for a reasonable recreational exposure scenario (EPA, 1996; SITWGS, 1996). Workers will likely require protection against inhalation of dust during facility closure and demolition.

This letter report is divided into four main sections. The first provides a review of existing data reports pertaining to the Rhone-Poulenc Silver Bow Plant. The second main section describes site sampling methodology and procedures used for this radiological assessment. A summary of the analysis of the data collected during sampling efforts is presented in the third main section and the fourth section provides recommendations for closure based on the data evaluated.

Review of Existing Data

Two previous public reports have addressed radiological conditions related to the Rhone-Poulenc Silver Bow Plant. The first is a study of facility emissions conducted by EPA in 1982 (EPA, 1982). The EPA study focused on radioactive emissions from the active processes in the plant (at that time, the Stauffer Elemental Phosphorus Plant), but included some data relevant to this assessment. The relevant data include concentrations of radionuclides and radon emissions from ore, ore nodules, slag and facility soils. These data are summarized in Table 1. This study identified that although slag contained approximately as much radium-226 as the original ore, the ore was a significant source of radon and the slag was not. Radon flux from the ore was measured at rates over 60 pCi/m²-s and flux rates from slag were approximately 0.06 to 0.5 pCi/m²-s. Gamma radiation exposure rates on the slag pile were reported to average 150 μ R/hr

and ambient background was identified to be approximately 10 μ R/hr. The remainder of the results in the report relates to processes at the facility that are no longer operational.

The second report, prepared by the MDEQ in 1983, primarily addressed the radiological conditions off-site in Butte, Montana, where slag from the Silver Bow Plant (at that time, the Stauffer Chemical Company) had been used as fill and construction material and is not relevant to this investigation. However, the report does contain data for raw slag samples from the facility. These data are relatively similar to those collected by the EPA. These values are summarized in Table 1.

Gamma Radiation Survey and Sampling

An additional site radiological survey and sampling was performed over a four-day period from November 18 through 21, 1997, to collect data to estimate potential worker and post-closure recreational user exposure to NORM from the site. Previously available data (MDEQ, 1983; EPA, 1982) primarily relate to air quality monitoring of the operating plant and off-site use of slag. Therefore, additional data were required to appropriately determine exposure potential. Thirteen potentially impacted and eight background areas were surveyed for gamma radiation (Tables 2 and 6, respectively). Nine material types were sampled to provide radiological data for exposure modeling and site characterization. The materials sampled include: coarse and fine slag, facility soils, ore, process area, soils, tailings (pond sediments) roaster residue, building dust and background soils (see Table 3 for description of sample locations). The following subsections describe the radiological survey and sampling efforts in greater detail.

Site Field Gamma Radiation Survey

The field gamma radiation survey was conducted during the period November 18 through 21, 1997. A scintillation survey meter (Ludlum Model 19), calibrated against a pressurized ionization chamber, was used to collect a total of 793 gamma radiation exposure rate measurements on the site. The data collected during this survey are provided in Attachment A. A statistical summary of the data is provided in Table 2 and Figure 1 identifies average gamma radiation exposure rates for each area surveyed.

Background Field Gamma Radiation Survey, Sampling and Analysis

Applicable guidance, described below, defines the allowable on-site gamma radiation exposure in terms of exposure rates or concentrations "in excess of" or "in addition to" background. Therefore, background exposure rates and radium activity (concentration) were measured to determine numerical closure criteria for gamma radiation exposure and radium. The average background gamma radiation exposure rate at the site was determined from 213 separate gamma radiation survey measurements taken at eight locations outside of the immediate facility area and outside of the area of radiological influence of the facility. The background locations were sited primarily along the site boundary fence and are shown on Figure 1 and on the field map in Attachment A. Table 6 presents a summary of the direct exposure rate measurements from these eight sites measured in the field. The arithmetic mean of all background gamma radiation exposure measurements was 19 μ R/hr.

Sampling and Analysis for Radiological and Geotechnical Parameters

Twenty-nine samples representing potential source and background materials were collected during the field investigation to determine radiological and geotechnical properties necessary for comparison to federal radiation regulations and to evaluate radiological exposure of site workers and post-closure recreational users of the site. Samples were collected from:

- Stockpiled facility materials and by-products (coarse and fine slag, tailings and roaster residue);
- Soils within the process, ore storage and general facility areas;
- Dust in the process buildings; and
- Background areas.

Table 3 provides a summary of the location and number of samples collected. Analytical results are summarized in Tables 4 and 5 and the laboratory data are included in Attachment B.

The 29 samples were sent to Colorado State University in Fort Collins, Colorado, for gamma-ray spectral analysis. The results of the radiological laboratory analyses are summarized in Table 4. Activities of radionuclides measured and calculated by this analysis are required to calculate dose and potential risk from radionuclides that may be associated with future site use and to determine site closure requirements. All site soil samples and other materials collected for gamma-ray spectral analysis were dried, ground, sealed in cans and allowed in-growth of radon-222 and short-lived daughters before counting.

Five samples split from the 29 described above and representative of the primary radiological sources and background soils (potential cover materials) were submitted for geotechnical analysis to Montana State University and Gaston Engineering in Bozeman, Montana. Results of the geotechnical analyses for various potential source and background materials are presented in Table 5. Geotechnical parameters were determined from these materials for determination of potential site closure requirements.

Investigation Results

The results of radiological analyses of representative site materials, summarized in Table 4, include measured activities of radium-226, uranium-238, and thorium-232. Activity measurements for other radionuclides were calculated from these measured activities, using decay series relationships. These calculations indicate that other potential radionuclides exist at activities below levels of concern. The only calculated radionuclide activity that was above the lower detection limits is that of cesium-137, which is typically still present in surface soils within the Western United States due to nuclear weapons testing and the Chernobyl fire fallout. Uranium and thorium activities for site materials reported by EPA (1982) are similar to those measured during this investigation. Uranium and radium activities sampled from potential sources are above background levels of typical soils found in the Western United States. Activities in site background samples are similar to typical soils (Turner, 1992).

Both direct field gamma radiation survey measurements (Table 2) and laboratory radiological analyses (Table 4) indicate that the most significant source of gamma radiation at the site is the slag. Previous investigations (EPA, 1982; MDEQ, 1983) found that slag and ore were considered

to be the most significant concentrations of radium and uranium, sources of gamma radiation. However, very little ore is currently left on-site as it was processed prior to cessation of operations at the facility. This leaves slag as the only significant source of gamma radiation.

The relative magnitude of the field gamma radiation survey exposure rate readings for the different areas of the site and the concentration of radium-226 in samples primarily reflect the relative amount of slag mixed with other site materials. This is most clearly illustrated through comparison of the average field survey exposure rate for "Facility Soils," 28 $\mu\text{R/hr}$, and the average rate for "Mixed Use with Slag," 61 $\mu\text{R/hr}$ (Table 2). The only distinction between these two areas is that "Facility Soils" are disturbed areas without visible slag and "Mixed Use with Slag" areas were disturbed areas with visually identifiable slag. The Railroad Grade, Excavated Cells, and Dikes/Road areas were largely comprised of visually identifiable slag mixed with varying amounts of native materials.

As previously stated, there are currently no stockpiles of ore on site. Four samples of nodular ore and soil/ore mixtures were collected to represent the residual ore and ore storage areas as they currently exist. Sample ORE1 was a nodular ore sample from a small residual pile located at the southern extreme of the site. Samples ORE2 through ORE4 were samples of the soil in the former ore storage areas. ORE1 had the highest radium-226 activity of any samples collected and analyzed in 1997 (42 pCi/g), (see Table 4). This corresponds with the conclusions of the EPA (1982) and MDEQ (1983) reports that the ore was a significant source of ionizing radiation. The relatively lower values of measured radium-226 activities in the soil samples [ORE2 through ORE4] from the ore storage area (i.e., 18, 17 and 30 pCi/g, respectively), (see Table 4) indicate that while ore stockpiles have been removed from the storage area, residual amounts of radium remain mixed in the soils of that portion of the site. Field survey exposure rate readings of the ore storage area are also elevated over background (i.e., 95 $\mu\text{R/hr}$ compared to 19 $\mu\text{R/hr}$ for background). However, the readings are intermediate between background and the exposure rate readings of the slag areas, supporting the interpretation that residual ore is mixed with soils and other materials in the former ore storage areas.

Field survey exposure rate readings were made in three process pond cells from which the contents had been excavated: Cells J, I and L (see Figure 1 for location). Average field gamma radiation survey readings in these cells (144, 113, and 80 $\mu\text{R/hr}$, see Table 2) indicate that residual tailings and slag materials remain and provide a significant source of gamma radiation relative to background. However, some component of the field readings in each of the three cells is likely due to the influence of slag in the nearby roads and dikes and backfill in the cells.

At the instruction of personnel from Rhone-Poulenc, the revegetated tailings located west and east of the ponds (see Figure 1 and field map in Attachment A for location) were surveyed and sampled as representative of pond sediments. The reclaimed tailings exhibited moderate field gamma radiation exposure readings with an average of 69 $\mu\text{R/hr}$, which is intermediate to slag and background exposure readings.

Evaluation of Potential Closure Requirements

There are no regulations that directly apply to emissions of NORM (gamma radiation and radon) from an elemental phosphorous facility. However, EPA Region X, in conjunction with a Technical Work Group, has developed guidelines applicable to radiation levels from phosphorous slag. The Technical Work Group included:

- EPA,
- The State of Idaho,
- FMC,
- Monsanto,
- The Shoshone-Bannock Tribes,
- The ASTDR, and
- The communities of Soda Springs and Pocatello, Idaho.

These guidelines identify that for individual doses which exceed 500 mrem/year including background, additional protective action is recommended if a reduction of at least 100 mrem/year can be achieved. It is recommended that additional protective action be undertaken for doses between 100 mrem/year above background and 500 mrem/year including background, if a reduction of at least 100 mrem/year can be achieved. No protective actions are recommended for individual doses of less than 100 mrem/year above background. Therefore, the site survey and laboratory analyses were used, in conjunction with exposure assumptions, to calculate the dose commitment to site users based on current site conditions for comparison to these guidelines.

Department of Energy, Environmental Assessment Division software (RESRAD, v.5.2) was used to estimate potential exposure using the results of site sample radiological and geotechnical analyses as input parameters. Table 7 provides a summary of current radiological conditions at the site based on laboratory analyses of samples collected in November 1997. Full output from RESRAD is included in Attachment C.

The RESRAD program was run to provide an estimate of the dose to potential recreational users of the site based on current conditions for use in making site closure decisions. The model of radiation dose commitment with RESRAD conservatively used slag, the greatest source of radiation at the site, to represent the risk related to radiation from materials at the site. As detailed in Attachment C, the incremental dose (above background) calculated for recreational use of the slag area was found to be 28 mrem/year. This is based on a measured radium activity for the slag of 38 pCi/g (see Table 7) and an exposure scenario consistent with post-closure recreational use of the site. It should be noted that RESRAD and other risk assessment methodologies for radiation assume the risk of incurring either cancer or hereditary effects is linearly related to dose received in the relevant tissue (Gofman, 1981). Therefore, changes in inputs to the model related to activities (concentration) of radionuclides or duration of exposure will have a linear effect on the calculated dose (risk).

Based on this model and a recreational end land use, no additional measures would be required to meet the guidelines established by EPA Region X for slag from elemental phosphorous production in Idaho.

Mr. Jim Langseth

Page 9

January 21, 1999

Closing

The radiological assessment found that the dominant source of gamma radiation at the site is slag. The other materials at the site reflect relative mixtures of sources of gamma radiation (slag and residual ore) with native or other materials. However, based on appropriate exposure assumptions for a recreational end land use, and applying EPA's guidelines for phosphorous slag in Idaho, no additional measures are required to control radiation dose from these materials.

Additionally, thermoluminescent dosimeters (TLDs) were placed at the site during the field investigation in order to provide integrated field gamma radiation exposure values for correlation with the instantaneous field readings. The TLDs should be collected and analyzed in February 1998.

Please contact us to discuss the results presented in this letter report, answer any questions that you may have about the radiological assessment and determine when it would be convenient for you to have TREC personnel collect the TLDs. If you have any other questions concerning this transmittal, please call Matt Yovich or me at (406) 586-8364.

Sincerely,

TREC, Inc.

Douglass H. Graves, P.E.

Principal

cc: Cam Balentine, Rhone-Poulenc-MT (2 copies)
Jeff Lang, Rhone-Poulenc-NJ (1 copy)

203239

References

References

- Berger, J.D., 1993. "Manual for Conducting Radiological Surveys in Support of License Termination." Prepared for U.S. Nuclear Regulatory Commission. December.
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- Yu, C., et. al., 1993. "Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD," Version 5.0. Prepared for U.S. Department of Energy. September
- Yu, C., et. al., 1993. "RESRAD – A Computer Code for Evaluating Radioactively Contaminated Sites." Prepared by Argonne National Laboratory and U.S. Department of Energy. December.

Tables

Table 1
Review of Existing Data
Radiological Assessment
Rhone-Poulenc Silver Bow Plant

a. Activity of Radionuclides in Process Materials

Source Media	Activity (pCi/g)				
	U-238	U-234	Th-230	Th-232	Ra-226
Phosphate Ore ⁽¹⁾	26	26	43	0.19	24
Slag ⁽¹⁾	24	24	47	0.57	28
Montana Slag ⁽²⁾	21	20	20	0.77	28
Idaho Slag ⁽²⁾	41	40	35	0.50	48

Notes:

(1) EPA, 1982

(2) MDEQ, 1983

pCi/g = picocuries per gram

b. Radon Emanation Rates from Process Materials

Source Media	Rate (pCi/m ² -sec)
Facility Soils ⁽¹⁾	0.30
Ore (Top) ⁽¹⁾	0.88
Ore (East Berm) ⁽¹⁾	5.17
Ore (West Berm) ⁽¹⁾	0.60
Slag Pile ⁽¹⁾	0.06
Stauffer Phosphate Ore (Idaho) ⁽²⁾	63.7
Stauffer Crushed Slag (Idaho) ⁽²⁾	0.3
Monsanto Phosphate Ore (Idaho) ⁽²⁾	56.7
Monsanto Uncrushed Ore (Idaho) ⁽²⁾	0.3
Monsanto Crushed Slag (Idaho) ⁽²⁾	0.5

Notes:

(1) EPA, 1982

(2) MDEQ, 1983

pCi/m²-sec = picoCuries per meter-squared-second

Table 2
Summary of Radiological Field Gamma Survey Results
Radiological Assessment
Rhone-Poulenc Silver Bow Plant

	Coarse Slag	Fine Slag	North Slag Area	Facility Soils	Ore Storage Area	Processing Area	Mixed Use, with Slag	Reclaimed Tailings	Excavated Cell J	Excavated Cell I	Excavated Cell L	Dikes/Road	Railroad Grade
Average Exposure Rate ($\mu\text{R/hr}$)	145	140	111	28	95	46	61	69	144	113	80	114	70
Maximum ($\mu\text{R/hr}$)	170	150	138	55	125	60	115	80	150	115	95	150	105
Minimum (mR/hr)	100	100	65	17	45	25	33	50	130	110	65	60	40
Number of Samples	61	13	37	145	82	19	68	23	4	2	4	85	28
Standard Deviation ($\mu\text{R/hr}$)	16	13	20	6	15	8	17	6	9	4	12	21	19
Standard Deviation/Average ⁽¹⁾	0.11	0.09	0.18	0.23	0.16	0.18	0.27	0.09	0.07	0.03	0.15	0.19	0.27

Notes:

(1) The "standard deviation / average" ratio is used to help illustrate the range of data relative to the value of the associated mean value.

$\mu\text{R/hr}$ = microRoentgens per hour

Background statistics summarized in Table 6.

Table 3
Sample Locations
Radiological Assessment
Rhone-Poulenc Silver Bow Plant

Sample Number	Sample Type	Field Exposure Rate	
		(μ R/hr) ⁽¹⁾	Location
CSL1	Coarse slag	155	South center of pile
CSL2	Coarse slag	150	East center of pile
FSL1	Fine slag	140	South West of pile
FSL2	Fine slag	145	North West of pile
DS1	Slag (north area)	120	Slag north of road
FS1	Facility soil	21	East fence line
DS2	Facility soil	18	West of conveyor, S of Slag Piles
DS3	Facility soil		Refractory brick
ORE1	Ore (nodular)	50	South of slag piles
ORE2	Ore	100	Ore storage area
ORE3	Ore	90	Ore storage area
ORE4	Ore	110	Ore storage area
FS2	Process area	95	West of ore storage area
FS3	Process area	70	South East of silos
FS4	Process area	90	Equipment yard near RR tracks
FS5	Process area	42	By flagpole
WT1	Tailings	70	West reclaimed tailings
WT2	Tailings	68	West reclaimed tailings
ET1	Tailings	70	East reclaimed tailings
ET2	Tailings	80	East reclaimed tailings
RRE	Roaster residue	50	East of pile
RRW	Roaster residue	50	West of pile
BLDG1	Building dust	24	Kiln building
BLDG2	Building dust	40	Feed building
BLDG3	Building dust	21	Silo building
BLDG4	Building dust	30	Furnace building
BLDG5	Building dust	26	Feed building
BG1	Background	18	North West corner
BG5	Background	19	South East off-site

Notes:

μ R/hr = microRoentgens per hour

(1) Exposure readings obtained with field gamma survey instrument (scintillation survey meter) at sample location.

Radiological and geotechnical parameters for these samples are reported on Tables 4 and 5.

		Radium-226		Uranium-238		Thorium-232	
Sample		Activity	STD ⁽¹⁾	Activity	STD ⁽¹⁾	Activity	STD ⁽¹⁾
Number	Sample Type	(pCi/gram)	(pCi/gram)	(pCi/gram)	(pCi/gram)	(pCi/gram)	(pCi/gram)
CSL1	Coarse Slag	40	(0.94)	64	33.00	0.92	(0.91)
CSL2	Coarse Slag	39	(0.86)	22	(32.00)	<0.46	N/A
FSL1	Fine Slag	38	(0.85)	<18	N/A	1.2	(0.85)
FSL2	Fine Slag	38	(0.84)	52	(29.00)	0.49	(0.82)
DS1	Slag (north area)	38	(1.20)	34	(32.00)	0.59	(1.30)
FS1	Facility Soil	1.9	(0.40)	<18	N/A	2.1	(0.70)
DS2	Facility Soil	1.5	(0.57)	67	(37.00)	1.8	(1.10)
DS3	Facility Soil	3.6	(0.47)	<13	N/A	5	(0.86)
ORE 1	Ore (nodular)	42	(0.96)	15	(17.00)	0.26	(0.92)
ORE 2	Ore	18	(0.83)	45	(41.00)	0.62	(0.81)
ORE 3	Ore	17	(0.96)	66	(39.00)	0.68	(1.00)
ORE 4	Ore	30	(0.94)	69	(49.00)	0.44	(0.91)
FS2	Process Area	37	(0.84)	71	(42.00)	0.34	(0.83)
FS3	Process Area	17	(0.81)	62	46.00	1.3	(0.86)
FS4	Process Area	19	(0.83)	58	(37.00)	1.4	(0.84)
FS5	Process Area	24	(0.71)	62	(34.00)	1.4	(0.74)
WT1	Tailings	22	(0.80)	<18	N/A	0.67	(0.79)
WT2	Tailings	23	(0.86)	40	40.00	0.73	(0.86)
ET1	Tailings	32	(1.10)	35	(38.00)	0.94	(1.20)
ET2	Tailings	32	(0.99)	<15	N/A	0.43	(0.98)
RRE	Roaster Residue	1.6	(0.22)	<6.7	N/A	0.16	(0.33)
			(continued)				
		Radium-226		Uranium-238		Thorium-232	
Sample		Activity	STD ⁽¹⁾	Activity	STD ⁽¹⁾	Activity	STD ⁽¹⁾
Number	Sample Type	(pCi/gram)	(pCi/gram)	(pCi/gram)	(pCi/gram)	(pCi/gram)	(pCi/gram)
RRW	Roaster Residue	1.2	(0.27)	8.3	(15.00)	0.51	(0.41)
BLDG 1	Kiln Building	41	(1.00)	10	(16.00)	0.24	(0.99)
BLDG 2	Feed Building	35	(1.10)	25	(35.00)	1.2	(1.10)
BLDG 3	Silo Building	4.8	(0.36)	56	(32.00)	0.022	(0.40)
BLDG 4	Furnace Building	20	(1.00)	49	(32.00)	0.87	(1.10)
BLDG 5	Feed Building	39	(1.10)	56	(36.00)	0.52	(1.10)
BG1	Background	1.2	(0.23)	<9.5	N/A	1.6	(0.42)
BG5	Background	1.3	(0.28)	39	(32.00)	1.8	(0.54)
Notes:							
(1) STD = Standard deviation							
1.96 standard deviation is due to counting statistics only.							
pCi/gram = picoCuries per gram							
< = less than							
N/A = Not Applicable							

Table 6
Determination of Background Radiation
Radiological Assessment
Rhone-Poulenc Silver Bow Plant

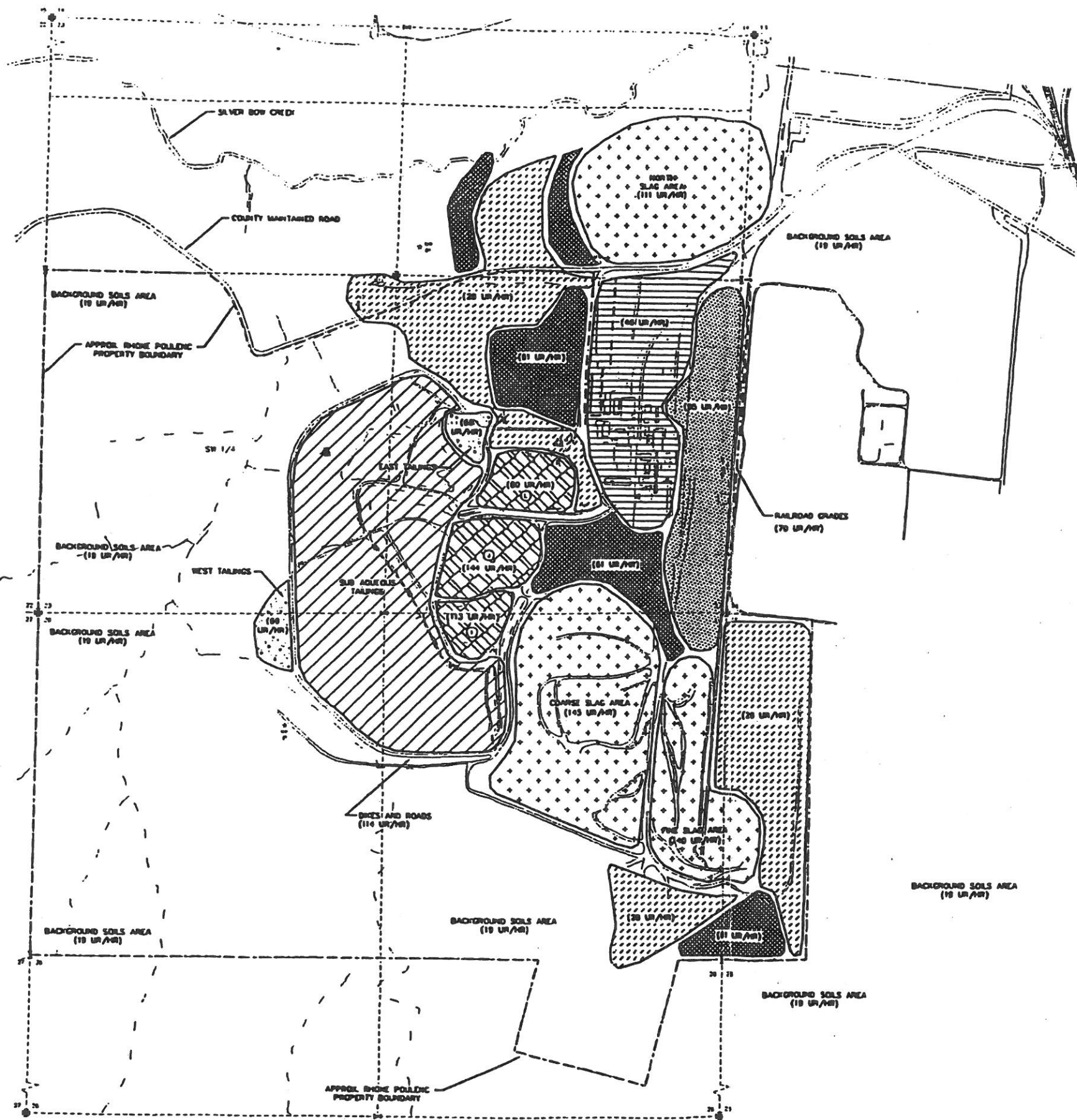
Station/Sample Number	BG1	BG2	BG3	BGNE	BG4	BG5	BG6	BG7	All Sites
Location	northwest corner	west off-site	southwest corner	northeast off-site	southeast corner	southeast off-site	south	west	NA
Average Exposure Rate ($\mu\text{R/hr}$) ⁽¹⁾	18.2	18.0	18.1	18.0	19.3	19.3	17.9	18.9	19
Number of Samples	36	1	36	1	36	36	19	48	213
Standard Deviation ($\mu\text{R/hr}$)	0.5	NA	0.6	NA	0.8	0.8	1.3	1.7	1.3
Standard Deviation/Average	0.03	NA	0.03	NA	0.04	0.04	0.07	0.09	0.07

Notes:

NA = not applicable

$\mu\text{R/hr}$ = microRoentgens per hour

Figures



LEGEND:

- APPROXIMATE BOUNDARY OF FACILITY
- (95 UR/HR) AVERAGE MICRODENTGENS PER HOUR FOR SURVEY AREA
- EXISTING PRODUCTION WELL
- * EXISTING MONITORING WELL
- [Pattern: Dotted] SLAG AREAS
- [Pattern: Diagonal lines \] FACILITY SOILS AREA
- [Pattern: Horizontal lines] DYE STORAGE AREA
- [Pattern: Vertical lines] PROCESSING AREA
- [Pattern: Cross-hatch] MIXED USE WITH SLAG AREAS
- [Pattern: Stippled] RECLAIMED TAILINGS AREA
- [Pattern: Diagonal lines /] SUB AQUEOUS TAILINGS AREA
- [Pattern: X-hatch] EXCAVATED TAILINGS CELLS

NOTES:

- 1. ALL BOUNDARIES ARE APPROXIMATE.

REFERENCES:
THIS MAP AND INFORMATION HEREON ARE
FOR INFORMATION PURPOSES ONLY. NO
WARRANTY IS MADE BY THE COMPANY
FOR THE ACCURACY OF THE DATA
OR THE QUALITY OF THE WORK.

SECOR

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PREPARED FOR
RHONE-POULENC BASIC CHEMICALS COMPANY
SILVER BOY, MONTANA

SITE PLAN

RADIOLOGICAL ASSESSMENT

SCALE

0 100 200 FEET

FIGURE 1

Attachment A

Field Survey Data and Statistical Summary

Data for Determination of Background Radiation
Radiological Assessment
Rhone-Poulenc Silver Bow Plant

Station/Sample Number	BG1	BG2	BG3	BGNE	BG4	BG5	BG6	BG7	All Sites
		TLD4	TLD2		TLD11	TLD3			
	18.0	16.2	18.0	25.0	19.0	18.5	17.5		
	18.2		18.0		20.0	18.0	17.0		
	19.0		19.0		18.5	18.5	18.0		
	17.5		18.0		19.0	19.5	19.5		
	18.5		18.5		18.5	19.0	19.0		
	18.0		18.5		19.5	18.0	17.5		
	18.5		17.5		18.5	19.5	17.5		
	19.0		17.5		19.0	20.0	17.0		
	18.3		18.0		18.5	19.0	17.0		
	18.5		18.5		18.5	19.0	19.0		
	17.5		19.0		19.0	19.0	17.0		
	17.0		18.5		19.0	18.5	16.5		
	18.3		16.5		19.5	20.5	16.0		
	18.0		17.5		19.0	20.0	18.0		
	18.2		18.0		18.5	19.5	19.0		
	17.5		19.0		19.5	19.0	18.5		
	19.0		19.5		18.0	19.3	15.5		
	19.0		18.5		20.5	19.3	20.0		
	19.0		17.5		19.0	21.0	20.0		
	18.5		17.5		18.5	19.0		21.0	
	17.5		18.5		19.0	18.5		19.5	
	18.6		18.0		20.0	18.5		18.0	
	17.5		19.0		19.0	19.0		18.0	
	18.5		18.0		19.0	19.3		17.0	
	19.0		18.0		18.5	21.5		17.0	
	18.0		17.5		19.0	20.5		16.5	
	18.5		17.5		19.0	20.0		17.5	
	18.0		17.5		20.5	19.2		18.0	
	18.5		19.0		20.5	19.3		19.0	
	18.5		18.0		20.5	19.3		18.5	
	18.0		18.5		19.0	19.5		18.0	
	19.0		17.5		20.0	19.0		20.0	
	17.6		17.5		19.5	19.0		21.5	
	18.0		17.5		20.0	19.0		21.0	
	18.0		18.0		21.0	19.0		21.0	
	18.0		18.0		20.5	19.5		20.0	
								20.0	
								20.0	
								21.0	
								22.5	
								19.0	
								22.0	
								22.0	
								22.0	
								21.0	
								22.0	
								20.0	
								18.0	
								18.5	
								17.5	
								16.5	
								17.0	
								17.0	
								17.5	
								17.0	
								19.0	

Data for Determination of Background Radiation
Radiological Assessment
Rhone-Poulenc Silver Bow Plant

Station/Sample Number	BG1	BG2	BG3	BGNE	BG4	BG5	BG6	BG7	All Sites
								18.0	
								18.5	
								18.0	
								18.0	
								18.5	
								18.5	
								18.0	
								18.0	
								17.5	
								18.0	
								16.0	
Location	northwest corner	west off-site	southwest corner	northeast off-site	southeast corner	southeast off-site	south	west	NA
Average Exposure Rate ($\mu\text{R/hr}$) ⁽¹⁾	18.2	18.0	18.1	18.0	19.3	19.3	17.9	18.9	19
Number of Samples	36	1	36	1	36	36	19	48	213
Standard Deviation ($\mu\text{R/hr}$)	0.5	NA	0.6	NA	0.8	0.8	1.3	1.7	1.3
Standard Deviation/Average	0.03	NA	0.03	NA	0.04	0.04	0.07	0.09	0.07

Notes:

NA = not applicable

$\mu\text{R/hr}$ = microRoentgens per hour

Radiological Field Gamma Survey Results
Rhone-Poulenc Silver Bow Plant
Readings in microRoentgens per hour (μR/hr)

Transect	Exposure (mR/hr)	Field Comment		Coarse Slag	Fine Slag	Slag North of Road	Facility Soils	Ore Storage Area	Processing Area	Mixed Use, with Slag	Reclaimed Tailings	Excavated Cell J	Excavated Cell I	Excavated Cell L	Dikes/Road	Railroad Grade
A1	55	fence					55									
	70	RR														70
	110	pile						110								
	75							75								
	70		nodules					70								
	90		nodules					90								
	125		nodules					125								
	70		nodules							70						
	100									100						
	68	pipe	slag							68						
	70	road	slag												70	
	70		slag							70						
	150	slag	slag	150												
	155	slag	slag	155												
	155	slag	slag	155												
	170	slag	slag	170												
	140	slag	slag	140												
	120	slag	slag	120												
	112														112	
	130														130	
	140	E bank ditch													140	
	150	W bank ditch													150	
	150	E side Cell I	Cell I												150	
	110	floor of Cell I	Cell I										110			
	115	floor of Cell I	Cell I										115			
	145	dike	dike												145	
	130	Cell J	Cell J									130				
	150	Cell J	Cell J									150				
	145	Cell J	Cell J									145				
	150	W side Cell J	Cell J									150				
	150	dike	btw Cells G/H												150	
	120	dike	btw Cells G/H												120	
	120	dike	btw Cells G/H												120	
	120	dike	btw Cells G/H												120	
	130	dike	btw Cells G/H												130	
	135	dike	btw Cells G/H												135	
	120	dike	btw Cells G/H												120	
	130	dike	btw Cells G/H												130	
	135	dike	btw Cells G/H												135	
	140	intersection													140	
	125	dike	btw Cells F/G												125	
	130	dike	btw Cells A/B												130	
	130	dike	btw Cells A/B												130	
	135	dike	btw Cells A/B												135	
	135	dike	btw Cells A/B												135	
	130	dike	btw Cells A/B												130	
	125	dike	btw Cells A/B												125	
	125	dike	btw Cells A/B												125	
	130	dike	btw Cells A/B												130	
A2	130	dike	W side Cell A												130	
	68	reclaimed tailings									68					
	70	reclaimed tailings									70					
	72	reclaimed tailings									72					
	70	reclaimed tailings									70					
	78	reclaimed tailings									78					
	70	reclaimed tailings									70					
	65	reclaimed tailings									65					
	68	reclaimed tailings									68					
	71	reclaimed tailings									71					

Radiological Field Gamma Survey Results
Rhone-Poulenc Silver Bow Plant
Readings in microRoentgens per hour (μR/hr)

Transect	Exposure (mR/hr)	Field Comment		Coarse Slag	Fine Slag	Slag North of Road	Facility Soils	Ore Storage Area	Processing Area	Mixed Use, with Slag	Reclaimed Tailings	Excavated Cell J	Excavated Cell I	Excavated Cell L	Dikes/Road	Railroad Grade
A3	60	reclaimed tailings									60					
	50	reclaimed tailings									50					
	70	reclaimed tailings									70					
	80	reclaimed tailings									80					
	75	reclaimed tailings									75					
	70	reclaimed tailings									70					
	75	reclaimed tailings									75					
	75	reclaimed tailings									75					
	65	reclaimed tailings									65					
A4	70	reclaimed tailings									70					
	29						29									
	24						24									
	22						22									
A5	22	fence					22									
	23	berm					23									
	27						27									
	28						28									
	20						20									
	65														65	
A6	90	W dike Cell B													90	
	95														95	
	100														100	
	100														100	
	105														105	
	100														100	
	100														100	
	100	curve													100	
	110														110	
	105														105	
	100														100	
	110														110	
	110														110	
	110														110	
	110														110	
	110														110	
	105														105	
	100														100	
	110														110	
	110														110	
	120														120	
	110														110	
	110														110	
	115														115	
	120	dike Pond C													120	
	120	dike outlet pipe													120	
	110														110	
	100														100	
	115														115	
	120														120	
	120														120	
	110														110	
	115	intersection													115	
	110														110	
	115														115	
A7	65	E reclaimed tailings									65					
	65	E reclaimed tailings									65					
	70	E reclaimed tailings									70					
	72	E reclaimed tailings									72					

Radiological Field Gamma Survey Results
Rhone-Poulenc Silver Bow Plant
Readings in microRoentgens per hour (μR/hr)

Transect	Exposure (mR/hr)	Field Comment		Coarse Slag	Fine Slag	Slag North of Road	Facility Soils	Ore Storage Area	Processing Area	Mixed Use, with Slag	Reclaimed Tailings	Excavated Cell J	Excavated Cell I	Excavated Cell L	Dikes/Road	Railroad Grade
A8	110	road													110	
	80	Cell L	Cell L											80		
	80	Cell L	Cell L											80		
	65	Cell L	Cell L											65		
	95	Cell L	Cell L											95		
	100														100	
	110														110	
	110														110	
	120														120	
	130														130	
A9	150	slag													150	
	150														150	
	140														140	
	130														130	
	105	W ditch bank													105	
	140	NE ditch crossing													140	
	100														100	
	110	E ditch bank													110	
	80									80						
	70									70						
	65	RR track														65
	90	W edge debris pile						90								
	90							90								
	85							85								
	105							105								
	95							95								
	90		coke					90								
	70		coke					70								
	80		coke					80								
	90		coke					90								
A10	90	RR track/fence														90
B1	80	RR track														80
	90	RR track														90
	90	RR track														90
	90	RR track														90
	100	RR track														100
	100	RR track														100
	105	RR track														105
	100	RR track														100
	55	RR track/fence														55
B2	50	RR track/fence														50
	110							110								
	140		roaster residu	140												
	140		roaster residu	140												
	150		roaster residu	150												
	150		roaster residu	150												
	140	road													140	
	150	do not enter sign	pit slag	150												
	160	coarse slag	pit slag	160												
	160	coarse slag	pit slag	160												
	160	coarse slag	pit slag	160												
	160	coarse slag	pit slag	160												
	160	coarse slag	pit slag	160												
	160	coarse slag	pit slag	160												
	160	coarse slag	pit slag	160												
	160	coarse slag	pit slag	160												
	155	coarse slag	pit slag	155												
	150	coarse slag	pit slag	150												
	150	coarse slag	pit slag	150												

Radiological Field Gamma Survey Results
Rhone-Poulenc Silver Bow Plant
Readings in microRoentgens per hour (μR/hr)

Transect	Exposure (mR/hr)	Field Comment		Coarse Slag	Fine Slag	Slag North of Road	Facility Soils	Ore Storage Area	Processing Area	Mixed Use, with Slag	Reclaimed Tailings	Excavated Cell J	Excavated Cell I	Excavated Cell L	Dikes/Road	Railroad Grade
	150	coarse slag	pit slag	150												
	140	coarse slag	pit slag	140												
	150	coarse slag	pit slag	150												
	150	coarse slag	pit slag	150												
	150	coarse slag	pit slag	150												
	160	coarse slag	pit slag	160												
	140	coarse slag	pit slag	140												
	150	coarse slag	pit slag	150												
	155	coarse slag	pit slag	155												
	165	coarse slag	pit slag	165												
	160	coarse slag	pit slag	160												
	160	coarse slag	pit slag	160												
	160	coarse slag	pit slag	160												
	155	coarse slag	pit slag	155												
B3	150	coarse slag	pit slag	150												
C1	65	RR														65
	50	RR														50
	50	RR														50
C2	85							85								
	105							105								
	105							105								
	80							80								
	50								50							
	50								50							
	40		RR													40
	40								40							
	40								40							
	40								40							
	40								40							
	60								60							
	55								55							
	55								55							
C3	40	fence							40							
C4	40	fence							40							
	40								40							
	50								50							
	45								45							
	40		RR													40
	70							70								
	65							65								
	70		RR													70
	70							70								
	55		NU west ore					55								
	115		NU west ore					115								
	110		unwashed ore					110								
	105		unwashed ore					105								
	100		unwashed ore					100								
	70	RR														70
C5	60	fence/RR														60
	60	RR														60
	60	RR														60
	60	RR														60
	65	RR														65
C6	65	RR														65
	75							75								
	90							90								
	45							45								
	100	pile						100								
	90							90								

Radiological Field Gamma Survey Results
Rhone-Poulenc Silver Bow Plant
Readings in microRoentgens per hour (μR/hr)

Transect	Exposure (mR/hr)	Field Comment	Coarse Slag	Fine Slag	Slag North of Road	Facility Soils	Ore Storage Area	Processing Area	Mixed Use, with Slag	Reclaimed Tailings	Excavated Cell J	Excavated Cell I	Excavated Cell L	Dikes/Road	Railroad Grade
	85						85								
	105						105								
	50	RR													50
	100						100								
	70						70								
	95						95								
	45	pavement						45							
	50	pavement						50							
	50	pavement						50							
	25	sidewalk						25							
C7	50	fence						50							
D1	95	ore storage area					95								
	110						110								
	110						110								
	105						105								
	110						110								
	100						100								
	100						100								
	90						90								
	90						90								
	85						85								
	75						75								
	80						80								
	90						90								
	90						90								
	90						90								
	90						90								
	100						100								
	110						110								
	100						100								
	95						95								
	90						90								
	80						80								
	80						80								
	110						110								
	125	approaching slag	125												
	130		130												
	125	road btw slag piles	125												
	125	do not enter sign	125												
	135	road btw slag piles	135												
	140	road btw slag piles	140												
	155	road btw slag piles	155												
	155	road btw slag piles	155												
	150	road btw slag piles	150												
	150	road btw slag piles	150												
	160	road btw slag piles	160												
	160	road btw slag piles	160												
	160	road btw slag piles	160												
	145	fine slag on road		145											
	140	fine slag on road		140											
	150	road btw slag piles	150												
	125	road btw slag piles	125												
	120	road btw slag piles	120												
	120	road btw slag piles	120												
	120	road btw slag piles	120												
	120	road btw slag piles	120												
	120	road btw slag piles	120												
	120	road btw slag piles	120												
	105	road btw slag piles	105												

Radiological Field Gamma Survey Results
Rhone-Poulenc Silver Bow Plant
Readings in microRoentgens per hour (μR/hr)

Transect	Exposure (mR/hr)	Field Comment		Coarse Slag	Fine Slag	Slag North of Road	Facility Soils	Ore Storage Area	Processing Area	Mixed Use, with Slag	Reclaimed Tailings	Excavated Cell J	Excavated Cell I	Excavated Cell L	Dikes/Road	Railroad Grade
	120	road btw slag piles		120												
	100	road btw slag piles		100												
	60	intersection													60	
	60									60						
	55									55						
	30	conveyor					30									
	25						25									
	25						25									
	28						28									
	30						30									
D2	20	south edge of site					20									
E1	60	intersection													60	
	80	road													80	
	60	road													60	
	60	road													60	
	70	road													70	
	100	road onto fine slag	granulator slag		100											
E2	140		granulator slag		140											
	140		granulator slag		140											
	140		granulator slag		140											
E3	150		granulator slag		150											
	150		granulator slag		150											
	150		granulator slag		150											
	145		granulator slag		145											
	140		granulator slag		140											
	140		granulator slag		140											
E4	140		granulator slag		140											
F1	22						22									
	23						23									
	23.5						24									
	28						28									
	27						27									
	30	E of S end slag					30									
	38						38									
	41						41									
	44						44									
	42						42									
	42						42									
	39	E of N end slag					39									
	37						37									
	32						32									
	28						28									
	24	MW					24									
	27	big rock					27									
	22						22									
	21						21									
	20						20									
	19						19									
	19.5						20									
	19						19									
	19						19									
	22						22									
	22						22									
	20.5						21									
	20						20									
	20						20									
	20						20									
	21						21									
	21						21									

Radiological Field Gamma Survey Results
Rhone-Poulenc Silver Bow Plant
Readings in microRoentgens per hour (μR/hr)

Transect	Exposure (mR/hr)	Field Comment		Coarse Slag	Fine Slag	Slag North of Road	Facility Soils	Ore Storage Area	Processing Area	Mixed Use, with Slag	Reclaimed Tailings	Excavated Cell J	Excavated Cell I	Excavated Cell L	Dikes/Road	Railroad Grade
	20						20									
F2	20.5	fence corner					21									
F3	19.5						20									
	21						21									
	23						23									
	23						23									
	24						24									
	24.5						25									
	23						23									
	24						24									
	24						24									
	23						23									
	24						24									
	24						24									
	23						23									
	24						24									
	24						24									
	23						23									
	25						25									
	27						27									
	27						27									
	28						28									
	29.5						30									
	32						32									
	32						32									
	37						37									
	37						37									
	40						40									
F4	42	approach slag pile					42									
G1	30						30									
	25						25									
	40						40									
	80	drainage w/ slag fill								80						
	50									50						
	35						35									
	30						30									
G2	40						40									
	55	fine slag								55						
	60	fine slag								60						
	95	nodular ore								95						
	60	fine slag								60						
	60	fine slag								60						
G3	50	fence								50						
	23						23									
OT	36	fine slag								36						
OT	41	fine slag								41						
	22.5						23									
G4	24						24									
OT	44	nodular ore								44						
OT	45	nodular ore								45						
OT	80	nodular ore								80						
OT	100	roaster residue?														
OT	16.5	fence corner					17									
OT	26	NW corner office					26									
H1	100							100								
	100							100								
	90							90								
	105							105								
	110							110								
	115							115								
	115							115								

Radiological Field Gamma Survey Results
Rhone-Poulenc Silver Bow Plant
Readings in microRoentgens per hour (μR/hr)

Transect	Exposure (mR/hr)	Field Comment		Coarse Slag	Fine Slag	Slag North of Road	Facility Soils	Ore Storage Area	Processing Area	Mixed Use, with Slag	Reclaimed Tailings	Excavated Cell J	Excavated Cell I	Excavated Cell L	Dikes/Road	Railroad Grade
	118							118								
	108							108								
	100							100								
	95							95								
	100							100								
	105							105								
	105							105								
	105							105								
	110							110								
	100							100								
	105							105								
	120	S edge of pile						120								
OT	110	pile top						110								
	105	N edge of pile						105								
	85	road								85						
	70									70						
	60	W side of N pile								60						
	70	RR													70	
	60									60						
	55									55						
	55									55						
H2	70	gate								70						
II	70	gate at Port				70										
	92					92										
	100					100										
	105					105										
	130					130										
	122	Sample DSI				122										
	130					130										
	138					138										
	130					130										
	130					130										
	120					120										
	120					120										
	120					120										
	112					112										
	108					108										
	112					112										
	100	end of slag gravel				100										
	70	N of plant entrance								70						
	68									68						
	70									70						
	65									65						
	53	fence								53						
	40									40						
	28	E of gully					28									
	24	W of gully					24									
	21						21									
	23						23									
	24						24									
	24						24									
	25	gully					25									
	48	road E of well								48						
	48	road W of well								48						
I2	23						23									
	24						24									
	26	streamside tailings					26									
	27	streamside tailings					27									
	26	streamside tailings					26									

Radiological Field Gamma Survey Results
Rhone-Poulenc Silver Bow Plant
Readings in microRoentgens per hour (μR/hr)

Transect	Exposure (mR/hr)	Field Comment	Coarse Slag	Fine Slag	Slag North of Road	Facility Soils	Ore Storage Area	Processing Area	Mixed Use, with Slag	Reclaimed Tailings	Excavated Cell J	Excavated Cell I	Excavated Cell L	Dikes/Road	Railroad Grade
	27	streamside tailings				27									
	35	streamside tailings				35									
	60	slag							60						
J1	38	road W of well							38						
	48	road E of well							48						
	25					25									
	23					23									
	22					22									
	23					23									
	28					28									
	26					26									
	24	manhole				24									
	28.5	fence				23									
	30					30									
	63	dike							63						
	40								40						
	43								43						
	44								44						
	65	edge of slag gravel							65						
	125	slag gravel			125										
	115				115										
	125				125										
	110				110										
	125				125										
	125				125										
	128				128										
	120				120										
	125				125										
	125				125										
	132				132										
	122				122										
	115				115										
	110				110										
	105				105										
	90				90										
	80				80										
	72				72										
	70				70										
J2	65	fence			65										
K1	42	stairs bottom							42						
	40	stairs top							40						
	45	road							45						
	40	road							40						
	62	road							62						
	68	road							68						
	80	road							80						
	70	road							70						
	60	road							60						
	50	road							50						
	34	grassy bank				34									
	33					33									
	34					34									
	62	slag							62						
	100	slag							100						
	115	slag							115						
	68	slag							68						
	48	slag							48						
	35					35									
	32					32									

Radiological Field Gamma Survey Results
Rhone-Poulenc Silver Bow Plant
Readings in microRoentgens per hour (μR/hr)

Transect	Exposure (mR/hr)	Field Comment	Coarse Slag	Fine Slag	Slag North of Road	Facility Soils	Ore Storage Area	Processing Area	Mixed Use, with Slag	Reclaimed Tailings	Excavated Cell J	Excavated Cell I	Excavated Cell L	Dikes/Road	Railroad Grade
	33					33									
	31	fence				31									
	31					31									
	30					30									
	26	barbed wire fence				26									
	28					28									
	30					30									
	30	monitoring well				30									
	30					30									
	33					33									
	82	slag piles							82						
	61	slag piles							61						
	48	slag piles							48						
	28					28									
	27					27									
	30					30									
	30	base of substation				30									
	37					37									
	49	slag fill?							49						
	32					32									
	31					31									
	46								46						
	60	well road							60						
	25					25									
	27					27									
	27					27									
	28					28									
	30					30									
	34					34									
	80								80						
	33								33						
	65								65						
	34					34									
	32					32									
	32					32									
	30					30									
	32					32									
	35					35									
	35					35									
	36					36									
	36					36									
Average Exposure Rate (μR/hr)			145	140	111	28	95	46	61	69	144	113	80	114	70
Maximum (μR/hr)			170	150	138	55	125	60	115	80	150	115	95	150	105
Minimum (mR/hr)			100	100	65	17	45	25	33	50	130	110	65	60	40
Number of Samples			61	13	37	145	82	19	68	23	4	2	4	85	28
Standard Deviation (μR/hr)			16	13	20	6	15	8	17	6	9	4	12	21	19
Standard Deviation/Average ⁽¹⁾			0.11	0.09	0.18	0.23	0.16	0.18	0.27	0.09	0.07	0.03	0.15	0.19	0.27

Notes:

(1) The "standard deviation / average" ratio is used to help illustrate the range of data relative to the value of the associated mean value.

μR/hr = microRoentgens per hour

Background reported on Table 6.

Attachment B

Laboratory Results



GASTON ENGINEERING SURVEYING / SOILS TESTING

MOISTURE DENSITY RELATIONSHIP (ASTM D693)

PROJECT: Secor, Inc.
LOCATION SAMPLED: S-607 "Tailings"
MATERIAL TYPE: Pond Sediment
TESTED BY: Jon Wilkinson
EXAMINED FOR: Sieve Analysis

DATE: 12/1/97
W.O.#: 97-599
METHOD: ASTM D-698
CU.FT. MOLD: 0.333
TEST NO.: _____

TEST DATA

Water Added, ML	0	100	75			
WT. Mold & Sample, lbs	12.875	12.938	12.875	12.375		
WT. Mold, lbs	9.25	9.25	9.25	9.25		
CU. FT. of Mold	.0333	.0333	.0333	.0333		
WT. Of Wet Soils (lbs.)	3.625	3.6875	3.625	3.125		
Wet Density, PCF	108.86	110.74	108.86	93.84		

MOISTURE CONTENT, %

Can #	11	3	9	1		
Wt of Can	21.93	21.86	21.84	21.91		
WT. Wet Soil gms	115.11	85.39	130.83	104.24		
WT. Dry Soil, gms	88.83	62.95	94.88	88.96		
WT. Water, gms	26.28	22.44	35.95	15.28		
Moisture content, %	29.69	35.6	37.9	17.2		

DRY DENSITY, PCF

Dry Density, lbs/cu. ft.	84.0	81.7	78.94	80.1		

moisture.den

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GASTON ENGINEERING SURVEYING / SOILS TESTING

AGGREGATE TEST REPORT

PROJECT: Secor, Inc.
LOCATION SAMPLED: S-607 "Tailings"
MATERIAL TYPE: Pond Sediment
TESTED BY: Jon Wilkinson
EXAMINED FOR: Sieve Analysis

DATE: 12/1/97
W.O.# 97-599
METHOD: _____
TEST NO.: _____

ATTERBURG LIMITS: LL _____ PL _____ PI _____

SIEVE ANALYSIS:

Total Wt. Of sample	11.125	lbs		%
Total Wt. retained 4-mesh		lbs		%
Total Wt. passing 4-mesh		lbs		%

Before Wash 393.9

After Wash 38.78

LBW 355.12

Cum. Wt. Retained	Sieve Size	Cum. Wt. Passing	Pct. Passing	Spec.
	6"			
	3"			
	2"			
	1½"			
	1"			
	¾"			
	½"			
	⅜"			
0	4M	11.125	100%	
4.4	10M	389.5	99%	
9.46	40M	384.4	98%	
15.74	80M	378.16	96%	
36.54	200M	357.38	90.7%	

SOIL CLASSIFICATION: _____

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GASTON ENGINEERING SURVEYING / SOILS TESTING

MOISTURE DENSITY RELATIONSHIP (ASTM D693)

PROJECT: Secor, Inc.
LOCATION SAMPLED: S-609 "Background"
MATERIAL TYPE: _____
TESTED BY: Jon Wilkinson
EXAMINED FOR: Sieve Analysis

DATE: 12/3/97
W.O.#: 97-599
METHOD: ASTM D-698
CU.FT. MOLD: 0.333
TEST NO.: _____

TEST DATA

Water Added, ML	0	100	75			
WT. Mold & Sample, lbs	13.0	13.44	13.31	12.813		
WT. Mold, lbs	9.25	9.25	9.25	9.25		
CU. FT. of Mold	.0333	.0333	.0333	.0333		
WT. Of Wet Soils (lbs.)	3.75	4.19	4.06	3.56		
Wet Density, PCF	112.61	125.8	122.0	107.0		

MOISTURE CONTENT, %

Can #	17	2	9	7		
Wt of Can	21.7	21.74	21.85	21.34		
WT. Wet Soil gms	115.65	123.69	132.7	125.34		
WT. Dry Soil, gms	105.48	108.75	112.67	119.15		
WT. Water, gms	10.17	14.94	20.03	6.19		
Moisture content, %	9.6	13.7	17.8	5.2		

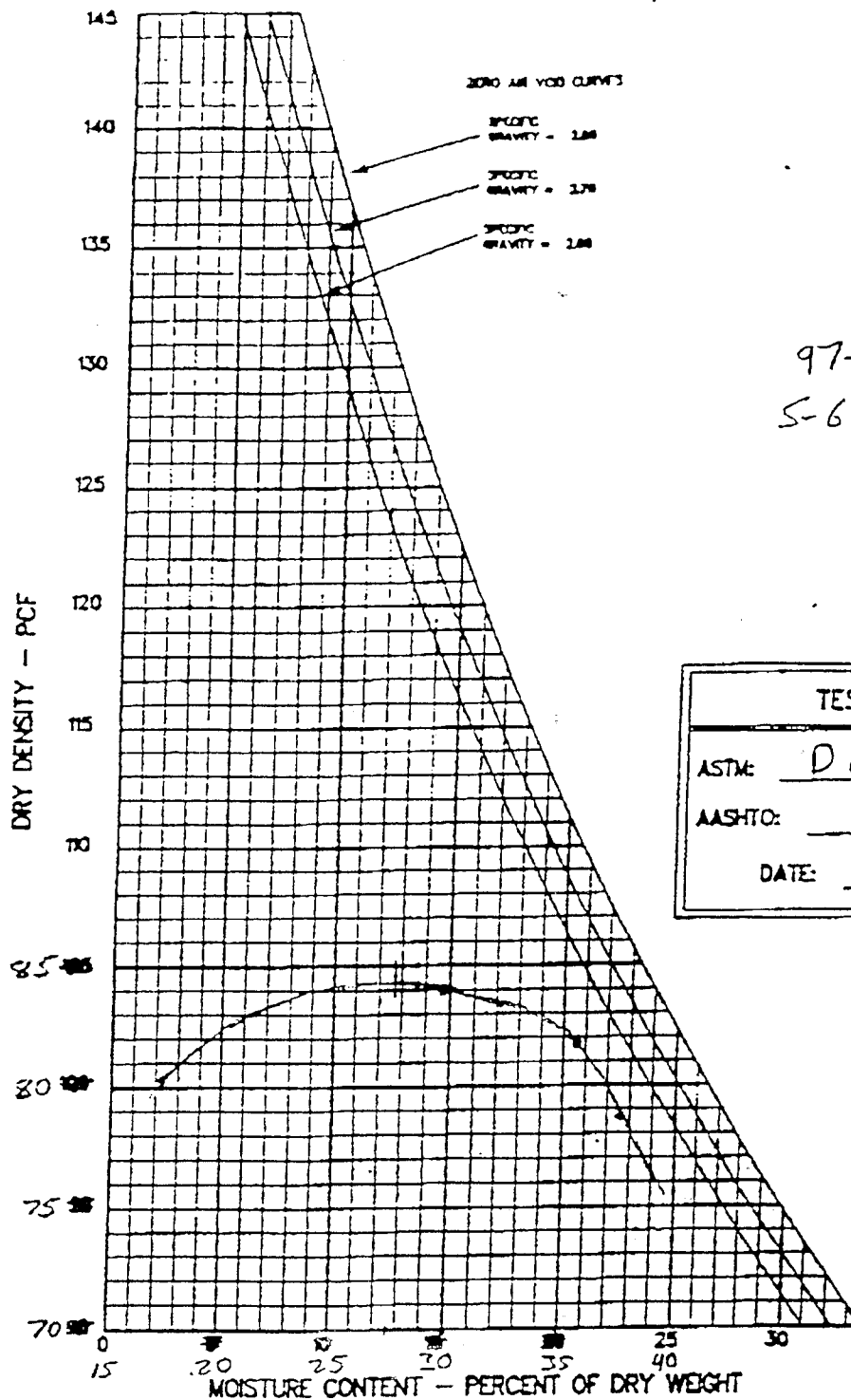
DRY DENSITY, PCF

Dry Density, lbs/cu. ft.	102.7	110.6	103.6	101.7		

moisture.den

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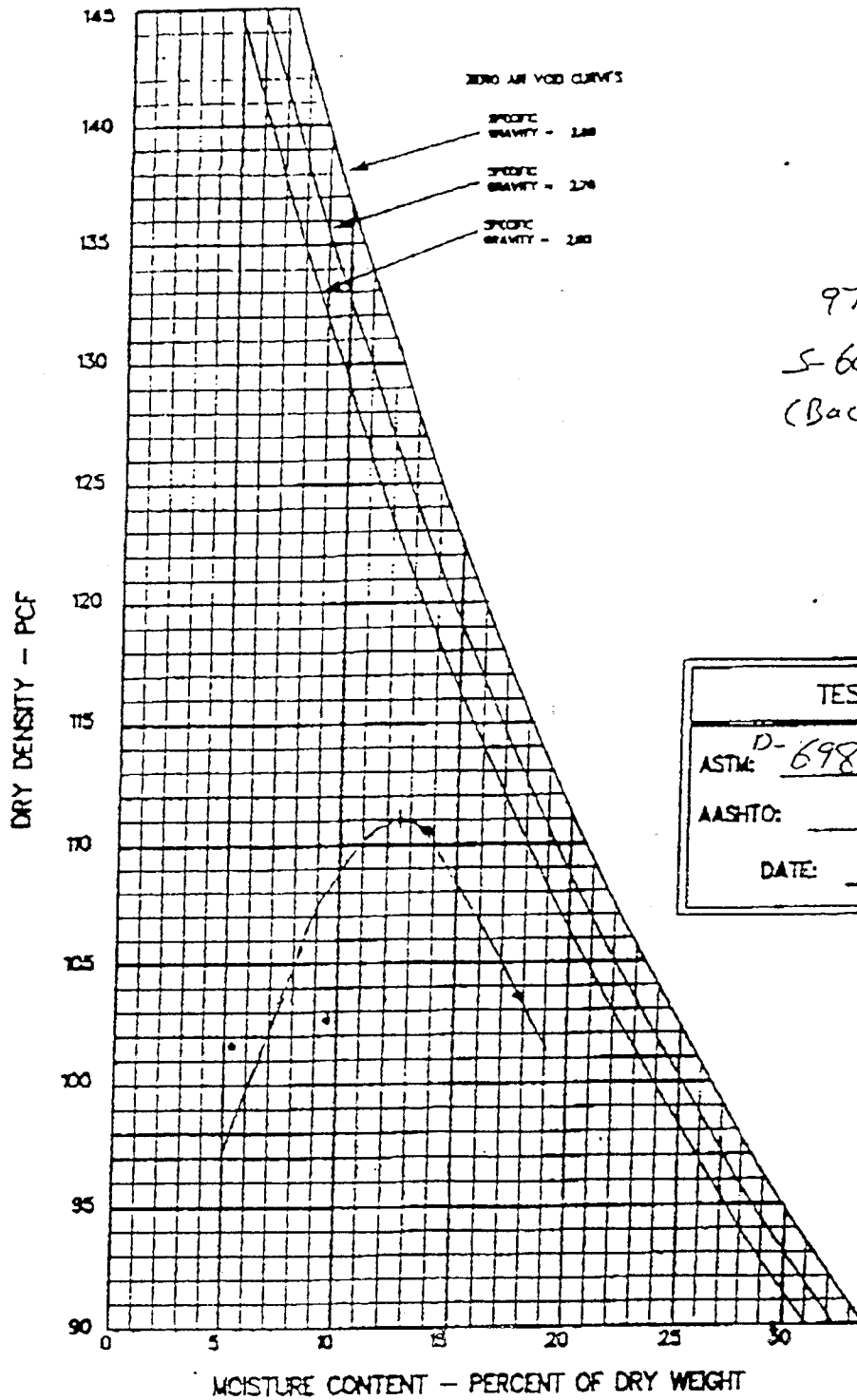
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97-599
S-607 "Tailings"
(Pond Sediment)

TEST METHOD	
ASTM:	D 698
AASHTO:	
DATE:	12/3/97

MAXIMUM DRY DENSITY: 84.2 pcf		OPTIMUM MOISTURE CONTENT: 27.5 %	
SOIL TYPE:		GRAVEL: %	LIQUID LIMIT:
SAMPLE NO.:		SAND: %	PLASTICITY INDEX:
LOCATION:		SILT AND CLAY (-200): %	
BORING NO.:		DEPTH:	
MOISTURE-DENSITY RELATIONSHIPS			FIG.



97-599
S-609
(Background)

TEST METHOD	
ASTM:	D-698
AASHTO:	
DATE:	12/3/97

MAXIMUM DRY DENSITY: 111 pcf		OPTIMUM MOISTURE CONTENT: 12.5 %	
SOIL TYPE:		GRAVEL: %	LIQUID LIMIT:
SAMPLE NO.:		SAND: %	PLASTICITY INDEX:
		SILT AND CLAY(-200): %	
LOCATION:		BORING NO.:	DEPTH:
MOISTURE-DENSITY RELATIONSHIPS			FIG.

SECOR MATERIAL TESTING SUMMARY

1. **Coarse Slag**
S-605

S.G. = 2.16
Unit Weight = 100.4 lb/CF

$n = 0.4$

2. **Fine Slag**
S-606

S.G. = 2.52
Unit Weight = 101.4 lb/CF

3. **Tailings (Pond Sediments)**
S-607

S.G. = 2.65
Unit Weight = 77.3 lb/CF

Proctor: Max. Density = 84.2 lb/CF
Opt. Moisture = 27.5%

% Passing - 200 sieve = 90.7%

4. **Roaster**
S-608

S.G. = 1.14
Unit Weight = 42.7 lb/CF

5. **Background**
S-609

S.G. = 2.64
Unit Weight = 86.1 lb/CF

Proctor: Max. Density = 111 lb/CF
Opt. Moisture = 12.5%

% Passing - 200 sieve = 48.7 %

Carol Lee-Roark
SECOR
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Bozeman, MT 59715

Soil Analytical Lab
Plant & Soil Science Dept.
Montana State University
Bozeman, Montana 59715

FY 1997 Recieved 11/26/97 Sent 12/11/97

Sample Number	Client's ID Number	% H2O 15 Bar	
S852	Smpl BG	14.0	(Background)
S853	Smpl ET	6.4	(TAHHS)

Attachment C

RESRAD Output

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AAAAAAAAAAAAAAAAAAAA

Effective Dose Equivalent and Cancer Risk
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Calculation Results with Base Data	
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Amount of Intake Quantities	7
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Total Cancer Risk Components (from Risk Conversion Factor)	9
Total Cancer Risk Components (from Slope Factors)	10

Dose and Risk Conversion Factor (and Related) Parameter Summary

Menu	Parameter	Current Value	Default	Pa

	Cancer risk/dose conversion factor (risk/mrem)	7.600E-07	7.600E-07	RDC
DCF1	Groundshine, surface DCF's, (mrem/yr)/(pCi/cm**2):			
DCF1	Ra-226+D	1.940E+00	1.940E+00	DCF
DCF1				
DCF1	Groundshine, volume DCF's, (mrem/yr)/(pCi/cm**3):			
DCF1	Ra-226+D, soil density = 1.6 g/cm**3	1.120E+01	1.120E+01	DCF
DCF1				
DCF2	Dose conversion factors for dust inhalation, mrem/pCi:			
DCF2	Ra-226+D	8.600E-03	8.600E-03	DCF
DCF2				
DCF3	Dose conversion factors for ingestion, mrem/pCi:			
DCF3	Ra-226+D	1.330E-03	1.330E-03	DCF
DCF3				
DCF4	Air immersion DCF's, (mrem/yr)/(pCi/m**3):			
DCF4	Ra-226+D	1.040E-02	1.040E-02	DCF
DCF4				
Sf-1	Groundshine, surface SF's, 1/yr per (pCi/cm**2):			
Sf-1	Ra-226+D	1.470E-06	1.470E-06	SLP
Sf-1				
Sf-1	Groundshine, volume SF's, 1/yr per (pCi/g):			
Sf-1	Ra-226+D	6.700E-06	6.700E-06	SLP
Sf-1				
Sf-2	Inhalation, slope factors, 1/(pCi):			
Sf-2	Ra-226+D	2.700E-09	2.700E-09	SLP
Sf-2				
Sf-3	Ingestion, slope factors, 1/(pCi):			
Sf-3	Ra-226+D	3.000E-10	3.000E-10	SLP
Sf-3				
Sf-4	Air immersion, slope factors, 1/yr per (pCi/m**3):			
Sf-4	Ra-226+D	7.900E-09	7.900E-09	SLP
Sf-4				
SfRn	Radon inhalation slope factors, 1/(pCi):			
SfRn	Rn-222	1.800E-12	1.800E-12	SLP
SfRn	Po-218	3.700E-12	3.700E-12	SLP
SfRn	Pb-214	6.200E-12	6.200E-12	SLP
SfRn	Bi-214	1.500E-11	1.500E-11	SLP
SfRn	Rn-220	1.900E-13	1.900E-13	SLP
SfRn	Po-216	3.000E-15	3.000E-15	SLP
SfRn	Pb-212	3.900E-11	3.900E-11	SLP

Dose and Risk Conversion Factor (and Related) Parameter Summary (continued)

Menu	Parameter	Current Value	Default	Pa
SfRn	Bi-212	3.700E-11	3.700E-11	SLP

Note: Radionuclides are Class A human carcinogens.

- (g) Dose conversion factors are taken from EPA FGR nos. 11 & 12.
Volume, inhalation and ingestion slope factors are taken from Heast (March 1994). exco
Air immersion and surface slope factors are taken from EPA 402-R-93-076. except where
- (a) Values are calculated using DCF and risk coefficient ($7.60e-4$ cancer incidence risk/re
(b) Values taken from EPA 402-R-93-076 (June 1994).
(c) Value taken from individual radionuclides given in Heast (not from Pu-241+D).
(d) DCF value was zero, slope factor was also assumed to be zero.
(e) Slope factor from EPA report was unreasonably small, calculated from DCF and risk coef
(f) DCF value increased by 50% to account for dermal absorption of H-3 in vapor form.

Site-Specific Parameter Summary

Menu	Parameter	User Input	Default	Used by RES (If different)
R011	Surface concentration in soil (pCi/m**2): Ra-226	0.000E+00	0.000E+00	
R011	Volume concentration in soil (pCi/g): Ra-226	3.800E+01	0.000E+00	
R012	Indoor air concentration (pCi/m**3): Ra-226	0.000E+00	0.000E+00	
R012	Outdoor air concentration (pCi/m**3): Ra-226	0.000E+00	0.000E+00	
R013	Concentration in plant (pCi/kg): Ra-226	not used	0.000E+00	
R013	Concentration in meat (pCi/kg): Ra-226	not used	0.000E+00	
R013	Concentration in milk (pCi/L): Ra-226	not used	0.000E+00	
R014	Concentration in fish (pCi/kg): Ra-226	not used	0.000E+00	
R014	Concentration in shell fish (pCi/kg): Ra-226	not used	0.000E+00	
R015	Concentration in drinking water (pCi/L): Ra-226	not used	0.000E+00	
R015	Concentration in pond water (pCi/L): Ra-226	not used	0.000E+00	
R016	Indoor Radon-222 concentration (pCi/m**3)	not used	0.000E+00	
R016	Outdoor Radon-222 concentration (pCi/m**3)	not used	0.000E+00	
R016	Indoor Radon-220 concentration (pCi/m**3)	not used	0.000E+00	
R016	Outdoor Radon-220 concentration (pCi/m**3)	not used	0.000E+00	
R016	Equilibrium fraction of Radon-222 daughters	not used	5.000E-01	
R016	Radon-222 daughter concentrations (pCi/m**3): Po-218, indoors	not used	0.000E+00	0.0
R016	Po-218, outdoors	not used	0.000E+00	0.0
R016	Pb-214, indoors	not used	0.000E+00	0.0
R016	Pb-214, outdoors	not used	0.000E+00	0.0
R016	Bi-214, indoors	not used	0.000E+00	0.0
R016	Bi-214, outdoors	not used	0.000E+00	0.0
R016	Equilibrium fraction of Radon-220 daughters	not used	1.000E+00	

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RKS (If different)
Radon-220 daughter concentrations (pCi/m**3):				
R016	Po-216, indoors	not used	0.000E+00	0.0
R016	Po-216, outdoors	not used	0.000E+00	0.0
R016	Pb-212, indoors	not used	0.000E+00	0.0
R016	Pb-212, outdoors	not used	0.000E+00	0.0
R016	Bi-212, indoors	not used	0.000E+00	0.0
R016	Bi-212, outdoors	not used	0.000E+00	0.0
Density of soil (pCi/g)				
B011	Thickness of contaminated soil (m)	8.000E+00	1.000E+00	.
B011	Organic carbon content of soil	not used	2.000E-01	.
Fruits, vegetables, and grain consumption (kg/d)				
B012	Meat and poultry consumption (kg/d)	not used	5.000E-01	.
B012	Milk consumption (L/d)	not used	2.500E-01	.
B012	Fish consumption (kg/d)	not used	1.700E-01	.
B012	Other seafood consumption (kg/d)	not used	1.500E-02	.
B012	Drinking water intake (L/d)	not used	2.500E-03	.
B012	Incidental water intake (swimming) (L/d)	not used	1.400E+00	.
B012	Soil ingestion (child) (g/d)	not used	1.300E-01	.
B012	Soil ingestion (adult) (g/d)	not used	2.000E-01	.
Inhalation rate indoors (m**3/d)				
B013	Inhalation rate outdoors (m**3/d)	2.000E+01	2.000E+01	.
B013	Time fraction outdoors	2.000E+01	2.000E+01	.
B013	Shielding factor for groundshine	3.300E-01	3.300E-01	.
B013	Exposure duration for child (yr)	7.000E-01	7.000E-01	.
B013	Total exposure duration (yr)	not used	6.000E+00	.
B013	Average body weight for child (kg)	1.000E+00	3.000E+01	.
B013	Average body weight for adult (kg)	not used	1.500E+01	.
B013	Average life time (yr)	not used	7.000E+01	.
Contamination fractions:				
B014	ingested plant	not used	5.000E-01	.
B014	ingested meat	not used	1.000E+00	.
B014	ingested milk	not used	1.000E+00	.
B014	ingested aquatic food	not used	5.000E-01	.
B014	ingested drinking water	not used	1.000E+00	.
B014	ingested soil	not used	1.000E+00	.
B014	incidentally (swimming) ingested water	not used	1.000E+00	.
B014	dermal absorption from swimming	not used	1.000E+00	.
B014	dermal absorption from shower water	not used	1.000E+00	.
B014	dermal absorption from soil contact	not used	1.000E+00	.
Exposure frequencies (d/yr):				
B015	inhalation and external radiation	3.000E+01	3.500E+02	.
B015	plant ingestion	not used	3.500E+02	.
B015	meat ingestion	not used	3.500E+02	.
B015	milk ingestion	not used	3.500E+02	.
B015	aquatic food ingestion	not used	3.500E+02	.
B015	drinking water ingestion	not used	3.500E+02	.

Summary : RESRAD-BASELINE Sample Data File

File: SLAG1.BSE

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RES (If different)
B015	soil ingestion	not used	3.500E+02	.
B015	incidental (swimming) water ingestion	not used	7.000E+00	.
B015	dermal absorption from swimming	not used	7.000E+00	.
B015	dermal absorption from shower water	not used	3.500E+02	.
B015	dermal absorption from soil contact	not used	3.500E+02	.
B016	Dermal absorption parameters:			
B016	skin surface area for water contact (cm**2)	not used	2.000E+04	.
B016	skin surface area for soil contact (cm**2)	not used	5.000E+03	.
B016	soil to skin adherence (mg/cm**2-event)	not used	2.000E-01	.
B016	duration for showering (min/event)	not used	1.000E+01	.
B016	duration for swimming (hr/event)	not used	5.000E-01	.
B016	duration for soil contact (hr/event)	not used	1.200E+01	.

Summary of Pathway Selections

Pathway	User Selection
1 -- groundshine (R)	active (R)
2 -- inhalation (B)	active (R)
3 -- plant ingestion (B)	suppressed
4 -- meat ingestion (B)	suppressed
5 -- milk ingestion (B)	suppressed
6 -- aquatic foods ingestion (B)	suppressed
7 -- drinking water ingestion (B)	suppressed
8 -- soil ingestion (B)	suppressed
9 -- radon (R)	suppressed
10 -- incidental water ingestion (B)	suppressed
11 -- air immersion (R)	suppressed
12 -- dermal absorption from swimming (C)	suppressed
13 -- dermal absorption from shower water (C)	suppressed
14 -- dermal absorption soil contact (C)	suppressed

Note: (B), (C) and (R) under pathway denotes the applicability for both chemical and radiological, chemical, or radiological risk assessment, respectively.

(B), (C) and (R) under user selection denotes user's choice to conduct both chemical and radiological, chemical, or radiological risk assessment, respectively.

<<<< Calculation Results with Base Data >>>>

Amount of Intake Quantities INTX(i,p) for Individual Radionuclides
 and Pathways (p) as pCi/yr

	Inhalation	Plant	Meat	Milk	Fish	Drinking Water	Soil	Radon
Radio- Nuclide	AAAAA pCi/yr	AAAAA pCi/yr	AAAAA pCi/yr	AAAAA pCi/yr	AAAAA pCi/yr	AAAAA pCi/yr	AAAAA pCi/yr	AAAAA pCi/yr
AAAAA	AAAAA	AAAAA	AAAAA	AAAAA	AAAAA	AAAAA	AAAAA	AAAAA
Ra-226	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii

Note: * Sum of all ingestion pathways.

<<<< Calculation Results with Base Data >>>>

Total Dose Components DOSE(i,p) for Individual Radionuclides (i) and Pa
 as mrem/yr and Fraction of Total Dose

	Ground		Inhalation		Plant		Meat		Milk	
Radio-	AAAAA		AAAAA		AAAAA		AAAAA		AAAAA	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
AAAAA	AAAAA	AAAAA	AAAAA	AAAAA	AAAAA	AAAAA	AAAAA	AAAAA	AAAAA	AAAAA
Ra-226	2.795E+01	1.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii
Total	2.795E+01	1.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000

	Drinking Water		Soil		Radon		Incidental Water		Air Immersion	
Radio-	AAAAA		AAAAA		AAAAA		AAAAA		AAAAA	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
AAAAA	AAAAA	AAAAA	AAAAA	AAAAA	AAAAA	AAAAA	AAAAA	AAAAA	AAAAA	AAAAA
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000

Note: The dose for Rn-222 and/or Rn-220 includes contribution from decay daughters (Po-, Pb-, an

<<<< Calculation Results with Base Data >>>>

Total Cancer Risk Components RISK1(i,p) (from Risk/Dose Conversion Fac
 for Individual Radionuclides (i) and Pathways (p) and Fraction of Total
 Risk/Dose Conversion Factor = 7.600E-07 risk/mrem Total Exposure Duration = 1

	Ground		Inhalation		Plant		Meat		Milk	
Radio-	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
Nuclide	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
Ra-226	2.124E-05	1.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii
Total	2.124E-05	1.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000

	Drinking		Soil		Radon		Incidental		Air	
	Water						Water		Immersion	
Radio-	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
Nuclide	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000

Note: The risk for Rn-222 and/or Rn-220 includes contribution from decay daughters (Po-, Pb-, an

<<<< Calculation Results with Base Data >>>>

Total Cancer Risk Components RISK2(1,p) (from Slope Factors) for
 Individual Radionuclides (1) and Pathways (p) and Fraction of Total
 Total Exposure Duration = 1.00E+00 years

	Ground		Inhalation		Plant		Meat		Milk	
Radio-	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
Nuclide	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
AAAAAA	AAAAAA	AAAAAA	AAAAAA	AAAAAA	AAAAAA	AAAAAA	AAAAAA	AAAAAA	AAAAAA	AAAAAA
Ra-226	1.672E-05	1.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii
Total	1.672E-05	1.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000

	Drinking Water		Soil		Radon		Incidental Water		Air Immersion	
Radio-	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
Nuclide	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
AAAAAA	AAAAAA	AAAAAA	AAAAAA	AAAAAA	AAAAAA	AAAAAA	AAAAAA	AAAAAA	AAAAAA	AAAAAA
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii	iiiiiii
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000

Note: The risk for Rn-222 and/or Rn-220 includes contribution from decay daughters (Po-, Pb-, an

Program execution time = 0.94 seconds

Attachment D

RADON Output

Title: Radon Emission Results from RADON computer
Model for the Rhone-Poulenc Silver Bow Plant

Date: 01/12/98
By: MJZ

Purpose:

To model radon emission from source materials at the Rhone-Poulenc Silver Bow Plant Site and to estimate depth of required cover material to limit radon emissions to Environmental Protection Agency (EPA) standards, at the site.

Methods:

The Nuclear Regulatory Commission computer program RADON (version 3.64) was used to calculate radon emissions from site materials including; Slag (coarse and fine combined), Ore Area Soils, Tailings, Roaster Residue, and Background Soils. A variety of radiological and geotechnical data from laboratory analyses of samples collected at the site were required as inputs for the radon model. These data include; Radium activity, Long-term moisture content, Density, Specific Gravity, and Porosity. The values of these are listed in Table 1. Unit conversions and porosity calculations, for use in the Radon model, are also presented.

To estimate cover thickness required at the site to control radon emissions, source materials were theoretically placed in a repository and layered based on individual radon flux rates. The material with the highest flux rate (slag) was placed on the bottom. Ore area soil was placed as the next layer followed by tailings and then cover material (background soils). Roaster Residue showed similar radon flux rates as background soils and was not used in this model. The total radon flux rate from the cover layer due to this layering was set to EPA standards and the cover layer thickness required to achieve this rate was calculated using the computer program.

Results:

Output for each of the source media from the RADON program are presented in this report and the calculated radon flux rates are listed in Table 1. Based on the theoretical layering of source materials described above, the depth of soil cover needed to limit radon emissions to 20 pCi/m²-sec as required by the EPA, using soils from the surrounding area, is approximately one foot.

Table 1

**Current Site Conditions Based On
Radiological and Geotechnical Analysis of Field Samples
Rhone-Poulenc Silver Bow Plant**

Source Media	Radon Flux ⁽¹⁾ (pCi/sq.m./sec)	Average Radium Activity (pCi/g)	Moisture Content (%)	Density (g/cu.cm)	Specific Gravity	Porosity
Background Soils	1.49	1.25	14	1.38	2.64	0.48
Tailings	38.14	27.25	6.4	1.2	2.65	0.53
Ore	56.96	26.75	NA	NA	NA	NA
Fine Slag	80.91	38	NA	1.6	2.52	0.35
Course Slag	83.04	39	NA	1.6	2.16	0.25
Roaster Residue	1.27	1.4	NA	0.68	1.14	0.4

Notes:

(1) Flux calculated using RADON model based on geotechnical and radiological analysis of field samples.

pCi/sq.m./sec = picocuries per square meter per second

pCi/g = picocuries per gram

g/cu.cm = grams per cubic centimeter

SECOR

JOB NAME Rhone - Poulenc
 JOB NO. 7H 002-001-01
 CALCULATED BY MJZ DATE 12/23/97
 CHECKED BY _____ DATE _____
 SHEET 1 OF 2

Rhone - Poulenc

Input Parameters for Radon Model:

Density: (Lab)

$$\text{Course Slag} : 100.4 \frac{\text{lb}}{\text{ft}^3} \times \frac{453.59 \text{ g}}{1 \text{ lb}} \times \frac{1 \text{ ft}^3}{28,316.8 \text{ cm}^3} = \boxed{1.6 \text{ g/cm}^3} \quad (1)$$

$$\text{Fine Slag} : 101.4 \frac{\text{lb}}{\text{ft}^3} \times \frac{453.59 \text{ g}}{1 \text{ lb}} \times \frac{1 \text{ ft}^3}{28,316.8 \text{ cm}^3} = \boxed{1.6 \text{ g/cm}^3} \quad (1)$$

$$\text{Tailings} : \frac{77.3 \text{ lb}}{\text{ft}^3} \times \frac{453.59 \text{ g}}{1 \text{ lb}} \times \frac{1 \text{ ft}^3}{28,316.8 \text{ cm}^3} = \boxed{1.2 \text{ g/cm}^3}$$

$$\text{Background Soils} : \frac{86.1 \text{ lb}}{\text{ft}^3} \times \frac{453.59 \text{ g}}{1 \text{ lb}} \times \frac{1 \text{ ft}^3}{28,316.8 \text{ cm}^3} = \boxed{1.38 \text{ g/cm}^3}$$

Moisture Content: (Lab)

$$\text{Tailings} : \boxed{6.4 \%} \quad \text{combined Slag} : 0 \% (2)$$

$$\text{Background Soils} : \boxed{14 \%} \quad \text{ORE} : 0 \% (2)$$

Porosity: n $e = \frac{G_s \gamma_w}{\gamma_d} - 1$

$$n = \frac{e}{1+e}$$

G_s = Specific gravity of source

γ_d = density source

γ_w = density water

n = porosity

e = void ratio

$$\text{Course Slag} \quad e_{cs} = \frac{(2.16)(62.4)}{100.4} - 1 = .34$$

$$n_{cs} = \frac{e}{1+e} = \frac{.34}{1.34} = \boxed{0.25}$$

$$\text{Fine Slag} \quad e_{fs} = \frac{(2.52)(62.4)}{101.4} - 1 = .55$$

$$n_{fs} = \frac{.55}{1.55} = \boxed{0.35}$$

$$\text{Tailings} \quad e_t = \frac{(2.65)(62.4)}{77.3} - 1 = 1.14$$

$$n_t = \frac{1.14}{2.14} = \boxed{0.53}$$

SECOR

JOB NAME Rhone-Poulenc
JOB NO. 7H 002-001-01
CALCULATED BY MJZ DATE 12/23/97
CHECKED BY _____ DATE _____
SHEET 2 OF 2

Porosity: n

Background soils:

$$e = \frac{(2.64)(62.4)}{86.1} - 1 = 0.913$$

$$n_s = \frac{0.913}{1.913} = \boxed{0.48}$$

Radium Activity: (Average values from independent sample analysis for each source material)

- Slag (course + fine) - 38.6 picocuries/gram
- Tailings - 27.25 picocuries/gram
- Ore - 26.75 pC/g
- Background Soils (3) - 1.25 pC/g

NOTES:

- (1) Radium activity values are essentially identical for course and fine Slag, therefore these two materials are combined into one source. Average density and porosity input parameter values are used in the RADON model.
- (2) No moisture content available from laboratory analysis of samples, therefore assumed as 0% for model.
- (3) Background soils are used as cover materials in the RADON model.

Output from the RADON program
for Source Materials
at the Rhone-Poulenc Silver Bow Plant Site

Roaster Residue

RADON V1.2

CALCULATION OF RADON FLUX ATTENUATION BY EARTHEN

URANIUM MILL TAILINGS COVERS

U.S. NUCLEAR REGULATORY COMMISSION

REGULATORY GUIDE 3.64, June 1989

TITAN ENVIRONMENTAL CORPORATION

RADON DECAY CONSTANT .0000021 per sec.
RADON WATER/AIR PARTITION COEFFICIENT .26
SPECIFIC GRAVITY OF TAILINGS 2.65
NUMBER OF LAYERS: 2
RADON FLUX LIMIT: 20 pCi m⁻² s⁻¹
LAYER THICKNESS NOT OPTIMIZED
SURFACE RADON CONCENTRATION 0 pCi/l
RADON FLUX INTO LAYER 1 0 pCi m⁻² s⁻¹
SURFACE FLUX PRECISION .01 (pCi m⁻² s⁻¹)

LAYER 1 roaster residue

THICKNESS 500 cm
POROSITY: .4
MEASURED MASS DENSITY .68 gm/cc
MEASURED RADIUM ACTIVITY 1.4 pCi/gm
DEFAULT LAYER EMANATION COEFFICIENT .3499999940395355
CALCULATED SOURCE TERM CONCENTRATION
1.749299970209598D-06 pCi cm⁻³ s⁻¹
WEIGHT % MOISTURE 0 %
MOISTURE SATURATION FRACTION 0
CALCULATED DIFFUSION COEFFICIENT 7.000000029802322D-02
cm² s⁻¹

LAYER 2 residue

THICKNESS 200 cm
POROSITY: .4
MEASURED MASS DENSITY .68 gm/cc
MEASURED RADIUM ACTIVITY 1.4 pCi/gm
DEFAULT LAYER EMANATION COEFFICIENT .3499999940395355

Roaster Residue

CALCULATED SOURCE TERM CONCENTRATION

1.749299970209598D-06 pCi cm⁻³ s⁻¹

WEIGHT % MOISTURE 0 %

MOISTURE SATURATION FRACTION 0

CALCULATED DIFFUSION COEFFICIENT 7.000000029802322D-02
cm² s⁻¹

N F01 CN1 ICOST CRITJ ACC
2 0 0 0 20 0

LAYER	DX	D	P	Q	XMS	RHO
1	5.000D+02	7.000D-02	4.000D-01	1.749D-06	0.000D+00	0.680
2	2.000D+02	7.000D-02	4.000D-01	1.749D-06	0.000D+00	0.680

BARE SOURCE FLUX FROM LAYER 1: 1.267D+00 pCi m⁻² s⁻¹

RESULTS OF DIFFUSION CALCULATIONS:

LAYER THICKNESS EXIT FLUX EXIT CONC.

(cm) (pCi m⁻² s⁻¹) (pCi/l)
1 5.000D+02 4.252D-01 5.534D+02

2 2.000D+02 1.276D+00 0.000D+00

Background Soils

RADON V1.2

CALCULATION OF RADON FLUX ATTENUATION BY EARTHEN
URANIUM MILL TAILINGS COVERS
U.S. NUCLEAR REGULATORY COMMISSION
REGULATORY GUIDE 3.64, June 1989

TITAN ENVIRONMENTAL CORPORATION

RADON DECAY CONSTANT .0000021 per sec.
RADON WATER/AIR PARTITION COEFFICIENT .26
SPECIFIC GRAVITY OF TAILINGS 2.65
NUMBER OF LAYERS: 2
RADON FLUX LIMIT: 20 pCi m⁻² s⁻¹
LAYER THICKNESS NOT OPTIMIZED
SURFACE RADON CONCENTRATION 0 pCi/l
RADON FLUX INTO LAYER 1 0 pCi m⁻² s⁻¹
SURFACE FLUX PRECISION .01 (pCi m⁻² s⁻¹)

LAYER 1 background soils

THICKNESS 500 cm
POROSITY: .48
MEASURED MASS DENSITY 1.38 gm/cc
MEASURED RADIUM ACTIVITY 1.25 pCi/gm
DEFAULT LAYER EMANATION COEFFICIENT .3499999940395355
CALCULATED SOURCE TERM CONCENTRATION
2.641406205017119D-06 pCi cm⁻³ s⁻¹
WEIGHT % MOISTURE 14 %
MOISTURE SATURATION FRACTION .4024999910034239
CALCULATED DIFFUSION COEFFICIENT 2.905060093833234D-02
cm² s⁻¹

LAYER 2 bkg soils

THICKNESS 200 cm
POROSITY: .48
MEASURED MASS DENSITY 1.38 gm/cc
MEASURED RADIUM ACTIVITY 1.25 pCi/gm
DEFAULT LAYER EMANATION COEFFICIENT .3499999940395355

Background Soils

CALCULATED SOURCE TERM CONCENTRATION

2.641406205017119D-06 pCi cm⁻³ s⁻¹

WEIGHT % MOISTURE 14 %

MOISTURE SATURATION FRACTION .4024999910034239

CALCULATED DIFFUSION COEFFICIENT 2.905060093833234D-02
cm² s⁻¹

N F01 CN1 ICOST CRITJ ACC

2 0 0 0 20 0

LAYER DX D P Q XMS RHO

1 5.000D+02 2.905D-02 4.800D-01 2.641D-06 4.025D-01 1.380

2 2.000D+02 2.905D-02 4.800D-01 2.641D-06 4.025D-01 1.380

BARE SOURCE FLUX FROM LAYER 1: 1.491D+00 pCi m⁻² s⁻¹

RESULTS OF DIFFUSION CALCULATIONS:

LAYER THICKNESS EXIT FLUX EXIT CONC.

(cm) (pCi m⁻² s⁻¹) (pCi/l)

1 5.000D+02 2.722D-01 1.028D+03

2 2.000D+02 1.491D+00 0.000D+00

Tailings

RADON V1.2
CALCULATION OF RADON FLUX ATTENUATION BY EARTHEN
URANIUM MILL TAILINGS COVERS
U.S. NUCLEAR REGULATORY COMMISSION
REGULATORY GUIDE 3.64, June 1989

TITAN ENVIRONMENTAL CORPORATION

RADON DECAY CONSTANT .0000021 per sec.
RADON WATER/AIR PARTITION COEFFICIENT .26
SPECIFIC GRAVITY OF TAILINGS 2.65
NUMBER OF LAYERS: 2
RADON FLUX LIMIT: 20 $\text{pCi m}^{-2} \text{s}^{-1}$
LAYER THICKNESS NOT OPTIMIZED
SURFACE RADON CONCENTRATION 0 pCi/l
RADON FLUX INTO LAYER 1 0 $\text{pCi m}^{-2} \text{s}^{-1}$
SURFACE FLUX PRECISION .01 ($\text{pCi m}^{-2} \text{s}^{-1}$)

LAYER 1 tailings

THICKNESS 500 cm
POROSITY: .53
MEASURED MASS DENSITY 1.2 gm/cc
MEASURED RADIUM ACTIVITY 27.25 pCi/gm
DEFAULT LAYER EMANATION COEFFICIENT .3499999940395355
CALCULATED SOURCE TERM CONCENTRATION
4.53481124352734D-05 $\text{pCi cm}^{-3} \text{s}^{-1}$
WEIGHT % MOISTURE 6.4 %
MOISTURE SATURATION FRACTION .1449056571384646
CALCULATED DIFFUSION COEFFICIENT 5.329364293389862D-02
 $\text{cm}^2 \text{s}^{-1}$

LAYER 2 tailings

THICKNESS 200 cm
POROSITY: .53
MEASURED MASS DENSITY 1.2 gm/cc
MEASURED RADIUM ACTIVITY 27.25 pCi/gm
DEFAULT LAYER EMANATION COEFFICIENT .3499999940395355

Tailings

CALCULATED SOURCE TERM CONCENTRATION

4.53481124352734D-05 pCi cm⁻³ s⁻¹

WEIGHT % MOISTURE 6.4 %

MOISTURE SATURATION FRACTION .1449056571384646

CALCULATED DIFFUSION COEFFICIENT 5.329364293389862D-02
cm² s⁻¹

Tailings

N	F01	CN1	ICOST	CRITJ	ACC	
2	0	0	0	20	0	
LAYER	DX	D	P	Q	XMS	RHO
1	5.000D+02	5.329D-02	5.300D-01	4.535D-05	1.449D-01	1.200
2	2.000D+02	5.329D-02	5.300D-01	4.535D-05	1.449D-01	1.200

BARE SOURCE FLUX FROM LAYER 1: 3.814D+01 pCi m⁻² s⁻¹

RESULTS OF DIFFUSION CALCULATIONS:

LAYER	THICKNESS (cm)	EXIT FLUX (pCi m ⁻² s ⁻¹)	EXIT CONC. (pCi/l)
1	5.000D+02	1.089D+01	1.543D+04
2	2.000D+02	3.828D+01	0.000D+00

ORe

RADON V1.2
CALCULATION OF RADON FLUX ATTENUATION BY EARTHEN
URANIUM MILL TAILINGS COVERS
U.S. NUCLEAR REGULATORY COMMISSION
REGULATORY GUIDE 3.64, June 1989

TITAN ENVIRONMENTAL CORPORATION

RADON DECAY CONSTANT .0000021 per sec.
RADON WATER/AIR PARTITION COEFFICIENT .26
SPECIFIC GRAVITY OF TAILINGS 2.65
NUMBER OF LAYERS: 2
RADON FLUX LIMIT: 20 pCi m⁻² s⁻¹
LAYER THICKNESS NOT OPTIMIZED
SURFACE RADON CONCENTRATION 0 pCi/l
RADON FLUX INTO LAYER 1 0 pCi m⁻² s⁻¹
SURFACE FLUX PRECISION .01 (pCi m⁻² s⁻¹)

LAYER 1 ore

THICKNESS 500 cm
POROSITY: .3
MEASURED MASS DENSITY 1.6 gm/cc
MEASURED RADIUM ACTIVITY 26.75 pCi/gm
DEFAULT LAYER EMANATION COEFFICIENT .3499999940395355
CALCULATED SOURCE TERM CONCENTRATION
1.048599982142448D-04 pCi cm⁻³ s⁻¹
WEIGHT % MOISTURE 0 %
MOISTURE SATURATION FRACTION 0
CALCULATED DIFFUSION COEFFICIENT 7.000000029802322D-02
cm² s⁻¹

LAYER 2 ore

THICKNESS 200 cm
POROSITY: .3
MEASURED MASS DENSITY 1.6 gm/cc
MEASURED RADIUM ACTIVITY 26.75 pCi/gm
DEFAULT LAYER EMANATION COEFFICIENT .3499999940395355

ore

CALCULATED SOURCE TERM CONCENTRATION

1.048599982142448D-04 pCi cm⁻³ s⁻¹

WEIGHT % MOISTURE 0 %

MOISTURE SATURATION FRACTION 0

CALCULATED DIFFUSION COEFFICIENT 7.0000000029802322D-02
cm² s⁻¹

022

N	F01	CN1	ICOST	CRITJ	ACC		
2	0	0	0	20	0		
LAYER	DX	D	P	Q	XMS	RHO	
1	5.000D+02	7.000D-02	3.000D-01	1.049D-04	0.000D+00	1.600	
2	2.000D+02	7.000D-02	3.000D-01	1.049D-04	0.000D+00	1.600	

BARE SOURCE FLUX FROM LAYER 1: 5.696D+01 pCi m⁻² s⁻¹

RESULTS OF DIFFUSION CALCULATIONS:

LAYER	THICKNESS	EXIT FLUX	EXIT CONC.

	(cm)	(pCi m ⁻² s ⁻¹)	(pCi/l)

1	5.000D+02	1.912D+01	3.317D+04

2	2.000D+02	5.738D+01	0.000D+00

Fine Slag

RADON V1.2
CALCULATION OF RADON FLUX ATTENUATION BY EARTHEN
URANIUM MILL TAILINGS COVERS
U.S. NUCLEAR REGULATORY COMMISSION
REGULATORY GUIDE 3.64, June 1989

TITAN ENVIRONMENTAL CORPORATION

RADON DECAY CONSTANT .0000021 per sec.
RADON WATER/AIR PARTITION COEFFICIENT .26
SPECIFIC GRAVITY OF TAILINGS 2.65
NUMBER OF LAYERS: 2
RADON FLUX LIMIT: 20 pCi m⁻² s⁻¹
LAYER THICKNESS NOT OPTIMIZED
SURFACE RADON CONCENTRATION 0 pCi/l
RADON FLUX INTO LAYER 1 0 pCi m⁻² s⁻¹
SURFACE FLUX PRECISION .01 (pCi m⁻² s⁻¹)

LAYER 1 fine slag

THICKNESS 500 cm
POROSITY: .35
MEASURED MASS DENSITY 1.6 gm/cc
MEASURED RADIUM ACTIVITY 38 pCi/gm
DEFAULT LAYER EMANATION COEFFICIENT .3499999940395355
CALCULATED SOURCE TERM CONCENTRATION
1.276799978256226D-04 pCi cm⁻³ s⁻¹
WEIGHT % MOISTURE 0 %
MOISTURE SATURATION FRACTION 0
CALCULATED DIFFUSION COEFFICIENT 7.000000029802322D-02
cm² s⁻¹

LAYER 2 fine slag

THICKNESS 200 cm
POROSITY: .35
MEASURED MASS DENSITY 1.6 gm/cc
MEASURED RADIUM ACTIVITY 38 pCi/gm
DEFAULT LAYER EMANATION COEFFICIENT .3499999940395355

Fine Slag

CALCULATED SOURCE TERM CONCENTRATION

1.276799978256226D-04 pCi cm⁻³ s⁻¹

WEIGHT % MOISTURE 0 %

MOISTURE SATURATION FRACTION 0

CALCULATED DIFFUSION COEFFICIENT 7.000000029802322D-02
cm² s⁻¹

fine Slag

N	F01	CN1	ICOST	CRITJ	ACC	
2	0	0	0	20	0	
LAYER	DX	D	P	Q	XMS	RHO
1	5.000D+02	7.000D-02	3.500D-01	1.277D-04	0.000D+00	1.600
2	2.000D+02	7.000D-02	3.500D-01	1.277D-04	0.000D+00	1.600

BARE SOURCE FLUX FROM LAYER 1: 8.091D+01 pCi m⁻² s⁻¹

RESULTS OF DIFFUSION CALCULATIONS:

LAYER	THICKNESS	EXIT FLUX	EXIT CONC.

(cm)	(pCi m ⁻² s ⁻¹)	(pCi/l)

1	5.000D+02	2.716D+01	4.039D+04
2	2.000D+02	8.151D+01	0.000D+00

Course Slag

RADON V1.2
CALCULATION OF RADON FLUX ATTENUATION BY EARTHEN
URANIUM MILL TAILINGS COVERS
U.S. NUCLEAR REGULATORY COMMISSION
REGULATORY GUIDE 3.64, June 1989

TITAN ENVIRONMENTAL CORPORATION

RADON DECAY CONSTANT .0000021 per sec.
RADON WATER/AIR PARTITION COEFFICIENT .26
SPECIFIC GRAVITY OF TAILINGS 2.65
NUMBER OF LAYERS: 2
RADON FLUX LIMIT: 20 pCi m⁻² s⁻¹
LAYER THICKNESS NOT OPTIMIZED
SURFACE RADON CONCENTRATION 0 pCi/l
RADON FLUX INTO LAYER 1 0 pCi m⁻² s⁻¹
SURFACE FLUX PRECISION .01 (pCi m⁻² s⁻¹)

LAYER 1 coarse slag

THICKNESS 500 cm
POROSITY: .25
MEASURED MASS DENSITY 1.6 gm/cc
MEASURED RADIUM ACTIVITY 39 pCi/gm
DEFAULT LAYER EMANATION COEFFICIENT .3499999940395355
CALCULATED SOURCE TERM CONCENTRATION
1.834559968757629D-04 pCi cm⁻³ s⁻¹
WEIGHT % MOISTURE 0 %
MOISTURE SATURATION FRACTION 0
CALCULATED DIFFUSION COEFFICIENT 7.000000029802322D-02
cm² s⁻¹

LAYER 2 coarse slag

THICKNESS 200 cm
POROSITY: .25
MEASURED MASS DENSITY 1.6 gm/cc
MEASURED RADIUM ACTIVITY 39 pCi/gm
DEFAULT LAYER EMANATION COEFFICIENT .3499999940395355

Course Slag

CALCULATED SOURCE TERM CONCENTRATION

1.834559968757629D-04 pCi cm⁻³ s⁻¹

WEIGHT % MOISTURE 0 %

MOISTURE SATURATION FRACTION 0

CALCULATED DIFFUSION COEFFICIENT 7.000000029802322D-02
cm² s⁻¹

N F01 CN1 ICOST CRITJ ACC

2 0 0 0 20 0

LAYER DX D P Q XMS RHO

1 5.000D+02 7.000D-02 2.500D-01 1.835D-04 0.000D+00 1.600

2 2.000D+02 7.000D-02 2.500D-01 1.835D-04 0.000D+00 1.600

BARE SOURCE FLUX FROM LAYER 1: 8.304D+01 pCi m⁻² s⁻¹

RESULTS OF DIFFUSION CALCULATIONS:

LAYER THICKNESS EXIT FLUX EXIT CONC.

(cm) (pCi m⁻² s⁻¹) (pCi/l)

1 5.000D+02 2.787D+01 5.804D+04

2 2.000D+02 8.366D+01 0.000D+00

Results for Capping Requirements

RADON V1.2

CALCULATION OF RADON FLUX ATTENUATION BY EARTHEN
URANIUM MILL TAILINGS COVERS
U.S. NUCLEAR REGULATORY COMMISSION
REGULATORY GUIDE 3.64, June 1989

TITAN ENVIRONMENTAL CORPORATION

RADON DECAY CONSTANT .0000021 per sec.
RADON WATER/AIR PARTITION COEFFICIENT .26
SPECIFIC GRAVITY OF TAILINGS 2.65
NUMBER OF LAYERS: 4
RADON FLUX LIMIT: 20 pCi m⁻² s⁻¹
LAYER TO BE OPTIMIZED: 4
SURFACE RADON CONCENTRATION 0 pCi/l
RADON FLUX INTO LAYER 1 0 pCi m⁻² s⁻¹
SURFACE FLUX PRECISION .1 (pCi m⁻² s⁻¹)

LAYER 1 slag

THICKNESS 500 cm
POROSITY: .3
MEASURED MASS DENSITY 1.6 gm/cc
MEASURED RADIUM ACTIVITY 38.6 pCi/gm
DEFAULT LAYER EMANATION COEFFICIENT .3499999940395355
CALCULATED SOURCE TERM CONCENTRATION 1.51311997423172D-04 pCi cm⁻³ s⁻¹
WEIGHT % MOISTURE 0 %
MOISTURE SATURATION FRACTION 0
CALCULATED DIFFUSION COEFFICIENT 7.000000029802322D-02 cm² s⁻¹

LAYER 2 ore

THICKNESS 500 cm
POROSITY: .3
MEASURED MASS DENSITY 1.6 gm/cc
MEASURED RADIUM ACTIVITY 26.75 pCi/gm
DEFAULT LAYER EMANATION COEFFICIENT .3499999940395355
CALCULATED SOURCE TERM CONCENTRATION 1.048599982142448D-04 pCi cm⁻³ s⁻¹
WEIGHT % MOISTURE 0 %
MOISTURE SATURATION FRACTION 0
CALCULATED DIFFUSION COEFFICIENT 7.000000029802322D-02 cm² s⁻¹

LAYER 3 tailings

THICKNESS 500 cm
POROSITY: .53
MEASURED MASS DENSITY 1.2 gm/cc
MEASURED RADIUM ACTIVITY 27.25 pCi/gm
DEFAULT LAYER EMANATION COEFFICIENT .3499999940395355
CALCULATED SOURCE TERM CONCENTRATION 4.53481124352734D-05 pCi cm⁻³ s⁻¹
WEIGHT % MOISTURE 6.4 %
MOISTURE SATURATION FRACTION .1449056571384646
CALCULATED DIFFUSION COEFFICIENT 4.612859583262557D-02 cm² s⁻¹

LAYER 4 cover

THICKNESS 500 cm
POROSITY: .48
MEASURED MASS DENSITY 1.38 gm/cc
MEASURED RADIUM ACTIVITY 1.25 pCi/gm
DEFAULT LAYER EMANATION COEFFICIENT .3499999940395355
CALCULATED SOURCE TERM CONCENTRATION 2.641406205017119D-06 pCi cm⁻³ s⁻¹
WEIGHT % MOISTURE 14 %
MOISTURE SATURATION FRACTION .4024999910034239
CALCULATED DIFFUSION COEFFICIENT 1.943709159271586D-02 cm² s⁻¹

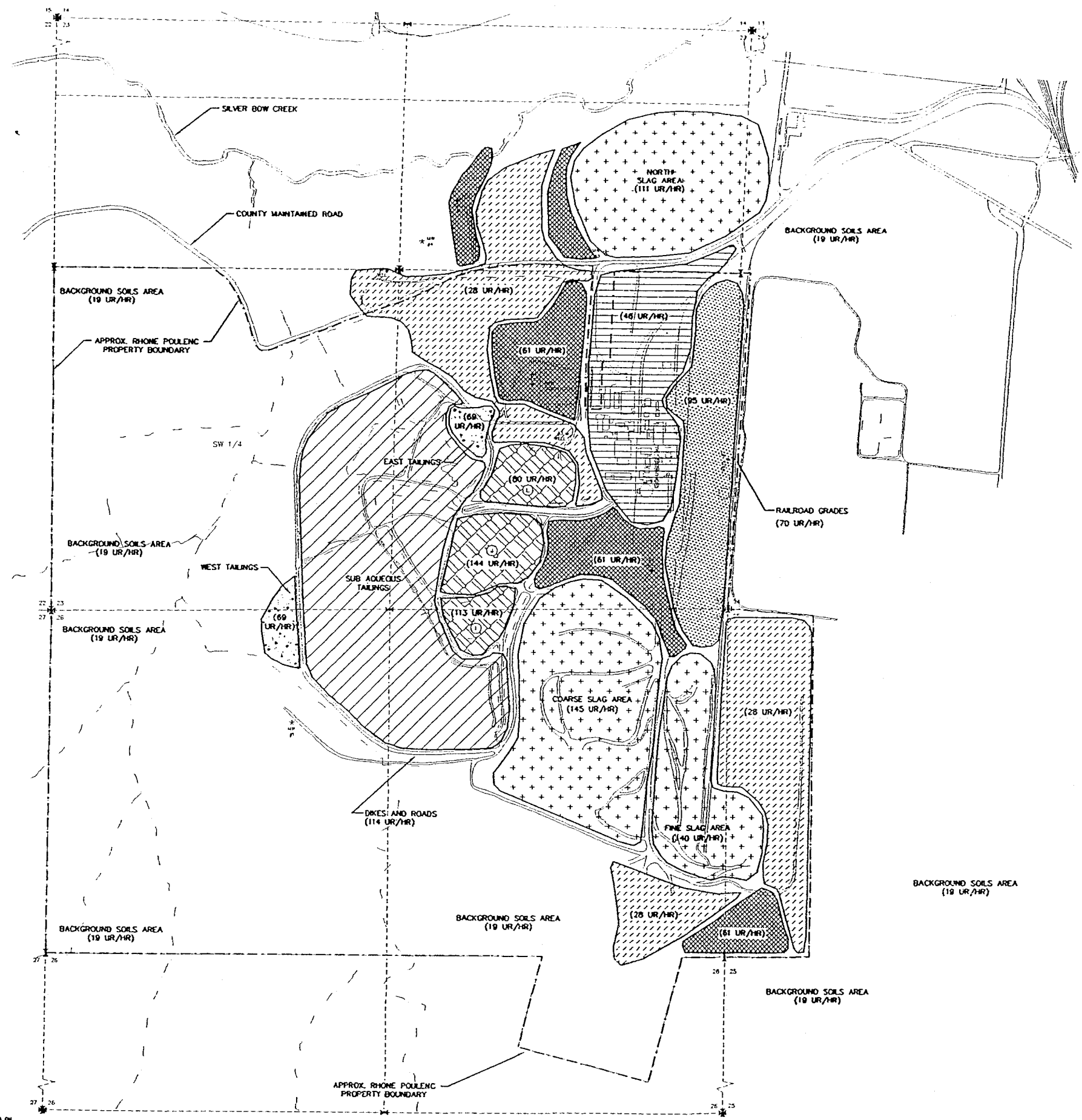
N	F01	CN1	ICOST	CRITJ	ACC				
4	0	0	4	20	0				
LAYER	DX	D	P	Q	XMS	RHO			
1	5.000D+02	7.000D-02	3.000D-01	1.513D-04	0.000D+00	1.600			
2	5.000D+02	7.000D-02	3.000D-01	1.049D-04	0.000D+00	1.600			
3	5.000D+02	4.613D-02	5.300D-01	4.535D-05	1.449D-01	1.200			
4	5.000D+02	1.944D-02	4.800D-01	2.641D-06	4.025D-01	1.380			

BARE SOURCE FLUX FROM LAYER 1: $8.219\text{D}+01 \text{ pCi m}^{-2} \text{ s}^{-1}$

RESULTS OF DIFFUSION CALCULATIONS:

LAYER THICKNESS EXIT FLUX EXIT CONC.

	(cm)	($\text{pCi m}^{-2} \text{ s}^{-1}$)	(pCi/l)
1	$5.000\text{D}+02$	$1.379\text{D}+01$	$5.997\text{D}+04$
2	$5.000\text{D}+02$	$1.818\text{D}+01$	$3.555\text{D}+04$
3	$5.000\text{D}+02$	$2.185\text{D}+01$	$9.073\text{D}+03$
4	$3.125\text{D}+01$	$2.113\text{D}+01$	$0.000\text{D}+00$



LEGEND:

- APPROXIMATE BOUNDARY OF FACILITY
- (95 UR/HR) AVERAGE MICRODENTGENS PER HOUR FOR SURVEY AREA
- EXISTING PRODUCTION WELL
- * EXISTING MONITORING WELL
- + + SLAG AREAS
- [diagonal lines] FACILITY SOILS AREA
- [dots] ORE STORAGE AREA
- [horizontal lines] PROCESSING AREA
- [cross-hatch] MIXED USE WITH SLAG AREAS
- [stippled] RECLAIMED TAILINGS AREA
- [diagonal lines] SUB AQUEOUS TAILINGS AREA
- [cross-hatch] EXCAVATED TAILINGS CELLS

NOTES:

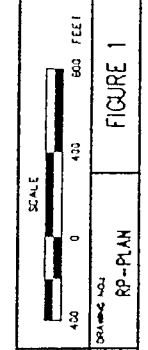
- 1. ALL BOUNDARIES ARE APPROXIMATE.

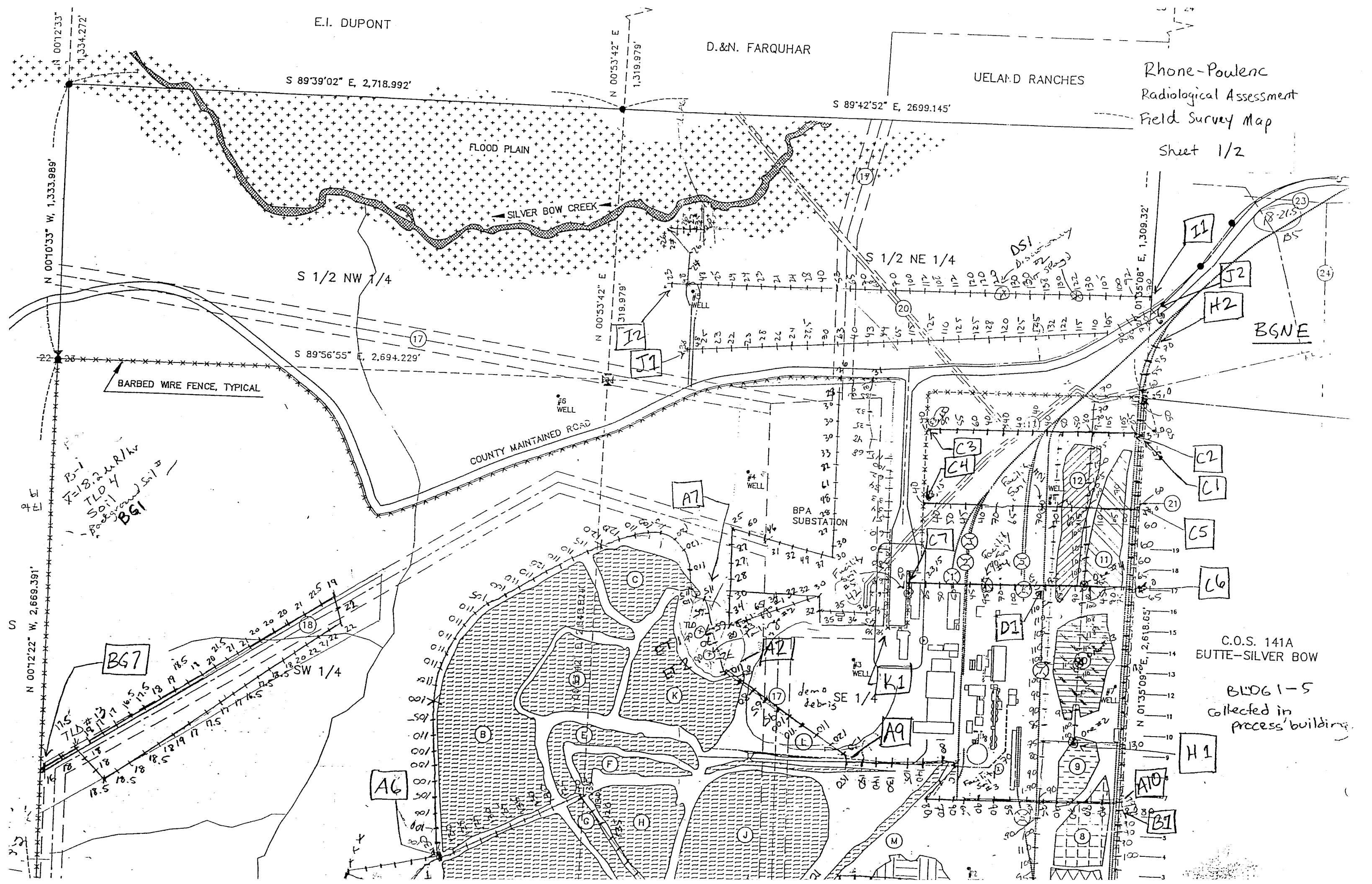
REFERENCES:
SITE MAP AND COORDINATE GRID BASED ON
TOPOGRAPHY PROVIDED BY HANCOCK LAWSON
ASSOCIATES. SECOR INTERNATIONAL DOES NOT
ASSUME LIABILITY FOR THE INTEGRITY OF
THIS DATA.

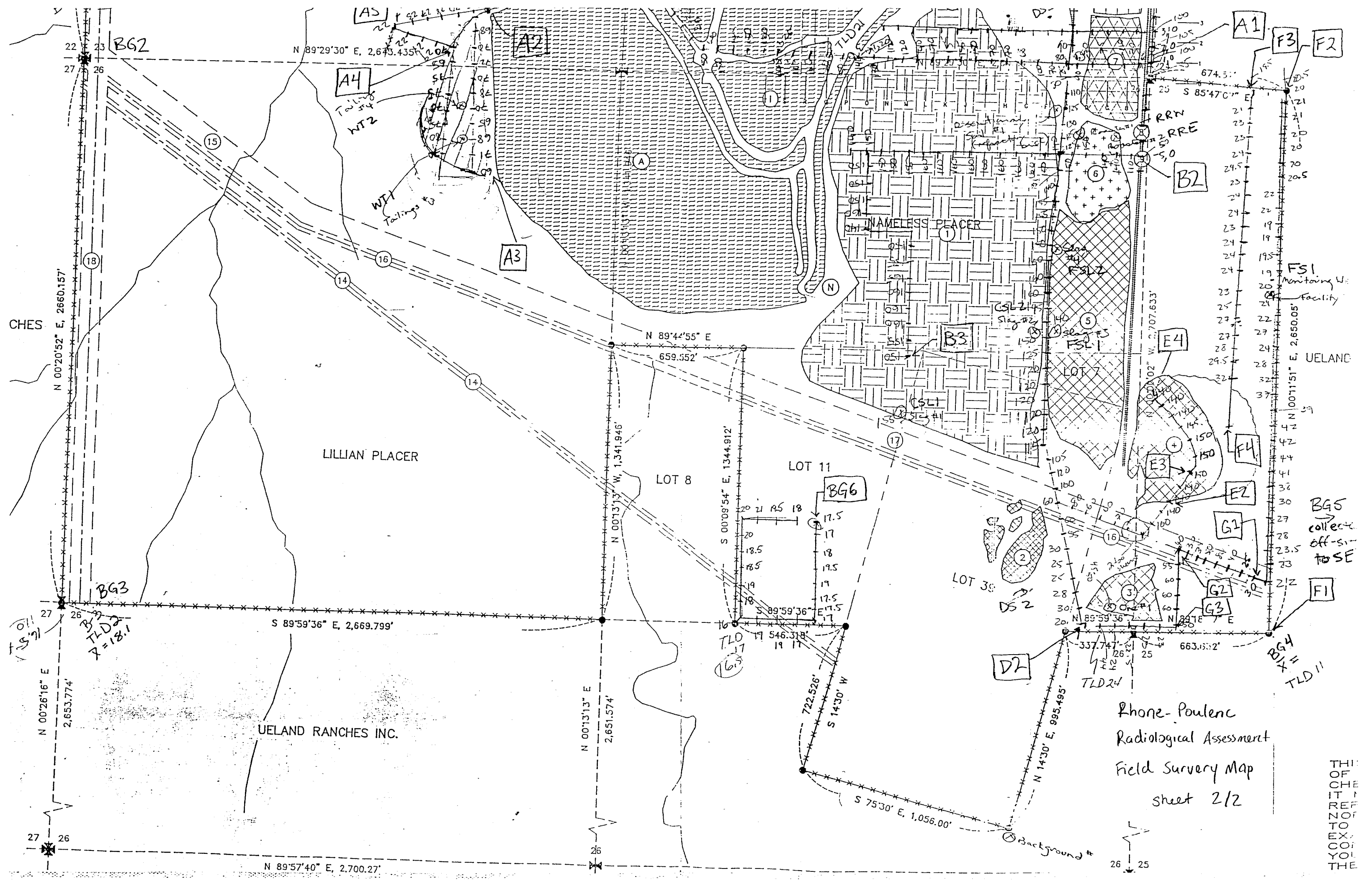
PREPARED FOR
RHONE-POULENC BASIC CHEMICALS COMPANY
SILVER BOW, MONTANA

SITE PLAN
RADIOLOGICAL ASSESSMENT

SECOR
25 NORTH WILSON, SUITE F - BOZEMAN, MT 59715
406 596.8364 - FAX 406 596.2335







UELAND RANCHES INC.

Phone-Poulenc
Radiological Assessment
Field Survey Map
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Appendix 1-H

**Emissions of Naturally Occurring Radioactivity, Stauffer
Elemental Phosphorus Plant, November 1982**

EPA-520/6-82-019
November 1982

EMISSIONS OF NATURALLY OCCURRING RADIOACTIVITY
STAUFFER ELEMENTAL PHOSPHORUS PLANT

by

Vernon E. Andrews
Office of Radiation Programs-LVF
U.S. Environmental Protection Agency
Las Vegas, Nevada 89114

and

Project Officer

Tom Bibb
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U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

This report was prepared with the technical support
of PEDCo Environmental Inc. contract 68-12-2811

Office of Radiation Programs - Las Vegas Facility
U.S. Environmental Protection Agency
Las Vegas, Nevada 89114

FORWARD

The Office of Radiation Programs (ORP) of the U.S. Environmental Protection Agency (EPA) conducts a national program for evaluating exposure of humans to ionizing and nonionizing radiation. The goal of this program is to develop and promote protective controls necessary to ensure the public health and safety.

In response to the 1977 amendments to the Clean Air Act the Las Vegas Facility was given the responsibility to collect field data on emissions to the atmosphere of natural radioactivity from operations involved in the mining, milling, and smelting of minerals other than uranium and coal. This report is one of a series which describes an individual facility and the associated radioactivity emissions.

ORP encourages readers of the report to inform the Director, ORP-Las Vegas Facility, of any omissions or errors. Comments or requests for further information are also invited.

A handwritten signature in cursive script that reads "Wayne A. Bliss".

Wayne A. Bliss, Acting Director
Office of Radiation Programs
Las Vegas Facility

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SECTION 1

BACKGROUND

The Clean Air Act, as amended in August 1977, required the Administrator of the Environmental Protection Agency (EPA) to determine whether emissions of radionuclides into ambient air should be regulated under the Act. In December 1979 the Administrator listed radionuclides as a hazardous pollutant under Section 112 of the Clean Air Act.

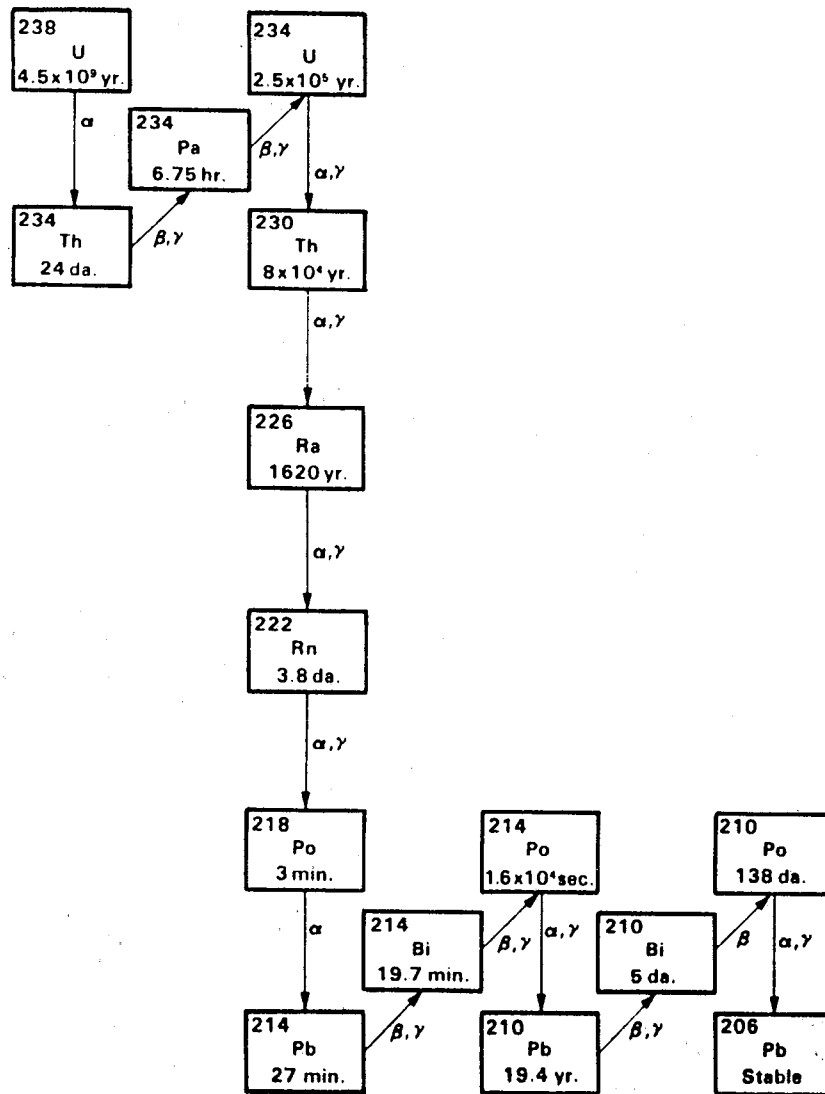
The naturally occurring radionuclides most likely to be emitted in significant quantities are those in the uranium-238 and thorium-232 decay series (Figure 1). These radionuclides and their daughter products occur naturally in widely varying amounts in the soils and rocks that make up the earth's crust. Average values for uranium-238 and thorium-232 in soils are approximately 1.8 ppm (0.6 pCi/g) and 9 ppm (1 pCi/g) respectively (1). The radioactivity concentration of each of the daughter products in the two series is approximately equal to that of the uranium-238 or thorium-232 parent.

Almost all operations involving removal and processing of soils and rocks release some of these radionuclides into the air. These releases become potentially important when the materials being handled contain above-average radionuclide concentrations or when processing concentrates the radionuclides significantly above the average amounts in soils and rocks.

Because mining and milling operations involve large quantities of ore, and because there is little information about how these activities release radioactive emissions, EPA, in 1978, began to measure airborne radioactive emissions from various mining, milling, and smelting operations. These surveys were screening studies designed to identify important sources of airborne emissions of radionuclides at individual facilities.

Operations were selected for study on the basis of their potential to emit significant quantities of naturally occurring radionuclides to the atmosphere. Some of the factors in the selection included typical mine size, annual U.S. production, measured working levels of radon daughters in underground mines and associated ventilation rates, production rate and process of individual facilities, and previous association with naturally occurring radionuclides. Usually, we chose to look at large facilities in order to improve the chances of obtaining emission samples with radioactivity contents significantly greater than background.

URANIUM — 238 DECAY SERIES



THORIUM — 232 DECAY SERIES

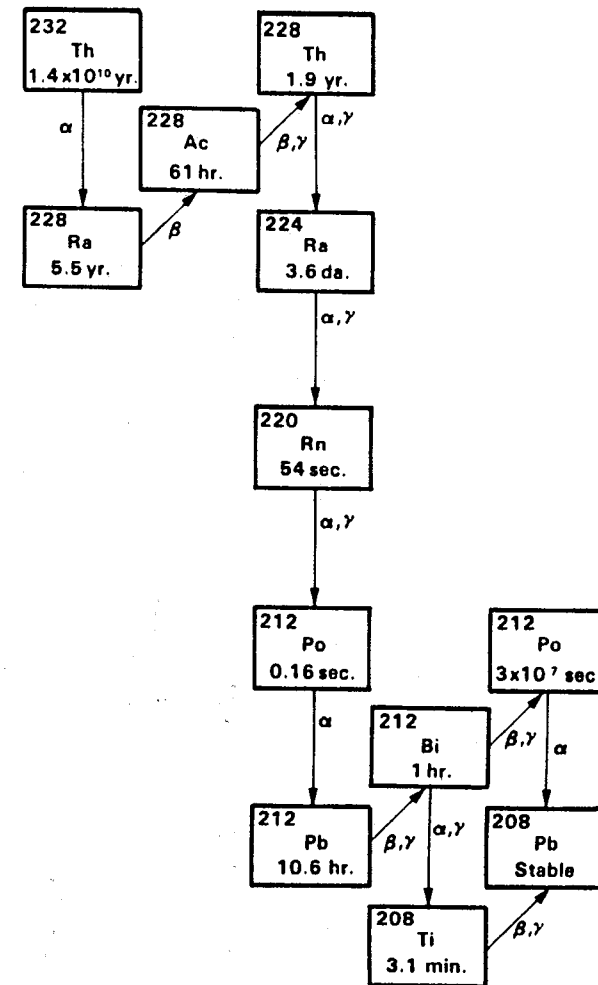


Figure 1. Uranium and Thorium Radioactivity Decay Schemes

SECTION 2

INTRODUCTION

As early as 1908 it was recognized that phosphate rock contained above-normal concentrations of uranium and thorium (2). Those concentrations have been observed in the United States to range from 8 to 399 ppm (2.7 to 133 pCi/g) of uranium-238 and 2 to 19 ppm (0.22 to 2.1 pCi/g) of thorium-232 (3). South Carolina ores had the highest concentrations, while the lowest were found in Tennessee. During the 1950's uranium was recovered as a byproduct of phosphate production.

Since 1974 the EPA has studied various aspects of the radioactivity released to plant environs during beneficiation and processing of the phosphate ores. The EPA had conducted a comprehensive radiological survey of a thermal phosphate (elemental phosphorus) plant in 1975 (4). However, problems associated with the analyses for lead-210 had greatly reduced the accuracy of the measurements of both lead-210 and polonium-210. Under the added emphasis provided by the Clean Air Act Amendments the decision was made to include at least two elemental phosphorus plants in this series of surveys. The first of the plants surveyed was the Stauffer Chemical Company plant in Silver Bow, Montana.

PEDCo Environmental, under contract with EPA, conducted the survey and collected samples (5). Before the survey, representatives of PEDCo Environmental and EPA visited the plant to select sampling locations. During the period October 15-31, 1979 PEDCo Environmental, accompanied by an EPA representative, conducted the sampling and measurement program, collecting particulate and gas samples from plant effluents and ambient air as well as information on plant operations. Stauffer provided meteorological data collected by one of their meteorology stations.

SECTION 3

SUMMARY

PEDCo Environmental collected samples of particulate and gaseous emissions from all controlled sources at the Stauffer Chemical Company plant. Ambient particulate and gaseous samples were collected at a site 1.6 km east of the plant. Radon-222 emanation rates were measured from soil around the plant, from an ore storage pile, and the slag pile.

The kiln stacks emitted essentially all of the radioactivity emitted from controlled sources. They accounted for 99 percent of the lead-210, 97 percent of the polonium-210, and 98 percent of the radon-222. Annual emission rates of the three radionuclides from all stacks were measured at 280 mCi for lead-210, 200 mCi for polonium-210, and 8.2 Ci for radon-222. An additional estimated release of 1.2 Ci/y of radon-222 is produced by ore in storage. Annual emission rates of uranium-238 and -234, thorium-230, and radium-226 were measured at an average amount of 0.22 mCi for each radionuclide. The estimated release of each of those radionuclides, based on measured mass emission rates and assuming that the radioactivity concentration in the emitted particulates was the same as in the materials handled by the process was 4.2 mCi/year.

The radon emanation rate from the slag pile, with an average radium-226 concentration of 27 pCi/g was 3.5 ± 3.7 pCi/m²-min; much less than the soil emanation rate of 18 ± 9 pCi/m²-min. The average emanation rate from the ore pile was 117 ± 138 pCi/m²-min.

SECTION 4

PLANT OPERATIONS

PRODUCT FLOW

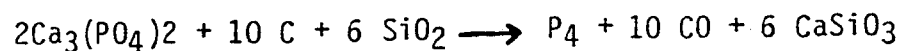
The Stauffer Chemical Company Silver Bow Plant is located in the community of Silver Bow, approximately 11 km west of Butte, Montana (Figure 2). Ore is delivered by rail from a mine in Idaho. The plant product is elemental phosphorus. A by-product is ferrophosphorus (FeP), which is sold as a steel alloying additive. The other solid product is slag, which can be either a by-product or a waste product. Stauffer sold their slag for use as highway aggregate until shortly before this survey. Pending further radiation studies, Stauffer voluntarily withdrew their slag from the market.

Figure 3 is a schematic of the plant operation. Ore railcars are dumped into a pit from which ore is moved to one of two large storage piles (Figure 4). The process of ore blending begins at this point as the ore stockpile is built up by layers. One pile is built while ore is drawn from the other pile. Because of the severe winter weather, ore is shipped during the summer and stockpiled for year-round use.

The ore is further blended when it is recovered from the stockpile and moved into a pit where it is transferred by hoppers in the kiln feed building.

It is necessary to form the finely divided ore into larger, stable agglomerates for proper operation of the reduction furnaces. This is accomplished by passing the ore through two rotary kilns at about 1300°C. The temperature of the ore is raised to its incipient melting point and the tumbling action forms the ore into the desired nodular form. The hot nodules pass through coolers and crushers before being conveyed to storage silos.

The furnace feed consists of a mix of ore nodules, silica rock, and coke. A proper fraction of silica is required to form slag with the necessary flow properties to facilitate removal from the furnace. The content of silica occurring naturally in the ore must be augmented with added silica. Coke is added as a carbon source to reduce the calcium phosphate ore to elemental phosphorus. The approximate reaction is:



Nodules, coke, and silica are fed from storage silos by means of a proportioning belt and skip hoist to "burden bins" which provide a continuous feed to the furnaces.

Feed material enters the electric arc furnaces from the top and progresses downward until reaching the molten layer on the bottom. Phosphorus and CO are

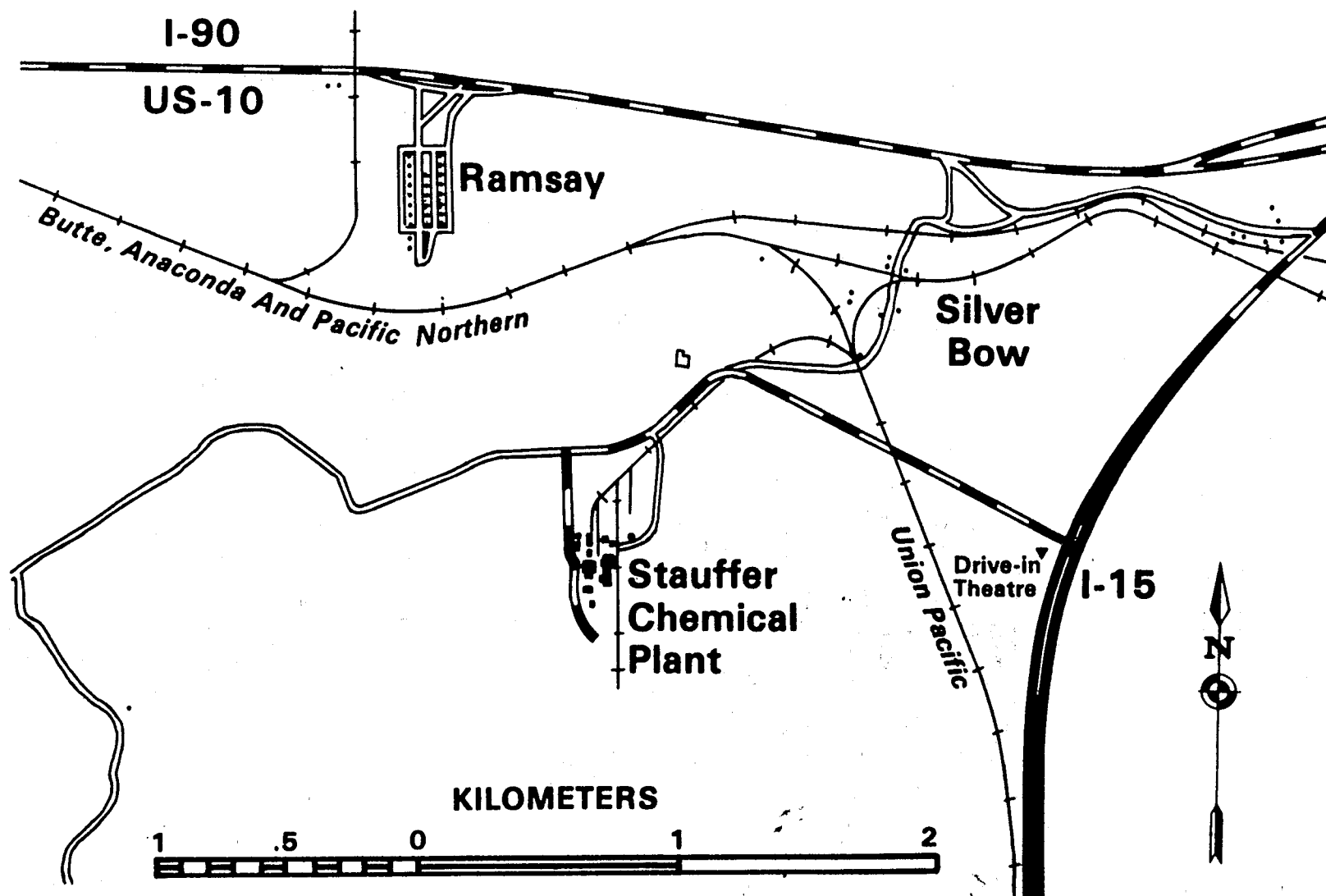


Figure 2. Stauffer Chemical Plant Location

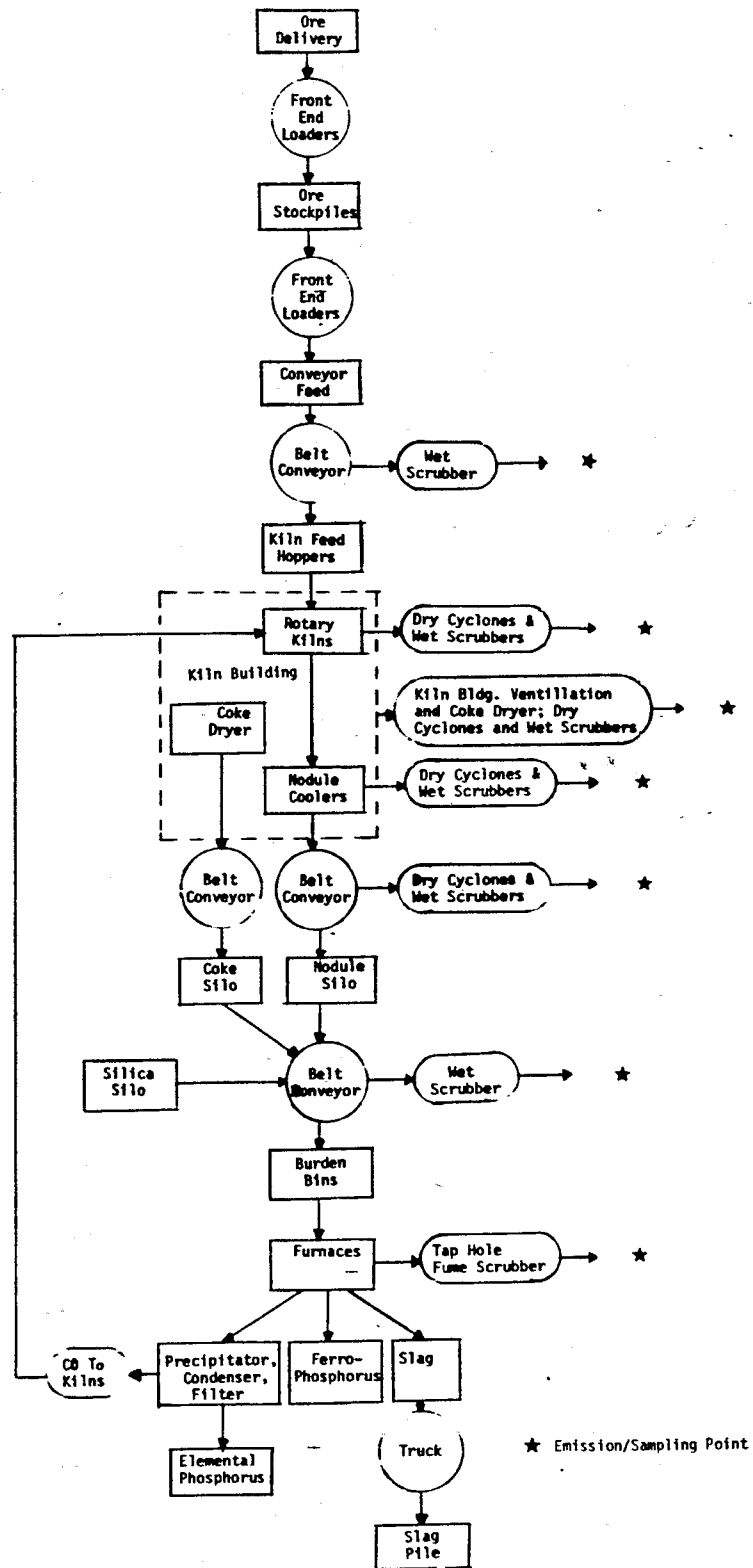


Figure 3. Stauffer Chemical Plant Flow Diagram

driven off as gases and are piped off near the top of the furnace. The slag and FeP which are continually collecting in the furnace are periodically tapped off. FeP is tapped for about 20 minutes each 8-hour shift. Slag is tapped (or flushed) in an 80 to 90 minute operation about seven or eight times per 24-hour period. FeP is cooled and crushed for shipment. Slag is disposed of on site.

The product gases through an electrostatic precipitator where particulate contaminants are removed, and then through a spray tower where water sprays cool the phosphorus to below the condensation point. The molten phosphorus is filtered to remove any carry-over particulates and piped into rail tank cars for shipment. The remainder of the gas stream, primarily CO, is used as fuel in the kilns. Sludge resulting from the phosphorus filtering operation is roasted to recover any residual phosphorus. Roaster residue is spread in a 6-inch layer on the stockpile prepared for winter use to prevent the damp ore from freezing in the pile and hampering recovery.

EMISSION POINTS

Dust generated while conveying ore to the kiln feed building hoppers is collected by a hooding system. The air is discharged through a wet scrubber.

Exhaust gases from the rotary kilns are cleaned by multiple air cleaning devices which remove both particulates and fluorine.

Exhaust gases from the nodule coolers are treated by two sets of multiple air cleaning devices to remove particulates.

Emissions occurring within the kiln building from materials handling and coke drying are collected by the ventilator collector system. This system exhausts through two sets of multiple air cleaning devices.

Emissions arising from transfer to and storage in the burden bins of nodules, coke, and silica are collected by a hooding system and discharged through a wet scrubber.

A small amount of phosphorus is released during slag and FeP tapping. Upon oxidizing in air the phosphorus forms a dense white cloud of P_2O_5 fumes. Collecting hoods intercept most of the P_2O_5 fumes and other emissions and discharges them through the tap hole fume scrubber.

With the installation of air pollution control systems on most of the sources of particulate emissions, the visible emissions during the period of the survey originated from two primary sources. One is a periodic release of some of the fumes produced during furnace tapping. The other source is the nodule storage silo area. Material handling at the burden bins generates considerable dust which exits the building through roof ridgeline ventilators. No satisfactory method has been devised to control these dust emissions. The point of emission is also inaccessible to sampling.

Other potential sources of airborne radioactivity were the ore storage piles and slag piles. These were considered as possible sources of gaseous radon-222.

SECTION 5

SAMPLE COLLECTION AND ANALYSIS

SAMPLE COLLECTION

Most samples were collected using EPA reference methods (6). Stack sampling points were selected according to EPA Method 1. Stack gas velocity and volumetric flow rate were determined by EPA Method 2. Gas samples for radon analysis were collected using EPA Method 3. (Radon in this report means radon-222). Total suspended particulates (TSP) in ducts and exhaust stacks were determined using EPA Method 5. High volume ambient TSP samples were collected in accordance with the Reference Method for the Determination of Suspended Particulates in the Atmosphere (7).

PEDCo collected Method 5 TSP samples on 7.6-cm (3-inch) diameter glass fiber filters. Ambient TSP samples were collected on 20.3- by 25.4-cm (8- by 10-inch) Microsorban polystyrene fiber filters. Stack gas and ambient whole air samples for radon analysis were collected in 30 liter Tedlar bags.

PEDCo sampled each of the emission points described on page 8 except the silo fugitive emissions. They collected two to four samples each of TSP and gas samples from each point. These points are shown in Figure 3. Where more than one exhaust of a given type existed, such as kiln exhausts, they only sampled one. At two locations it was possible to obtain simultaneous samples from the inlet and outlet of an emission control system.

Radon emanation rates from the surface of the ore pile and surrounding soil areas was measured at the locations shown in Figure 4 by means of charcoal canisters. U.S. Army M-11 gas canisters containing activated charcoal were placed on the surface to collect radon gas emitted. The canisters were left in position for the duration of the survey. Radon emanation rates from the slag pile were measured using inverted tubs sealed to the surface (Figure 4). The tubs were sealed to the slag pile using dry bentonite clay powder moistened in place. A valve and gas cock in the bottom of the tub permitted the collection of air samples at the time of placement and after an elapsed time of 2 to 3 hours. The change of radon concentration in the 53-liter tub made it possible to calculate the rate of emanation from the surface beneath the tub.

Samples of process materials were collected to relate radionuclide emission rates to the radioactivity of the material handled at each emission point and to permit a radionuclide balance through the process.

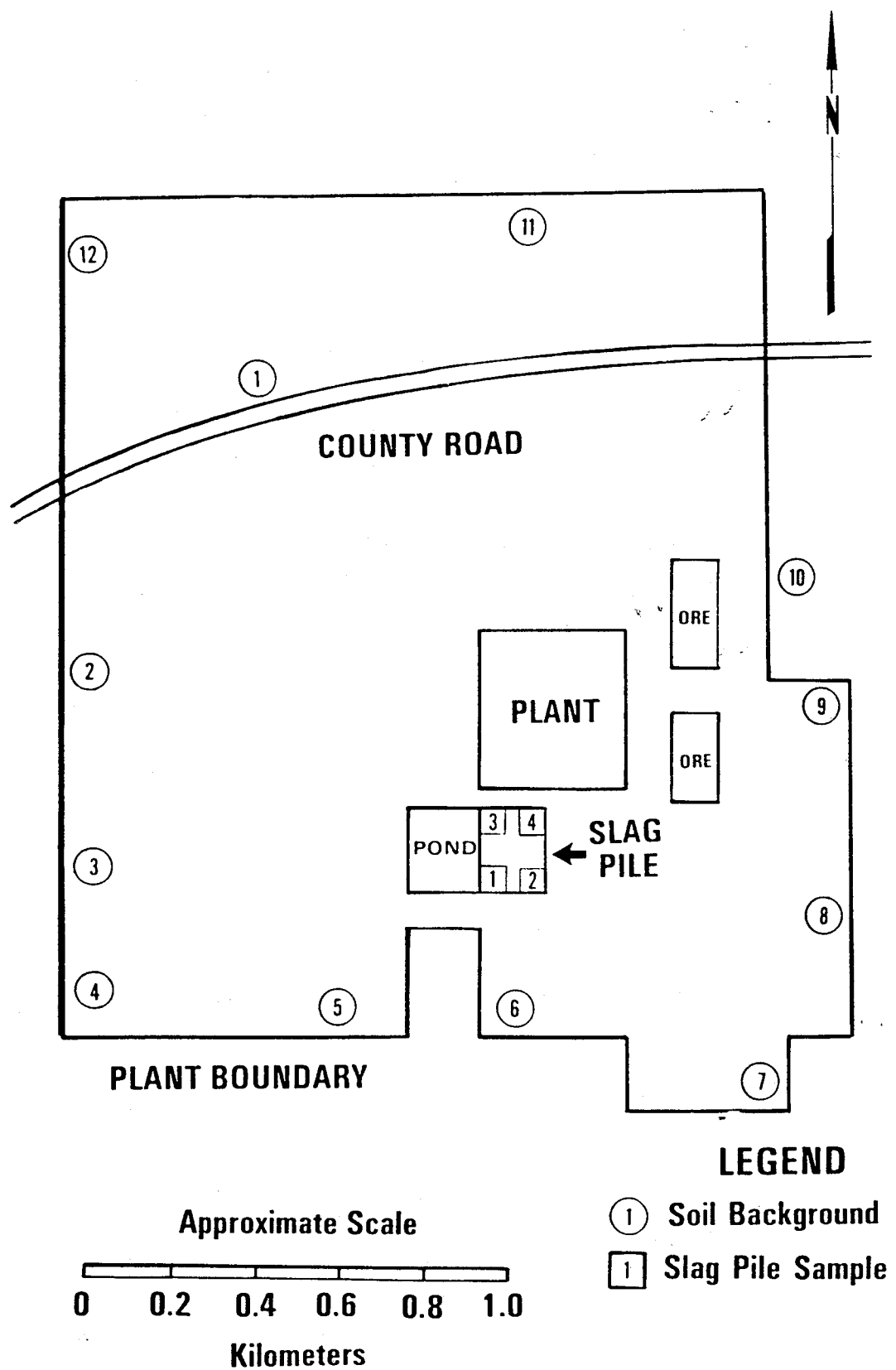


Figure 4. Sampling Sites for Radon Emanation from Soil, Ore, and Slag

SAMPLE ANALYSIS

PEDCo made mass determinations on TSP samples before forwarding them to Eberline Instrument Corporation (EIC) for radiochemical analysis. Stack and ambient gas samples were shipped to EIC for arrival within 2 days of collection.

EIC analyzed process and TSP samples by dissolving the samples and separating the elements of interest by chemical techniques. The separated uranium and thorium fractions were counted on alpha spectrometers for individual isotopic quantitation. An alpha scintillation counter measured the polonium-210. Lead was separated and set aside for about 2 weeks to allow for ingrowth of bismuth-210 from lead-210. After the ingrowth period the bismuth-210 was separated from the lead and was counted on a beta counter to quantitate lead-210. Radium was separated and enclosed as a solution in a sealed tube to allow for ingrowth of radon from radium-226. After 3 weeks of ingrowth the radon gas was evolved and collected in an alpha scintillation cell to be counted. Stack and ambient gas samples were transferred to alpha scintillation cells and counted for radon.

The EPA's project officer collected the slag pile radon samples directly into evacuated alpha scintillation cells and counted for radon the same day.

PEDCo shipped the radon emanation canisters by air express to the EPA Eastern Environmental Radiation Facility in Montgomery, Alabama. EPA analyzed the canisters on a gamma spectrometer and reported the results as radon flux (emission rate per unit area) from the surface.

DATA REPORTING

The radioactivity reported for each sample, except for charcoal canisters, is the net radioactivity plus or minus twice the standard deviation (2s) based on counting statistics. The net radioactivity is the gross sample radioactivity minus counter background and (1) for filter samples, minus an average value for the radioactivity content of a blank filter, or (2) for stack radon samples, minus the ambient radon concentration. The counting variation, plus the variable radioactivity content of individual blank filters, occasionally results in a net radioactivity of less than 0. Of course, there is no negative radioactivity. In these cases, as with all others, the net negative results must be considered along with the 2s uncertainty.

The sample standard deviation is based only on the random variations inherent in radioactivity counting and is propagated only in those situations of either duplicate emission samples or samples describing process materials. This uncertainty is not propagated when samples are collected at different times yet are combined to describe a source average. In these cases where multiple samples are averaged, the standard deviation is calculated from the variance in the samples. Since there is no adequate way of describing the variability in daily emissions for the control technology, the annual emissions have no associated error term.

SECTION 6

SAMPLE RESULTS

PROCESS SAMPLES

The average concentration in ore of radionuclides of the uranium-238 series was 32 pCi/g (Table 1). The apparent departures from secular equilibrium reported for the individual nuclides of the uranium series in ore samples are due primarily to a combination of statistical variations in counting and analytical biases. Uranium was above the normal concentration in rock by about a factor of 50. The thorium series was at a normal concentration level.

Although a large fraction of the ore was removed as elemental phosphorus and oxygen, the radionuclide concentrations in slag are similar to those in ore due to the diluting effect of the added silica. The major differences between ore and slag concentrations are for lead-210 and polonium-210, both of which are volatilized and driven off during processing. Radionuclide concentrations in the nodules show that about half the lead-210 and essentially all of the polonium-210 are lost during calcining. The rest of the lead-210 is lost during the thermal reduction process. FeP contains significant concentrations of uranium-234 and -238. However, the FeP is produced in much smaller quantity than slag and most of the uranium is found in the slag. Radionuclide concentrations in the four slag pile samples are in very close agreement, reflecting the uniformity of blended feedstock and overall operations.

AMBIENT AIR SAMPLES

Radon-222 concentrations measured at the background station are shown in Table 2. The samples collected from 1440 to 1758 hours on October 17 and on October 18 were collected during periods when the wind direction was primarily from the plant to the sampling site. All other samples were collected during periods when the sampling site was either upwind or crosswind from the plant. No effect of plant operation is apparent from the results and all samples are considered to represent ambient concentrations. Ambient radon concentrations vary from less than 0.1 to about 1 nCi/m³, depending on time of day, season, and meteorology (1).

Three filters from the background high volume samplers were analyzed for ambient particulate radioactivity concentrations. The results are in Table 3. The measured concentrations of the uranium, thorium, lead, and radium isotopes are comparable to those found throughout the United States (1). The polonium-210 concentrations of 0.020 and 0.029 pCi/m³ in the October 18-21 and October 26-28 samples are an order of magnitude higher than the normal back-

TABLE 1. PROCESS MATERIALS RADIOACTIVITY CONCENTRATIONS

Material	Radioactivity Concentrations (pCi/g) ^a							
	U-238	U-234	Th-230	Ra-226	Pb-210	Po-210	Th-232	Th-228
Phosphate Ore	29 ± 3	29 ± 3	54 ± 11	31 ± 9	41 ± 2	33 ± 3	0.20 ± 0.23	0.20 ± 0.23
Phosphate Ore	<u>24 ± 2</u>	<u>23 ± 2</u>	<u>24 ± 6</u>	<u>21 ± 6</u>	<u>34 ± 2</u>	<u>38 ± 3</u>	<u>0.32 ± 0.30</u>	<u>0.84 ± 0.50</u>
Average ^b	27 ± 2	26 ± 2	39 ± 6	26 ± 5	38 ± 1	36 ± 2	0.26 ± 0.19	0.52 ± 0.28
Nodules	26 ± 2	26 ± 2	51 ± 11	21 ± 6	22 ± 2	2.7 ± 3.9	0.06 ± 0.13	0.06 ± 0.13
Coke	0.24 ± 0.10	0.31 ± 0.12	0.31 ± 0.29	0.11 ± 0.03	0.52 ± 0.76	0.3 ± 2.8	0.06 ± 0.13	0.06 ± 0.13
Silica	0.14 ± 0.07	0.24 ± 0.09	0.48 ± 0.31	0.18 ± 0.05	0.55 ± 0.78	-0.3 ± 2.7	0.04 ± 0.09	0.04 ± 0.09
Fresh Slag	26 ± 2	26 ± 2	54 ± 13	31 ± 9	0.53 ± 0.90	0.0 ± 2.8	0.76 ± 0.47	0.43 ± 0.21
Fresh Slag	<u>25 ± 4</u>	<u>25 ± 4</u>	<u>46 ± 14</u>	<u>28 ± 8</u>	<u>-1.4 ± 1.8</u>	<u>1.8 ± 3.1</u>	<u>1.1 ± 0.6</u>	<u>0.07 ± 0.14</u>
Average ^b	26 ± 2	26 ± 2	50 ± 10	30 ± 6	-0.4 ± 1.0	0.9 ± 2.1	0.93 ± 0.38	0.25 ± 0.13
Ferrophosphorus	11 ± 3	7.6 ± 2.1	0.56 ± 0.44	0.35 ± 0.11	0.79 ± 0.88	-0.9 ± 2.5	0.08 ± 0.16	0.08 ± 0.16
Ferrophosphorus	<u>10 ± 3</u>	<u>9.6 ± 3.1</u>	<u>0.45 ± 0.38</u>	<u>0.39 ± 0.12</u>	<u>0.67 ± 1.7</u>	<u>0.6 ± 2.9</u>	<u>0.07 ± 0.15</u>	<u>0.07 ± 0.15</u>
Average ^b	11 ± 2	8.6 ± 1.9	0.51 ± 0.29	0.37 ± 0.08	0.73 ± 0.96	-0.2 ± 1.9	0.08 ± 0.11	0.08 ± 0.11
Slag, Drum Site 1	20 ± 2	20 ± 2	37 ± 8	24 ± 7	1.3 ± 0.9	6.8 ± 4.1	0.21 ± 0.21	0.21 ± 0.21
Slag, Drum Site 2	26 ± 2	26 ± 2	58 ± 18	29 ± 9	1.5 ± 0.8	1.1 ± 5.5	0.36 ± 0.28	0.95 ± 0.71
Slag, Drum Site 3	22 ± 2	22 ± 2	46 ± 18	21 ± 6	1.7 ± 1.3	1.4 ± 5.6	0.42 ± 0.28	0.73 ± 0.59
Slag, Drum Site 4	<u>26 ± 2</u>	<u>26 ± 2</u>	<u>39 ± 8</u>	<u>34 ± 10</u>	<u>2.6 ± 1.3</u>	<u>0.32 ± 2.1</u>	<u>0.57 ± 0.33</u>	<u>0.58 ± 0.41</u>
Average ^b	24 ± 1	24 ± 1	45 ± 7	27 ± 4	1.8 ± 0.6	2.7 ± 2.3	0.39 ± 0.14	0.62 ± 0.26

a Picocuries (10^{-12} curies) per gram plus or minus the standard deviation based on counting statistics.

b Counting statistic standard deviation propagated to average result.

ground of 0.001 to 0.003 pCi/m³. The polonium-210 concentration of 0.0043 ± 0.0028 pCi/m³ is in the range of expected background. Using the hourly average wind speed and direction data provided by Stauffer the estimated polonium-210 concentrations at the drive-in theater site were calculated. The estimates were made using a Gaussian plume diffusion model and Pasquill's diffusion categories (8). The calculated concentrations for the three sampling periods, including an estimated background of 0.001 pCi/m³, were 0.027, 0.003, and 0.001 pCi/m³. Of the first result, 0.021 pCi/m³ was due to a 1-hour observation with an average wind speed of 0.8 km/h, and the background site was 1.6 km from the plant. If that 1-hour observation is not used in the calculations the predicted concentration becomes 0.006 pCi/m³. From the calculations it is obvious that some polonium-210 above background would be expected at the drive-in theater site under the meteorological conditions observed on October 19-20 and 27-28. Considering the sensitivity of the predictive model to proper selection of stability factors and precise wind direction measurement, the measured values for polonium-210 concentration are believed to be valid.

TABLE 2. AMBIENT RADON-222 CONCENTRATIONS

Date	Time		Concentration (nCi/m ³) ^a
	On	Off	
10/17	0910	1418	0.39 ± 0.10
10/17	1440	1758	0.16 ± 0.06
10/18	1032	1319	0.32 ± 0.09
10/18	1320	1635	0.20 ± 0.09
10/22	1058	1314	0.13 ± 0.06
10/22	1315	1605	0.12 ± 0.04 ^b
10/22	1606	1859	0.17 ± 0.05

a Nanocuries (10⁻⁹ curies) per cubic meter plus or minus twice the standard deviation based on counting results only.

b Derived from duplicate samples.

TABLE 3. AMBIENT AND STACK PARTICULATE RADIOACTIVITY CONCENTRATIONS

Source	Time - Date Collected	Radioactivity Concentrations (pCi/m ³) ^a							
		U-238	U-234	Th-230	Ra-226	Pb-210	Po-210	Th-232	Th-228
Ambient Air	2355 - 10/18 0022 - 10/21	0.000049 ± 0.000076	0.00007 ± 0.00013	0.00008 ± 0.00035	-0.00013 ± 0.00045	0.020 ± 0.002	0.020 ± 0.002	0.00007 ± 0.00024	0.00008 ± 0.00018
Ambient Air	0026 - 10/26 0021 - 10/28	0.00016 ± 0.00010	0.00014 ± 0.00014	0.00037 ± 0.00039	0.00001 ± 0.00043	0.0074 ± 0.0023	0.029 ± 0.005	0.00009 ± 0.00025	0.00010 ± 0.00018
Ambient Air	0030 - 10/28 0049 - 10/30	0.00014 ± 0.00010	0.00013 ± 0.00014	0.00010 ± 0.00034	-0.00006 ± 0.00045	0.0074 ± 0.0014	0.0043 ± 0.0028	0.00008 ± 0.00025	0.00009 ± 0.00018
Kiln Feed Conveyor	0852 - 1032 10/30/79	-0.01 ± 0.22	0.12 ± 0.30	-0.02 ± 0.68	0.03 ± 0.42	0.7 ± 2.9	1.1 ± 1.4	-0.10 ± 0.44	-0.05 ± 0.42
Kiln Feed Conveyor	1305 - 1510 10/30/79	-0.01 ± 0.21	-0.02 ± 0.28	-0.03 ± 0.66	0.10 ± 0.42	0.3 ± 2.7	0.6 ± 1.3	-0.12 ± 0.42	-0.05 ± 0.40
Kiln 1 Scrubber Exhaust	1324 - 1627 10/25/79	0.34 ± 0.20	0.45 ± 0.26	0.26 ± 0.58	0.45 ± 0.34	380 ± 34	190 ± 27	-0.07 ± 0.33	-0.03 ± 0.32
Kiln 1 Scrubber Exhaust	1718 - 1943 10/25/79	0.32 ± 0.20	0.17 ± 0.24	0.42 ± 0.67	0.39 ± 0.34	420 ± 35	250 ± 28	-0.06 ± 0.35	-0.02 ± 0.34
Kiln 1 Scrubber Exhaust	1046 - 1701 10/26/79	0.19 ± 0.20	0.10 ± 0.25	-0.01 ± 0.15	0.40 ± 0.36	210 ± 7	290 ± 14	-0.07 ± 0.36	-0.03 ± 0.35
Nodule Cooler	0940 - 1610 10/19/79	0.36 ± 0.26	0.28 ± 0.31	0.4 ± 1.2	0.63 ± 0.45	0.3 ± 2.8	11 ± 3	-0.08 ± 0.45	-0.03 ± 0.43
Nodule Cooler	0941 - 1612 ^b 10/19/79	0.05 ± 0.18	0.05 ± 0.24	0.08 ± 0.56	0.06 ± 0.33	0.1 ± 2.2	7.4 ± 1.8	0.02 ± 0.39	0.06 ± 0.38
Nodule Cooler	0956 - 1225 ^b 10/24/79	-0.07 ± 0.18	-0.07 ± 0.24	-0.02 ± 0.55	0.20 ± 0.35	0.7 ± 2.4	0.8 ± 1.1	-0.08 ± 0.36	-0.04 ± 0.34

(continued)

TABLE 3. (Continued)

Source	Time - Date Collected	Radioactivity Concentrations (pCi/m ³) ^a							
		U-238	U-234	Th-230	Ra-226	Pb-210	Po-210	Th-232	Th-228
Kiln Building Ventilator	1305 - 1553 10/19/70	0.37 ± 0.29	0.37 ± 0.32	0.51 ± 0.77	0.57 ± 0.37	1.3 ± 2.2	0.19 ± 0.94	-0.02 ± 0.34	0.01 ± 0.33
Kiln Building Ventilator	0955 - 1225 10/24/79	0.36 ± 0.32	0.51 ± 0.41	1.3 ± 1.1	0.77 ± 0.51	0.02 ± 3.2	-0.4 ± 1.4	-0.11 ± 0.49	0.06 ± 0.47
Kiln Building Ventilator	1000 - 1224 10/24/79	0.29 ± 0.20	0.29 ± 0.23	0.29 ± 0.44	0.42 ± 0.29	0.5 ± 1.7	-0.14 ± 0.69	-0.06 ± 0.25	-0.03 ± 0.24
Silo System Exhaust	1015 - 1221 10/29/79	0.23 ± 0.21	0.32 ± 0.26	0.39 ± 0.58	0.77 ± 0.39	1.2 ± 2.0	0 ± 1.5	0.05 ± 0.35	0.08 ± 0.34
Silo System Exhaust	1421 - 1624 10/29/79	-0.06 ± 0.14	-0.06 ± 0.18	-0.03 ± 0.43	-0.11 ± 0.26	0.7 ± 1.8	0 ± 1.2	-0.08 ± 0.26	-0.05 ± 0.25
Tap Hole Fume Scrubber	1550 - 1805 10/16/79	0.01 ± 0.14	0.04 ± 0.18	-0.01 ± 0.41	-0.10 ± 0.25	0.6 ± 1.7	0 ± 0.75	-0.06 ± 0.26	-0.03 ± 0.25
Tap Hole Fume Scrubber	0935 - 1145 10/17/79	-0.04 ± 0.14	-0.06 ± 0.18	-0.02 ± 0.41	-0.04 ± 0.25	7.9 ± 1.1	15 ± 5.4	-0.07 ± 0.26	-0.04 ± 0.25
Tap Hole Fume Scrubber	1435 - 1637 10/17/79	-0.01 ± 0.14	-0.01 ± 0.18	-0.02 ± 0.43	-0.18 ± 0.26	4.2 ± 0.8	3.1 ± 3.9	-0.06 ± 0.27	-0.03 ± 0.26

^a Picocuries (10⁻¹² curies) per cubic meter plus or minus twice the standard deviation based on counting results only.

^b Results derived from duplicate samples.

EMISSION SAMPLES

Radon sampling results are shown in Table 4. Gross concentrations measured in the stacks, net concentrations above the measured ambient concentrations and average concentrations are given along with the derived annual emission rates. Annual emission rates were calculated assuming full-time operation of the process and annual average concentrations equal to the average obtained from the samples.

Two sources, the kilns and the silo system exhaust, had average concentrations which were significantly different from ambient. Net average radon concentrations were 12 ± 11 and 0.12 ± 0.17 nCi/m³ respectively. The associated annual releases were 8.2 and 0.034 curies. Thus, the kilns were responsible for essentially all the radon emitted from the plant stacks.

Particulate radioactivity concentrations measured in stack emissions are given in Table 3. These concentrations are calculated using the radionuclide activity on the filter media and the sample volume corrected to stack conditions. Using these values, the stack emission rates (pCi/sec) were determined and summarized in Table 5. These rates are calculated from the ratio of the stack flow rate (in standard ft³/hr, dry) to the sample volume (standard ft³, dry). Specific stack test and sample parameters are contained in the emission test report (5). PEDCo Environmental has calculated and summarized these ratios or "scaling factors."

Radioanalytical results for the kiln feed conveyor exhaust samples were not significantly different from zero. PEDCo reported an average mass emission rate from this source of 0.98 pounds per hour (0.12 g/sec). Using the measured radioactivity in ore, each of the uranium chain radionuclides should have been emitted at the rate of 4 pCi/sec from the kiln feed conveyor exhaust.

The emission rates of uranium-238 and -234, thorium-230, and radium-226 in the kiln scrubber exhaust averaged about 3.6 pCi/sec. Emission rates of lead-210 and polonium-210 from the kiln scrubber exhaust were 4,500 pCi/sec and 3,200 pCi/sec, respectively.

Measured concentrations and emission rates of uranium-238 and -234, thorium-230, radium-226, and lead-210 from the nodule cooler did not differ significantly from zero. Based on the measured mass emission rates and radioactivity of the nodules the best estimate of the release rates of each of those radionuclides would be 2.7 pCi/sec. Only polonium-210 was measured at concentrations significantly above zero. The average emission rate was 50 pCi/sec.

The kiln building ventilator is the major controlled source of particulates. As a consequence it was also the major source of uranium-238 and -234, thorium-230, and radium-226. Emissions of each of those radionuclides plus lead-210 averaged 15 pCi/sec.

TABLE 4. RADON-222 STACK EMISSIONS

Source	Time	Date	Concentration (nCi/m ³) ^a		Annual Release (Ci)
			Gross ^b	Net ^c	
Kiln Feed Conveyor	1106 - 1320	10/18	0.36 ± 0.13	0.04 ± 0.16	0.013
	1320 - 1623	10/18	0.23 ± 0.11	0.03 ± 0.14	
	1041 - 1309	10/22 ^d	0.22 ± 0.04	0.09 ± 0.07	
		Source Average		0.05 ± 0.03	
Kiln	0930 - 1328	10/18	14 ± 1	14 ± 1	4.1
	1328 - 1555	10/18	0.35 ± 0.14	0.15 ± 0.15	
	1025 - 1358	10/22 ^d	22 ± 1	22 ± 1	
		Source Average		12 ± 11	8.2
		Total for 2 kilns			
Nodule Cooler	1005 - 1420	10/18	0.33 ± 0.09	0.01 ± 0.13	0.020
	1627 - 1829	10/22 ^d	0.30 ± 0.05	0.13 ± 0.07	
		Source Average		0.07 ± 0.08	
		Total for 2 coolers			0.040
Kiln Building Ventilator	1153 - 1345	10/18	0.45 ± 0.13	0.13 ± 0.16	0.047
	1623 - 1823	10/22 ^d	0.16 ± 0.04	-0.01 ± 0.07	
		Source Average		0.06 ± 0.10	
		Total for 2 ventilators			0.094
Silo System Exhaust	1400 - 1643	10/22	0.12 ± 0.09	0.00 ± 0.10	0.034
	1646 - 1846	10/22	0.41 ± 0.04	0.24 ± 0.06	
		Source Average		0.12 ± 0.17	
Tap Hole Fume Scrubber	0933 - 1410	10/17	0.28 ± 0.10	-0.11 ± 0.14	-0.010
	1413 - 1740	10/17	0.23 ± 0.08	0.07 ± 0.10	
		Source Average		-0.02 ± 0.13	

a Nanocuries (10⁻⁹ curies) per cubic meter.

b Radon-222 concentration in sample as collected plus or minus twice the standard deviation based on counting statistics.

c Radon-222 concentration in sampling minus the concentration in ambient air during the sample collection period. Source averages are the mean of the samples plus or minus the standard deviation based on sample variance about the mean.

d Results derived from duplicate samples.

TABLE 5. PARTICULATE RADIOACTIVITY EMISSION RATES

		Radioactivity Emission Rates (pCi/sec) ^a							
Source	Time - Date Collected	U-238	U-234	Th-230	Ra-226	Pb-210	Po-210	Th-232	Th-228
Kiln Feed Conveyor	0852 - 1032 10/30/79	-0.13	1.2 ± 3.0	-0.22 ± 6.7	0.27 ± 4.2	7.2 ± 28	11 ± 13	-0.93 ± 4.3	-0.45 ± 4.2
Kiln Feed Conveyor	1305 - 1510 10/30/79	-0.9	-0.22 ± 2.8	-0.30 ± 6.5	1.0 ± 4.2	2.7 ± 27	5.7 ± 13	-1.2 ± 4.2	-0.52 ± 4.0
	Average	-0.11 ± 1.6	0.5 ± 2.1	-0.26 ± 4.7	0.64 ± 3.0	5.0 ± 19	8.4 ± 9.2	-1.1 ± 3.0	-0.49 ± 2.9
Kiln 1, Scrubber Exhaust	1324 - 1627 10/25/79	4.6 ± 2.7	6.0 ± 3.5	3.5 ± 7.8	6.0 ± 4.7	5000 ± 470	2500 ± 14	-0.97 ± 4.5	-0.47 ± 4.3
Kiln 1, Scrubber Exhaust	1718 - 1943 10/25/79	4.3 ± 2.7	2.3 ± 3.3	5.7 ± 9.0	5.2 ± 4.7	5800 ± 480	3300 ± 380	-0.80 ± 4.8	-0.28 ± 4.7
Kiln 1, Scrubber Exhaust	1046 - 1701 10/26/79	2.5 ± 2.6	1.3 ± 3.2	-0.13 ± 1.8	5.2 ± 4.5	2700 ± 100	3800 ± 180	-0.88 ± 4.7	-0.37 ± 4.5
	Average	3.8 ± 1.5	3.2 ± 1.9	1.9 ± 4.0	5.5 ± 2.7	4500 ± 230	3200 ± 140	-0.88 ± 2.7	-0.37 ± 2.6
Module Cooler	0940 - 1610 ^b 10/19/79	1.9 ± 1.5	1.0 ± 1.8	2.0 ± 5.8	3.0 ± 2.6	1.9 ± 17	85 ± 16	-0.24 ± 2.8	0.45 ± 2.7
Module Cooler	0956 - 1225 10/24/79	-1.3 ± 3.2	-1.3 ± 4.3	-0.33 ± 9.9	3.6 ± 6.2	13 ± 43	14 ± 20	-1.4 ± 6.4	-0.66 ± 6.1
	Source Average	0.30 ± 1.8	-0.15 ± 2.3	0.84 ± 5.7	3.3 ± 3.4	7.5 ± 23	50 ± 13	-0.82 ± 3.5	-0.11 ± 3.3
Kiln Building Ventilator	1305 - 1553 10/19/79	7.6 ± 5.9	7.6 ± 6.6	10 ± 16	12 ± 7.6	27 ± 44	4.0 ± 19	-0.48 ± 7.0	0.28 ± 6.7
Kiln Building Ventilator	0955 - 1225 ^b 10/24/79	12 ± 6.6	15 ± 8.6	28 ± 21	21 ± 11	9.0 ± 63	-9.0 ± 28	-3.1 ± 9.7	0.45 ± 9.6
	Source Average	9.8 ± 4.5	11 ± 5.4	19 ± 14	17 ± 6.7	18 ± 38	-2.5 ± 17	-1.8 ± 6.0	0.37 ± 5.9
Silo System Exhaust	1015 - 1221 10/29/79	2.5 ± 2.2	3.4 ± 2.8	4.1 ± 6.1	8.2 ± 4.1	12 ± 22	0 ± 16	0.51 ± 3.7	0.88 ± 3.6
Silo System Exhaust	1421 - 1624 10/29/79	-0.72 ± 1.7	-0.72 ± 2.2	0.41 ± 5.1	1.3 ± 3.2	7.9 ± 22	0 ± 14	-0.96 ± 3.2	-0.58 ± 3.0
	Average	0.89 ± 1.4	1.3 ± 1.8	2.3 ± 4.0	4.8 ± 2.6	10 ± 16	0 ± 11	-0.23 ± 2.4	-0.15 ± 2.3
Tap Hole Fume Scrubber	1550 - 1805 10/16/79	0.2 ± 2.6	0.70 ± 3.4	0.25 ± 7.7	1.9 ± 4.6	12 ± 32	0 ± 14	-1.1 ± 4.9	-0.5 ± 4.7
Tap Hole Fume Scrubber	0935 - 1145 10/17/79	-0.83 ± 2.6	-1.1 ± 3.4	-0.42 ± 7.9	-0.73 ± 4.8	150 ± 21	290 ± 100	-1.2 ± 5.0	-0.68 ± 4.8
Tap Hole Fume Scrubber	1435 - 1637 10/17/79	-0.15 ± 2.5	-0.15 ± 3.3	-0.35 ± 7.7	-3.3 ± 4.7	75 ± 15	55 ± 70	-1.2 ± 4.9	-0.61 ± 4.7
	Time-Weighted Average ^c					43 ± 13	85 ± 33		

^a Picocuries (10⁻¹² curies) per cubic meter.

^b Results derived from duplicate sample

^c Emission rates of nuclides other than Pb-210 and Po-210 were insignificant.

The average emission rates of the uranium chain radionuclides, less polonium-210, from the silo system exhaust was measured at 3.8 pCi/sec. Assuming that the particulate material sampled was due to nodule handling and that the radioactivity concentration of the particulates was the same as the nodules, the average emission rate of each, based on the mass emission rate, would be 3.1 pCi/sec, very close to the measured radioactivity emission rate.

The collection period of each tap hole fume scrubber sample included times when a furnace was being flushed or tapped. Analysis of the data showed that the primary source of lead-210 and polonium-210 from the source was FeP tapping. As shown in Table 3, the concentrations of other radionuclides did not differ significantly from zero and lead-210 and polonium-210 concentrations varied widely between samples. The time-weighted average emission rates based on 2-days tap and flush records and the three sample results were 43 pCi/sec for lead-210 and 85 pCi/sec for polonium-210.

Table 6 shows the annual emission rates calculated for each operation. These emission rates include the sum of two kiln stacks, two nodule cooler stacks, and two kiln building ventilator stacks. Approximately 99 percent of the lead-210 and 97 percent of polonium-210 emissions occur from the kiln stacks. The process sample results show that essentially all of the lead-210 and polonium-210 is driven off in the kiln and furnace. The observed difference in kiln annual emissions of 280 mCi and 200 mCi, may be real, due to different removal rates in pollution control equipment, or may be an artifact of analysis. The kilns also emit several tenths of a curie per year of the other uranium chain radionuclides, but most of them - about 1 Ci per year - are released from the kiln building ventilator systems.

The removal of radionuclides by emission control systems was determined on the number 1 kiln scrubber and the tap hole fume scrubber. As is common with kilns, Stauffer uses an effluent control system of multiple control devices in series. It was possible to obtain simultaneous samples on the inlet and outlet of the final stage scrubber. Simultaneous samples were also obtained at the inlet and outlet of the tap hole fume scrubber. The results are shown in Table 7. The kiln scrubber removed 75 percent of the total mass entering it. The average removal for uranium, thorium, and radium was essentially identical at 78 percent. Both lead-210 and polonium-210 showed a 54 percent removal. Only lead-210 and polonium-210 could be evaluated in the tap hole fume scrubber. The fume scrubber removed an average of 86 percent of those nuclides, compared to 91 percent of the mass. Lead and polonium, presumed to be present as fumes after condensing from vapors, are apparently more readily removed in the tap hole fume scrubber than in the kiln scrubber which is designed to remove particulates.

RADON EMANATION RESULTS

Radon emanation rates from soil around the plant generally ranged from 12 to 31 pCi/m²-min with an average of 21 ± 6 (Table 8). If two low results of 2.0 and 4.2 pCi/m²-min are included the average is 18 ± 9 . Radon emanation from the top of the ore pile covered with roaster residue average 53 ± 35 pCi/m²-min. Considerable difference was found between the emanation rates

TABLE 6. PARTICULATE RADIOACTIVITY ANNUAL EMISSION RATES

Source	Annual Emission Rate (mCi/y) ^a							
	U-238	U-234	Th-230	Ra-226	Pb-210	Po-210	Th-232	Th-228
Kiln Feed Conveyor	-0.003 ± 0.050	0.016 ± 0.066	-0.008 ± 0.15	0.020 ± 0.095	0.16 ± 0.60	0.26 ± 0.29	0.035 ± 0.095	-0.015 ± 0.091
Kiln 1 plus Kiln 2	0.24 ± 0.09	0.20 ± 0.12	0.12 ± 0.25	0.35 ± 0.17	280 ± 15	200 ± 7	-0.06 ± 0.17	-0.02 ± 0.16
Nodule Cooler 1 plus Nodule Cooler 2	0.02 ± 0.11	-0.009 ± 0.15	0.05 ± 0.36	0.21 ± 0.21	0.47 ± 1.5	3.2 ± 0.8	-0.05 ± 0.22	0.007 ± 0.21
Kiln Building Ventilator	0.62 ± 0.28	0.70 ± 0.34	1.2 ± 0.9	1.1 ± 0.4	1.1 ± 2.4	-0.16 ± 1.1	-0.12 ± 0.38	0.02 ± 0.38
Silo System Exhaust	0.028 ± 0.044	0.041 ± 0.057	0.07 ± 0.13	0.15 ± 0.08	0.32 ± 0.50	0 ± 0.35	-0.007 ± 0.076	-0.005 ± 0.073
Tap Hole Fume Scrubber ^b					1.4 ± 0.4	2.7 ± 1.0		

^a Millicuries (10⁻³ curies) per year plus or minus twice the standard deviation based on counting results only.

^b Emissions of nuclides other than Pb-210 and Po-210 were insignificant and time-weighted averages were not determined.

measured from the east berm of the ore pile and the west berm. The three measurements from the east berm averaged 310 ± 140 pCi/m²-min while those from the west berm averaged 36 ± 20 pCi/m²-min. No explanation has been found to explain the difference between the two berms. The average radon emanation rate from the ore pile was 110 ± 70 pCi/m²-min. The radon emanation rate from the ore pile in use should have been about equal to the berm average, or 170 ± 140 pCi/m²-min. Radon emanation rates measured on the slag pile averaged 3.5 ± 3.7 pCi/m²-min.

Radon emanation rates from soil were comparable to those measured at other locations in the United States as part of this survey, but were below the reported National average value of 35 pCi/m²-min (9).

It is estimated that the covered ore pile emits radon at the rate of 1.2 ± 0.8 μ Ci/min. The uncovered ore pile is estimated to release radon at the rate of 1.9 ± 1.5 μ Ci/min. The radon which would have been released from the soil beneath the ore piles was about 0.2 μ Ci/min. The net radon emanation rate for the two piles would be 1.0 ± 0.8 μ Ci/min or 0.53 Ci/year for the covered pile and 1.7 ± 1.5 μ Ci/min or 0.89 Ci/year for the pile in use.

Radon emanated from the slag pile at the rate of 0.8 μ Ci/min compared to an emission rate from the soil beneath of 0.4 μ Ci/min. The radon reduction provided by the slag cover is estimated to be 0.32 μ Ci/min or 0.17 Ci/year.

The net radon emanation rate from the ore and slag piles during the survey was estimated at 1.2 Ci/year. However, during part of the year only a portion of one ore pile would be in existence and snow and ice cover during the winter would reduce the radon emanation rate.

TABLE 7. SCRUBBER REMOVAL OF RADIONUCLIDES

Location	Fraction Removed (Percent)								Mass
	U-238	U-234	Th-230	Ra-226	U,Th,Ra Average	Pb-210	Po-210	Pb,Po Average	
Kiln 1	71	59	76	59	66	37	58	48	75
Kiln 1	85	93	85	81	86	68	66	67	74
<u>Kiln 1</u>	<u>69</u>	<u>87</u>	<u>100</u>	<u>69</u>	<u>81</u>	<u>57</u>	<u>38</u>	<u>48</u>	<u>76</u>
Average	75	80	87	70	78	54	54	54	75
Tape Hole Fume Scrubber						95	100	98	100
<u>Tape Hole Fume Scrubber</u>						<u>73</u>	<u>75</u>	<u>74</u>	<u>81</u>
Average						84	88	86	91

TABLE 8. RADON-222 EMANATION RATES FROM SOIL, ORE, AND SLAG

Soil		Ore Pile		Slag Pile	
Site	Emanation Rate (pCi/m ² -min)	Site	Emanation Rate (pCi/m ² -min)	Site	Emanation Rate (pCi/m ² -min)
1	18	<u>Top</u>			
2	17	1	75	1	1.8
3	22	2	100	2	8.6
4	18	3	22	3	3.3
5	4.2	4	30	4	0.1
6	12	5	35	Average	3.5 ± 3.7
7	24	Average	53 ± 34		
8	28				
9	13	<u>East Berm</u>			
10	25	6	150		
11	2.0	7	390		
12	31	8	380		
Average	18 ± 9	Average	310 ± 140		
		<u>West Berm</u>			
		9	13		
		10	48		
		11	47		
		Average	36 ± 20		

SECTION 7

POPULATION DISTRIBUTION

The Stauffer Chemical Company plant is located in a sparsely populated area. The processing facility is situated, as shown in Figure 4, near the east center portion of a company-owned site about 1 mile (1.6 km) square which is fenced to restrict access. Several ranches are located west of the plant, with the nearest residence in that direction being about 2 km away. One family lives at the drive-in theater 1.6 km east of the plant. Several residences are occupied in Silver Bow about 2.5 km northeast and about 50 people live in Ramsey, about the same distance to the north-northwest.

SECTION 8

DISCUSSION OF RESULTS

As mentioned earlier, analytical biases can result in consistent differences in activity levels between radionuclides of a decay chain that would normally have very nearly the same radioactivity. This can be seen in the process sample results of Table 1 and kiln building ventilator results in Tables 3, 5, and 6. Radionuclides of the uranium decay chain through radium-226 in ore, modules, and slag and probably in ventilator exhaust particulates should be at nearly equilibrium values.

Other results reported by EIC on known activity samples have shown similar biases with thorium-230 being about twice the activity of the other samples. Evaluation of those results has shown that thorium analyses by EIC have been more accurate than the others. Therefore, it is believed that the thorium-230 results reported for the samples mentioned are more representative of the uranium chain activities than the other radionuclides. However, no attempt has been made in this report to apply any correction to the data. More important than the specific radioactivities are the fractions of the radioactivity in the process which are emitted from the stack. Since the biases are probably consistent, the fractional values are considered to be valid.

A major environmental protection problem associated with thermal processing of phosphate is the emission of fluorides to the atmosphere. To combat that problem and control particulate emissions Stauffer uses multiple air cleaning systems in series on its kilns, nodule coolers, and kiln building ventilators. Although radioactive emissions were not a consideration when the pollution control system was installed, it removed large fractions of the particulate radionuclides and smaller, but still significant, fractions of the more volatile lead-210 and polonium-210.

Each exhaust stack emits a portion of the particulate material controlled by the exhaust system. Due to the above-average concentrations of naturally-occurring radioactivity in the process materials the particulate emissions result in radioactive emissions. Most of the radioactive particulate emissions from controlled sources come from the kiln building ventilator. Next in importance is the kiln. The kiln probably generates more airborne particulates, but because of the more complex pollution control system actually emits less than the ventilator.

The average measured emissions of uranium-234 and -238, thorium-230, and radium-226 from all controlled sources were 1.3 mCi/year. A better estimate is probably derived from the measured mass emission rates. Assuming that the particulate material, except for the tap hole fumes, are similar to ore in radionuclide concentration the calculated total emissions of each of the four radionuclides is 4.2 mCi/year.

The nodule cooler and tap hole fume scrubber are small sources of lead-210 and polonium-210. The kilns, however, are the major source, releasing 99 and 97 percent, respectively, of the total plant emissions of those nuclides.

As with lead-210 and polonium-210, the kilns are the major source of radon emissions. The average measured emission rate of 8.2 Ci/year may be low since it is based on results from four samples, one of which was extremely low. The estimate of 1.5 Ci/year of radon from the ore pile is probably an upper limit, considering the actual area of the ore piles averaged over the year and the effect of winter rain, snow, and ice on reducing emanation rates.

Comparison of radioactivity removed by the kiln scrubber and tap hole fume scrubber demonstrated that the fume scrubber removed the larger fraction of the lead-210 and polonium-210 from the exhaust gases. Within the limits of sampling and analytical accuracy, the kiln scrubber removes the other, nonvolatile radionuclides in the same proportion as total suspended particulates. As would be expected for a noble gas, no removal of radon was exhibited by the kiln scrubber.

Although slag was found to contain about as much radium-226 as the original ore it was found to not be a source of radon, as is the ore. The physical form of the slag, even when somewhat frothy in appearance reduces the rate at which radon gas is able to escape. Slag pile sites sampled included slag which has been in place for a few days to several weeks so that at some sites the radon would have been in equilibrium with radium-226. Gamma exposure rates were significant on the slag pile, averaging 0.15 milliroentgen per hour (mR/h). Ambient background gamma exposure rates were about 0.01 mR/h.

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TECHNICAL REPORT DATA <i>(Please read Instructions on the reverse before completing)</i>		
1. REPORT NO. EPA-520/6-82-019	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Emissions of Naturally Occurring Radioactivity: Stauffer Elemental Phosphorus Plant	5. REPORT DATE November 1982	
	6. PERFORMING ORGANIZATION CODE	
7. AUTHOR(S) Vernon E. Andrews	8. PERFORMING ORGANIZATION REPORT NO.	
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Environmental Protection Agency Office of Radiation Programs-Las Vegas Facility P.O. Box 18416 Las Vegas, Nevada 89114	10. PROGRAM ELEMENT NO.	
	11. CONTRACT/GRANT NO.	
12. SPONSORING AGENCY NAME AND ADDRESS Same as above	13. TYPE OF REPORT AND PERIOD COVERED	
	14. SPONSORING AGENCY CODE	
15. SUPPLEMENTARY NOTES This is the third in a series of reports covering work performed in response to the 1977 Clean Air Act Amendments		
16. ABSTRACT Naturally occurring radioactivity was measured in the atmospheric emissions and process materials of a thermal phosphate (elemental phosphorus) plant. Representative exhaust stack samples were collected from each process in the plant. The phosphate ore contained about 120 parts per million uranium. The radioactivity emitted in greatest quantity was radon-222 with an annual release from the plant of 8.3 curies. Emissions of lead-210 and polonium-210 were measured at 280 and 200 millicuries per year. Annual emissions of each of the other radionuclides of the uranium decay chain were estimated to be 4.2 millicuries. The slag pile was determined not to be a source of radon.		
17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Natural radioactivity Airborne wastes Exhaust gases	Technologically enhanced radioactivity	1808 1302 2102
18. DISTRIBUTION STATEMENT Release to public	19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES 28
	20. SECURITY CLASS (This page) Unclassified	22. PRICE

Appendix 1-I

**Evaluation of Radon Sources and Phosphate Slag in Butte,
Montana, June 1983**

EVALUATION OF RADON SOURCES AND
PHOSPHATE SLAG IN BUTTE, MONTANA

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Occupational Health Bureau
Montana Department of Health
and Environmental Sciences

This report was prepared under
EPA Contract No. 68-01-6100.

June, 1983

DISCLAIMER

The work upon which this report is based was supported in part by funds provided by the U. S. Environmental Protection Agency, Office of Radiation Programs.

Contents of this report do not necessarily reflect the views and policies of the U. S. Environmental Protection Agency. Mention of trade names or commercial products does not constitute their endorsement or recommendation for use by the U. S. Environmental Protection Agency or by the Montana Department of Health and Environmental Sciences.

ACKNOWLEDGEMENTS

This project was made possible by the U. S. Environmental Protection Agency's (EPA) Office of Radiation Programs through a contract (EPA Contract No. 68-01-6100) with the Montana Department of Health and Environmental Sciences (DHES).

It could not have been completed without the cooperation and assistance of numerous federal, state, and local governmental agencies, private individuals, and particularly the homeowners in Butte, Montana, and the surrounding areas.

The EPA's Las Vegas Facility and the Eastern Environmental Radiation Facility (Montgomery) provided both technical and laboratory support as needed throughout the duration of the study.

The U. S. Bureau of Mines provided radon and radon progeny calibration facilities and technical consultation at its Denver Research Center. The Bureau of Mines' Spokane Research Center computerized the bulk of the data acquired by DHES in addition to available geological information pertaining to the Butte area. The Bureau of Mines computer was used for data comparison and evaluation and for the graphic production of numerous figures in Section 5 of this report.

The U. S. Department of Energy's Environmental Measurement Laboratories (EML) provided DHES with semi-annual radon measurement intercomparison exchanges to assure the accuracy of radon measurement calibrations.

The Montana Bureau of Mines assisted in the evaluation and understanding of the Butte geology and with the description of the Butte geology.

The Anaconda Company provided DHES with a detailed geological map of the Butte area which was used extensively to locate veins, fractures, and surface geological formations.

The cooperation and assistance provided by the Butte/Silver Bow Government's Chief Executive's Office and Health Department helped to maintain good public relations throughout the study.

The friendly cooperation of Butte homeowners in allowing DHES to perform measurements in their homes was essential to the completion of the project.

A special appreciation is expressed to the DHES staff members who conducted the field operations of the study. Their continued commitment to detail, quality assurance, and accurate data collection was paramount to the successful conclusion of this project.

FOREWORD

In 1977, DHES initiated an investigation of phosphate slag use in the Butte and Anaconda areas. Phosphate slag, generated as a byproduct of an elemental phosphorous smelter, was of concern because of its elevated content of natural radioactivity, particularly radium-226.

During the investigation of phosphate slag, DHES discovered elevated radon and radon progeny concentrations in Butte structures. The cause of these elevated concentrations was unknown.

DHES requested assistance from the EPA. The EPA's Office of Radiation Programs subsequently provided DHES with a contract (EPA Contract No. 68-01-6100) to identify the source(s) of radon and radon progeny in structures and in the ambient air in the Butte area.

This report describes the DHES investigation of phosphate slag use in the Butte area, and also the DHES study to determine the sources of elevated radon and radon progeny concentrations in Butte structures and in the ambient air.

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ABSTRACT

In 1978, DHES began investigating the potential sources of radon (radon-222) which contribute to the elevated ambient and indoor concentrations of radon and its decay products in Butte, Montana. During the early stages of the investigation, efforts were directed toward the evaluation of phosphate slag which has been used extensively for paving and graveling and building materials in the Butte area. The phosphate slag proved not to be a significant source of radon.

In July, 1980, DHES contracted with the EPA to further investigate the potential sources of radon in Butte. Under the agreement with EPA, surface geological constituents, air, water and natural gas supplies, and building materials were investigated as potential radon sources.

Butte Geology

The northern part of Butte is located on a hill interlaced with geological fractures and richly mineralized veins. Extensive mining of gold, silver, copper, manganese and other metals has been conducted on the Butte hill during the past hundred years. The most prevalent rock type in the area, commonly known as "Butte granite", is technically quartz monzonite. Aplite and alaskite dikes are prevalent in the quartz monzonite. Rhyolite, which is of volcanic origin, is found in the most northwestern part of the city. Alluvium is the prevalent geology in the southern portions of the city. The alluvium is predominantly sand and gravel that resulted from the erosion of the surrounding hills so that in gross composition it is nearly the same as the quartz monzonite, rhyolite, and aplite.

Geological Constituents

Soil samples were collected throughout the Butte area and analyzed for radium (radium-226) content. The radium content of the samples ranged from 0.7 to 3.2 picocuries per gram (pCi/gm) with a mean of 1.84 pCi/gm.

Alpha track detectors were used to measure radon soil gas concentrations during both summer and winter months. The average radon soil gas concentration measured during summer months was 1082 picocuries per liter (pCi/l), whereas the average winter concentration was 1407 pCi/l. While radon soil gas concentrations of less than 100 pCi/l were measured, concentrations in excess of 5000 pCi/l were not uncommon. The highest radon soil gas concentrations were associated with measurement sites located over major fractures and mineralized veins. The lowest concentrations were measured in rhyolite. At many measurement sites it was impossible to determine if the underlying rock was quartz monzonite or aplite or if the alluvial cover was of sufficient depth to prevent the upward migration of radon to the detector location. Consequently, it was impossible to determine radon soil gas concentration differences resulting from these different formations.

Radon exhalation tests were performed on 25 cm depths of quartz monzonite, aplite, alluvium, and mineralized vein samples. The highest

radon exhalation rates were from mineralized vein material which averaged 2139 picocuries per square meter per minute ($\text{pCi}/\text{m}^2/\text{min}$). Aplite samples showed exhalation rates ($713 \text{ pCi}/\text{m}^2/\text{min}$. average) that are about three times the exhalation rates from quartz monzonite ($237 \text{ pCi}/\text{m}^2/\text{min}$. average) and alluvium ($226 \text{ pCi}/\text{m}^2/\text{min}$. average).

Air

Radon concentrations in ambient air were monitored at the Hebgen Park station, using radon gas monitors that provided hourly data printouts, from August 1980 through August 1981. Monthly average ambient radon concentrations ranged from a high of about $3 \text{ pCi}/\text{l}$ to a low of less than $0.25 \text{ pCi}/\text{l}$. The highest concentrations were observed between August and November. Concentrations diminished through the winter months and reached a low in May and June.

Outdoor air (not considered ambient because of the location of the intake) was monitored at the Hornet Street station from February 1982 through January 1983. Outdoor radon concentrations at this location averaged $3.25 \text{ pCi}/\text{l}$ for the entire monitoring period.

Water Supplies

The Butte municipal water supply system is fed by surface water sources. Of these sources, the highest dissolved radon content measured was $69 \text{ pCi}/\text{l}$, thus eliminating water supplies as a suspect radon source.

Natural Gas

The radon content of natural gas in Butte averaged $14 \text{ pCi}/\text{l}$. This low concentration eliminated natural gas as a suspect source.

Building Materials

Radon exhalation tests were performed on numerous building materials. Building materials proved not to be a significant radon source in Butte.

Following the investigation of potential radon sources in Butte, it was concluded that ambient air, soils and surface geology all contribute to Butte's radon problem.

It is believed that homes constructed over major fractures or mineralized veins are the most severely impacted. Aplite and quartz monzonite also contribute to the problem, but to a lesser extent. Ambient air is probably a major source of indoor radon in structures having low concentrations.

1. INTRODUCTION

Many mineral deposits contain uranium and thorium as natural constituents. When these naturally-occurring radionuclides and their radioactive decay products (see Figure 1-1) are underground, they normally present no significant impact to man except for the possibility of leaching into groundwaters. These naturally-occurring radionuclides become a concern when there is an insufficient layer of overburden to provide adequate gamma radiation shielding or to prevent the occurrence of abnormal radon entry into structures built on these locations. In some instances, the occurrence of insufficient layers of protective overburden is a natural phenomenon. In other instances, the mining and processing of mineral deposits removes the protective overburden and redistributes the radioactivity. Distribution of these naturally-occurring radioactive materials can increase the public exposure to ionizing radiation.

Studies performed by DHES have confirmed that the Butte, Montana vicinity has high levels of gamma radiation resulting from both natural phenomena and the redistribution of natural radioactivity from mining and smelting operations. Also, a large number of structures in the Butte vicinity have exhibited significantly elevated concentrations of the radioactive gas radon-222 (radon) and its particulate decay products (radon progeny).

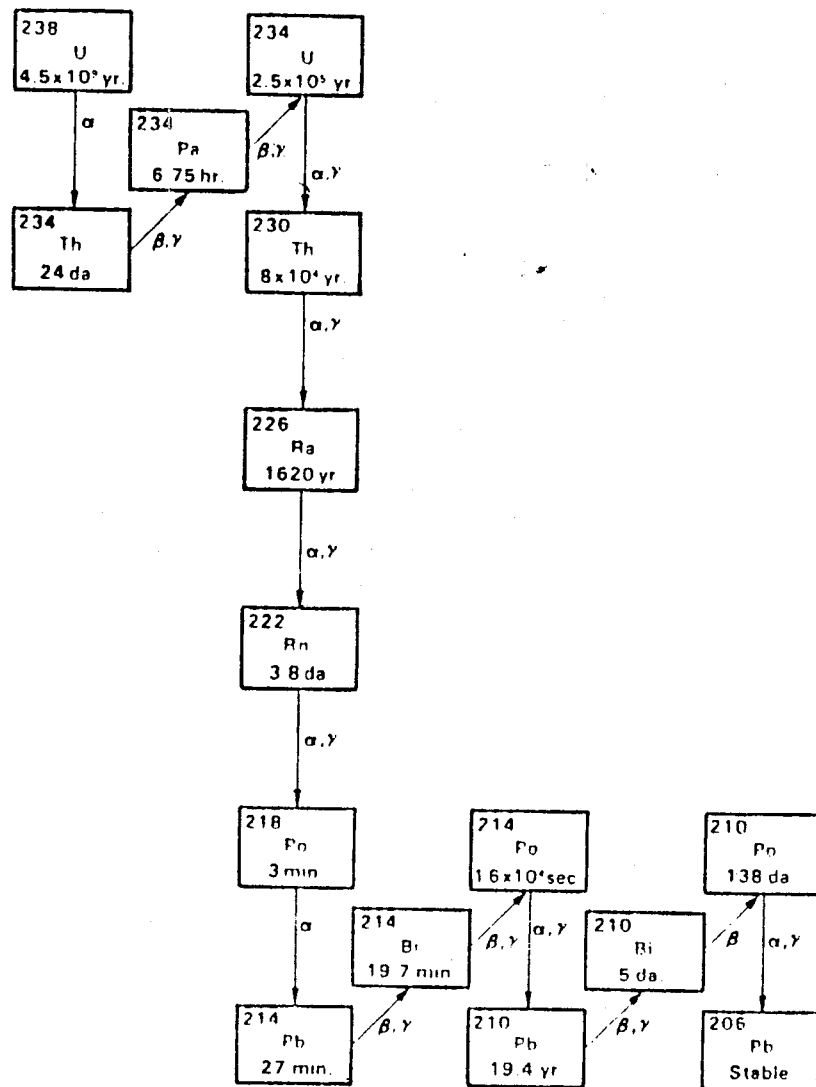
An elemental phosphorus smelter is located approximately seven miles west of Butte. In early 1977, DHES suspected that slag, which is produced as a byproduct at this smelter, was elevated in content of natural radioactivity. Slag samples were sent to the EPA Las Vegas Facility for analysis. As suspected, the EPA Laboratory reports revealed the slag to be elevated in uranium and radium-226 content.

During the period between the fall of 1977 and the spring of 1978, DHES learned that phosphate slag had been used extensively throughout the Butte area for construction purposes. Since the 1950's, slag had been used for ballast in railroad beds, for road and highway construction, for graveling roads, for building construction and for aggregate in asphalt surfacing materials.

EPA sent a van equipped with a large collimated gamma scintillation detector and a pressurized ion chamber to Butte in April, 1978. This van was used to identify locations in Butte having elevated gamma radiation levels. Data accumulated through the use of this van assisted DHES in locating numerous homes constructed with building materials containing phosphate slag.

It was suspected that the decaying radium present in concrete blocks containing phosphate slag could cause elevated radon and radon progeny concentrations in structures constructed of these materials. In April, 1978, DHES obtained from the EPA's Las Vegas Facility several Radon Progeny Integrating Sampling Unit (RPISU) instruments to measure radon progeny concentrations, and soon after began monitoring homes containing phosphate slag building materials. Numerous Butte homes were

URANIUM - 238 DECAY SERIES



THORIUM - 232 DECAY SERIES

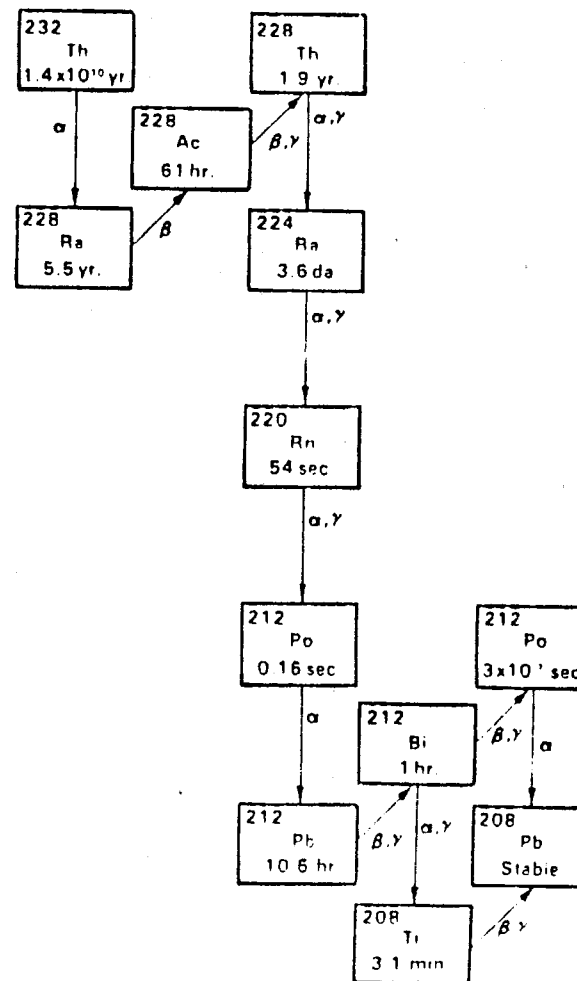


FIGURE 1-1

NATURALLY OCCURRING RADIONUCLIDES

found to have radon progeny concentrations sufficiently elevated to constitute a potential health risk.

Following this discovery, then Governor Thomas Judge was advised of the Butte area radiation problems and associated health risks. The Governor responded by supporting a program to determine the magnitude of the radiation problem, assess health risks and initiate necessary measures to protect the health and safety of the exposed people. Through the Governor's efforts, funds to initiate this program were made available July 1, 1978.

Many Butte homes having elevated radon progeny concentrations were identified by the fall of 1978, and it was determined that phosphate slag had been used extensively in the Butte and Anaconda areas for the paving and graveling of streets, parking lots, and playgrounds. Copper and manganese slags in the Butte and Anaconda areas were also found to be elevated in radioactivity, although to a lesser extent than the phosphate slag. For these reasons, DHES requested that the 1979 State Legislature fund a study to determine the extent of these radiation sources and, if necessary, initiate controls concerning the use of these materials. The legislature provided DHES with \$100,000 to conduct this study during the 1980-1981 biennium.

By early 1979, it was apparent that the source of indoor radon was not clear-cut. Some Butte structures did not contain phosphate slag, but were sampled to determine background levels. Of these structures, a number were found to have higher radon progeny concentrations than structures containing phosphate slag. It was determined that construction-related use of phosphate slag was not a principal radon source and that other sources would require investigation. It was determined that the radiation hazard associated with phosphate slag was primarily gamma radiation, and that the slag was not responsible for the elevated radon levels in Butte. Therefore, it was necessary to alter the direction of the study.

Numerous potential sources became suspect. There have been extensive disturbances to the surface and subsurface geology in the Butte area due to underground and surface mining. It was suspected that this mining activity in conjunction with the subsidence it creates and the presence of natural geologic fault zones could be causing a higher radon flux than would occur in an undisturbed location.

A study that originally appeared to be straightforward became more complex. During the original study it was envisioned that approximately 150 homes constructed with phosphate slag building materials would have to be investigated. The re-directed study required the investigation of several thousand homes.

Additional staff were needed to expand the scope of the Butte Radiation Study. In July, 1979, DHES made application to the EPA Office of Radiation Programs for a grant to enable DHES to expand the scope of the study during fiscal years 1980 and 1981. EPA awarded DHES a contract for \$81,804 to acquire data and information concerning the radon and radon progeny levels in Butte. The scope of the work

specified in the EPA/DHES contract consisted of two main tasks. The principal task was to perform measurements of radon and radon progeny inside and outside structures. The measurements were to be directed toward identifying, to the extent possible, the source of elevated radon concentrations inside structures and in the community. A second task was to emplace approximately 200 alpha-track detectors in the soil on a grid basis in the Butte area to determine radon soil-gas concentrations. The EPA and DHES agreed to keep the plan flexible in order to provide for additional work and re-direction as data was acquired.

2. BUTTE DESCRIPTION

History

Butte originated in 1864 as a gold mining camp following a placer strike. Later, underground silver mining led to the discovery of large deposits of copper and other metals, giving it the title of "the richest hill on earth." More than two hundred mines have operated in the Butte area during the past hundred years. These mines have honeycombed the Butte hill with shafts and tunnels and have littered the surface with mine wastes. During Butte's early years, nine smelters and numerous stamp mills were in operation. Subsidence resulting from underground mining is an ongoing phenomenon as the hill area continues to settle and shift.

The emphasis of mining operations in Butte shifted from underground to open pit mining in 1955 when The Anaconda Company began stripping overburden from the Berkeley Pit. In 1975 underground mining in Butte was discontinued.

The Anaconda Company was acquired by the Atlantic Richfield Company in the late 1970's. The Atlantic Richfield Company continued the Berkeley Pit operations until July, 1982, when mining in the pit ended. In early 1983, the Atlantic Richfield Company announced that its Butte mining operations would terminate on July 1, 1983.

Geography

Butte is a city with a population of approximately 25,000 people, and is situated on the west side of the Continental Divide in southwestern Montana. The city is sited on the north end of a high mountain valley which is surrounded, except to the west, by mountains. Butte has been called the "Mile High City" because its entire area is at least one mile above sea level. The Butte Airport which is located in the valley to the south of Butte has an elevation of 5540 feet.²

Climate

Severe seasonal temperature extremes are encountered in the Butte area. The annual mean temperature is 38.8°F (3.8°C) with extremes ranging from near -40°F (-40°C) to over 90°F (32°C).³ There are periods, especially during winter when the Butte area is subjected to severe atmospheric temperature inversions. During these times atmospheric pollutants are trapped in the valley bowl.

Geology

Butte lies within the Boulder Batholith, a mass of granitic rock that congealed from a molten liquid mass about 70 million years ago. The batholith is from 10-15 kilometers thick. As the liquid rock cooled, certain chemical elements became preferentially separated and as a result, different rock types were formed. The most prevalent type in the area, commonly termed the "Butte granite", is technically quartz

monzonite. Within the quartz monzonite are further effects of segregation. When the quartz monzonite solidified, aplite and alaskite dikes were still liquid or semi-liquid and were injected into cracks and fissures. Depending on the rate at which the injections cooled, aplite or alaskite resulted. Both rock types have approximately the same chemical composition, but different textures--individual grains (minerals) comprising alaskite grew to a larger size than those in aplite bodies. Another rock type commonly found in the northwest part of Butte is rhyolite. This rock also was molten, but was formed in a volcanic environment, either on the surface of the earth or in the neck of a volcano.

During the time the Boulder Batholith was created and cooled, the earth's crust was subjected to stresses coming from outside the immediate area. In addition, stress fields were established within the body as a result of cooling and solidification processes. Effects of these stresses are seen as breaks in the rocks (faults and fissures). The faults vary in size from a fraction of an inch thick to tens of feet thick and from simple tensional openings to much more complex structures with hundreds of feet of both horizontal and vertical movement. Because of their open nature, some of the faults of the Butte area provided a plumbing system for hot fluids that gave rise to many mineral deposits. In this case, veins formed along the faults and fissures. The more prominent faults, veins and rock types of Butte are shown in Figure 2-1. Although a multitude of separate veins exist at Butte, collectively they are regarded as a single deposit. Chemical zoning along particular veins both horizontally and vertically is duplicated in all of the veins so that the district as a whole exhibits zoning from a copper-rich central core to a silver-rich peripheral band.

From an areal viewpoint the most prevalent geologic unit in Butte is the alluvium along the flood plain of Silver Bow Creek and in the basin. This material is predominantly sand and gravel and resulted from the erosion of the surrounding hills so that in gross composition it is nearly the same as the quartz monzonite, rhyolite and aplite.

The Butte mineral deposit is a world class deposit. According to Meyer⁴ and others (1968) the Butte district produced 3.3×10^8 tons of ore from 1880 to 1964. From this ore more than 16 billion pounds of copper have been produced, greater than 4 billion pounds of zinc, 3 billion pounds of manganese, more than 600 million ounces of silver and in excess of two and a half million ounces of gold. Additionally, lead, cadmium, bismuth, arsenic, selenium and tellurium have been produced. In order to extract these metals, the area was opened by more than 40 miles of vertical shafts and literally thousands of miles of tunnels and other underground passageways. The latest mining resulted in the excavation of the Berkeley pit, an open pit mine within the town proper and two smaller pits on the eastern fringe of the residential area.

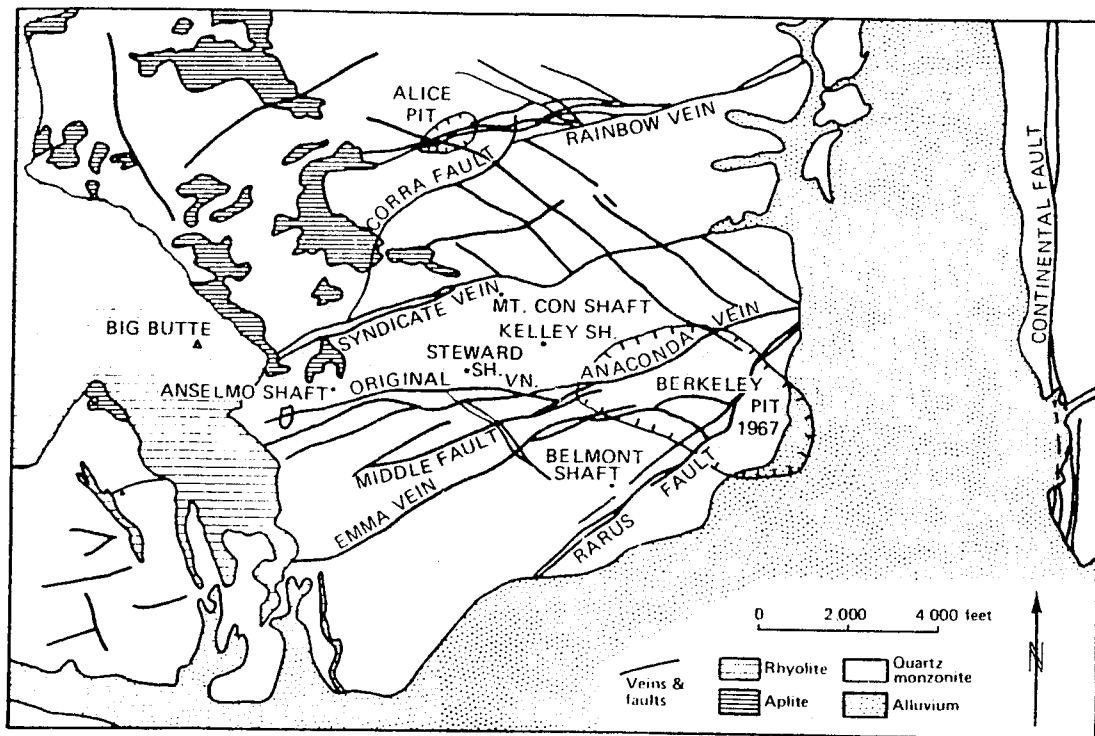


FIGURE 2-1
 PROMINENT FAULTS, VEINS, AND
 ROCK TYPES OF BUTTE

3. EVALUATION OF PHOSPHATE SLAG USE

Elevated radioactivity⁵ in phosphate rock was noted as early as 1908. According to Habashi⁵ uranium normally occurs in phosphate rock in concentrations⁶ ranging between 100 and 200 parts per million (ppm). Andrews and Bibb⁶ report that concentrations observed in the United States range from 8 to 399 ppm, with the highest concentrations being found in ore from South Carolina and the lowest in Tennessee ore. The radioactivity in phosphate rock is due almost exclusively to uranium and its decay products (see Figure 3-1).

An elemental phosphorus smelter operated by the Stauffer Chemical Company is sited approximately seven miles west of Butte. Phosphorus smelting at this plant began in the early 1950's. During its first decade of operation, the plant processed ore from an underground mine in the Maiden Rock area, which is about 25 miles south of the smelter. Mining at Maiden Rock was discontinued in the 1960's. The ore processed since that time has been shipped by rail from a mine-site located near Soda Springs, Idaho.

In early 1977, the DHES obtained samples of slag produced as a by-product from the smelting operation. The samples were sent to the EPA Las Vegas Facility for analyses. The results of the laboratory analyses for the slag from Montana mined ore and Idaho ore are in Table 3-1.

TABLE 3-1
RADIOACTIVITY IN PHOSPHATE SLAG PRODUCED
FROM ORE MINED IN MONTANA AND IN IDAHO

	Nuclide	pCi/gm 2 sigma
Montana Slag	²²⁶ Ra	28.0 ± 0.9
	²³⁸ U	21.0 ± 4.7
	²³⁵ U	1.3
	²³⁴ U	20.0 ± 4.6
	²³⁰ Th	20.0 ± 4.6
	²³² Th	0.77 ± 0.19
Idaho Slag	²²⁶ Ra	48.0 ± 1.2
	²³⁸ U	41.0 ± 6.2
	²³⁵ U	2.4 ± 1.6
	²³⁴ U	40.0 ± 6.3
	²³⁰ Th	35.0 ± 7.4
	²³² Th	0.5 ± 0.22

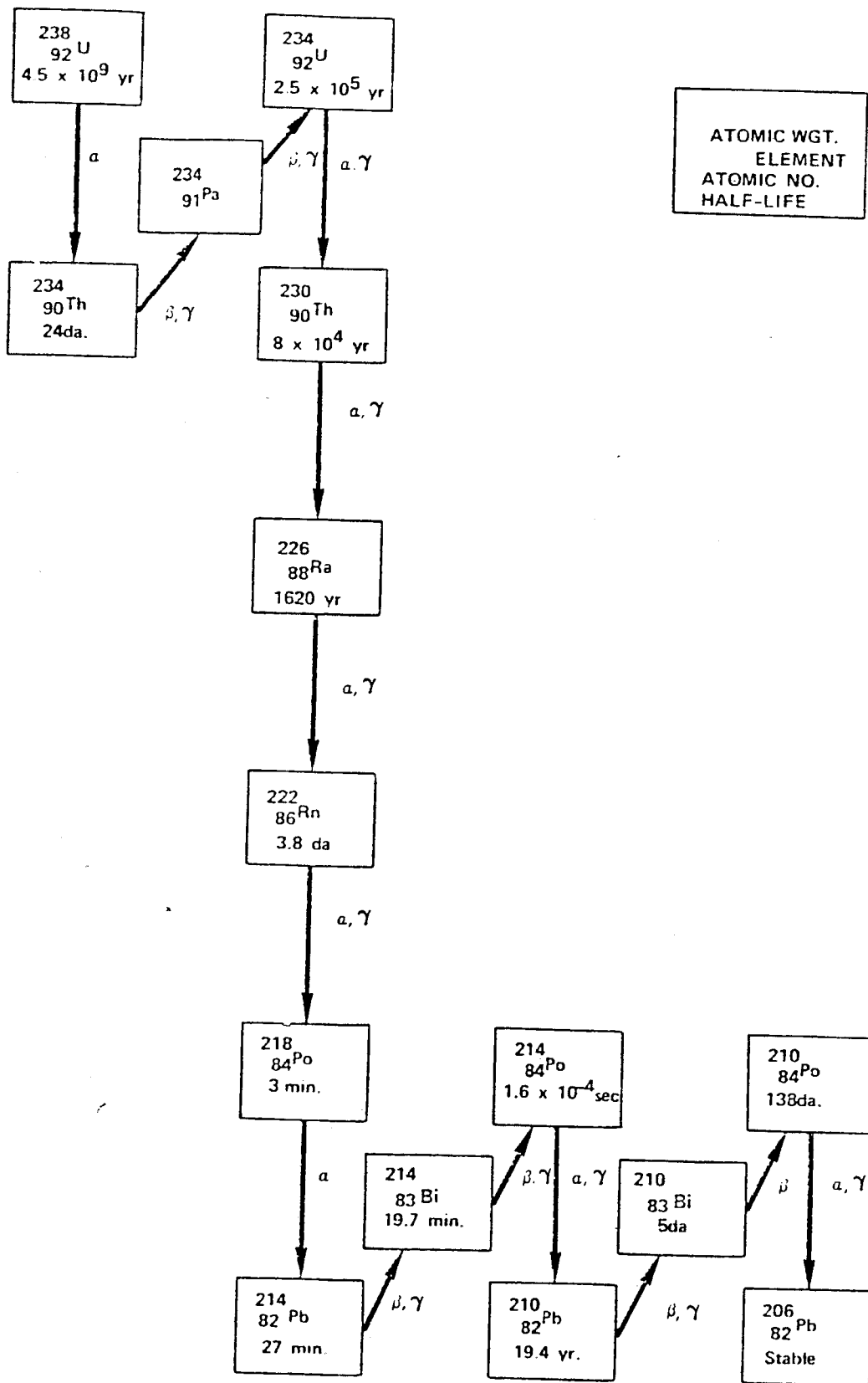


FIGURE 3-1
URANIUM-238 DECAY SERIES

As shown in Table 3-1, the radioactivity contained in the Idaho slag is nearly twice that of Montana slag.

Following the receipt of the EPA laboratory report, DHES initiated an investigation to determine the off-site uses of the phosphate slag. It was learned that slag had been used extensively throughout the Butte area for construction purposes.

Since the 1950's phosphate slag has been used for ballast on railroad beds, road and highway construction, graveling and for asphalt aggregates. Also, a company produced concrete blocks and pre-stressed concrete beams and slabs during the late 1950's, using phosphate slag for aggregate. These concrete products were used in the construction of homes, schools, hospitals and commercial buildings.

The EPA's Las Vegas Facility sent a van, fitted with a Pressurized Ion Chamber (PIC) and a collimated NaI (Tl) detector coupled to a multichannel analyzer, to Butte in April, 1978. Two EPA radiation specialists accompanied the van. Data accumulated through use of this van assisted in locating numerous homes containing phosphate slag building materials.

The occupants of each home containing slag were contacted and, with their permission, gamma radiation and radon progeny measurements were made. Similar measurements were also made in a number of homes that did not contain phosphate slag (non-slag homes).

Radon Progeny Integrating Sampling Units (RPISUs) loaned to DHES by the EPA Las Vegas Facility were used to measure indoor radon progeny concentrations. A RPISU was installed in a home for a period of one week and then the detector head was removed and sent to Las Vegas for analysis. The minimum time of data acquisition when using the RPISU approached one month because of the time requirements for sampling, transportation, readout and reporting.

After several months of sampling, it was apparent there was no difference in radon progeny concentrations between slag homes and non-slag homes.

Two Radon Gas Monitors (RGMs) were acquired in early 1979. These instruments enabled the direct measurement of radon. Using these RGMs, radon exhalation tests were performed on samples of phosphate ore, phosphate slag and decomposed granite soils from the Butte area.

Radon exhalation measurements were performed by placing a sample 25 cm deep in an air-tight cylindrical container having an inside diameter of 28 cm and a 35 cm depth. Air from the container was drawn into the RGM and recirculated back to the container in a closed-loop design. The rate of increase of the radon concentration in the air space above the sample and in the RGM scintillation cell was measured and the radon exhalation rate calculated. As the 25 cm sample depth does not constitute a diffusion path length for radon in the samples tested, the data derived are valid only for comparative purposes.

Data from the comparative radon exhalation measurements are shown in Table 3-2.

TABLE 3-2

COMPARATIVE RADON EXHALATION MEASUREMENTS
PERFORMED ON 25 CM DEPTHS OF PHOSPHATE ORE,
PHOSPHATE SLAG, AND DECOMPOSED GRANITE SOILS
FROM BUTTE

<u>Material</u>	<u>Radon Exhalation Rate (pCi/m²/min.)</u>
Stauffer Phosphate Ore (Idaho)	3822
Stauffer Crushed (3/4") Slag (Idaho)	18
Concrete Block (Phosphate Slag)	30
Butte Decomposed Granite Soils	100 - 1000
Monsanto Phosphate Ore (Idaho)*	3402
Monsanto Uncrushed Slag (Idaho)*	18
Monsanto Crushed (3/4") Slag (Idaho)*	30

*The Monsanto Corporation provided samples from their Pocatello, Idaho, phosphate smelting plant to enable DHES to conduct comparative measurements.

An evaluation of Table 3-2 shows that phosphate slag exhales less than 1 percent of the radon that is exhaled by the phosphate ore. The radium-226 content of the slag and the ore is essentially the same. The smelting of the ore apparently creates a matrix that inhibits the exhalation of radon. Table 3-2 also shows that phosphate slag exhales less radon than do native soils from the Butte area. In 1982, Andrews and Bibb⁶ reported results of radon flux measurements performed on phosphate ore, slag and soil at the Stauffer plant site. Their data concur with the DHES findings.

Elevated gamma radiation was found in building materials containing phosphate slag. A Pressurized Ion Chamber (PIC) was used to measure gamma radiation levels in approximately 90 homes partially constructed with concrete blocks containing phosphate slag and 12 homes not containing phosphate slag. A comparison between gamma radiation levels in slag homes and non-slag homes proved difficult. Due to the variability of the mineralized soils in the Butte area, gamma radiation measurements made at one meter above the ground ranged from a low of 15 μ R/hr to about 30 μ R/hr. The number and the placement of the concrete blocks varied from structure to structure. Some homes had foundations totally constructed of slag blocks. Other homes had only a shower stall or one or two basement walls constructed of the blocks. No home was identified where slag blocks were used in construction above the basement level.

The average gamma radiation level was 19.6 μ R/hr on the main floor of slag homes and 37.1 μ R/hr in the basement. In non-slag homes gamma radiation levels averaged 15.5 μ R/hr on the main floor and 20.7 μ R/hr in

the basement. All measurements were made at a distance of 1 meter above the floor.

The results indicate that use of the slag blocks for foundation construction elevates the gamma radiation level in basements by an average of 16 to 17 $\mu\text{R/hr}$ and by about 4 to 5 $\mu\text{R/hr}$ on the main floor.

Measurements made in three schools, where additions were constructed with phosphate slag beams in the ceilings, showed gamma radiation levels averaging 35.7 $\mu\text{R/hr}$ in the slag additions and 15.9 $\mu\text{R/hr}$ in the older parts of the buildings where slag building materials were not used. In these structures, the presence of phosphate slag appeared to increase the gamma radiation level by approximately 20 $\mu\text{R/hr}$. The presence of phosphate slag thus increases the gamma radiation dose to a school child exposed 6 hours per day, 180 days per year, by about 21 milliroentgens per year.

The determination of ambient gamma radiation attributable to use of phosphate slag for paving and other surfacing in Butte is difficult because of the many variables involved. Natural radiation levels vary by as much as 15 $\mu\text{R/hr}$. Most of the phosphate slag used for surfacing came from smelted Montana ore. Recently, slag produced by smelting Idaho ore has been used. Also, the depth of slag used in streets and for surfacing differs from project to project.

Street measurements of gamma radiation levels were made in Butte, Anaconda and Helena to determine background radiation levels. Measurements in Anaconda average 15 $\mu\text{R/hr}$; Helena, 13 $\mu\text{R/hr}$; and Butte, 19 $\mu\text{R/hr}$ in areas where no phosphate slag was present.

Radiation levels at one meter above Butte streets paved with Montana slag average 28 $\mu\text{R/hr}$; whereas, the radiation levels above streets paved with Idaho slag averaged approximately 45 $\mu\text{R/hr}$. Some measurements as high as 50 $\mu\text{R/hr}$ were recorded on streets paved with Idaho slag. Numerous streets which were originally paved using Montana slag have been repaved using Idaho slag. Radiation measurements on these streets generally range between 30 and 40 $\mu\text{R/hr}$.

Most streets, alleys, parking lots and some school grounds are paved or graveled with phosphate slag. It is estimated that approximately one-fourth to one-third of the populated area of Butte is covered with phosphate slag or phosphate slag bearing materials.

Because of the variability in natural background radiation levels, and in radiation levels measured in areas covered with phosphate slag, it was not possible to measure the overall radiation exposure attributable to the phosphate slag used in Butte. However, it has been estimated that the use of phosphate slag in Butte may have elevated the average radiation exposure rate within the city by as much as 10 $\mu\text{R/hr}$.

The use of phosphate slag for graveling creates another potential health risk. Phosphate slag is rapidly pulverized by traffic. During dry periods, roads graveled with phosphate slag become extremely dusty. Individuals driving on, or living near, these roads are exposed to high

concentrations of slag dust. Because of the elevated content of natural radioactivity contained in the phosphate slag (see Table 3-1), and particularly because of the radium-226 and thorium-230 content, phosphate slag should not be used for road gravel. When inhaled or ingested, if soluble, radium and thorium metabolize to the bone and increase the risk of bone tumors and leukemia.

The potential for contaminating ground and surface water by radioactivity leached from phosphate slag was investigated. Samples of phosphate slag were crushed into powder and placed in beakers containing water having pH values ranging between 5 and 9. Each sample was periodically agitated, then filtered after a period of 24 hours. One hundred ml of filtrate from each sample was dried in a planchette and counted for gross alpha and gross beta activity. Nothing above normal background levels was detected in any of the samples, indicating that phosphate slag was insoluble in water under most environmental conditions. As this was a short-term test, the potential for long-term chemical and solubility changes was not determined.

From the evaluation of data concerning use of phosphate slag for building and construction purposes, it is concluded that:

1. Phosphate slag should not be used as an ingredient when building structures for human occupancy. Such use elevates gamma radiation exposure rates and results in unnecessary radiation exposure to occupants.
2. Phosphate slag should not be used for road or area graveling. The slag is readily pulverized and produces dust elevated in radium-226, thorium-230 and other nuclides in the uranium-238 decay series. This potential hazard should be further studied.
3. Phosphate slag can be used for some purposes without significant risk to the public health. However, any use of phosphate slag should be strictly controlled. Some uses which may be acceptable on a case-by-case basis are construction of highways, airport runways, bridges, culverts and other underground pipe and for railroad ballast.

The use of phosphate slag should be limited to projects where no significant human exposure to increased gamma radiation levels will occur. Control measures should be implemented to prevent the use of slag for unacceptable purposes.

4. Human exposure to radon and radon progeny is not a health risk that is associated with use of phosphate slag for building and construction purposes since radon exhalation from phosphate slag is relatively insignificant. Radon exhalation rates from the slag are lower than those normally expected from native soils in the Butte area.

4. RADON/RADON PROGENY MEASUREMENTS

Selection of Homes for Measurement

Initially, homes containing phosphate slag building materials were the subject of investigation. Radon progeny measurements were made in these homes and other, non-slag homes using RPISUs. Equipment for making short-term "grab" sample (less than 10 minute) measurements was also acquired. Soon after this equipment was obtained, it was learned that the most severely impacted area of Butte was the northwest section. The first indication of elevated radon concentrations in northwest Butte occurred when a home on Waukesha Street, which contained phosphate building blocks, was found to have radon progeny concentrations in excess of 0.25 Working Levels (WL). Comparing measurements from other homes containing phosphate slag building materials, it was apparent that the phosphate slag was not responsible for this high radon progeny concentration.

Following the discovery of the elevated levels of radon progeny in the Waukesha Street home, measurement activities were intensified to determine the boundaries of the impacted area. Occupants were contacted on a house-to-house basis and were asked for permission to measure radon progeny concentrations. The people were generally cooperative, with only about a ten percent rejection rate.

The radiation study received considerable publicity from the news media. Consequently, many local homeowners became aware of the potential health risks and requested that radon progeny concentrations be measured in their homes. DHES performed measurements in each home where the measurement was requested.

In 1979, the U. S. Department of Housing and Urban Development (HUD) initiated a requirement that all HUD-subsidized housing be measured to determine radon progeny concentrations. At the same time, HUD's Federal Housing Administration (FHA) instituted a requirement that radon progeny concentrations had to be determined for all FHA-insured home loans. Following the initiation of HUD's measurement requirements, DHES entered into a contract with HUD to perform these measurements in HUD-subsidized housing.

After DHES acquired grab sampling equipment, all homes studied were initially measured using the grab sample method. Radon and radon progeny concentrations in structures are subject to significant variability. Because of this, RPISUs were installed in homes measuring 0.03 WL or higher to obtain long-term integrated measurements. Long-term measurements were also performed in numerous homes where the measurement was requested by the occupants.

In summary, structures chosen for grab sample measurement of radon progeny were selected because:

1. The homes contained phosphate slag building materials.

2. The homes were located in areas known to be elevated in indoor radon concentrations.
3. Individuals requested sampling of their homes because of health concerns.
4. The sampling was required by HUD or FHA.

Structures selected for long-term integrated measurement were, for the most part, homes in which grab samples showed elevated radon progeny concentrations.

Because of the selection criteria, structures chosen for both short-term and long-term measurements constitute a biased sample. Data obtained from these measurements should not be extrapolated for a city-wide average.

Indoor Measurement of Radon and Radon Progeny

Radon and radon progeny concentrations were determined by using both short-term and long-term sampling techniques. There are inherent advantages and disadvantages to each technique. Because of this, the purpose of measurement and data needs were carefully evaluated prior to beginning each phase of the study and determining which measurement technique would be used.

Measurement of Indoor Radon Progeny

Short-term sampling

The grab sample method for measuring radon progeny concentrations was used to obtain rapid measurements in many homes. This technique enabled the screening of large numbers of homes and apartments to determine which areas of the city were most severely affected.

Most screening by grab sampling was done during cold weather when it could be assured that doors and windows were closed. When homes were measured during warm periods, occupants were contacted in advance and asked to close all doors and windows for a period of at least eight hours prior to sampling. For HUD and FHA sampling, the occupant was requested to sign a statement that the house had not been ventilated for a period of at least three hours prior to measurement. No actual ventilation rate measurements were made.

Grab sampling provides a reasonably accurate measurement of the radon progeny concentration present at the time of sampling; however, extrapolation of short-term data to estimate long-term averages is subject to considerable error because of the daily and seasonal fluctuations in radon and radon progeny concentrations.

Long-term sampling

Long-term measurement of indoor radon progeny was used to estimate average concentrations for a period of one year. Throughout the study

RPISUs, loaned by the EPA Las Vegas Facility, were used to obtain integrated measurements of radon progeny concentrations.

In most homes, the RPISUs were used for a period of one week every three-months for a year. This sampling schedule was established to enable the collection of one week's data during each season of the year. The four week's data were equally weighted and averaged to estimate the "Annual Average Concentration."

Measurement of Indoor Radon

Short-term sampling

Short-term measurements of indoor radon concentrations were made using Eberline 500-ml scintillation cells. This measurement device provides an accurate assessment of the indoor radon concentration at the specific time of sample collection. Most radon grab samples were collected simultaneously with radon progeny grab samples. This enabled the calculation of the percentage equilibrium of the radon progeny with the parent radon-222.

Long-term sampling

Few long-term measurements of indoor radon concentrations were done during the study. DHES acquired two Eberline Radon Gas Monitors (Model RGM-1) in early 1980. These were the only integrating radon monitors available during most of the study, and were mainly used for ambient monitoring, radon exhalation and radon flux measurements.

Factors Affecting Radon and Radon Progeny Concentrations in Structures

Concentrations of indoor radon and its progeny are subject to variation. Factors that affect structure ventilation rates and those that affect radon soil gas concentrations in soils adjacent to structures are probably responsible for most of the fluctuations.

It is believed that radon soil gas concentrations near a structure can be elevated by the installation of adjacent concrete or asphalt slabs, driveways or sidewalks. These appurtenances create a capping effect that inhibits the exhalation of radon from the soil. This capping increases radon soil gas concentrations and can elevate the radon concentration within the structure itself.

Naturally-occurring phenomena that affect radon exhalation from the soil adjacent to structures can also change concentrations of indoor radon. Some examples of these phenomena are changes in soil moisture and the ground frost during winter.

Factors affecting structure air change rates are open doors and windows, wind speed and traffic in and out of the building. In structures that have combustion-type heating systems, the combustion air demands of the heating system can significantly affect the air exchange rate.

Radon progeny concentrations are also affected by ventilation changes and by conditions that alter the plateout of the progeny. The plate-out of radon progeny is affected by airborne nuclei concentrations, humidity, air motion, home furnishing types, the number of occupants and even the living habits of the occupants themselves.

Use of Indoor Measurements to Identify Geographical Areas Impacted by Elevated Indoor Radon Concentrations

During the period between early 1979 and mid-1981, emphasis was placed on research to determine the geographical areas of Butte most severely affected by elevated indoor radon concentrations. Initial screening of neighborhoods was conducted by the grab sample method. Homes were sampled only when the occupants provided assurance that the house had not been ventilated for at least three hours. Through September, 1981, 2884 grab samples had been collected in homes to determine radon progeny concentrations. Through December, 1982, the total increased to 3099 grab samples. These measurements were distributed in housing units as shown in Table 4-1. Many homes showing elevated radon progeny concentrations were sampled more than once to substantiate the measurements.

TABLE 4-1
INDOOR RADON PROGENY GRAB SAMPLE MEASUREMENTS
IN BUTTE (1979 - 1982)

<u>Working Level</u>	<u>Total Housing Units*</u>
Less than 0.010	1102
0.010 - 0.019	426
0.020 - 0.049	187
0.050 - 0.100	43
Greater than 0.100	13
Total Samples	<u>1771</u>

*A single family house or living unit in a multifamily structure is defined as a "housing unit".

Integrated radon progeny measurements were completed in 254 housing units with the use of RPISUs. The average annual concentrations in homes measured with RPISUs are shown in Table 4-2.

TABLE 4-2

AVERAGE ANNUAL CONCENTRATIONS OF RADON PROGENY IN HOUSING UNITS
MEASURED WITH RADON PROGENY INTEGRATING SAMPLING UNITS

<u>Working Level</u>	<u>Main Floor Measurements</u>	<u>Basement Measurements</u>
Less than 0.010	58	9
0.010 - 0.019	39	12
0.020 - 0.050	76	16
Greater than 0.050	37	7
Total Housing Units Measured	<u>210</u>	<u>44</u>

5. RADON SOURCE ASSESSMENT

Summary

The objective of this study was to identify, to the extent possible, the source or sources of the elevated radon in structures in Butte and the Butte vicinity.

Tasks performed in the radon source assessment were:

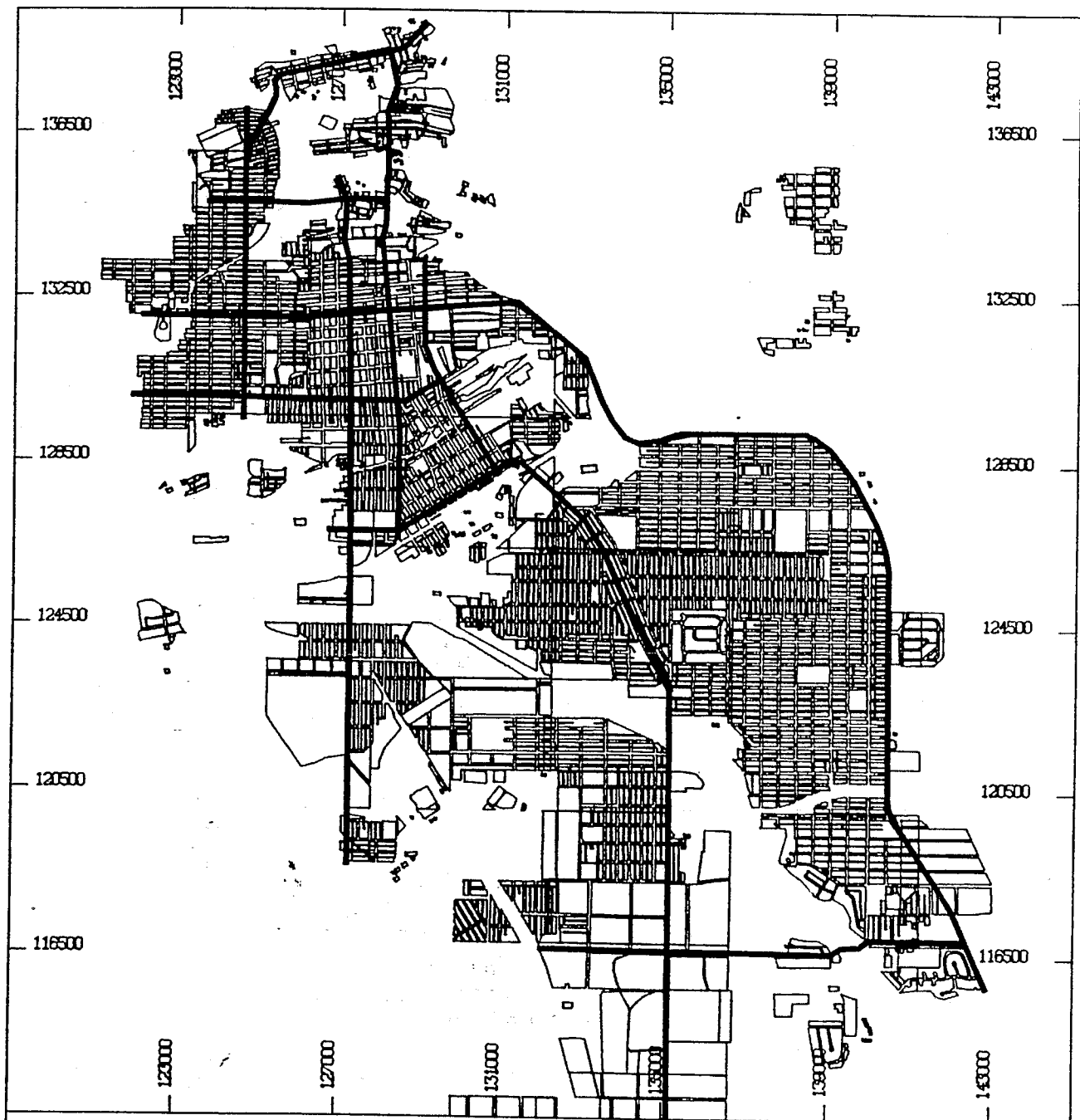
1. the measurement of radon and radon progeny in ambient air;
2. analysis of soil for radioactivity content;
3. measurement of radon/radon progeny concentrations in structures;
4. measurement of radon soil gas concentrations;
5. investigation of possible interrelationships between radon concentrations in structures, radon soil-gas concentrations and the surface geology;
6. measurement of dissolved radon concentrations in water supplies, and
7. evaluation of miscellaneous other potential sources of radon in structures.

Through an agreement with the U. S. Bureau of Mines (BOM), Spokane Research Center, acquired data were digitized and programmed into the BOM computer along with the coordinates of a Butte city map and available geological information. The BOM computer enabled the graphical display and evaluation of data. Numerous figures in this section were produced by the BOM computer system.

Figure 5-1 shows a city map of Butte with reference streets emphasized. The reference streets are identified by name in Figure 5-2. Reference streets shown in Figures 5-1 and 5-2 are used in most figures in this section to orient measurement sites. The grid markings shown in Figures 5-1 and 5-2 were established by the Anaconda Company for land survey purposes. The Anaconda grid was used by DHES and BOM to plot measurement sites and data points.

Ambient Measurements

In August, 1980, an ambient radon monitoring station was established at Hebgen Park (see Figure 5-2, location A). Hebgen Park is situated two blocks east of Arizona Street and one block north of Front Street. An Eberline Radon Gas Monitor, Model RGM-1, with an air intake located approximately 6 feet above ground level, was used to measure the ambient radon concentrations and was programmed to provide an hourly

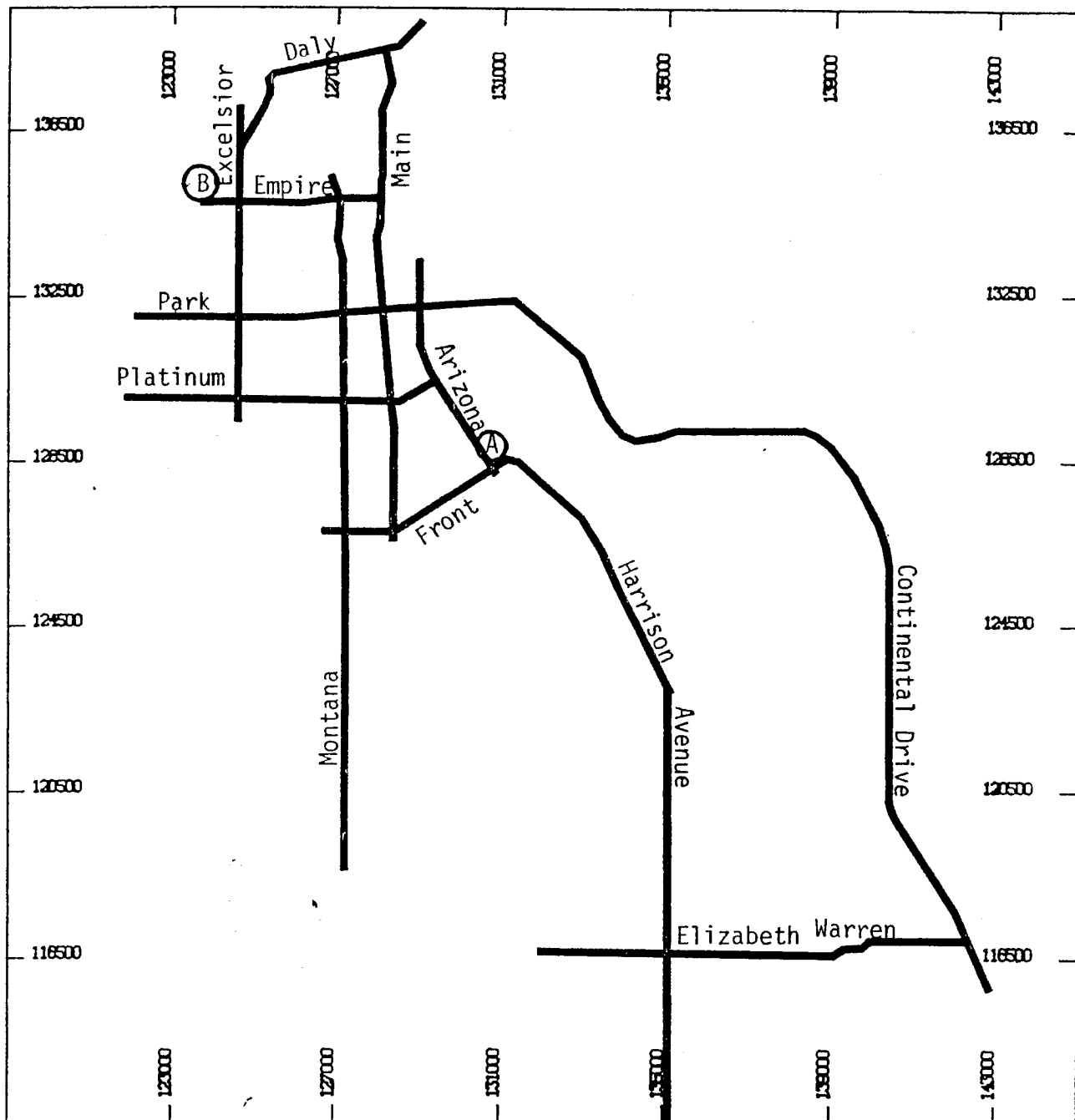


SCALE 1" = 4000. '

BOUNDARY			BOUNDARY	
EAST	= 145000.00	0	4000	NORTH = 139500.00
WEST	= 119000.00			SOUTH = 112500.00
		FEET		

FIGURE 5-1

CITY MAP OF BUTTE SHOWING
LOCATIONS OF REFERENCE STREETS



SCALE 1" = 4000. '

BOUNDARY			BOUNDARY	
EAST	= 145000.00	0	4000	NORTH = 139500.00
WEST	= 119000.00			SOUTH = 112500.00
FEET				

FIGURE 5-2

REFERENCE STREETS
AND OUTSIDE AIR MONITORING STATION LOCATIONS

printout of measurement data. Ambient radon measurements were collected almost continuously at the Hebgen Park Station between August, 1980, and August, 1981, with the exception of October, 1980. In October, the radon gas monitor was removed for maintenance and quality assurance tests.

The Butte area is subject to severe atmospheric thermal inversions that often trap atmospheric pollutants, including radon, in the Butte Basin during certain periods of the day. The inversion periods follow a diurnal pattern with the highest concentrations of radon occurring at approximately 6:00 a.m. and the lowest concentrations at about 6:00 p.m. The pattern of diurnal thermal inversions occurs throughout the year, but is frequently interrupted by winds and storms. The radon concentrations shown in Figures 5-3 through 5-6 are seasonally selected examples based on three-hour averages to show the effect of the diurnal thermal inversions on the ambient radon concentrations at the Hebgen Park monitoring station.

Figure 5-7 shows ambient radon concentrations averaged weekly and Figure 5-8 shows average monthly ambient radon concentrations at the Hebgen Park Monitoring Station for the period August, 1980 through August, 1981. It is interesting to note that average ambient radon concentrations ranged from a high of about 3 pCi/l to a low of less than 0.25 pCi/l. The highest concentrations were observed between August and November. Concentrations diminished through the winter months and reached a low in May and June.

Measurements of soil moisture were not made, but it is believed that the soil moisture content is probably responsible for the differing ambient radon concentrations seen in Figures 5-7 and 5-8. In the winter months, the soil in the Butte area freezes to a depth of several feet. DHES believes that the frozen soil produces a capping effect that inhibits radon exhalation. Radon soil gas measurements made in the alluvium at a depth of 30 inches showed a radon soil gas concentration in winter months 69 percent higher than in summer months.

The spring of 1981 was unusually wet in western Montana. Precipitation in Butte during the months of April, May and June totaled 7.62 inches. The ambient radon concentrations for May and June, when the soil was heavy with water, were the lowest of the year. These measurements also indicate that an inverse relationship most likely exists between soil moisture content and the soil radon flux.

In February, 1982, an outside radon and radon progeny monitoring station was established at 933 Hornet Street (see Figure 5-2, location B). This station is situated in the first block west of Excelsior Street, one block north of Empire Street. The Hornet Street monitoring site is in the area of the city exhibiting the highest radon soil gas concentrations and the highest density of homes affected by elevated radon concentrations.

Unlike the Hebgen Park station, the air intake for the Radon Gas Monitor at the Hornet Street station was located about one foot above the ground and between two houses that are spaced by only six feet. The

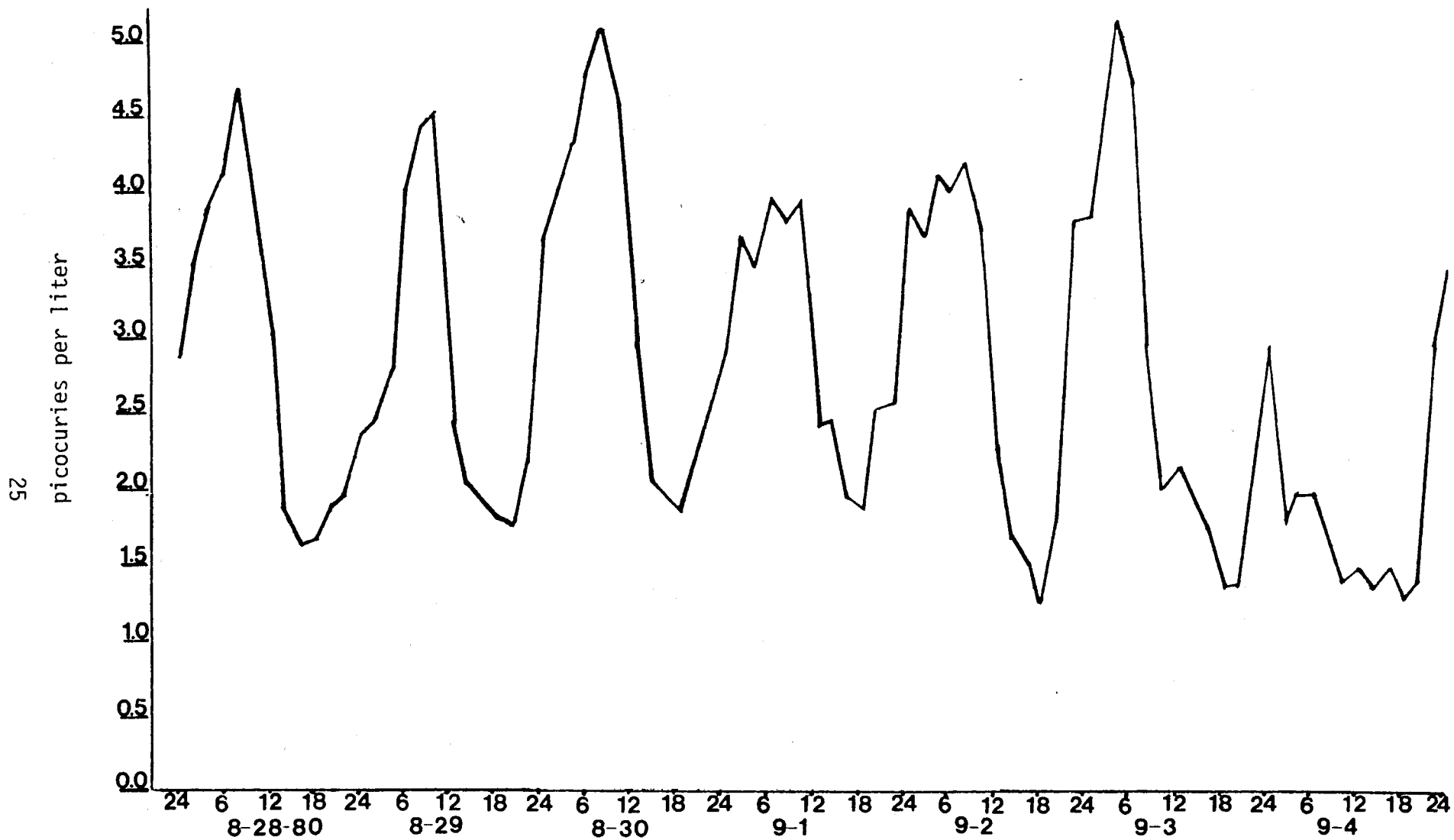


FIGURE 5-3

AMBIENT RADON CONCENTRATIONS
HEBGEN PARK MONITORING STATION, AUGUST 8 - SEPTEMBER 4, 1980

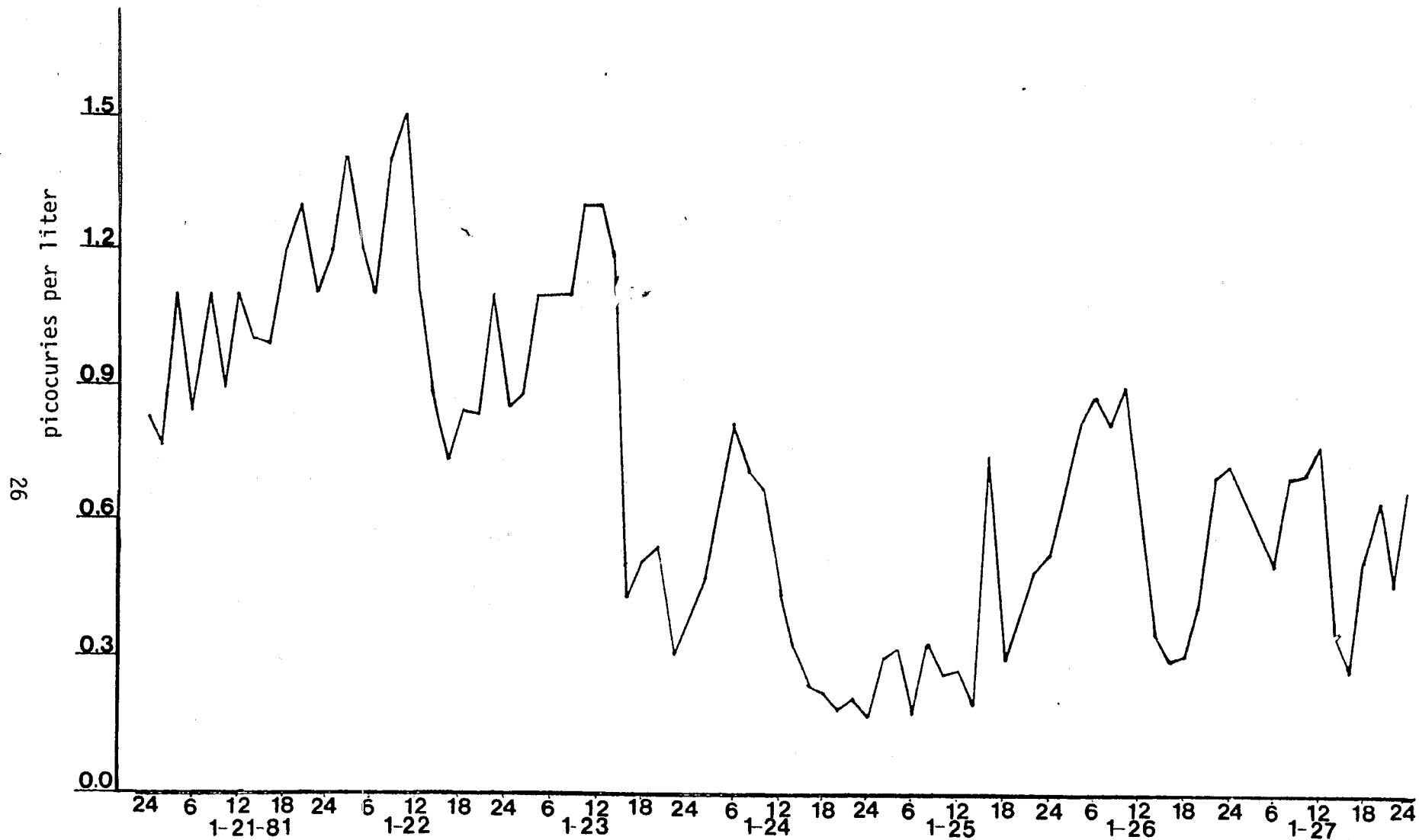


FIGURE 5-4

AMBIENT RADON CONCENTRATIONS
HEBGEN PARK MONITORING STATION, JANUARY 21 - JANUARY 27, 1981

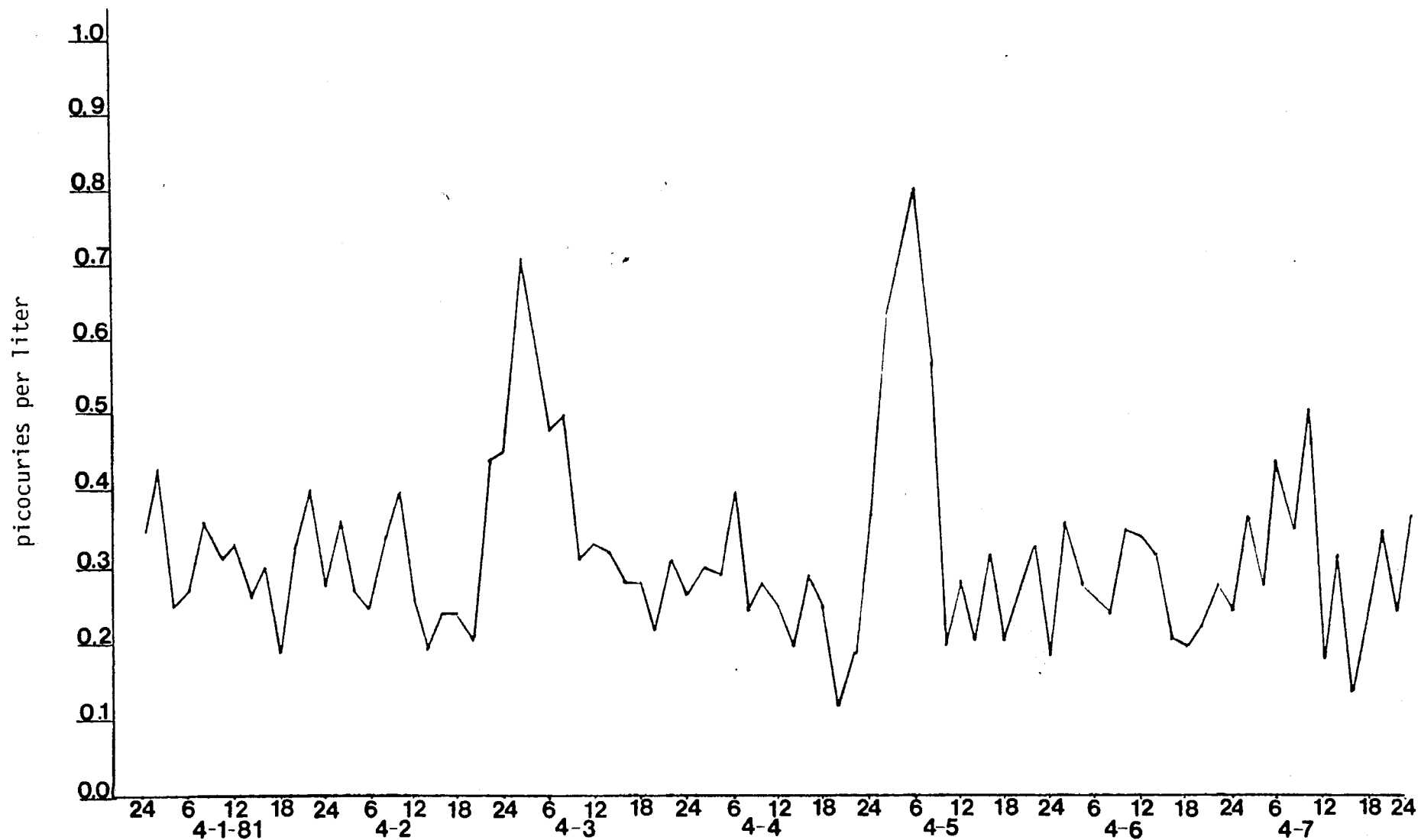


FIGURE 5-5

AMBIENT RADON CONCENTRATIONS
HEBGEN PARK MONITORING STATION, APRIL 1 - APRIL 7, 1981

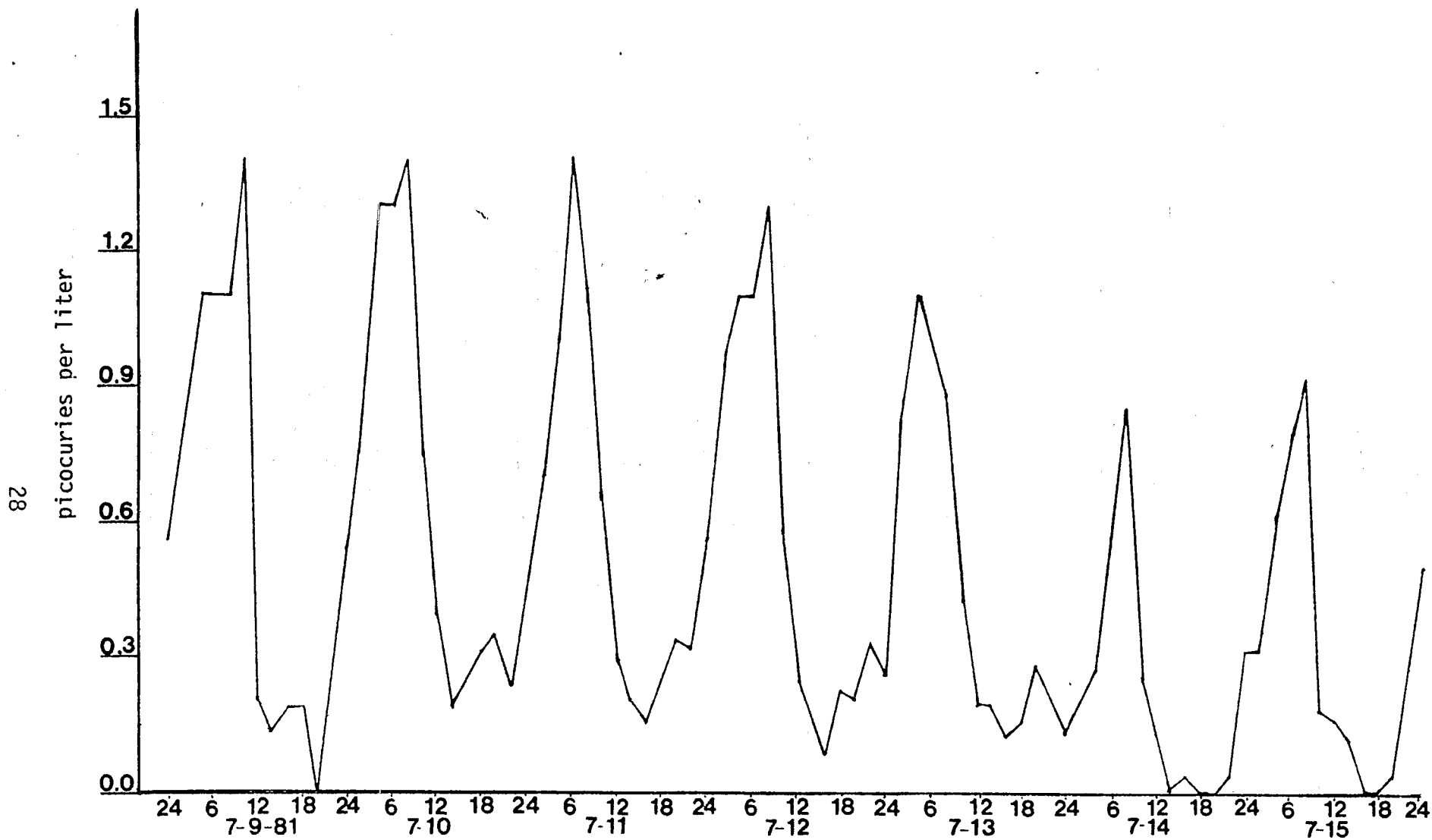


FIGURE 5-6

AMBIENT RADON CONCENTRATIONS
HEBGEN PARK MONITORING STATION, JULY 9 - JULY 15, 1981

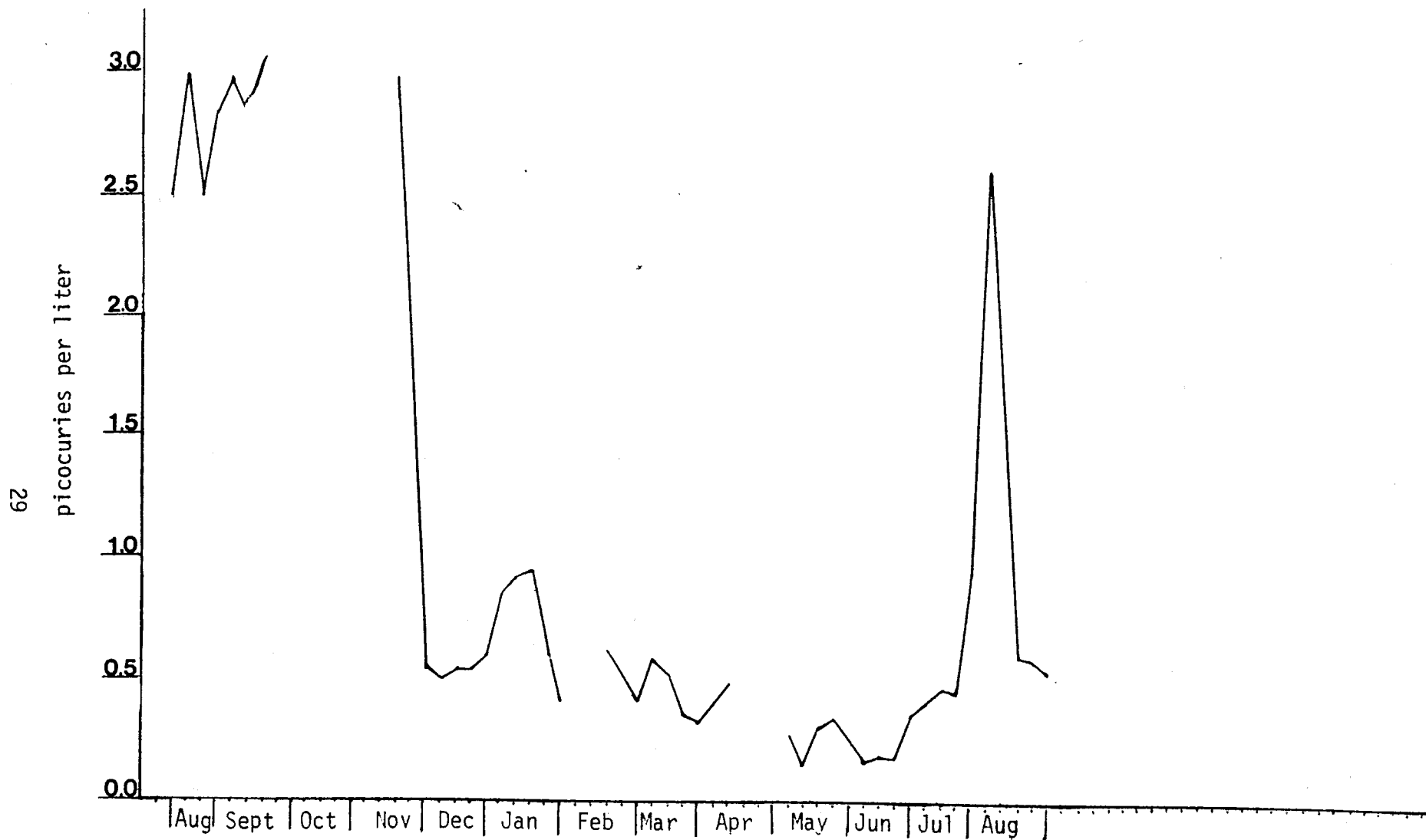


FIGURE 5-7

AVERAGE WEEKLY AMBIENT RADON CONCENTRATIONS
HEBGEN PARK MONITORING STATION, AUGUST, 1980 - AUGUST, 1981

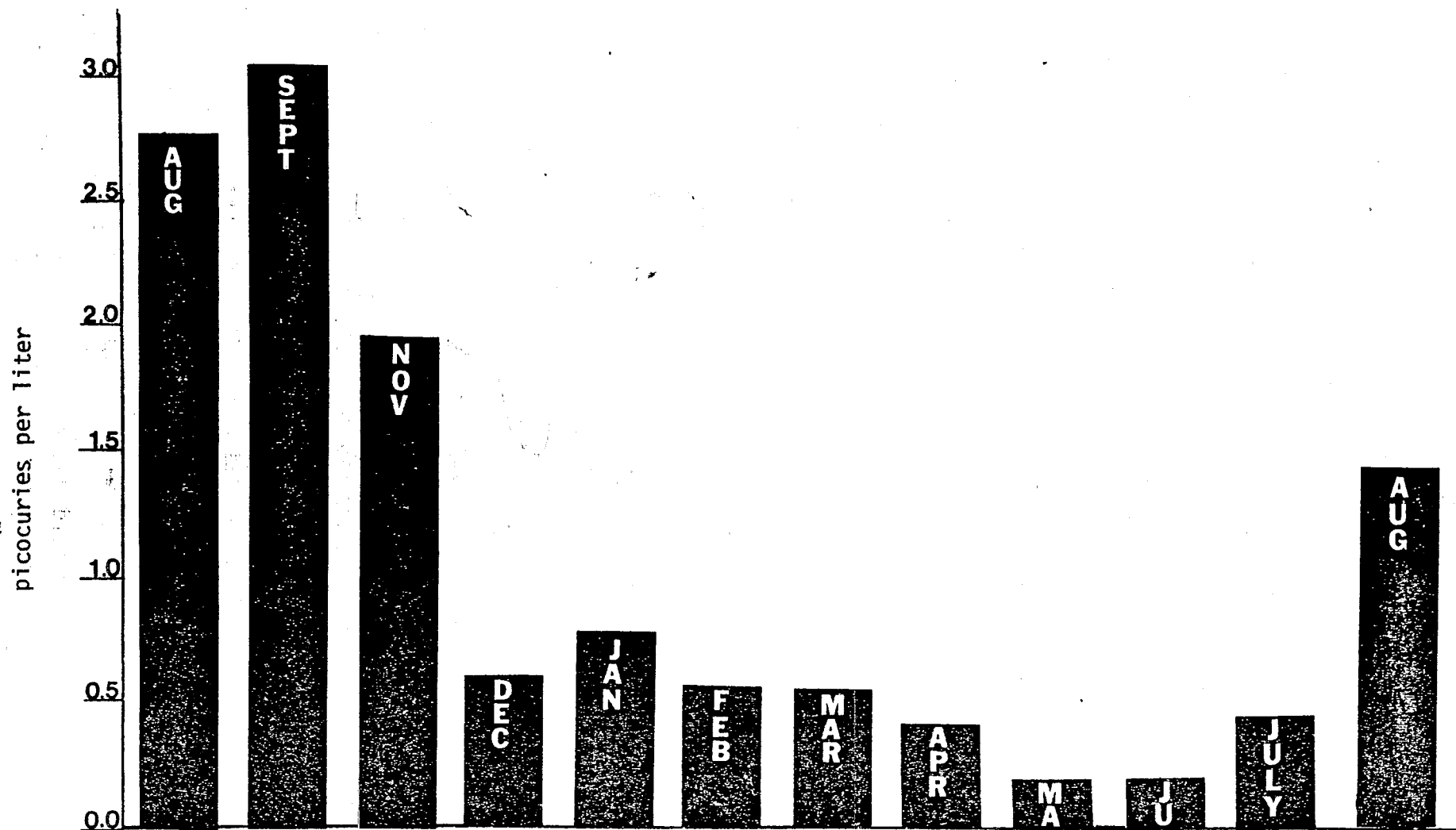


FIGURE 5-8

AVERAGE MONTHLY AMBIENT RADON CONCENTRATIONS
HEBGEN PARK MONITORING STATION, AUGUST, 1980 - AUGUST, 1981

location of the air intake probably accounts, at least partially, for the high outside radon measurements at the Hornet Street station.

Outside radon concentrations measured at the Hornet Street station averaged 3.25 pCi/l for the period February, 1982, through January, 1983. This average was substantially higher than the Hebgen Park station average of 0.98 pCi/l for the period August, 1980, through July, 1981.

The weekly average outside radon concentrations measured at the Hornet Street Station are shown in Figure 5-9. The average monthly measurements are presented in Figure 5-10. As seen in Figure 5-10, the monthly average outside radon concentrations at the Hornet Street Station ranged from a low of 1.47 pCi/l in February, 1982, to a high of 5.86 pCi/l in August, 1982.

The outside radon concentrations measured at the Hornet Street Station are higher than normally expected. Worldwide, ambient radon measurements normally vary from less than 0.1 pCi/l to about 1 pCi/l⁸.

A RPISU was used at the Hornet Street station to monitor outside radon progeny concentrations. The average outside radon progeny concentration for the period February, 1982, through January, 1983, was 0.0031 WL. The outside radon progeny/radon equilibrium averaged about 10 percent for the period. The equilibrium from November through February averaged 17.5 percent. The equilibrium during the remaining months averaged 7 percent.

Soil Sampling and Analysis

Twenty-six soil samples were collected at selected sites ranging from Walkerville on the north to the airport on the south. These sampling site locations are shown in Figure 5-11. With the exception of Sample No. 7 which was collected at a soil depth of 10-15 cm, all soil samples were collected from the top 5 cm of soil. The soil samples were analyzed at the EPA's Las Vegas Facility for U-234, U-235, U-238, Th-230, Th-232, and Ra-226 content. The data for these 26 soil samples are shown in Table 5-1.

The normal Radium-226 content of soils ranges from about 0.4 to 1.3 picocuries per gram of soil⁹. The Ra-226 content in the samples shown in Table 5-1 averages 1.58 ± 0.59 picocuries per gram of soil with a range of 0.7 to 3.2 picocuries per gram. The Ra-226 content of soil in sections of the city experiencing elevated indoor radon concentrations does not differ substantially from concentrations in areas experiencing little or no problem.

Measurement of Radon Progeny Concentrations (WL) in Structures

Radon progeny concentrations measuring 0.02 WL or greater are found in structures scattered throughout the Butte area. The majority of the severely affected structures are in the northwest section of the city roughly bounded by Excelsior Street on the east and Park Street on the south.

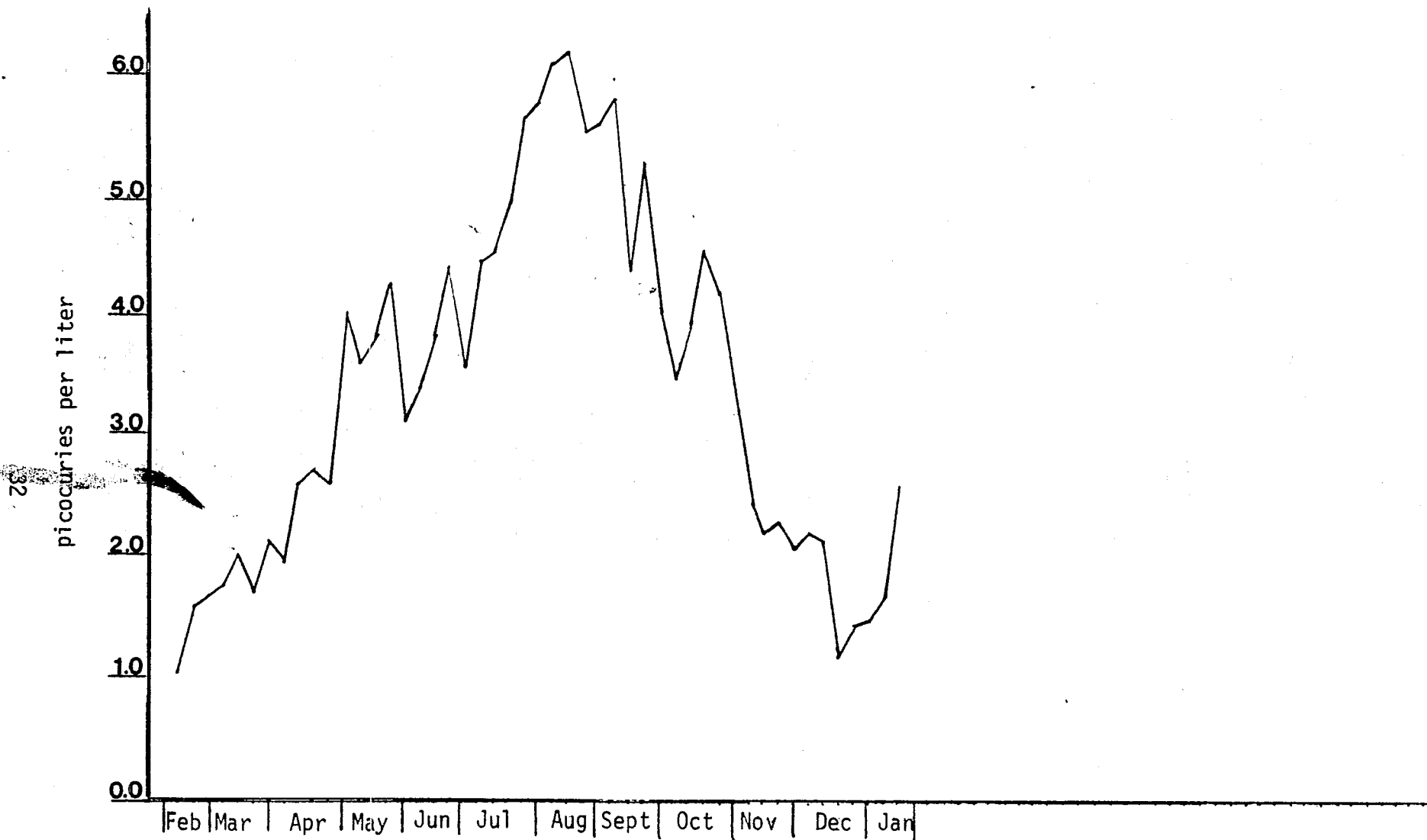


FIGURE 5-9

AVERAGE WEEKLY OUTSIDE RADON CONCENTRATIONS
HORNET STREET MONITORING STATION, FEBRUARY, 1982 - JANUARY, 1983

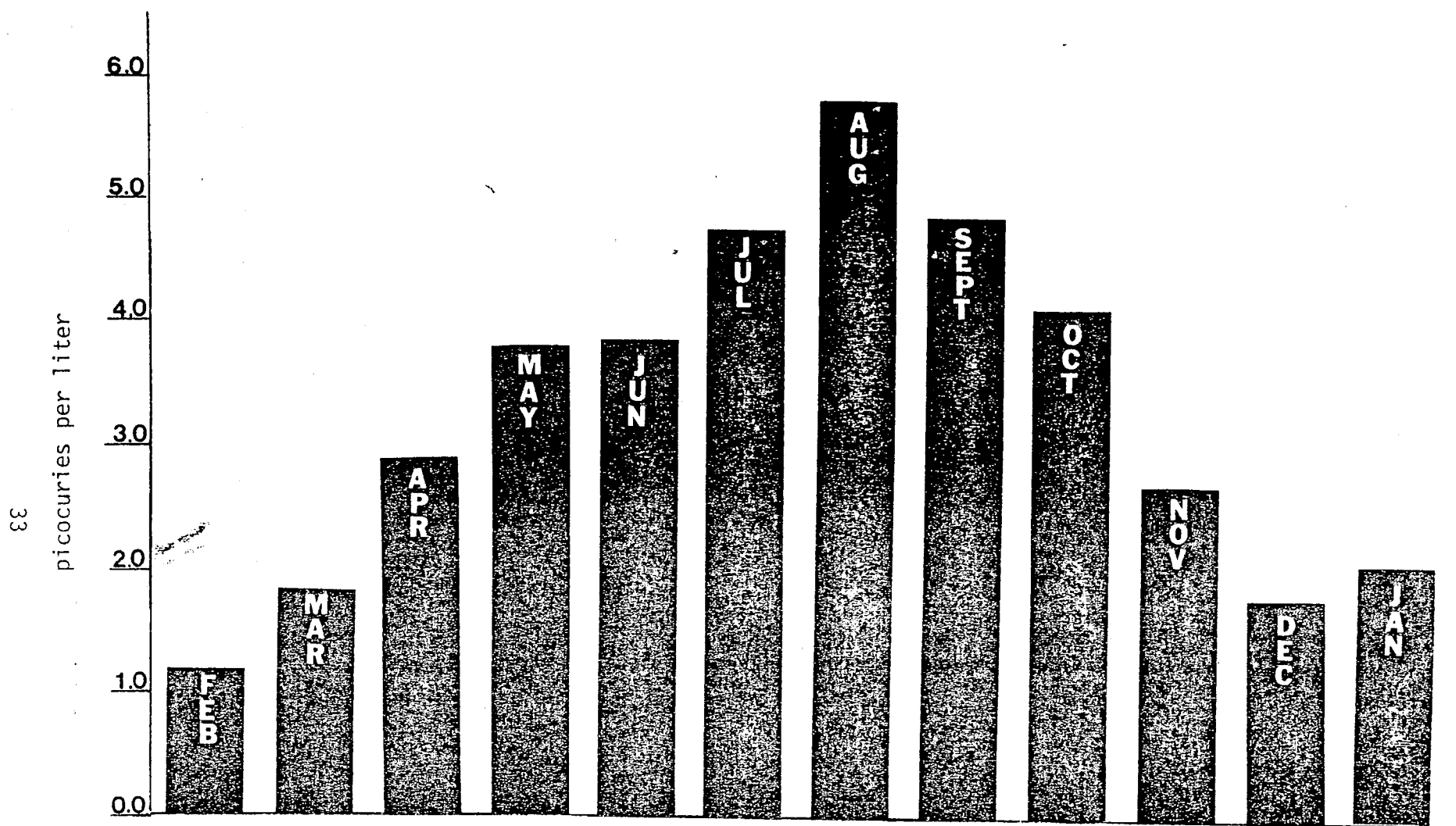
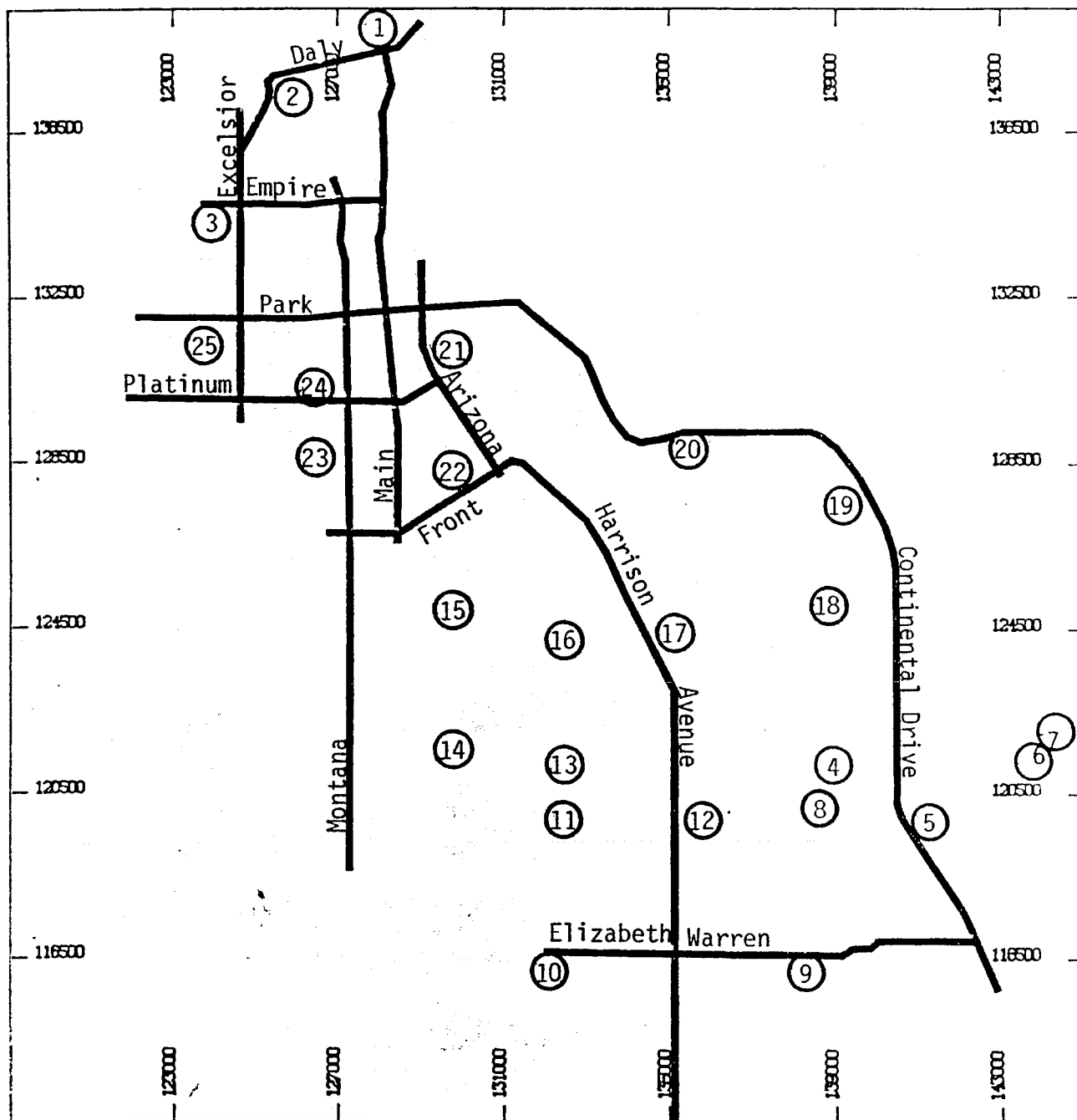


FIGURE 5-10

AVERAGE MONTHLY OUTSIDE RADON CONCENTRATIONS
HORNET STREET MONITORING STATION, FEBRUARY, 1982 - JANUARY, 1983



SCALE 1" = 4000.

BOUNDARY		BOUNDARY	
EAST =	145000.00	0	4000
WEST =	119000.00	NORTH = 139500.00	
		SOUTH = 112500.00	
		FEET	

FIGURE 5-11

SOIL SAMPLING SITE LOCATIONS

TABLE 5-1

RADIOACTIVITY IN SOIL SAMPLES FROM BUTTE

Sample no.	Analysis	Result	2 Sigma*	Units
1 Walkerville-Sunview Terrace	234U	1.3E00	1.2E-01	PCI/GM
	235U	3.4E-02	1.9E-02	PCI/GM
	238U	1.4E00	1.3E-01	PCI/GM
	232TH	2.1E00	2.9E-01	PCI/GM
	230TH	1.3E00	2.0E-01	PCI/GM
	226RA	1.7E00	2.3E-01	PCI/GM
2 Walkerville-Missoula Gulch	234U	1.4E00	1.3E-01	PCI/GM
	238U	1.3E00	1.2E-01	PCI/GM
	235U	4.4E-02	2.1E-02	PCI/GM
	232TH	1.8E00	2.5E-01	PCI/GM
	230TH	1.5E00	2.1E-01	PCI/GM
	226RA	2.2E00	2.6E-01	PCI/GM
3 Western at Waukesha	235U	4.1E-02	2.1E-02	PCI/GM
	234U	7.5E-01	9.0E-02	PCI/GM
	238U	7.7E-01	9.2E-02	PCI/GM
	232TH	6.4E-01	2.3E-01	PCI/GM
	230TH	7.7E-01	2.7E-01	PCI/GM
	226RA	1.0E00	1.8E-01	PCI/GM
4 Amherst at Sheridan	238U	2.0E00	1.6E-01	PCI/GM
	234U	1.9E00	1.6E-01	PCI/GM
	235U	5.9E-02	2.4E-02	PCI/GM
	232TH	2.9E00	4.6E-01	PCI/GM
	230TH	1.8E00	3.0E-01	PCI/GM
	226RA	1.4E00	2.1E-01	PCI/GM
5 Keokuk at Continental	234U	2.5E00	1.9E-01	PCI/GM
	238U	2.6E00	1.9E-01	PCI/GM
	235U	1.0E-01	3.2E-02	PCI/GM
	232TH	8.2E00	1.2E00	PCI/GM
	230TH	3.2E00	5.1E-01	PCI/GM
	226RA	3.0E00	3.0E-01	PCI/GM
6 Foothills East Ridge	235U	<2.7E-02		PCI/GM
	234U	1.0E00	1.1E-01	PCI/GM
	238U	1.0E00	1.1E-01	PCI/GM
	232TH	1.9E00	2.7E-01	PCI/GM
	230TH	1.1E00	1.7E-01	PCI/GM
	226RA	1.3E00	2.0E-01	PCI/GM

Sample No.	Analysis	Result	2 Sigma*	Units
7 Foothills East Ridge	234U	1.2E00	1.1E-01	PCI/GM
	238U	1.3E00	1.2E-01	PCI/GM
	235U	4.9E-02	2.2E-02	PCI/GM
	232TH	2.4E00	3.8E-01	PCI/GM
	230TH	1.4E00	2.5E-01	PCI/GM
	226RA	1.4E00	2.1E-01	PCI/GM
8 Quincy at Banks	235U	< 3.6E-02		PCI/GM
	234U	1.6E00	1.6E-01	PCI/GM
	238U	1.4E00	1.5E-01	PCI/GM
	232TH	3.0E00	3.8E-01	PCI/GM
	230TH	1.6E00	2.2E-01	PCI/GM
	226RA	3.2E00	3.1E-01	PCI/GM
9 Greenlane	238U	7.0E-01	8.9E-02	PCI/GM
	234U	7.5E-01	9.2E-02	PCI/GM
	235U	< 2.9E-02		PCI/GM
	232TH	1.5E00	2.1E-01	PCI/GM
	230TH	7.0E-01	1.4E-01	PCI/GM
	226RA	9.6E-01	1.8E-01	PCI/GM
10 Lowell at Warren	235U	4.3E-02	2.1E-02	PCI/GM
	234U	1.4E00	1.3E-01	PCI/GM
	238U	1.3E00	1.3E-01	PCI/GM
	230TH	1.5E00	2.3E-01	PCI/GM
	232TH	2.3E00	3.3E-01	PCI/GM
	226RA	1.8E00	2.4E-01	PCI/GM
11 Wynne at Garfield	234U	1.0E00	1.1E-01	PCI/GM
	238U	1.0E00	1.1E-01	PCI/GM
	235U	3.5E-02	1.9E-02	PCI/GM
	230TH	1.1E00	1.9E-01	PCI/GM
	232TH	1.9E00	2.9E-01	PCI/GM
	226RA	1.3E00	2.1E-01	PCI/GM
12 Butte Ranger Station	235U	4.0E-02	2.2E-02	PCI/GM
	234U	1.1E00	1.2E-01	PCI/GM
	238U	1.1E00	1.2E-01	PCI/GM
	230TH	1.4E00	2.1E-01	PCI/GM
	232TH	2.1E00	3.1E-01	PCI/GM
	226RA	1.6E00	2.3E-01	PCI/GM
13 Shelly at Hill	238U	1.5E00	1.3E-01	PCI/GM
	234U	1.5E00	1.3E-01	PCI/GM
	235U	5.2E-02	2.2E-02	PCI/GM
	230TH	1.3E00	4.6E-01	PCI/GM
	232TH	1.7E00	4.7E-01	PCI/GM
	226RA	2.0E00	2.5E-01	PCI/GM

Sample No.	Analysis	Result	2 Sigma*	Units
14 Colusa at Hobson	235U	4.8E-02	2.3E-02	PCI/GM
	234U	1.3E00	1.3E-01	PCI/GM
	238U	1.4E00	1.3E-01	PCI/GM
	230TH	1.2E00	2.6E-01	PCI/GM
	232TH	2.7E00	4.0E-01	PCI/GM
	226RA	1.7E00	2.3E-01	PCI/GM
15 Cobban at Lexington	234U	1.7E00	1.5E-01	PCI/GM
	238U	1.7E00	1.5E-01	PCI/GM
	235U	6.2E-02	2.5E-02	PCI/GM
	230TH	1.5E00	1.9E-01	PCI/GM
	232TH	3.8E00	3.4E-01	PCI/GM
	226RA	1.4E00	2.1E-01	PCI/GM
16 Warren at A Street	235U	5.6E-02	2.4E-02	PCI/GM
	234U	1.3E00	1.3E-01	PCI/GM
	238U	1.3E00	1.2E-01	PCI/GM
	230TH	1.4E00	1.3E-01	PCI/GM
	232TH	1.9E00	1.5E-01	PCI/GM
	226RA	1.8E00	2.4E-01	PCI/GM
17 Mass at Majors	234U	1.4E00	1.3E-01	PCI/GM
	238U	1.3E00	1.2E-01	PCI/GM
	235U	5.1E-02	2.3E-02	PCI/GM
	230TH	1.5E00	1.7E-01	PCI/GM
	232TH	1.9E00	1.9E-01	PCI/GM
	226RA	2.0E00	2.5E-01	PCI/GM
18 Cobban at Porter	235U	5.5E-02	2.5E-02	PCI/GM
	234U	1.5E00	1.4E-01	PCI/GM
	238U	1.5E00	1.4E-01	PCI/GM
	230TH	1.6E00	2.1E-01	PCI/GM
	232TH	2.5E00	2.7E-01	PCI/GM
	226RA	2.2E00	2.6E-01	PCI/GM
19 Lafayette at Grand	234U	2.0E00	1.7E-01	PCI/GM
	238U	1.9E00	1.6E-01	PCI/GM
	235U	5.9E-02	2.5E-02	PCI/GM
	230TH	1.9E00	1.4E-01	PCI/GM
	232TH	2.0E00	1.4E-01	PCI/GM
	226RA	2.6E00	2.8E-01	PCI/GM
20 Silverbow at Carolina	235U	8.7E-02	2.9E-02	PCI/GM
	234U	2.4E00	1.8E-01	PCI/GM
	238U	2.3E00	1.7E-01	PCI/GM
	230TH	2.1E00	1.5E-01	PCI/GM
	232TH	2.3E00	1.6E-01	PCI/GM
	226RA	2.0E00	2.5E-01	PCI/GM

Sample No.	Analysis	Result	2 Sigma*	Units
21 Ohio at Davidson	238U	1.2E00	1.2E-01	PCI/GM
	234U	1.0E00	1.1E-01	PCI/GM
	235U	3.1E-02		PCI/GM
	230TH	9.8E-01	2.9E-01	PCI/GM
	232TH	1.8E00	3.9E-01	PCI/GM
	226RA	1.8E00	2.4E-01	PCI/GM
22 1st at California	235U	7.7E-02	2.9E-02	PCI/GM
	234U	2.2E00	1.8E-01	PCI/GM
	238U	2.1E00	1.7E-01	PCI/GM
	230TH	1.9E00	4.6E-01	PCI/GM
	232TH	1.0E00	3.4E-01	PCI/GM
	226RA	2.2E00	2.6E-01	PCI/GM
23 Zinc Street	238U	1.0E00	1.1E-01	PCI/GM
	234U	1.0E00	1.1E-01	PCI/GM
	232TH	1.5E00	1.2E-01	PCI/GM
	235U	4.2E-02	2.1E-02	PCI/GM
	230TH	1.2E00	1.1E-01	PCI/GM
	226RA	7.0E-01	1.5E-01	PCI/GM
24 Jackson at Gold	232TH	3.1E00	3.6E-01	PCI/GM
	235U	5.5E-02	2.2E-02	PCI/GM
	230TH	2.0E00	2.8E-01	PCI/GM
	234U	1.6E00	1.3E-01	PCI/GM
	238U	1.6E00	1.3E-01	PCI/GM
	226RA	2.3E00	2.6E-01	PCI/GM
25 Diamond at Girard	232TH	3.5E00	2.3E-01	PCI/GM
	234U	1.2E00	1.2E-01	PCI/GM
	230TH	2.0E00	1.6E-01	PCI/GM
	238U	1.4E00	1.3E-01	PCI/GM
	235U	4.1E-02	2.2E-02	PCI/GM
	226RA	2.3E00	2.6E-01	PCI/GM
26 Sutter Street	232TH	2.5E00	1.8E-01	PCI/GM
	235U	4.4E-02	2.0E-02	PCI/GM
	230TH	2.1E00	1.6E-01	PCI/GM
	234U	1.6E00	1.3E-01	PCI/GM
	238U	1.5E00	1.3E-01	PCI/GM
	226RA	2.0E00	2.4E-01	PCI/GM

*The number following the "E" is the exponent of ten by which the preceding number should be multiplied. There is a 95 percent assurance that the true value lies between the reported value ± 2 sigma.

An intrusive rhyolite plug known as "Big Butte" adjoins the northwest side of this area. The remainder of the Butte surface geology consists primarily of quartz monzonite interspersed with aplite dikes and areas of alluvium. The Butte hill is interspersed with mineralized veins which have been actively mined for the last hundred years. The surface geology is highly fractured. The fracturing becomes extreme at the periphery of Big Butte, and underlies the area of the city most seriously affected by high indoor radon concentrations.

The surface geology of the Butte hill is shown in Figure 5-12. Veins and fractures are shown in Figure 5-13. Veins are shown as solid lines and fractures by dashed lines.

Efforts to correlate specific geologic types with indoor radon measurements and with radon soil gas concentrations were only partly successful. No home investigated that was built over rhyolite had indoor radon progeny concentrations exceeding 0.02 WL. Radon soil gas measurements in rhyolite were low. Six radon soil gas measurements (see Figure 5-21, sampling sites numbers 54, 55, 92, 108, 116 and 117) in rhyolite averaged 80 pCi/l during summer months as compared to an average of 1082 pCi/l for the Butte area as a whole.

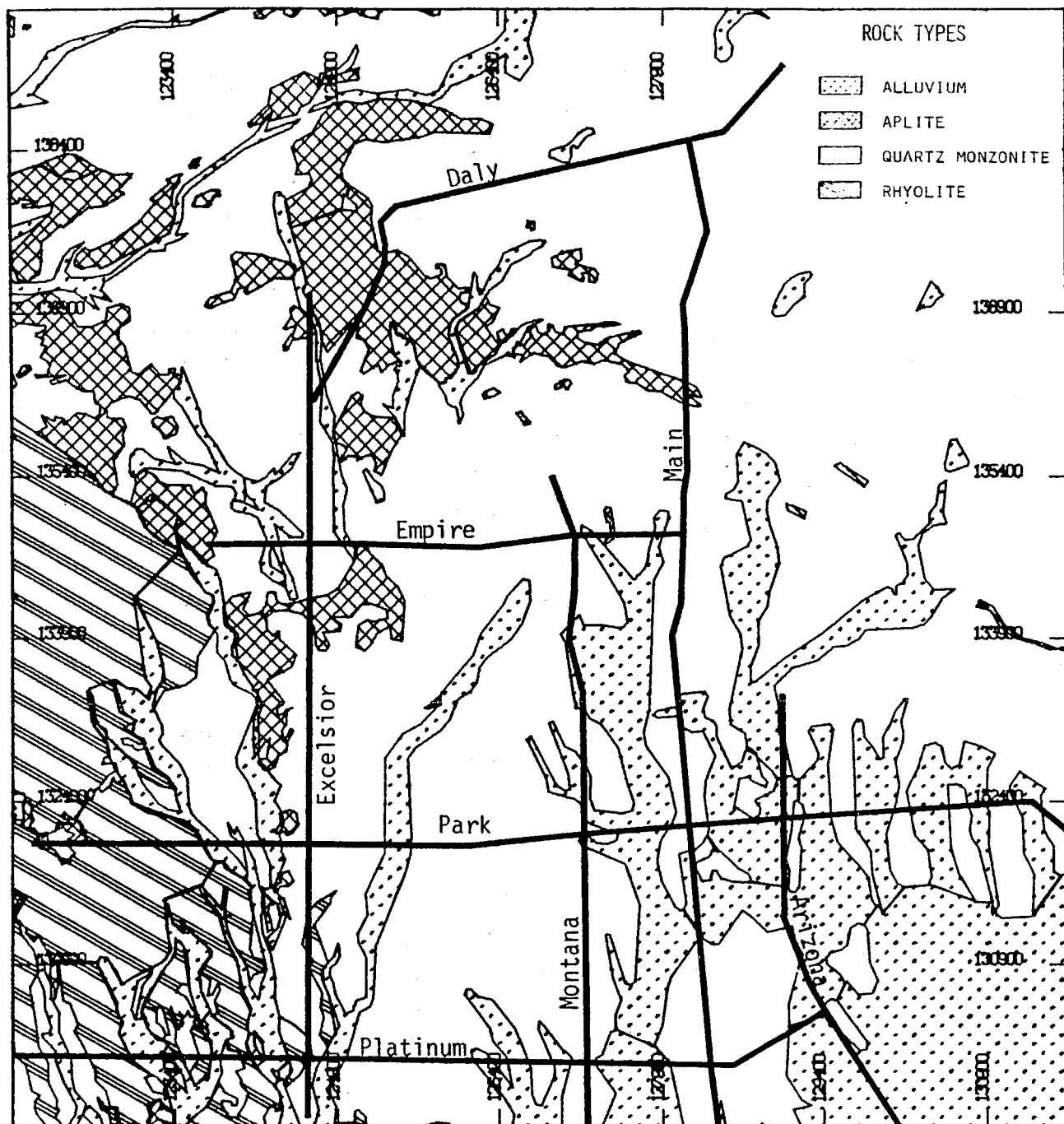
In an area west of Excelsior Street and particularly between Lewisohn Street on the south and Zarelda Street on the north, dramatic changes were noted in indoor radon progeny concentrations as measurements progressed from structures built over rhyolite to structures built over aplite and quartz monzonite. In some instances measurements changed from less than 0.02 WL to over 0.1 WL in less than one city block.

Most of the homes that measured in excess of 0.10 working levels were in the northern section of the city west of Excelsior Street (see Figure 5-14). The surface geology in this area is primarily quartz monzonite with some outcroppings of aplite, is severely fractured and interlaced with mineralized veins. McClernan¹⁰ believes that the severe fracturing in this area resulted when the rhyolite plug forming Big Butte was thrust upward through the underlying quartz monzonite basement rock.

Radon soil gas measurements in this area are high and fluctuate erratically with location as do indoor measurements of radon and radon progeny. The rock type upon which structures are built is not totally responsible for the elevated indoor radon concentrations. Measurements of radon soil gas concentrations over mineralized veins and over major fractures show radon levels considerably higher than those measured in the surrounding rock.

The elevated radioactivity content of mineralized veins is easily demonstrated by a portable gamma scintillometer. The gamma radiation levels of some veins are an order of magnitude higher than the gamma measurements of surrounding rocks.

It is believed that many structures having high concentrations of indoor radon are built over mineralized veins or over fractures which

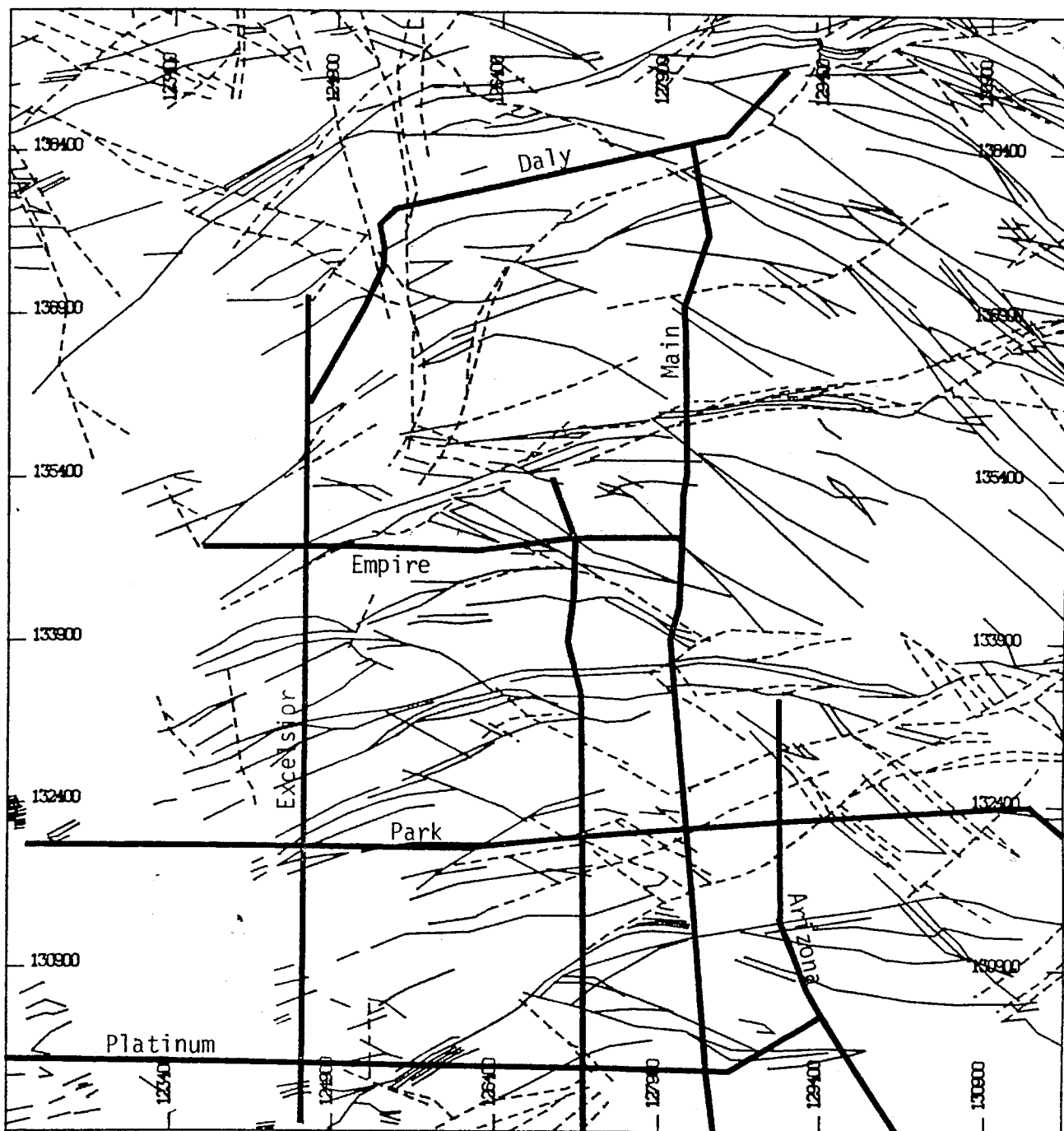


SCALE 1" = 1500. '

BOUNDARY			BOUNDARY	
EAST	= 131625.00	0	1500	NORTH = 139700.00
WEST	= 121900.00			SOUTH = 129400.00
		FEET		

FIGURE 5-12

NORTHWEST BUTTE SURFACE GEOLOGY

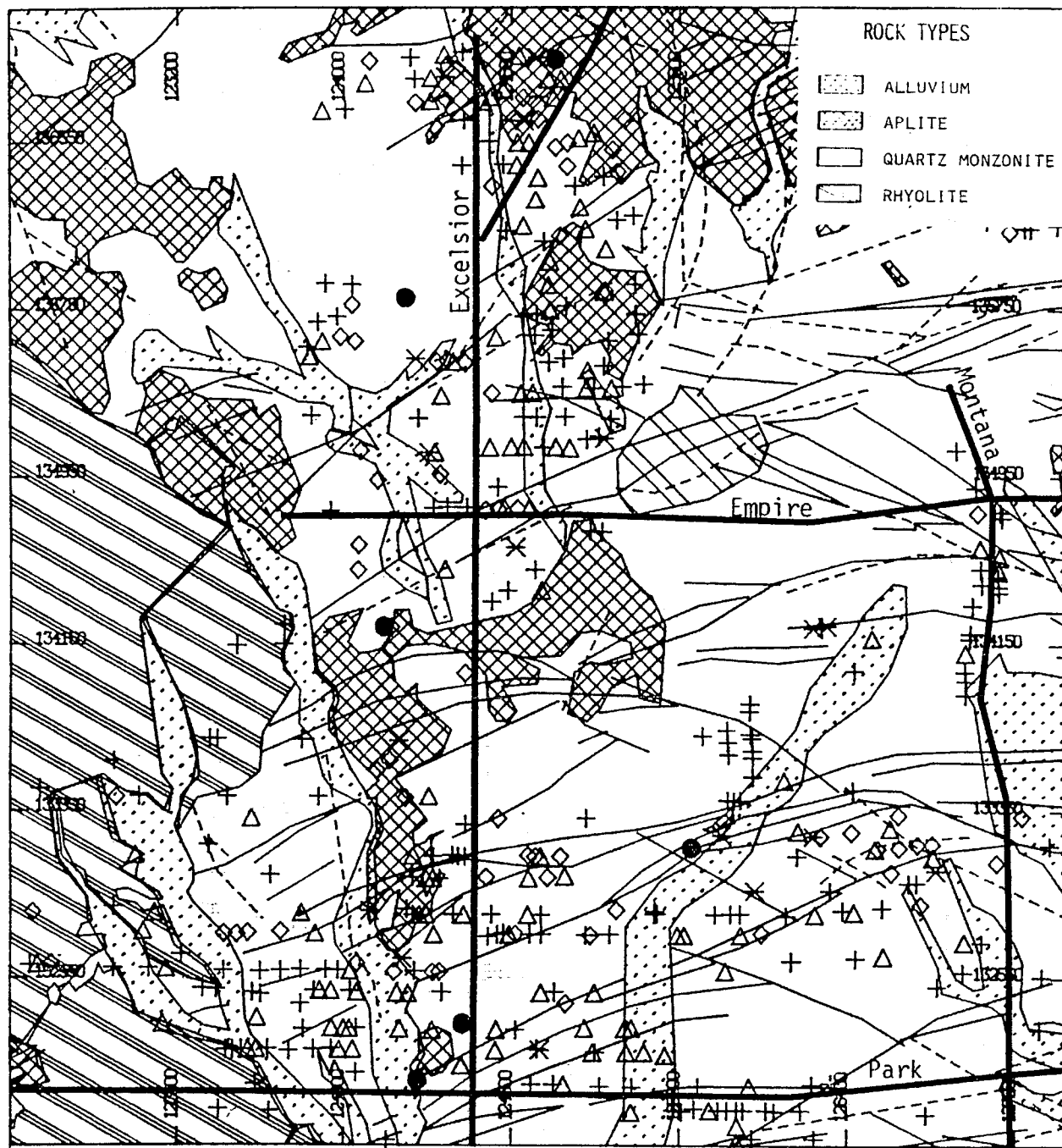


SCALE 1" = 1500. '

BOUNDARY			BOUNDARY	
EAST	= 131625.00	0	1500	NORTH = 139700.00
WEST	= 121900.00			SOUTH = 129400.00
		FEET		

FIGURE 5-13

VEINS AND FRACTURES IN
NORTHWEST BUTTE GEOLOGY



8/8/79-1/31/83

SCALE 1" = 800. '

BOUNDARY
 EAST = 127450.00
 WEST = 122400.00
 NORTH = 137200.00
 SOUTH = 131750.00

0 800
 FEET

+ BELOW .01
 △ .01 TO .01999
 ◇ .02 TO .04999
 × .05 TO .09999
 ● .10 (OR ABOVE)

FIGURE 5-14

BUTTE GEOLOGY/INDOOR RADON PROGENY CONCENTRATIONS (WL)
 IN INDIVIDUAL STRUCTURES

act as conduits for transporting radon to the structure. This theory would also account for the erratic soil gas measurements in fractured areas and areas interlaced by veins.

Structures having radon progeny concentrations exceeding 0.02 WL are distributed throughout the city. Figures 5-15 and 5-16 show the aggregate average of all indoor radon progeny measurements based upon a 300 foot grid.

Besides the northwest section of the city, two other areas have a relatively high density of structures with indoor radon progeny concentrations that exceed 0.02 WL. A community housing project known as Silver Bow Homes is in one of these areas. Silver Bow Homes consists of 19 two-story apartment buildings, and is on the east side of Arizona Street between Park and Front Streets. Skyway Park is in the second area. Skyway Park is located on the south side of the city just north of the airport, between Harrison Avenue and Continental Drive. Except for a multi-family housing project known as Town and Country Apartments, the Skyway Park addition consists primarily of single-family housing.

Silver Bow Homes

In September, 1979, HUD initiated a requirement that all subsidized housing units in Butte must have radon progeny concentrations of 0.02 WL or less. Under contract with HUD, DHES measured each apartment in the Silver Bow Homes complex, with results as shown in Figure 5-17. Fifty-seven of the 225 apartments in the Silver Bow Homes complex exceeded the 0.02 WL criteria established by HUD. In 1980, HUD provided funds to Silver Bow Homes to remediate the radon problem.

In 1982, the remediation of Silver Bow Homes was accomplished by sealing penetrations between the crawl spaces and the apartments. The undersides of the floors were sprayed with one and one-half inches of closed-cell polyurethane foam and passive ventilation stacks were installed from the crawl space through the roof of each structure.

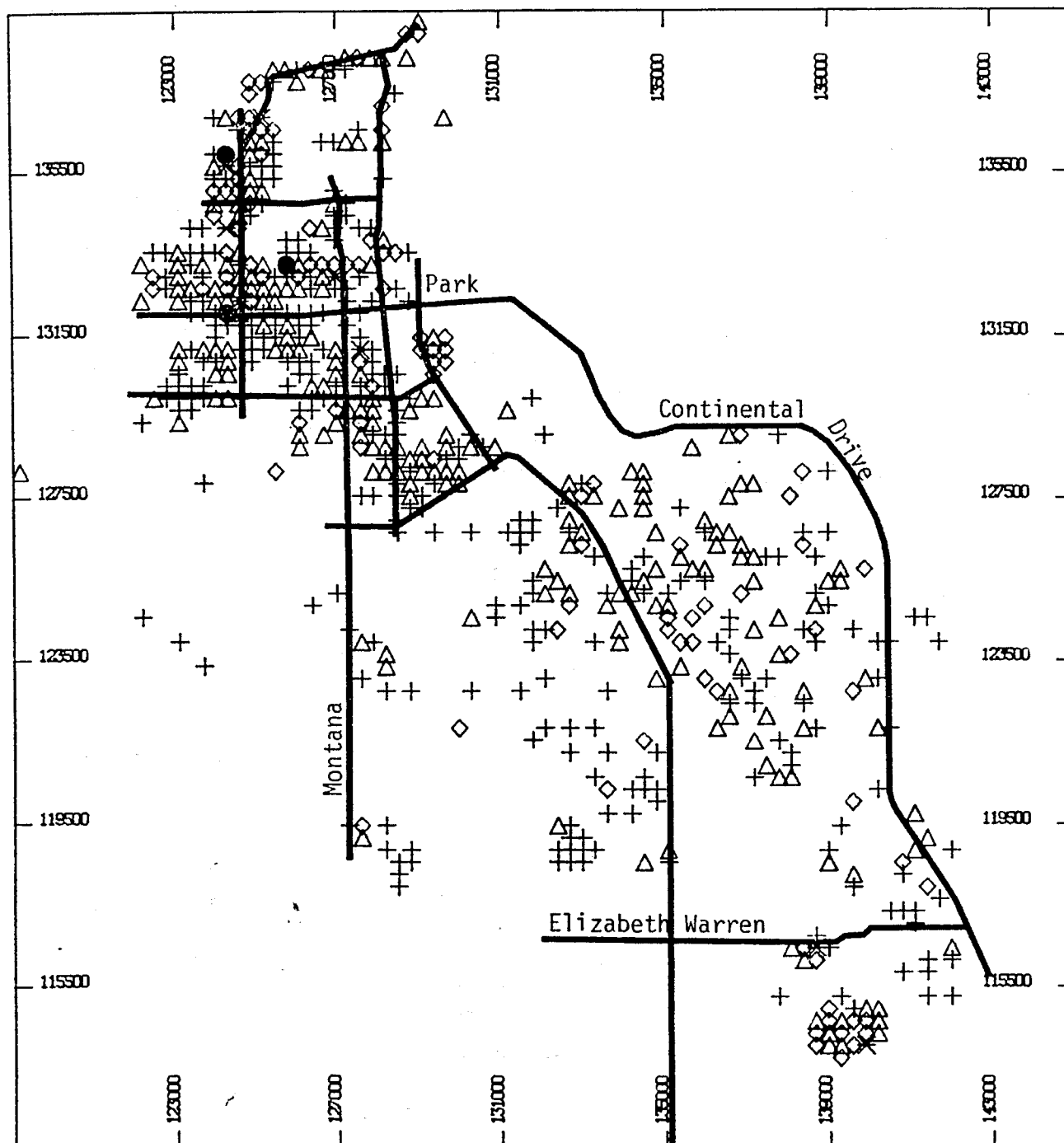
After remediation, each apartment which originally measured in excess of 0.02 WL was remeasured. All apartments were found to meet the HUD criterion.

Skyway Park

The surface geology in Skyway Park is alluvium estimated to be approximately one hundred feet deep. Because of the deep alluvium, it was not anticipated that structures in this area would be troubled by indoor radon; however, measurements of radon progeny concentrations in some Skyway Park structures were surprisingly high. These measurements are shown in Figure 5-18.

Radon Soil Gas Measurements

Soil gas measurement sites were located throughout the Butte area on a one-half mile grid. In northwest Butte additional sampling sites were established on a sub-grid of one city block.



8/8/79-1/1/83

SCALE 1" = 4000.

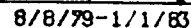
BOUNDARY
 EAST = 145000.00
 WEST = 119000.00
 NORTH = 139500.00
 SOUTH = 111500.00

0 4000
 FEET

+ BELOW .01
 Δ .01 TO .01999
 ◇ .02 TO .04999
 × .05 TO .09999
 ● .10 (OR ABOVE)

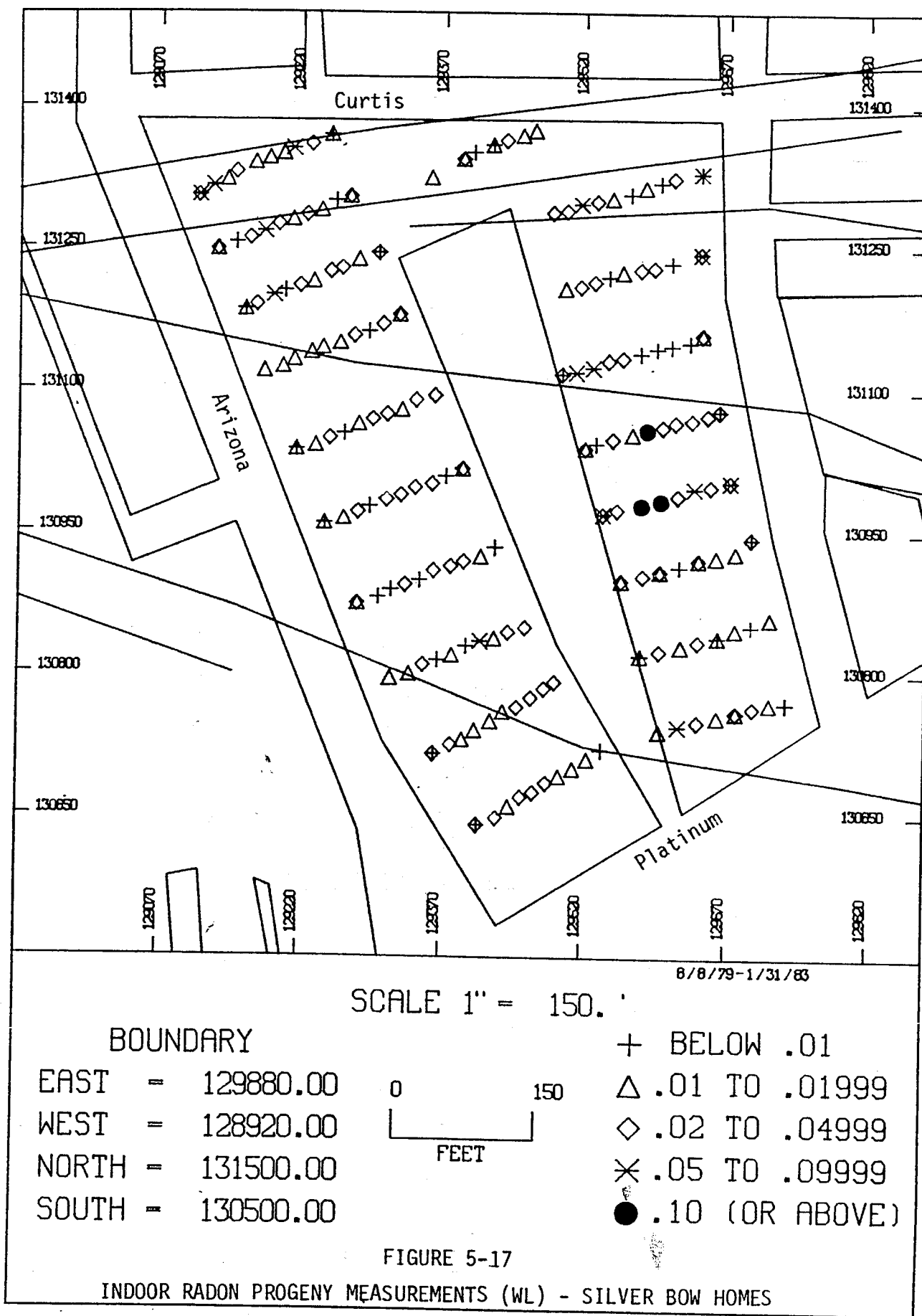
FIGURE 5-15

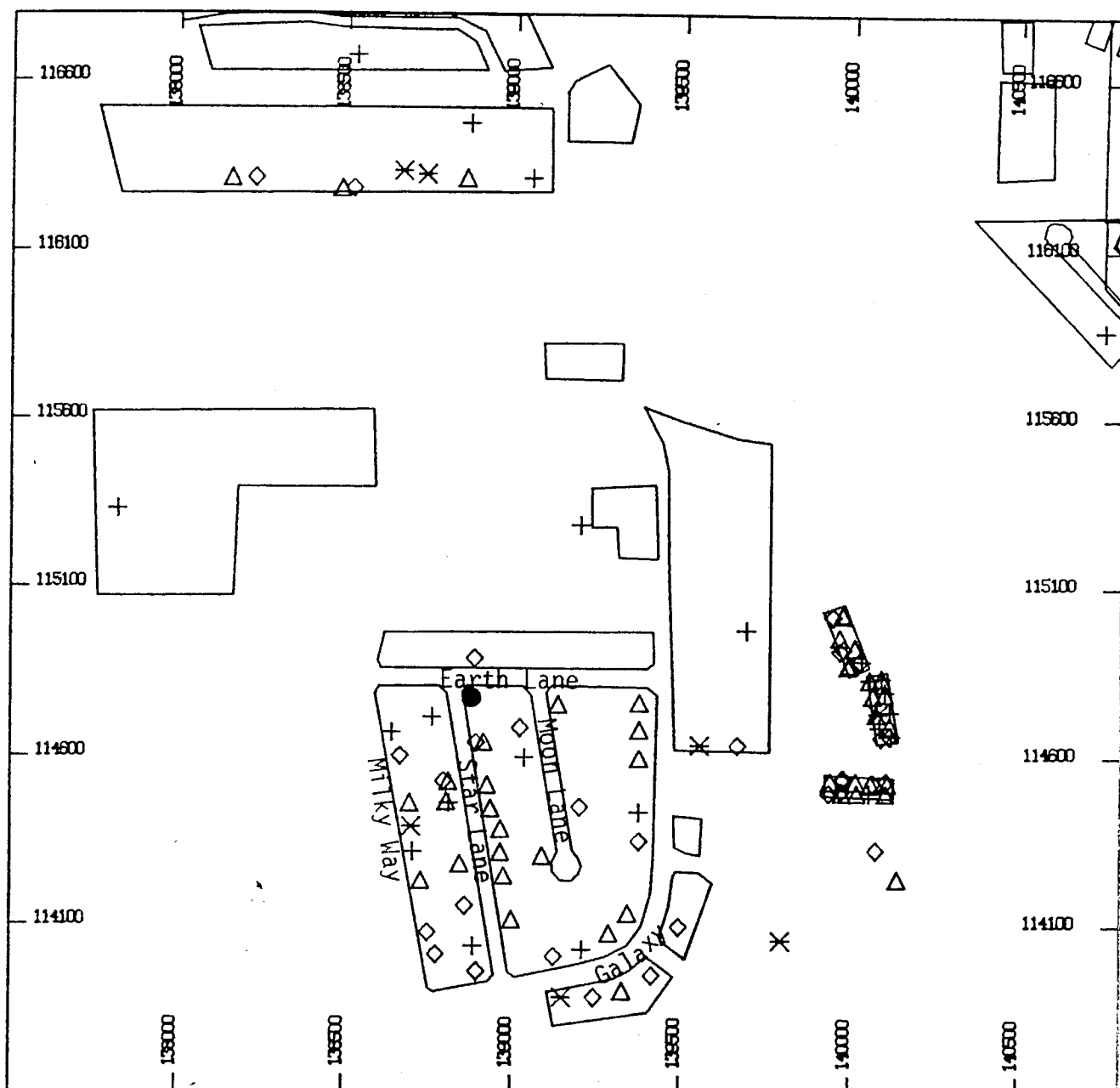
THREE HUNDRED FOOT AGGREGATE AVERAGE OF INDOOR RADON PROGENY
 CONCENTRATIONS (WL) IN BUTTE



● .10 (OR ABOVE)

THREE HUNDRED FOOT AGGREGATE AVERAGE OF INDOOR RADON PROGENY
CONCENTRATIONS (WL) IN N.W. BUTTE





8/8/79-1/31/83

SCALE 1" = 500. '

BOUNDARY
 EAST = 140800.00
 WEST = 137500.00
 NORTH = 116800.00
 SOUTH = 113600.00

0 500
 FEET

+ BELOW .01
 △ .01 TO .01999
 ◇ .02 TO .04999
 ✕ .05 TO .09999
 ● .10 (OR ABOVE)

FIGURE 5-18

INDOOR RADON PROGENY MEASUREMENTS (WL) - SKYWAY PARK

Alpha track detectors were used for measurement of radon soil gas concentrations. The alpha-track detector is a plastic chip which, after processing, shows tracks (damaged areas) where the detector was struck by alpha particles. The tracks are counted under magnification. The number of tracks in a given area is proportional to the concentration of radon to which the detector was exposed and to the time of exposure.

The alpha-track detectors were placed in plastic cups, with the tops covered by a thin membrane (thoron filter) that prevents the penetration of thoron (radon-220) but allows the entry of radon (radon-222).

Precautions were taken during the placement of the alpha-track detectors. For the safety of personnel and to assure that underground utilities would not be damaged while digging holes, utility companies were given maps showing proposed measurement site locations. Utilities included were electric, natural gas, telephone and cable television. After a review by the companies, two sites had to be relocated a few feet to avoid lines.

When alpha-track detectors are used for uranium exploration, the location of the detector is generally marked with a flag. There was concern that the detectors would be removed by vandals or curiosity seekers if the locations of the detectors were visibly marked in a populated area. To simplify recovery and to prevent theft, the alpha-track detectors were placed at a soil depth of 30 inches in a 4-inch PVC sleeve. A string was attached to the detector cup to lower it into the sleeve. An ample length of string was attached to the detector cup to allow the string to extend through the top of the sleeve. A pipe cap was then placed on the sleeve. The sleeves were cut at a length of 26 inches to provide for a detector depth of 30 inches with a 4-inch soil cover over the pipe cap. An iron washer was placed on top of the pipe cap prior to covering the cap with soil.

The location of each detector was carefully logged with reference to readily identifiable landmarks. For recovery, a metal detector was used to locate each sleeve. Only 3 out of more than 400 detectors which were emplaced were lost. These detectors were lost because road grading excavations had removed the iron washer or possibly even the sleeve and detector.

Figure 5-19 shows the alpha-track detector placed in the PVC sleeve assembly. Figure 5-20 shows the locations where alpha-track detectors were placed throughout Butte on a one-half mile grid. Figure 5-21 shows the locations where alpha-track detectors were placed in northwest Butte on a grid of one city block.

Alpha-track detectors were emplaced from July through October, 1980, and again from October, 1980, through April, 1981, to obtain measurements in both the summer and winter seasons. The radon soil gas concentration measured at each site during each sampling period is shown in Table 5-2. In Table 5-2 there is an uncertainty of the stated concentrations in pCi/l. It is believed that the relative intercomparisons between values are more valid.

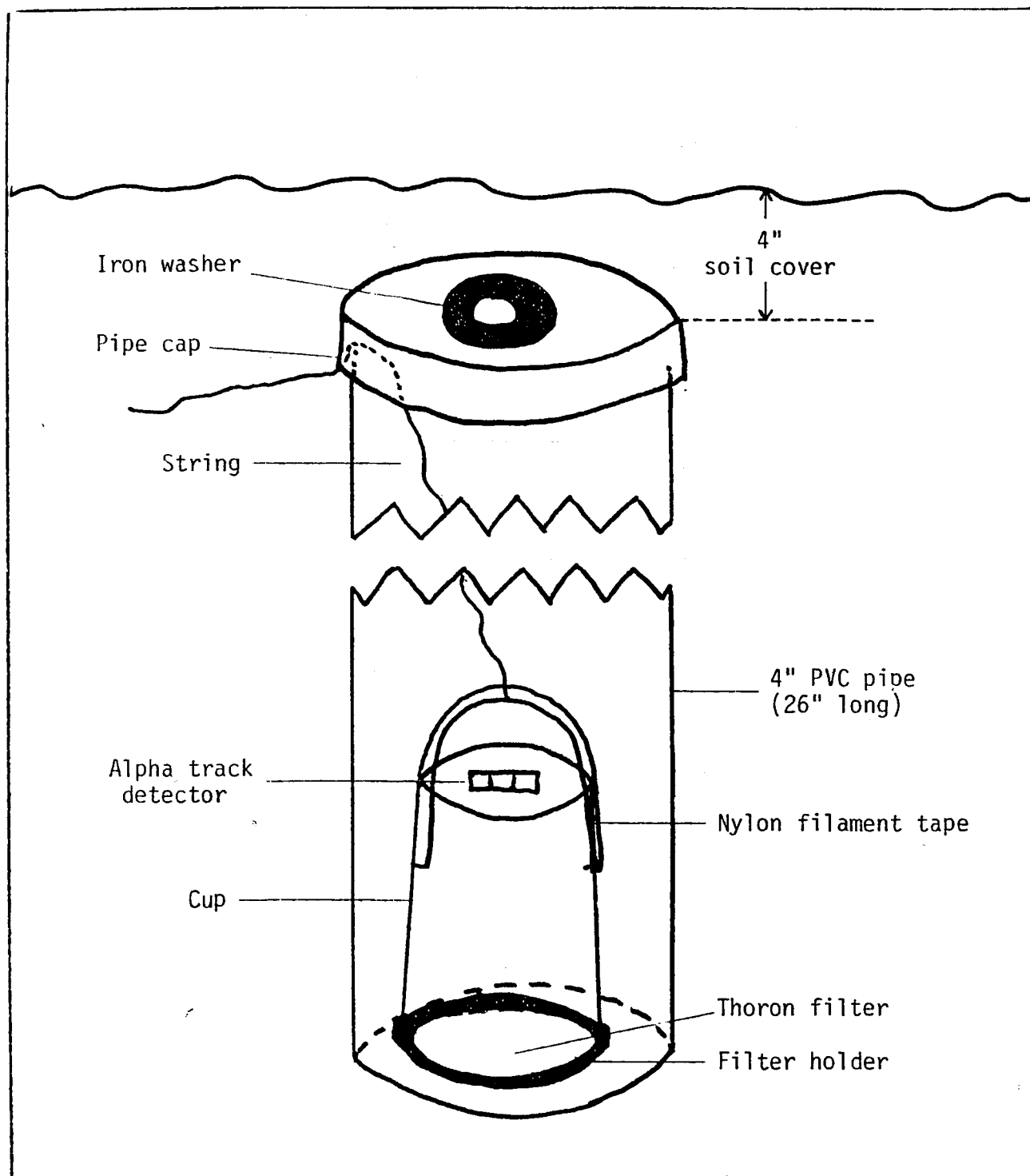
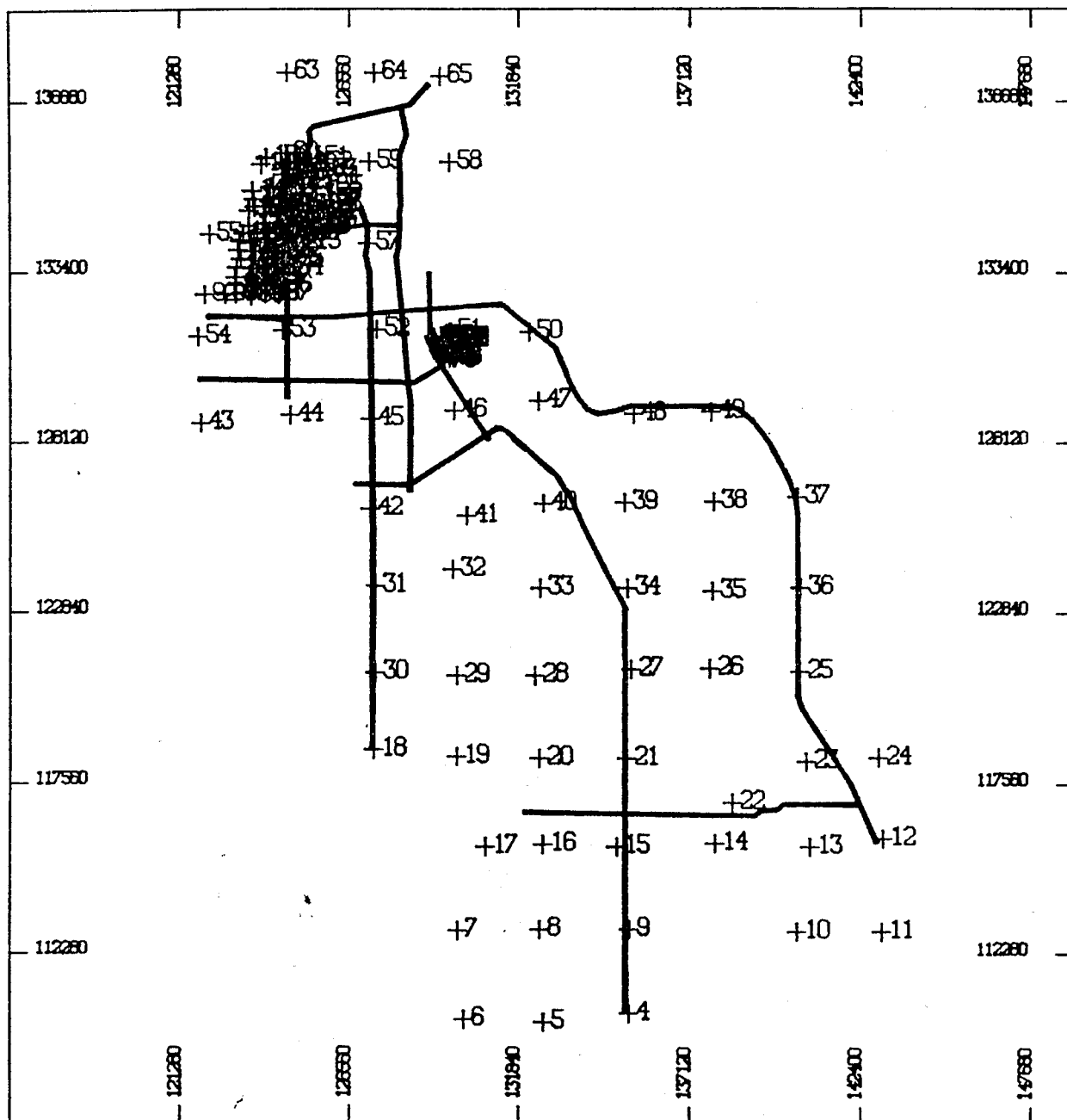


FIGURE 5-19

ALPHA TRACK DETECTOR IN PVC SLEEVE ASSEMBLY

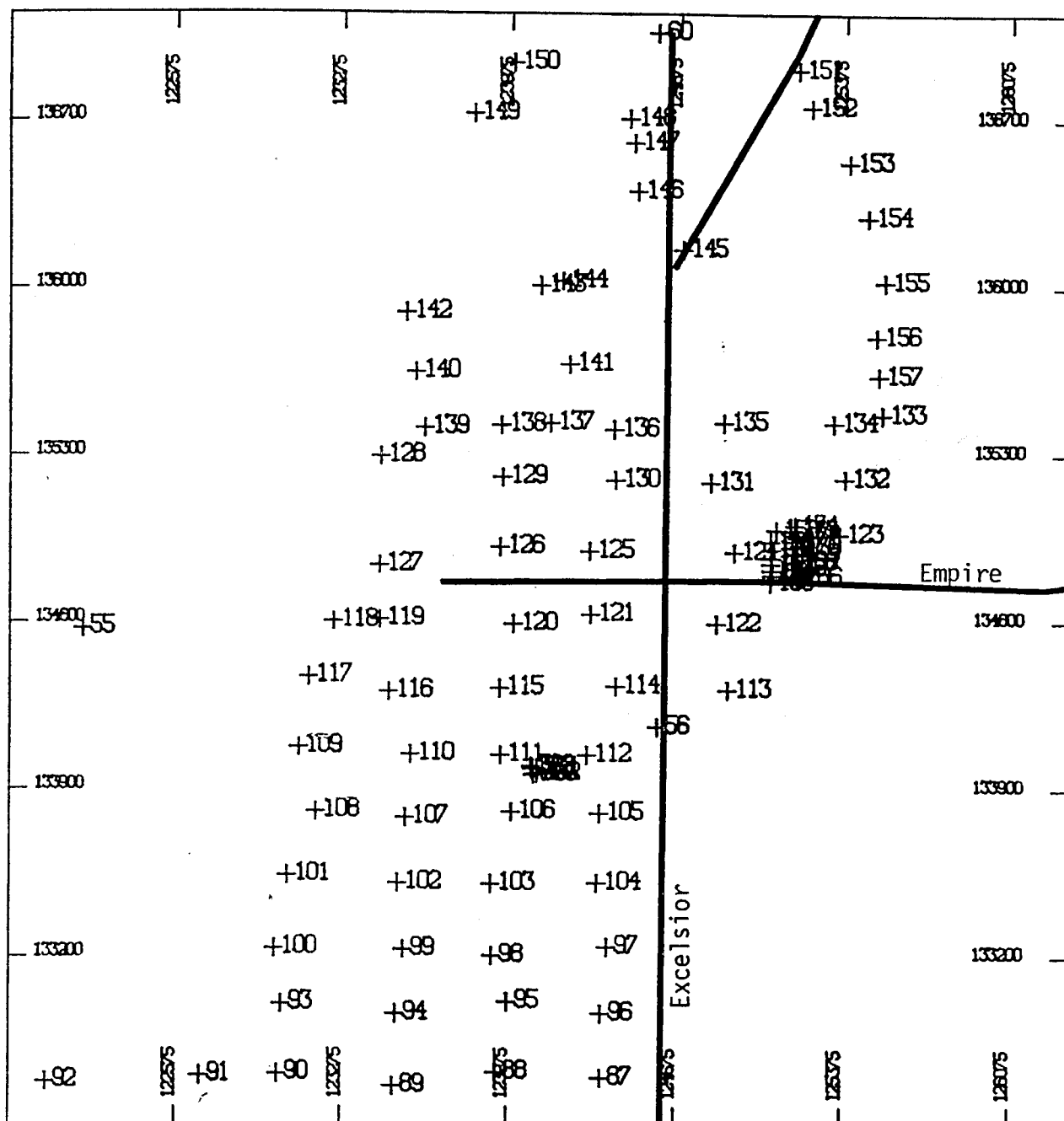


SCALE 1" = 5280. (TE 11/24/80-11/24/80)

BOUNDARY		BOUNDARY	
EAST = 149000.00	0	5280	NORTH = 141500.00
WEST = 116000.00			SOUTH = 107000.00
		FEET	

FIGURE 5-20

BUTTE RADON SOIL GAS MEASUREMENT SITES



SCALE 1" = 700.

(TE 11/24/80-7/15/82)

BOUNDARY		BOUNDARY	
EAST	= 126325.00	0	700 NORTH = 137150.00
WEST	= 121875.00		SOUTH = 132500.00
		FEET	

FIGURE 5-21

RADON SOIL GAS MEASUREMENT SITES IN N.W. BUTTE

TABLE 5-2

RADON SOIL GAS MEASUREMENTS
IN BUTTE, 1980-1981

Measurement Site	July, 1980 - December, 1980 pCi/l	October, 1980 - April, 1981 pCi/l
001 Harrison-5 Mile	362.35	757.19
002 So. End Warren	277.67	261.34
003 500 Ft. West No. 2	131.15	596.42
004 Harrison-Legion Lane	246.95	709.11
005 Motor View-Warren	363.13	1337.19
006 West End Motor View	263.91	999.11
007 4 Mile View-Utah	462.35	423.62
008 4 Mile View-Warren	640.93	450.67
009 4 Mile View-Harrison	404.80	869.89
010 NW Norm Ch-4 Mile View	678.64	814.29
011 4 Mile View-McGuiness	696.50	1277.09
012 Continental Dr-Fleecer Dr	434.57	495.75
013 Blacktail-Rampart	533.98	1338.69
014 Highland-Meadow Lark	364.92	279.38
015 Harrison-Lowell	387.54	407.09
016 Lowell-Warren	698.48	1520.50
017 Lowell-Western	438.53	277.87
018 South Montana	825.48	470.20
019 Nansen Road-Holmes	316.70	670.05
020 Holmes-Warren	540.53	842.84
021 Harrison-Holmes	192.88	201.24
022 N End Burning Tree	462.35	548.34
023 Burlington-Augusta	1083.44	1628.69
024 Burlington-Interstate	519.89	1168.90
025 Continental-Edwards	213.24	1134.34
026 Porter-Edwards	999.17	1123.82
027 Harrison-I15	688.45	766.21
028 Hill-Sampson	523.95	665.54
029 Lexington-Sampson	385.86	1194.45
030 Montana-Hanson Rd	743.28	1106.54
031 Montana-Greenwood	372.79	974.69
032 Lexington-Greenwood	278.08	68.47
033 Warren-C Street	165.64	1412.22
034 Ottawa-Massachusetts	491.68	1718.26
035 Ottawa-Porter	584.88	460.09
036 Ottawa-Continental	381.80	259.84
037 Continental-Gagnon	345.24	574.19
038 Porter-George	980.89	924.82
039 George-Massachusetts	509.74	1332.87
040 George-Whitman	253.85	530.37

Measurement Site	July, 1980 - December, 1980 pCi/l	October, 1980 - April, 1981 pCi/l
041 George-Lexington	120.63	241.71
042 Montana-Silverbow Cr	264.01	802.40
043 I15-South Big Butte	773.74	702.66
044 Excelsior-I15	400.07	1593.57
045 Montana-Iron	1751.59	1668.38
046 3rd-Utah	312.75	813.74
047 1st-Warren	237.61	602.91
048 Monroe-Pine	696.57	1706.92
049 Stuart-Pine	2290.77	1720.52
050 Continental-Warren	566.60	1462.09
051 Mercury-Ohio	38.07	73.95
052 Montana-Mercury	74.30	201.24
053 Galena-Excelsior	556.73	129.72
054 Oredigger Field	76.76	322.95
055 Big Butte M	176.68	112.34
056 Lewisohn-Excelsior	1209.36	1038.17
057 Montana-Boardman	2296.86	1137.91
058 Bennett	868.18	689.05
059 La Platta-Montana	566.60	963.36
060 17th-Excelsior	1620.60	1230.86
061 Brown's Gulch Road	960.98	1060.84
062 W of Ryan's Tower	464.63	1634.38
063 E of Ryan's Tower	798.26	2470.89
064 WM Street Walkerville	558.78	734.39
065 E of Walkerville	2014.07	*
066 Silver Bow Homes 107	361.49	371.91
067 Silver Bow Homes 106	276.19	1118.28
068 Silver Bow Homes 206	501.61	2346.41
069 Silver Bow Homes 306	521.92	476.20
070 Silver Bow Homes 406	132.82	469.20
071 Silver Bow Homes 506	259.95	1181.32
072 Silver Bow Homes 606	233.54	754.05
073 Silver Bow Homes 706	218.11	217.81
074 Silver Bow Homes 806	278.22	1106.61
075 Silver Bow Homes 906	371.64	1223.35
076 Silver Bow Homes 1006	542.23	334.55
077 Silver Bow Homes 1909	148.60	747.04
078 Silver Bow Homes 1902	605.86	1410.14
079 Silver Bow Homes 1107	378.66	655.98
080 Silver Bow Homes 1207	315.21	1029.56
081 Silver Bow Homes 1306	452.35	1487.19
082 Silver Bow Homes 1407	665.22	2311.39
083 Silver Bow Homes 1506	478.96	590.61
084 Silver Bow Homes 1607	245.62	653.65
085 Silver Bow Homes 1707	268.20	1428.82
086 Silver Bow Homes 1806	350.72	348.56
087 Granite-Excelsior	760.18	1774.37
088 Granite-Henry	727.41	1641.29
089 Granite-Emmett	1022.31	1420.49
090 Granite-Western	515.52	964.22

Measurement Site		July, 1980 - December, 1980 pCi/l	October, 1980 - April, 1981 pCi/l
091	Granite-Prospect	178.25	308.32
092	Granite-Ophir	44.61	27.67
093	Quartz-Western	323.83	270.89
094	Quartz-Emmett	526.50	*
095	Quartz-Henry	2821.95	2673.46
096	Quartz-Excelsior 18"	315.02	923.22
097	Copper-Excelsior	697.23	2495.23
098	Copper-Henry	637.75	777.07
099	Copper-Emmett	249.81	459.82
100	Copper-Western	266.55	780.64
101	Caledonia-Western 18"	203.48	216.94
102	Caledonia-Emmett	210.03	294.04
103	Caledonia-Henry	253.94	227.70
104	Caledonia-Excelsior	1649.45	910.85
105	Woolman-Excelsior 14"	169.18	424.93
106	Woolman-Henry	1057.41	2338.13
107	Woolman-Emmett	106.40	69.91
108	Woolman-Western	66.09	252.80
109	Antimony-Western	414.15	190.04
110	Antimony-Emmett	54.85	40.86
111	Antimony-Henry 15"	592.22	367.56
112	Antimony-Excelsior	867.99	3837.12
113	Lewisohn-Alabama	727.85	437.49
114	Lewisohn-Excelsior	1586.80	3478.51
115	Lewisohn-Henry	2271.70	3944.71
116	Lewisohn-Emmett 13"	28.75	158.96
117	Lewisohn-Western	94.26	394.45
118	Waukesha-Western	211.57	292.25
119	Waukesha-Emmett	1528.89	5271.57
120	Waukesha-Henry	1953.01	5250.05
121	Waukesha-Excelsior	1624.66	3885.44
122	Waukesha-Alabama 11"	362.56	2010.44
123	Empire-Clark	933.75	1504.26
124	Empire-Alabama	920.07	463.38
125	Empire-Excelsior	1351.03	1432.97
126	Empire-Henry	4282.26	5706.97
127	Kennedy School	1073.99	4491.43
128	Brown's Gulch-Zarelda	679.51	723.60
129	Hornet-Henry	1857.24	1896.37
130	Hornet-Excelsior	2544.73	3814.15
131	Hornet-Alabama	1228.42	1076.50
132	Hornet-Pit	3554.12	4455.78
133	Zarelda-Clark East	1228.42	2495.23
134	Zarelda-Clark	186.33	484.77
135	Zarelda-Alabama	292.61	862.62
136	Zarelda-Excelsior 20"	1490.66	3457.68
137	Zarelda-Henry 21"	855.75	3029.93
138	Zarelda-Henry	434.78	2709.11
139	Zarelda-Hornet	10295.22	7172.21
140	End Prospect	5472.54	6454.99

Measurement Site		July, 1980 - December, 1980 pCi/l	October, 1980 - April, 1981 pCi/l
141	616 Butte Fire St 20"	1371.56	7172.21
142	Missoula West End	244.30	54.80
143	Missoula Green Apt.	2870.91	3872.99
144	Missoula White Apt.	678.62	281.49
145	Excelsior-Walker 20"	630.31	1004.09
146	Excelsior-12th	2022.05	2402.68
147	Excelsior-14th	1269.82	1169.05
148	Excelsior-15th	775.24	720.79
149	Henry-15th	625.71	1384.22
150	Henry-17th 20"	156.66	92.32
151	Excelsior-17th	1469.96	3119.90
152	14th-Clark 20"	1863.33	989.75
153	11th-Clark 20"	1055.89	846.30
154	9th-Clark 20"	743.03	1047.12
155	Missoula-Clark	683.22	2689.57
156	Clark-6th	394.75	591.69
157	Kenwood-Clark	502.41	824.79
158	Alabama-Empire 20"	1059.78	2920.99
159	Alabama-Empire	1839.62	3401.67
160	Alabama-Empire	*	1663.85
161	Alabama-Empire	1066.44	451.07
162	Alabama-Empire 20"	290.61	1116.62
163	Alabama-Empire 20"	679.86	843.01
164	Alabama-Empire 30"	737.62	650.74
165	Alabama-Empire 15"	249.68	204.57
166	Alabama-Empire	1327.09	3327.72
167	Alabama-Empire	978.22	2699.14
168	Alabama-Empire	1347.61	3253.77
169	Alabama-Empire 20"	515.33	2292.42
170	Alabama-Empire	1005.58	3031.92
171	Alabama-Empire	1015.84	2551.24
172	Alabama-Empire	1224.48	4030.24
173	Alabama-Empire	2202.70	6285.71
174	Alabama-Empire	1522.05	3253.77
175	Silver Bow Homes 1904	140.92	232.92
176	Silver Bow Homes 1904	214.11	573.09
177	Silver Bow Homes 1904	239.47	467.71
178	Silver Bow Homes 1904	249.13	691.41
179	Silver Bow Homes 1112	400.27	769.06
180	Silver Bow Homes 1112	240.85	103.51
181	Silver Bow Homes 1112	185.64	84.28
182	Silver Bow Homes 1112	724.63	1072.25
Mean		1082.39	1407.2

*Alpha-track detector lost.

Gingrich¹¹ reports that worldwide radon soil gas concentrations average about 100 pCi/l. According to Gingrich, radon soil gas concentrations can be expected to vary by a factor of about 2 to 5 from the 100 pCi/l value. Gingrich's information is based on data acquired from more than 300 different surveys in which the alpha-track detectors were used. According to Gingrich, only 12 of the 300 areas measured had radon soil gas concentrations averaging above 1000 pCi/l. Butte was one of the 12 areas.

The average radon soil gas concentration measured during summer months was 1082 pCi/l. The average radon soil gas concentration measured in the winter was 1407 pCi/l. The higher winter concentration was attributed to the capping effect created by the freezing of the top layers of soil.

The depth to which soil freezes in Butte during the winter exceeds the depth at which the alpha-track detectors were placed. The difference between the winter and summer measurements would likely have been greater if the detectors had been placed below the frost line.

From Table 5-2, it can be seen that radon soil gas concentrations ranged from lows of less than 100 pCi/l to a high that exceeded 10,000 pCi/l.

Homes having indoor radon progeny concentrations of 0.02 WL or less were not considered to have a significant indoor radon problem based on the U. S. Surgeon General's guidelines for Grand Junction, Colorado, and the EPA standards for inactive uranium mill sites (10 CFR 192). Generally, radon progeny concentrations in homes did not exceed 0.02 WL where radon soil gas concentrations were less than 500 pCi/l. However, there were exceptions. These exceptions may be due to construction differences or variations in radon soil gas concentrations between structure locations and the sites where radon soil gas concentrations were measured.

As seen in Table 5-2, radon soil gas concentrations frequently exceed 1000 pCi/l in northwest Butte where high levels of indoor radon are found.

There appears to be a sufficient enough relationship between radon soil gas measurements and indoor radon concentrations to predict that elevated radon soil gas concentrations may be an indicator of potential indoor radon problems in Butte.

Localized Measurements of Radon Soil Gas Concentrations

In addition to the grid measurements of radon soil gas, alpha-track detectors were used to measure radon soil gas concentrations in straight lines traversing identifiable fractures, mineralized veins, and areas of specific geologic composition.

Silver Bow Homes

At Silver Bow Homes, alpha-track detectors were placed between apartment buildings at locations shown in Figure 5-22. The values to the left of the site location (+) are measurements made during the months of August, September and October, 1981. The values to the right of the site marker are measurements made between the months of November, 1981 and April, 1982.

At Silver Bow Homes the average radon soil gas concentration in the summer (362 pCi/l) and in the winter (964 pCi/l) was lower than the overall average soil gas concentration for the city during the summer and winter (1082 pCi/l and 1407 pCi/l, respectively).

Mineralized veins, shown as solid lines in Figure 5-22, traverse the Silver Bow complex in an east-west direction. The veins are covered with soil and are not visible.

Figure 5-23 shows radon soil gas measurement sites traversing two mineralized veins. Positioning the alpha-track detectors proved difficult due to the rock encountered while digging in the southernmost sites shown in Figure 5-23.

Skyway Park

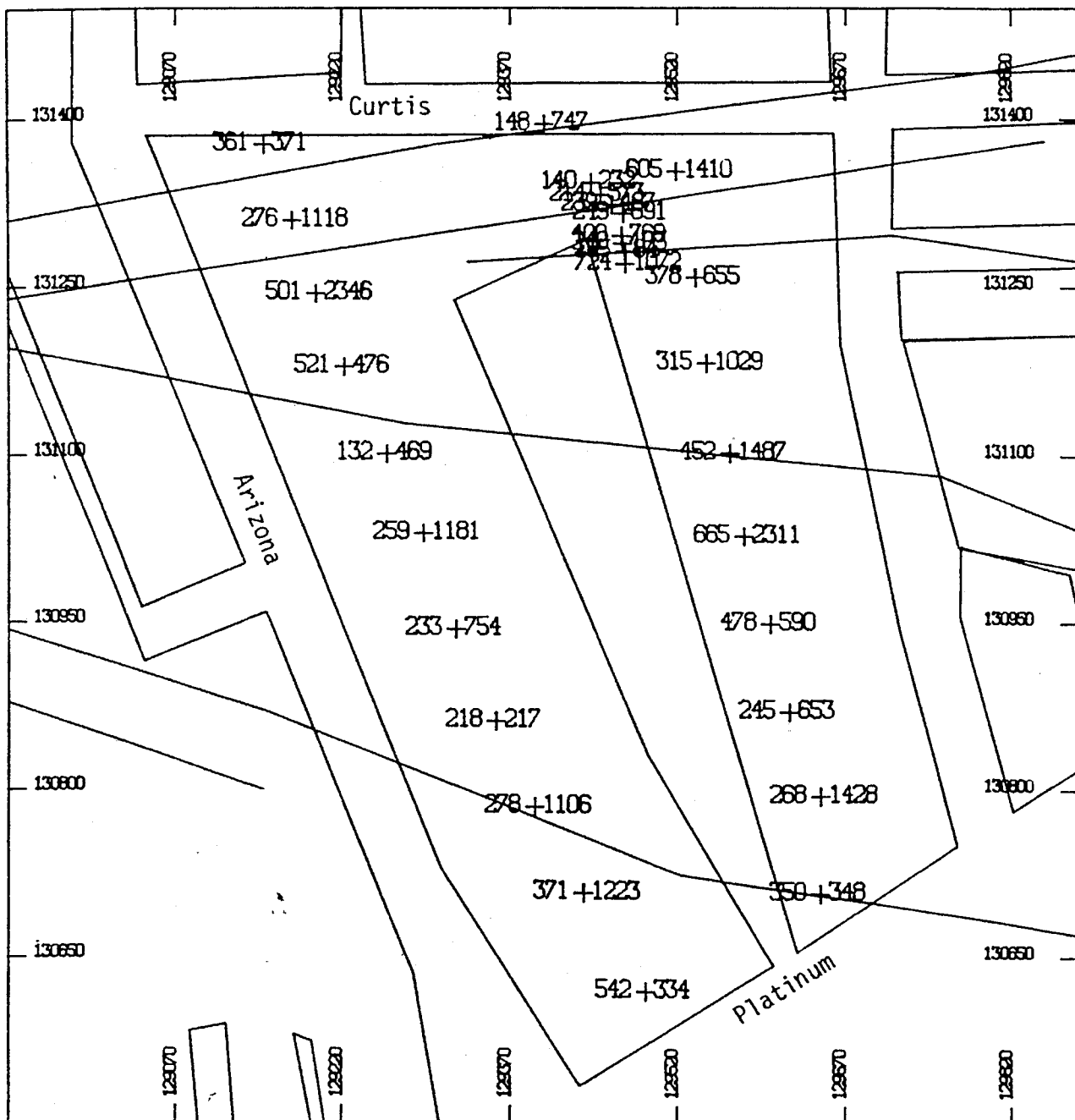
Skyway Park is in the Butte valley where the alluvium is estimated to range between 80 and 200 feet in depth.

Radon soil gas measurements were made in Skyway Park between November, 1981, and April, 1982. Difficulty was encountered in establishing locations where alpha-track detectors could be placed in this area. The streets in Skyway Park are paved and there are no alleys. Nearly all the residences have been landscaped. It would have been desirable to position some alpha-track detectors near homes having elevated indoor radon concentrations but this was generally not possible due to the landscaping. With few exceptions, the alpha-track detectors were placed on vacant lots.

The average radon soil gas measurement in Skyway Park was 666 pCi/l which is less than half the average radon soil gas concentration measured in Butte during the winter months, yet still significantly higher than what Gingrich considers normal. The Skyway Park radon soil gas measurement sites and data in pCi/l are shown in Figure 5-24.

Radon and radon progeny concentrations were measured in several Skyway Park homes by long-term integrating methods; however, most homes were measured by grab sampling. Of the 56 homes tested in the Skyway Park area, 22 measured in excess of 0.02 Working Levels.

No mineralized veins, fractures, or unusual geologic features are found in Skyway Park, and the radon soil gas concentrations are relatively constant. It is not known if the difference in radon progeny concentrations between homes in this area is due to structural



SCALE 1" = 150. '

(TE 11/24/80-7/15/82)

BOUNDARY

BOUNDARY

EAST = 129880.00

0

150

NORTH = 131500.00

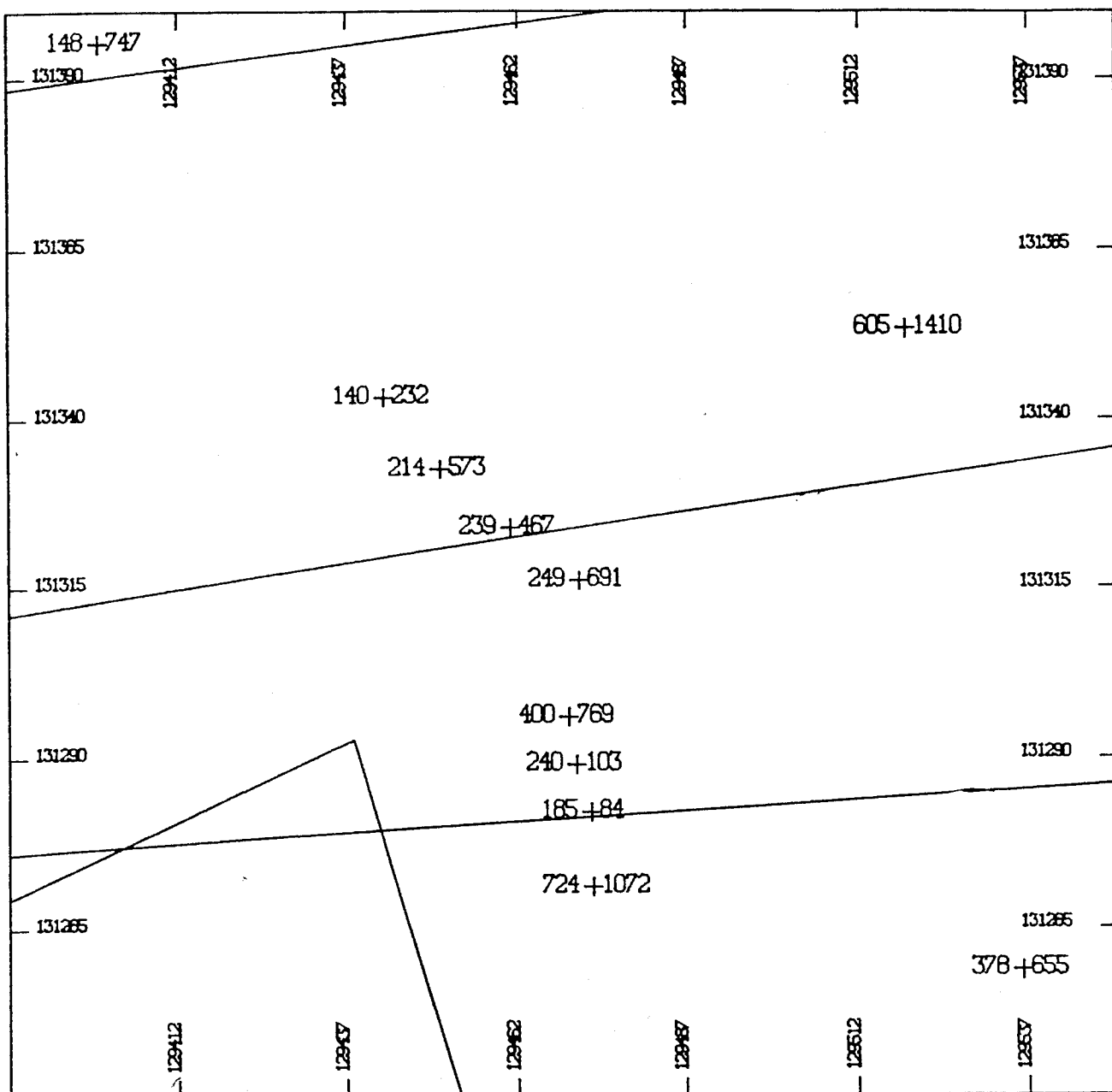
WEST = 128920.00

FEET

SOUTH = 130500.00

FIGURE 5-22

RADON SOIL GAS CONCENTRATIONS (pCi/l) - SILVER BOW HOMES



SCALE 1" = 25.

(TE 11/24/80-7/15/82)

BOUNDARY

EAST = 129550.00
WEST = 129387.00
= Veins

0 25
FEET

BOUNDARY

NORTH = 131400.00
SOUTH = 131240.00
+ = Measurement Location
xxx+yyy = Summer & Winter
Measurement

FIGURE 5-23

RADON SOIL GAS CONCENTRATIONS (pCi/l) AT MEASUREMENT SITES
TRAVERSING MINERALIZED VEINS - SILVER BOW HOMES

differences, differing lifestyles or if there are localized areas having high soil radium-226 content that were not indicated by the radon soil gas measurements.

McClernan¹⁰ believes that Skyway Park was marshy or underwater at one time and that there may be small localized areas having soils with elevated radium content that may have resulted from either the precipitation or organic concentration of radium.

Walkerville

Radon soil gas measurements were made in aplite in the Walkerville area which is located on the north side of Butte. The measurement site selected was from about 30 to 200 feet west of Walkerville Drive with the northernmost sampling point approximately 200 feet south of where Walkerville Drive curves into Daly Street. Eleven alpha-track detectors were emplaced in October, 1981, and recovered in April, 1982. The measurements and locations are shown in Figure 5-25.

The line of alpha-track detectors crossed a major fracture (shown as a dotted line in Figure 5-25). The radon soil gas measurements at the two measurement points near the fracture averaged 7171 pCi/l; whereas, the other nine measurement points averaged 1226 pCi/l. The average of the nine measurement points located away from the fracture compares closely with the overall average for the Butte area during winter months (1407 pCi/l).

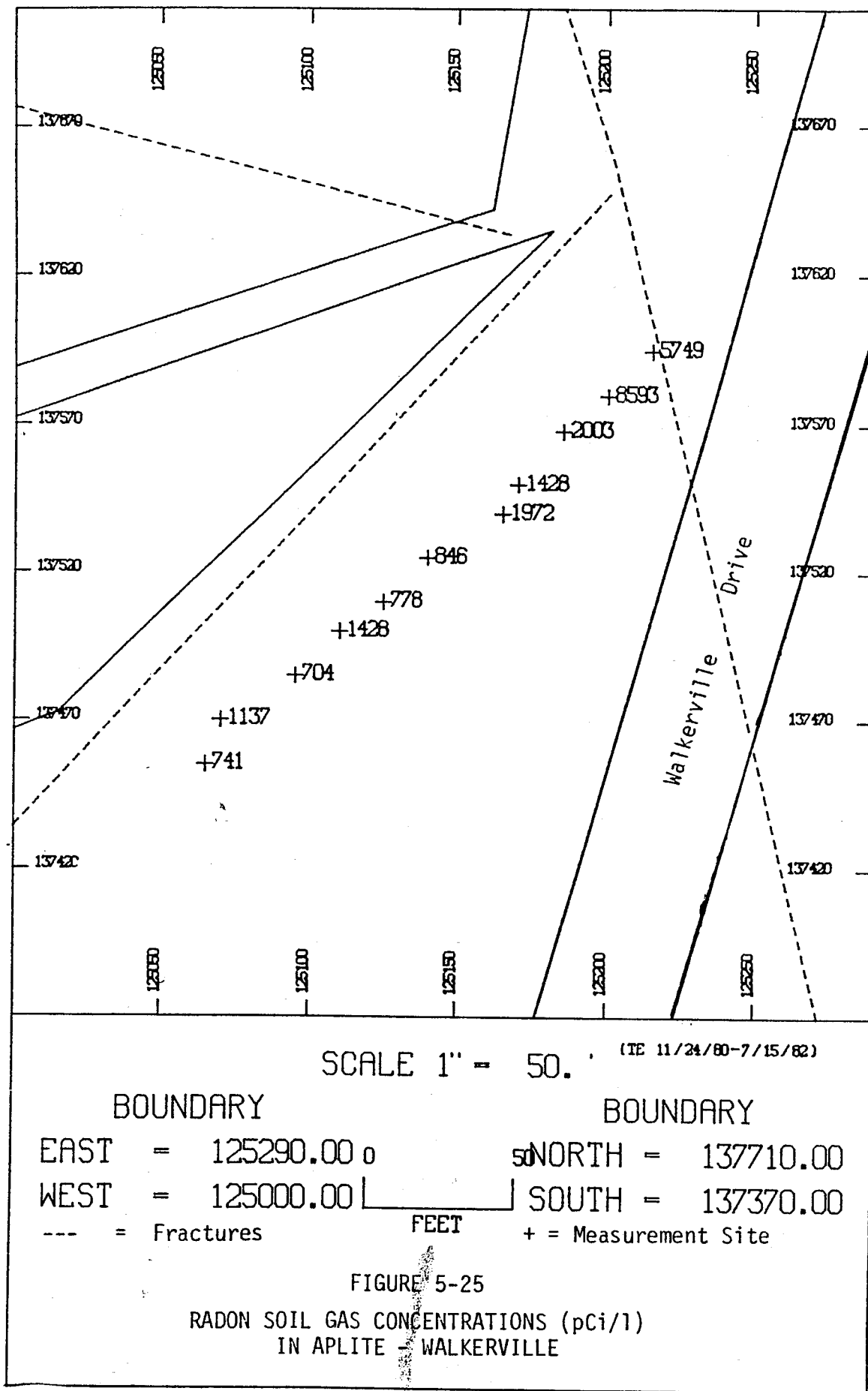
Fractures in underlying geology are believed to act as conduits for transporting radon to the surface. The measurements at the two sites near the fracture support this theory.

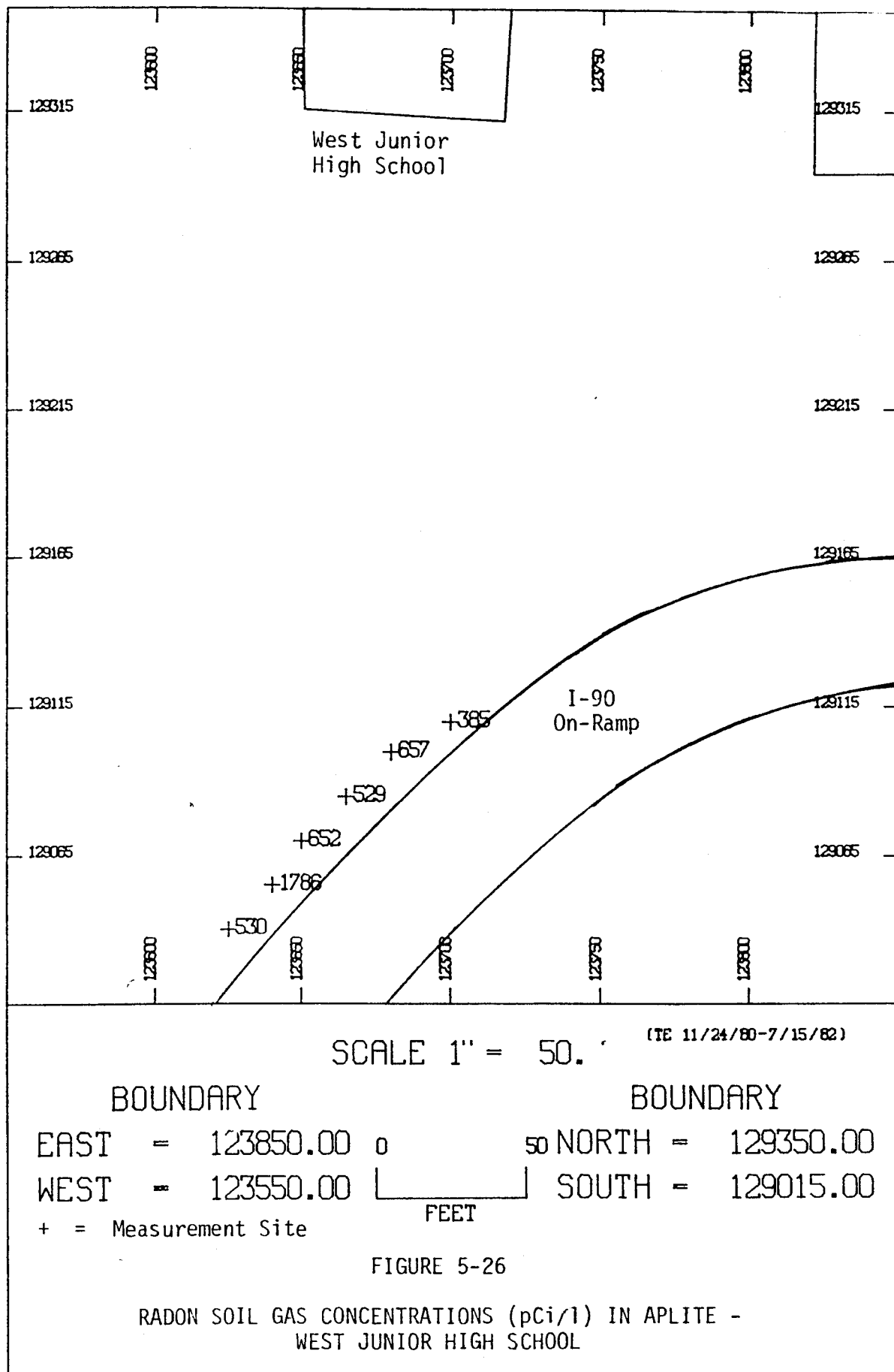
The purpose in placing the alpha-track detectors in the aplite was to determine if the radon soil gas concentrations in the aplite varied significantly from the concentrations measured in other surface rock and soil types. When the two measurement points near the fracture are excluded, the average (1226 pCi/l) compares closely with the overall radon soil gas concentration average for Butte, but is still nearly double the average measurement for the Skyway Park area and is about 25% higher than the average radon soil gas concentration during a comparable time period at Silver Bow Homes.

West Junior High School

Six measurement points in aplite were established at a site north of the Interstate 90 on-ramp at a distance of about 200 feet south of the West Junior High School. The locations of the measurement points and the radon soil gas measurement data in pCi/l are shown in Figure 5-26. Fairly consistent concentrations averaging 547 pCi/l were measured at five of the six sampling points. The sixth point measured 1766 pCi/l. The anomalous measurement was near a small mineralized vein.

If the anomalous measurement is discounted, the radon soil gas measurements at the West Junior High School average only about one-half





the concentration measured at the Walkerville site. Although no laboratory analyses were made, it appears that either the radium content of the aplite varies or that the radon permeability of aplite varies between the two sites.

Yellow Jacket Vein

Radon soil gas measurements were made on both sides of Alabama Street between Hornet and Empire Streets, traversing two forks of the Yellow Jacket Vein. The sampling points and measurement data in pCi/l are displayed in Figure 5-27. The measurements recorded to the left of the sampling point (+) are summer measurements and the measurements on the right side are winter measurements. As seen in Figure 5-27, the radon soil gas concentrations measured over veins are higher than measurements which were not over veins.

Gold Street

Radon soil gas measurements were made at a site near Gold and Jackson Streets. At this site a number of exposed mineralized veins traverse Jackson Street in an east-northeast direction. Six alpha-track detectors were placed, traversing the exposed veins as shown in Figure 5-28. The average radon soil gas concentration at this site was 3396 pCi/l, approximately three times the average for the Butte area.

Henry Street

Another series of exposed mineralized veins traverses Henry Street at its intersection with Antimony Street. As at the Gold Street site, the veins traverse Henry Street in an east-northeast direction.

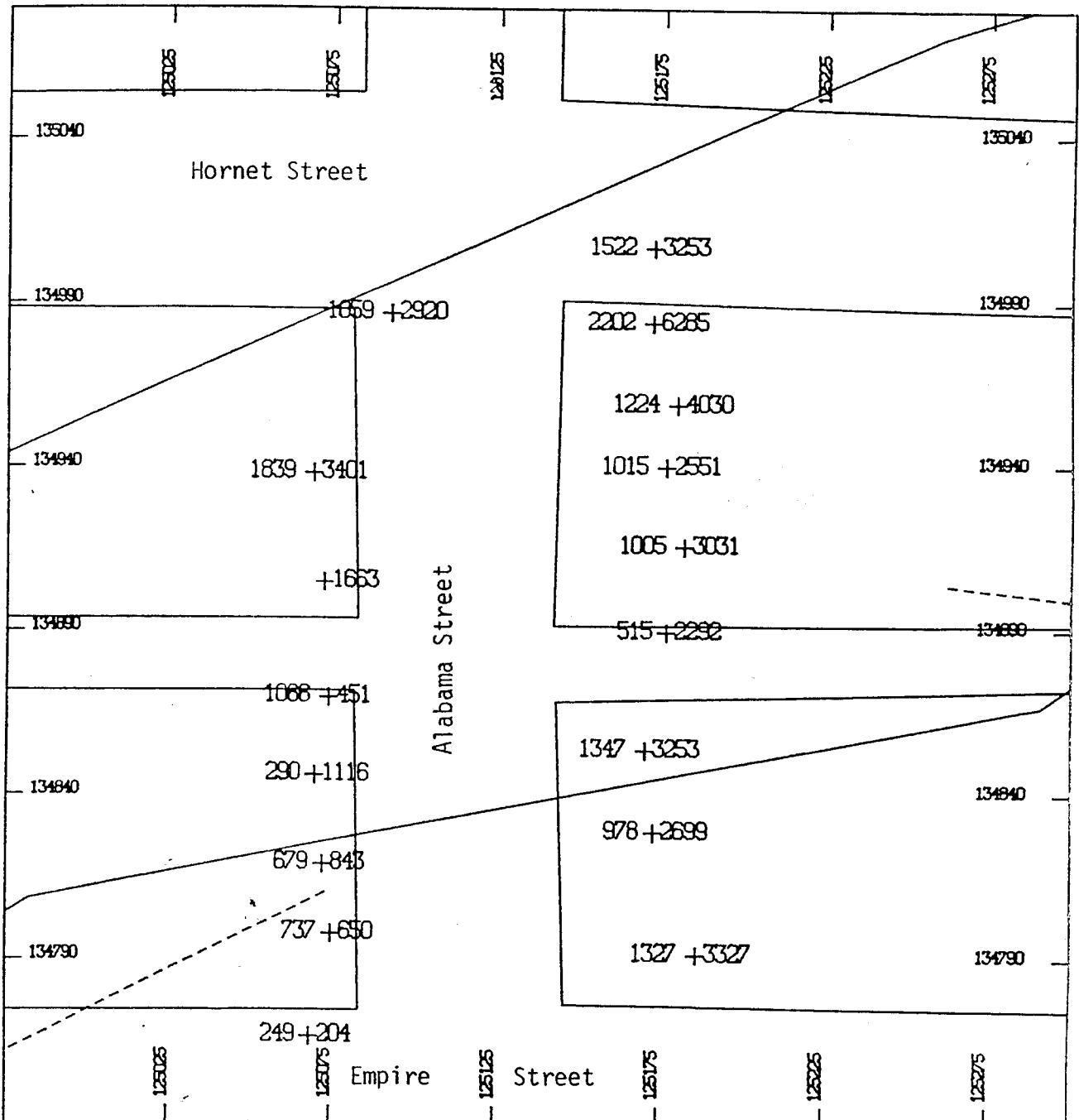
The average radon soil gas measurement at the Henry Street site was 4979 pCi/l, about four times the average for the Butte area, with a range from 1391 to 10591 pCi/l. The mineralized veins (solid lines) and radon soil gas measurement data for this site are displayed in Figure 5-29.

Radon Exhalation Measurements

Rock and Soil

Rock and soil samples were collected at ten sampling sites located in and near Butte. The locations of eight of these sampling sites are shown in Figure 5-30. Sites numbers 9 and 10 are located on Homestake Pass, eight miles east of Butte where Interstate 90 crosses the Continental Divide. Comparative radon exhalation measurements were made using 25 cm sample depths with results as shown in Table 5-3.

As seen in Table 5-3, the highest radon exhalation rates were from mineralized vein material. The aplite samples showed exhalation rates that are about three times the exhalation rates from quartz monzonite and alluvium. From these tests, mineralized vein material and aplite appear to be the most important sources of radon in the Butte area.



SCALE 1" = 50.

(TE 11/24/80-7/15/82)

BOUNDARY

EAST = 125300.00
 WEST = 124975.00
 — = Veins

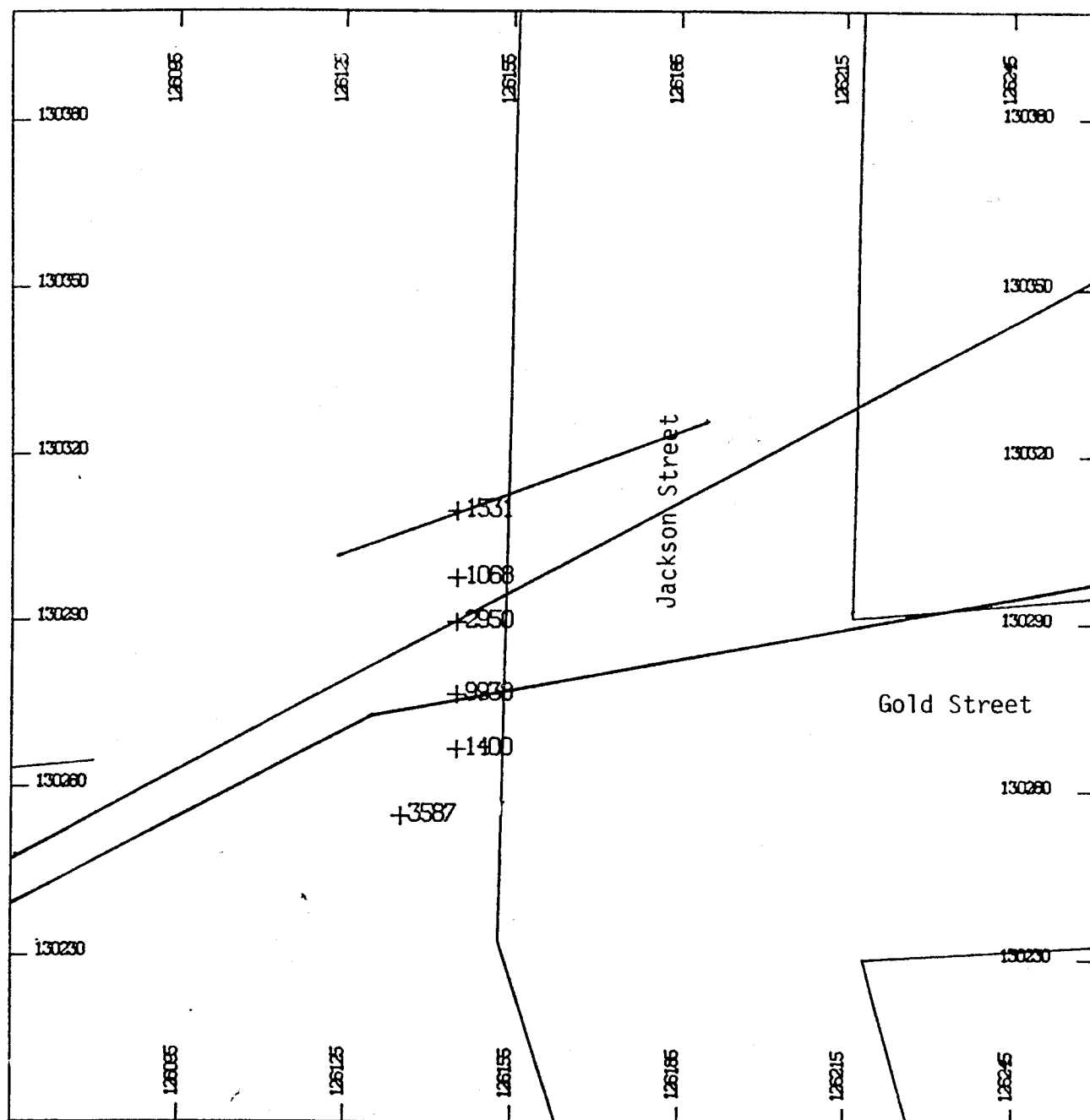
0 50
 FEET

BOUNDARY

NORTH = 135080.00
 SOUTH = 134740.00
 + = Measurement Sites
 xxx+yyy = Summer & Winter
 Measurements

FIGURE 5-27

RADON SOIL GAS CONCENTRATIONS (pCi/l) AT
 MEASUREMENT POINTS TRAVERSING THE YELLOW JACKET VEIN



SCALE 1" = 30. '

(TE 11/24/80-7/15/82)

BOUNDARY

EAST = 126260.00

WEST = 126065.00

_____ = Veins

0 30
FEET

BOUNDARY

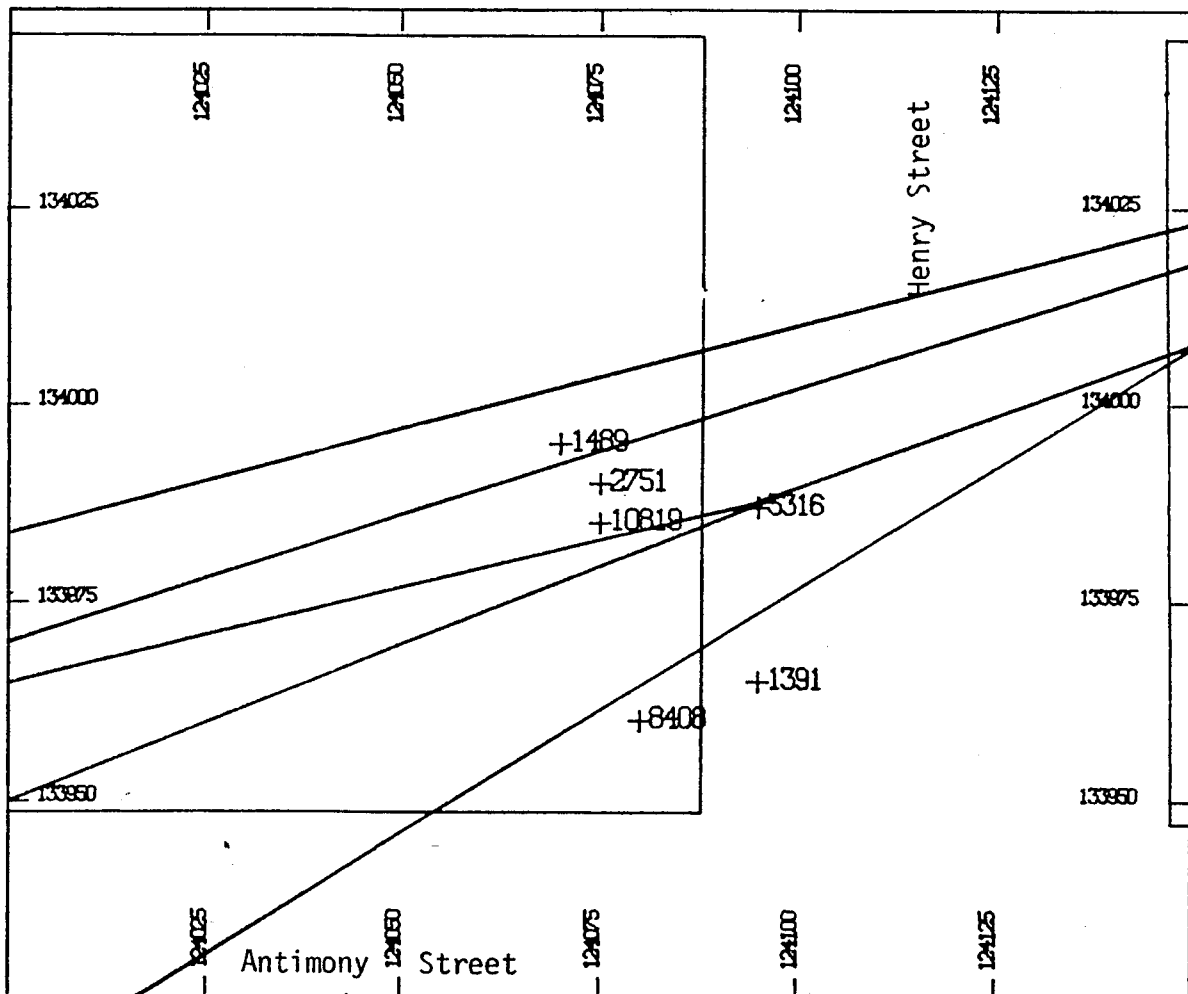
NORTH = 130400.00

SOUTH = 130200.00

+ = Measurement Sites

FIGURE 5-28

RADON SOIL GAS CONCENTRATIONS (pCi/l) AT MEASUREMENT SITES
TRAVERSING MINERALIZED VEINS - GOLD AND JACKSON STREETS

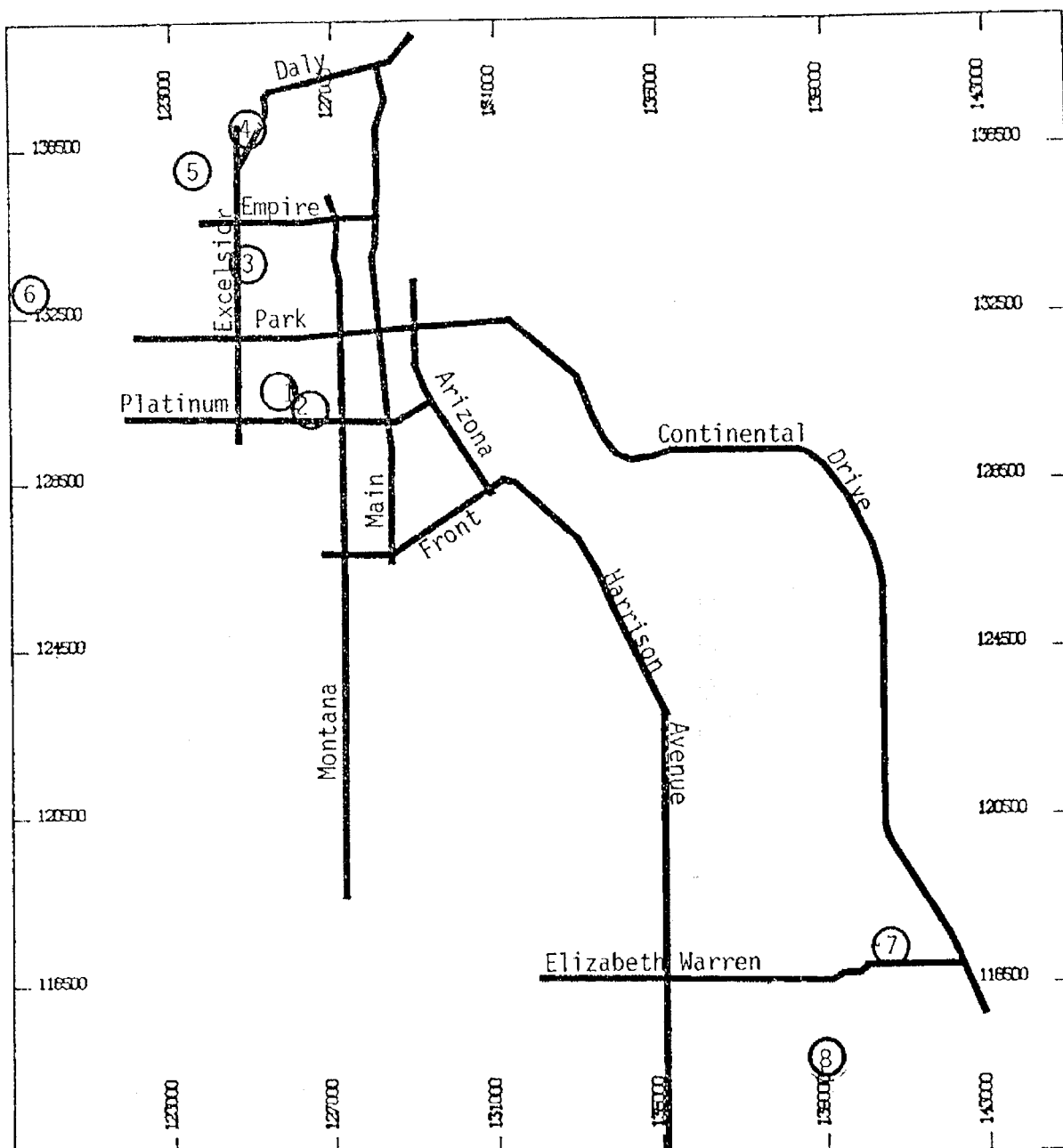


SCALE 1" = 25. (TE 11/24/80-7/15/82)

BOUNDARY		BOUNDARY	
EAST	= 124150.00	0	25 NORTH = 134050.00
WEST	= 124000.00		SOUTH = 133925.00
— = Veins		FEET	+ = Measurement Sites

FIGURE 5-29

RADON SOIL GAS CONCENTRATIONS (pCi/l) AT MEASUREMENT SITES
TRAVERSING MINERALIZED VEINS - HENRY AND ANTIMONY STREETS



SCALE 1" = 4000. '

BOUNDARY		BOUNDARY	
EAST	= 145000.00	0	4000
WEST	= 119000.00	NORTH = 139500.00	
		SOUTH = 112500.00	
		FEET	

FIGURE 5-30

ROCK AND SOIL COLLECTION SITES
FOR RADON EXHALATION TESTS

TABLE 5-3
COMPARATIVE RADON EXHALATION MEASUREMENTS
OF BUTTE AREA ROCK AND SOIL SAMPLES

Sample No.	Sample Location	Sample Type	Radon Exhalation Rate (pCi/m ² /min)
1	Jackson & Gold Sts.	Aplite	520
2	Jackson & Gold Sts.	Vein Material	1663
3	Antimony & Henry Sts.	Vein Material	2615
4	Walkerville Drive	Aplite	727
5	Emmett & Missoula Sts.	Aplite	1001
6	West Junior High Sch.	Aplite	602
7	Columbus & East Lake Streets	Alluvium	301
8	100 Star Lane	Alluvium	151
9	Homestake Lake	Quartz Monzonite	305
10	Homestake Pass	Quartz Monzonite	169

Building Materials

Building materials were evaluated to determine if they were a source of radon in structures. Activated charcoal canisters were obtained from the EPA Eastern Environmental Radiation Facility (EERF) in Montgomery, Alabama, to measure radon exhalation rates from these materials. The following building materials were evaluated:

1. Concrete
2. Conventional concrete blocks
3. Concrete blocks containing slag from smelting operations
4. Bricks (red and white)
5. Gypsum board
6. Plaster

Radon exhalation measurements were performed by making an air-tight seal between the activated charcoal canister and the material to be tested using duct tape. The canister was attached to the material being tested from 48 to 96 hours. During each measurement, additional canisters were simultaneously placed to measure ambient radon. Following each measurement, the canisters were sealed to prevent further radon exposure, and were returned to the EERF for analysis by gamma spectroscopy.

The ambient radon measurements during each test were higher than the measurements made with the canisters which were sealed to the material being evaluated, thus eliminating building materials as suspect sources.

Dissolved Radon in Water

Butte city water supplies originate from surface water sources; however, these water supplies were measured to determine dissolved radon content. In addition, springs and private water supplies outside the city were measured. Liquid scintillation vials were obtained from the EERF for sample collection. A measured volume of each water sample was injected into duplicate scintillation vials and returned to the laboratory for analysis.

Data obtained from analyses of Butte water samples for dissolved radon content are presented in Table 5-4. As seen in Table 5-4, the dissolved radon concentrations in the Butte surface water supplies are so low that they cannot be accurately measured. Groundwater supplies in the Butte area are elevated in dissolved radon content but not to the point where they are considered as a significant source of indoor radon.

Radon Measurements in Underground Sewers

It is possible that the entry route of radon into some structures is through unsealed service entries or through plumbing fixtures having dry traps or no traps at all. For this reason, measurements of radon concentrations in underground sewers were made.

Samples were collected by lowering an intake tube through manhole cover ventilation holes to a depth of six to eight feet and drawing air from this intake tube through a 500 ml scintillation cell. This method of sample collection was preferred to removing the manhole cover, since it prevented abnormal air circulation at the point of sampling.

Measurements were made at 41 locations throughout the city as shown in Table 5-5. Measurements ranged from lows of less than 1 pCi/l to a high of more than 400 pCi/l. Generally the highest radon concentrations were measured in areas demonstrating high indoor radon concentrations. The highest measurements were again found in the northwest part of the city.

Structures have not been evaluated to determine the degree of radon entry through unsealed service entries or through dry-trapped or untrapped plumbing fixtures. The radon concentrations measured in underground sewers does demonstrate the need to evaluate service entrances as potential routes of radon entry into structures.

Radon In Natural Gas Supplies

The radon content of natural gas was measured to determine if unvented gas appliances contribute significantly to indoor radon concentrations. The radon content of natural gas in Butte averaged 14 pCi/l. Thus, the natural gas contribution to indoor radon concentrations is negligible.

TABLE 5-4

DISSOLVED RADON CONCENTRATIONS IN
WATER SOURCES IN THE BUTTE AREA

Sample Location	Sample Number	Dissolved Radon Concentration (pCi/l + 2 sigma)*		
Butte Water Co., 129 W. Galena (Big Hole River Supply)	1	- 4	+	1359%
	2	12	<u>+</u>	455%
Blaine Elementary School (Moulton Reservoir Supply)	1	- 6	+	905%
	2	69	<u>+</u>	79%
Hawthorne Elementary School (Basin Creek Reservoir Supply)	1	- 38	+	141%
	2	- 49	<u>+</u>	111%
Hoeffner's Pump Station (Anaconda) - 3 wells (55-70 feet)	1	510	+	13%
	2	464	<u>+</u>	14%
Private Residence (Lost Creek) private well (55 feet)	1	2913	+	3%
	2	2938	<u>+</u>	3%
Private Residence (Roosevelt Drive), private well (115 feet)	1	3346	+	2%
	2	3277	<u>+</u>	2%
Spring Water from Source 1000 Block between Zarelda and Lexington Streets	1	4029	+	2%
	2	4110	<u>+</u>	2%

*There is a 95 percent assurance that the true value lies between the reported value $\pm$ 2 sigma.

TABLE 5-5

RADON CONCENTRATIONS IN
BUTTE UNDERGROUND SEWERS

<u>Date</u>	<u>Location</u>	<u>Radon (pCi/l)</u>
12/3/80	Excelsior & 17th	0.2
	Excelsior & 15th	0.8
	Excelsior & 11th	0.4
	Excelsior & Missoula	12.6
	Thornton between Pine & Walnut	0.8
	Thornton between Continental & Pine	0.3
	Stuart between Pine & Walnut	1.1
	Garfield between Silver Bow & Locust	2.1
	Blacktail & 4 Mile Vue	2.6
	Blacktail & 4 Mile Vue	0.4
12/10/80	Elizabeth Warren & Bartoletti Prop.	1.1
	KOA & Kaw	72.0
	George & Silver Bow Creek	84.7
	Farragut & Yale (west)	59.4
12/11/80	Farragut & Yale (east)	3.1
	Hill & Evans (SW)	4.9
	Hill & Evans (east)	5.9
	Hill & Evans (NW)	5.2
	Lexington & Majors	105.1
	Oregon (W) & Silver Bow Creek (N)	105.0
12/18/80	US-10 & Hamblin Heights	52.4
1/14/81	Excelsior & Woolman (SE)	110.5
	Excelsior & Woolman (SW)	283.4
	Caledonia & Excelsior (W)	403.8
	Emmett & Park	1.5
	Mercury (S) between Girard & Emmett	1.1
	Silver & Emmett	16.1
	Silver between Emmett & Girard	12.6
	Gold between Emmett & Girard	22.1
	Platinum between Emmett & Girard	1.3
	Girard between Platinum & Steele	1.9
1/16/81	Waukesha & Emmett	125.6
1/15/81	Woolman & Emmett	10.4
	Galena & Clark	20.9
	Silver & Colorado	167.1
	Colorado & Aluminum	219.8
1/16/81	Nevada & 1st	1.0
1/15/81	Atlantic & 1st	20.0
	Monroe & Wall	7.6
	Lafayette & Irene (SE)	0.8
	Hannibal & Hancock	1.8

6. CONCLUSIONS

Radon Sources

Phosphate slag

Phosphate slag produced near Butte by the Stauffer Chemical Company is elevated in radium-226 content. However, tests have confirmed that radon exhalation from the slag is not a significant health concern. The radium content of the slag is essentially the same as that of the phosphate ore, but the slag exhales less than one percent as much radon as the ore.

Outside Air

Monthly averages of radon in ambient air ranged from low of about 0.25 pCi/l at the Hebgen Park Station to a high of 5.86 pCi/l at the Hornet Street Station. Ambient air is not responsible for the high radon and radon progeny concentrations measured in homes; however, when radon concentrations are high, the contributions from the ambient air should be considered when measuring indoor radon and radon progeny concentrations.

The high ambient radon concentrations measured in Butte show the need to consider ambient radon when standards are developed that relate to maximum permissible concentrations of indoor radon or radon progeny. The average outside radon concentration (3.25 pCi/l) measured at the Hornet Street Station, when drawn into a structure, produces a radon progeny concentration of 0.010 WL at an equilibrium of 32 percent (the average integrated measurement equilibrium for the 20 study homes). If the equilibrium should increase to 45 percent, as measured in some homes, the ambient contribution to the indoor radon progeny concentration would be 0.015 WL.

Soil

The radium-226 content of soil in the Butte area ranges from about one to three picocuries per gram. The radium in the soil undoubtedly contributes to indoor radon concentrations; however, except for the Skyway Park area, sources other than soils are thought to be responsible for the high indoor radon concentrations observed in the Butte area. Soil is believed to be the most substantial source of radon in Skyway Park; however Skyway Park is not as severely impacted by elevated indoor radon concentrations as is northwest Butte.

Surface Geology

Radon soil gas measurements made in rhyolite were generally less than 100 pCi/l. Indoor radon and radon progeny concentrations measured in structures built on rhyolite were low. Rhyolite is not considered a source of Butte's indoor radon problem.

It was difficult to determine the rock types at the radon soil gas measurement sites; however, radon soil gas measurements in aplite and

quartz monzonite appeared to be about the same as the average for Butte as a whole. Measurements in aplite in Walkerville were about twice the levels measured in aplite near the West Junior High School. This measurement difference probably results from the structure of the aplite because radon exhalation tests on aplite from these locations did not show a substantial difference.

Radon exhalation measurements made on mineralized vein material, aplite, quartz monzonite and alluvium show the vein material exhales substantially more radon than do other rock and soil samples tested. Tests on aplite indicate that the aplite exhales approximately three times the radon that is exhaled from quartz monzonite and alluvium.

Fractures and mineralized veins are the surface geology features believed to be the cause of the most severely elevated indoor radon concentrations. Radon soil gas measurements over fractures and over mineralized veins were often five to ten times higher than the average concentrations measured in the Butte area. Gamma radiation measurements at mineralized veins also are often an order of magnitude higher than measurements of surrounding rocks.

Other Measurements

Measurements of radon in natural gas, dissolved radon in water, and radon exhalation rates from common building materials showed that they make no significant contribution to the indoor radon concentrations in Butte.

Summary

Ambient air, soils and surface geology all contribute to the indoor radon problem in Butte. It is believed that homes constructed over major fractures or mineralized veins are the most severely affected. Aplite and quartz monzonite and soils also contribute to the problem, but to a lesser extent. It is possible that ambient air is a significant source of indoor radon during certain atmospheric conditions in structures having no other substantial source of radon.

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Appendix 1-J

MODFLOW/MT3D Modeling of Tailing Basin Closure

MODFLOW/MT3D Modeling of Tailing Basin Closure

Rhodia Silver Bow Plant, Silver Bow, Montana

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Appendix C	Arsenic Batch Sorption Experiments on Soils Found at the Silver Bow Plant, Montana
Appendix D	Transport Simulation Mass Balance Summaries

1.0 Introduction

This report summarizes a ground water flow and arsenic transport modeling project in support of closure activities at the Silver Bow Plant (Figure 1). The modeling project was intended to address the following types of questions:

- What is the hydraulic relationship between the tailing basin, ground water flowing beneath the basin and toward Silver Bow Creek in the shallow sediments, and ground water withdrawn from the plant production wells in the deeper sediments?
- Do sediments in the predevelopment stream bed transmit a large amount of water from beneath the basin?
- What effect would basin closure have on ground water flow and arsenic transport beneath the basin?
- What is the mass loading rate of arsenic to Silver Bow Creek?

The objective of the flow and transport modeling was to produce a model that captures the important hydrologic features and processes in the most straightforward manner possible. This report presents:

- a review of data from previous investigations at the site and in the region used to develop a conceptual hydrogeologic model for the Silver Bow Plant ,
- development and calibration of a multiple-layer MODFLOW ground water flow model,
- data gathering and calibration of an MT3DMS model of arsenic transport for the Silver Bow Plant vicinity.

Results of the data review are presented in Section 2. The conceptual hydrogeologic model is discussed in Section 3. Development of the MODFLOW model is described in Section 4. Model calibration is discussed in Section 5. Arsenic transport modeling methods and model calibration are described in Section 6.

2.0 Geologic Setting

2.1 Regional Geology

The Silver Bow Plant is located in a structural depression referred to as a graben. A graben is bounded on two sides by faults with relative downward movement of the central block. A schematic representation of development of the structure is shown on Figure 2. The faults bounding the graben cut through Cretaceous-age intrusive igneous rocks of the Boulder Batholith and Tertiary-age extrusive igneous rocks called the Lowland Creek Volcanics (MBMG, 1978; Derkey and Bartholomew, 1988; MBMG, 1990).

The graben has been partially filled with sediment eroded from the surrounding highlands. The sediments are primarily Tertiary in age and have been partially consolidated (Derkey and Bartholomew, 1988). The Tertiary sedimentary rocks are called the Melrose Basin Sequence. Low-lying areas receiving sediment are called basins, but since the topic of this report is the tailing basin at the Silver Bow Plant, the sediments filling the graben are referred to as “graben-fill” rather than the more standard term “basin-fill.” The thickness of the graben-fill sequence is unknown over much of its areal extent, although the graben appears to be asymmetric, with a much thicker fill sequence on the east than on the west (Weight, 1998; Borduin, 1999). Figure 3 shows the available data regarding thickness of the graben-fill sequence.

Silver Bow Creek and its tributaries have deposited Quaternary-aged alluvium on top of the Melrose Basin Sequence. The Quaternary-aged alluvial deposits of Silver Bow Creek have been characterized extensively due to deposition of mine tailings from ore mills in Butte (for example, Titan Environment, 1994). The Silver Bow Creek deposits contain minor fine-grained, low-permeability deposits that interfinger with more permeable channel, bar, and alluvial fan deposits (Titan Environmental, 1994, p. 64). Overall, the alluvial deposits beneath Silver Bow Creek are believed to have a higher hydraulic conductivity than the other graben-fill material (Borduin, 1999).

2.2 Site Geology

The graben-fill beneath the Silver Bow Plant consists primarily of clays with lesser amounts of sands, silts, and loosely consolidated shale, silty shale, and silty sandstone. Seven production wells have been installed at the Silver Bow Plant. None of these wells extends to igneous rock. Driller's logs and the distribution of perforations in the well casings indicate that most of the yield from these wells comes from

deeper in the formation. Well logs for the on-site production wells show that the graben-fill deposits extend to a depth of at least 400 feet below the ground surface.

The graben-fill appears to consist of a heterogeneous mix of alluvial fan or mudflow deposits and small fluvial channel deposits. Some of the clay deposits may also represent weathered and/or reworked tuff and ash deposits derived from volcanic activity in the vicinity of the site. Coarse-grained units are intermixed with fine-grained units and appear to have limited lateral extent. Boring logs for the production wells suggest that thicker intervals of coarse-grained materials (sands and gravels) may be more prevalent in the deeper portion of the graben-fill materials screened by the wells; however, these units were not observed to be laterally continuous between production wells.

Chert-filled hydrothermal veins are present in outcrops of the graben-fill throughout the site. Most chert veins observed at the surface are about one inch wide and greenish-brown to blue and white in color. Driller's logs for the production wells indicate chert layers of up to 30 feet thick at depths over 100 feet below ground surface.

A sequence of fluvial valley deposits was identified and delineated beneath the Plant's tailing basin at the top of the graben-fill. The fluvial deposits follow the topographic valley formerly located beneath the tailing basin (see Figure 4-6 of the Voluntary Cleanup Plan (VCP) Report (Barr, 1999)). This topographic valley corresponds to the historic reach of Sheep Gulch prior to construction of the Plant. The fluvial materials consist of channel sands and associated backwater and lag deposits.

The lowermost unit in this fluvial sequence consists of a discontinuous arkosic sand lag unit deposited by high-energy water scouring the top of the underlying graben-fill sediments and leaving behind angular gravels and sands. Fine-grained backwater deposits that consist of clay and organic clay overlie the lag deposit. The backwater deposits are cut by higher energy channel deposits that consist mostly of sand. Similar fluvial materials were found beneath the reach of Sheep Gulch on adjacent property to the south.

3.0 Conceptual Hydrogeologic Model

A conceptual hydrogeologic model is a simplified representation of a ground water flow system. It must be a valid representation of the important hydrologic features and processes, but should also be the simplest representation possible (Anderson and Woessner, 1992, p. 28). The conceptual hydrogeologic model is shown in Figure 4 and described below.

3.1 Aquifers, Aquitards, and Aquicludes

Rocks and sediments capable of transmitting significant quantities of water under ordinary hydraulic gradients (aquifers, as defined by Freeze and Cherry, 1979, p. 47) in the area include:

- Quaternary-age sediments associated with the area streams,
- Coarse-grained zones in the Tertiary-age graben-fill sedimentary rocks,
- Interflow zones in the extrusive igneous rocks (Foxworthy, et al, 1988, p. 28), and
- Weathered zones in the intrusive and extrusive igneous rocks (Botz, 1969)

Less-permeable layers in a stratigraphic sequence are referred to as aquitards. The graben-fill sequence is likely made up of a series of aquifer layers (coarse-grained sediments and sedimentary rocks) enclosed in a matrix of aquitard material (finer-grained sediments and sedimentary rocks). The coarser sediments would have been deposited in the beds of streams crossing the graben. The locations of the stream beds typically change with time during filling of sedimentary basins, but data on the distribution of aquifer layers in the graben-fill sequence are sparse. The unweathered portions of the igneous rocks of the Boulder Batholith have widely-spaced, saturated fractures (Botz, 1969); but are presumed to be incapable of transmitting significant quantities of water under ordinary hydraulic gradients (i.e., are aquicludes).

3.2 Extent of the Local Ground Water Flow System

The extent of the local ground water flow system is defined as follows (Figure 4):

- The Continental Divide to the south. It is assumed that the water table in the graben-fill sequence mimics surface topography. In other words, it is logical to assume that a ground water flow divide

has developed in the vicinity of the continental divide and no ground water flow occurs beneath the divide. This type of boundary is referred to as a hydraulic boundary (Anderson and Woessner, 1992, p. 103) and should be used with caution in transient simulations and predictive steady-state simulations because the model will not allow the boundary to change in response to changes in other boundary conditions. Since this boundary is so far removed from the area of interest and coincides with a major topographic divide, this is considered an appropriate boundary condition.

- The margins of the graben-fill sediments to the east and west. It is assumed that the weathered zone on the basement rocks can be lumped with the graben-fill material and that the unweathered basement rocks act essentially as impermeable boundaries. These margins are considered to transmit no flow. Some underflow may occur into the basin from the east beneath Silver Bow Creek and out of the basin to the west. This is discussed further below.
- The margins of the graben-fill sediments north of Silver Bow Creek. Although the extrusive igneous rocks in contact with the graben-fill sequence may transmit water in the interflow zones, this was not considered in the flow model because of the distance from the area of interest and the uncertainty associated with the potential flux from these rocks

In other words, the graben is closed to ground water flow around most of its perimeter; the only exceptions appear to be at the upstream and downstream ends of Silver Bow Creek. At the inlet to the graben, the alluvial deposits are approximately 1300 feet wide (Botz, 1969, Plate 1) and are not believed to transmit large amounts of water (Botz, 1969, p. 13). At the outlet, the Silver Bow Creek alluvial deposits narrows from a typical width of 1000 to 2000 feet to a width of approximately 200 feet west of Miles (Derkey and Bartholomew, 1988). The underflow into and out of the graben-fill sequence through these constrictions is unknown, but is likely a small portion of the hydrologic budget.

3.3 Sources and Sinks for Water

Sources of water to the ground water flow system include:

- Infiltration of precipitation.
- Loss of discharge from the streams flowing from outside the margins of the graben-fill sequence (Botz, 1969).

- Seepage from the tailing basin.
- Underflow from beyond the limits of the graben. As described above, this appears to be limited by the narrow width and hydraulic properties of the Silver Bow Creek alluvial aquifer at the inlet to the graben (Botz, 1969, p. 13).

Sinks for water from the ground water system include:

- Gaining portions of streams further down the valley (Botz, 1969). In the vicinity of the Silver Bow Plant, this includes a pond north of the tailing basin referred to as the beaver pond. This pond is located in the trace of the former stream bed in the valley that was dammed to form the tailing basin.
- Evapotranspiration. Over most of the model domain, the water table is expected to be below the extinction depth for evapotranspiration. Evapotranspiration may remove a significant volume of water from the flow system near Silver Bow Creek where the water table intersects or is within 1 to 2 meters of the ground surface.
- Discharge to Silver Bow Creek and the gaining portions of the tributaries to Silver Bow Creek.
- Underflow out of the graben in the sediments underlying Silver Bow Creek. Like the inflow, this component is likely minor due to the constriction at the downstream end of the graben.
- Pumping from wells within the graben-fill sequence.

3.4 Site Hydrogeology

Details on the site geology and hydrogeology are presented in Section 4 of the VCP Report (Barr, 1999) and summarized below. For reference, the site well locations are shown on Figure 5.

Ground water beneath the Silver Bow Plant is typically unconfined and is found at depths of up to 66 feet below the ground surface. The average depth to ground water is approximately 30 feet below the ground surface. Water level measurements from the monitoring wells show that the direction of ground water flow in the shallow portion of the graben-fill is north toward Silver Bow Creek.

Ground water elevations in monitoring wells that are screened in the graben-fill alluvium are consistently higher than the water elevations in Silver Bow Creek. During plant operation, ground water elevations were lower than the surface water elevation of the tailing basin, and lower than the surface topography of Sheep Gulch and its intermittent tributary south of the tailing basin. These ground water–surface water elevation relationships indicate that the tailing basin and the reach of Sheep Gulch located upstream (south) of the tailing basin had the potential to leak water into the underlying graben-fill alluvium and that ground water north of the tailing basin leaked upward and discharged to Silver Bow Creek.

Water levels in the reach of Sheep Gulch from German Gulch Road (the road between the Silver Bow Plant and Silver Bow Creek) south to the portion alongside the tailing basin are generally comparable to ground water levels. This suggests that Sheep Gulch may gain or lose discharge to ground water in this reach. During plant operation, this reach of Sheep Gulch and the beaver pond typically gained discharge from ground water, however, both were periodically dry during years with below-normal precipitation.

The ground water elevation contour maps indicate that the shallow ground water surface drops about 30 feet over a distance of 5,000 feet between the upgradient wells (MW97-1 and MW97-5) on the south and German Gulch Road on the north. The resulting horizontal hydraulic gradient is approximately 0.006 feet per foot toward the north. The gradient appears to be steeper north of German Gulch Road, in the proximity of Silver Bow Creek.

Water level measurements from the monitoring wells that are screened deeper in the graben-fill (monitoring wells MW97-2 and MW97-4) and the water level measurements from the corresponding shallow wells (monitoring wells MW97-1 and MW97-3) were used to assess local vertical hydraulic gradients within the graben-fill alluvium near the water table. The November 1997 and October 1998 data indicate downward gradients of 0.004 to 0.005 feet per foot in the upgradient (southern) well nest (MW97-1 and MW97-2). In contrast, vertical gradients in the downgradient (northern) well nest (MW97-3 and MW97-4) were 0.001 feet per foot upward in 1997 and 0.0004 feet per foot downward in 1998. These data suggest that ground water is recharged (via losing streams or precipitation) south of the site and is neutral or discharging to surface water around the northwestern margin of the tailing basin.

Anecdotal information from Plant staff suggests that water levels in Sheep Gulch and the beaver pond decrease in response to increased pumping of the Silver Bow Plant Production Wells. Thus, the shallow and deeper portions of the graben-fill appear to be hydraulically connected, and shallow ground water levels will respond to pumping of the production wells.

4.0 Ground Water Flow Modeling Methods

4.1 Code Selection and Description

The ground water flow simulation code MODFLOW was chosen because of its wide usage and acceptance and because (when coupled with MT3DMS) it is well-suited for assessing the nature of contaminant transport for the contaminants of concern at the Silver Bow Plant. MODFLOW simulates steady and nonsteady flow in an irregularly-shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. Flow to or from hydraulic features such as wells, areal recharge, evapotranspiration, drains, and river beds can be simulated. Hydraulic conductivities or transmissivities for any layer may differ spatially and be anisotropic, and the storage coefficient may be heterogeneous. The model requires input of the ratio of vertical hydraulic conductivity to distance between vertically adjacent block centers. Specified head and specified flux boundaries can be simulated as can a head-dependent flux across the model's outer boundary that allows water to be supplied to/from a boundary block in the modeled area at a rate proportional to the simulated head difference between a "source" of water outside the modeled area and the boundary block.

MODFLOW solves the following ground-water flow equation using the finite-difference approximation (McDonald and Harbaugh, 1988):

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) - W = S_s \frac{\partial h}{\partial t}$$

where:

K_{xx} , K_{yy} , and K_{zz} are values of hydraulic conductivity in the x, y, and z directions, respectively, in units of length (L) per time (T^{-1});

h is the value of hydraulic head, L;

W represents the volumetric flux per unit volume to sources and sinks of water in the flow system, T^{-1} ;

S_s is the specific storage of the porous medium, L^{-1} ; and

t is time, T.

The flow region is subdivided into blocks in which the properties of the porous medium can be simulated as uniform. In plan view, a rectangular discretization results from a grid of mutually perpendicular lines that may be variably spaced. The flow region may be subdivided vertically into layers of varying thickness. Several algorithms have been developed for solving the associated matrix problem; the user can choose the best solver for the particular problem. The PCG solver (Hill, 1990) with damping as described in Harbaugh and McDonald (1996) was used in this modeling project. Mass balances are computed for each time step and may be saved as a cumulative volume from each source and type of discharge.

Modifications were made to MODFLOW-96 (distributed by the USGS) and to the public domain version of MODFLOW distributed with MT3DMS to allow more stable performance with the automated calibration program PEST98 (Watermark Computing, 1994, 1998). The block-centered flow module was modified to prevent unconfined cells from drying up. If the head in a cell drops below the base elevation of the cell, the saturated thickness is set to 1 meter and the cell was then treated as confined (i.e., the head for that cell was set so inflow and outflow to the cell balance without regard to the elevation of the base of the cell). The effect of this modification is to allow the model to remain stable under changing conditions imposed by the automated calibration software by preventing the downgradient “cascading” of dry, inactive cells as upgradient cells dry up. This approach allows for continuity in the flow system and greater model stability. These modifications are described on page 24 of Watermark Computing (1994). The source code and executable are provided as described in Appendix A.

Ground water flow modeling was performed using the Department of Defense’s Groundwater Modeling System (GMS) software and S.S. Papadopoulos & Associates software ModIME as pre- and post-processors for MODFLOW. The MODFLOW packages used to simulate the various features in the hydrogeologic conceptual model and model inputs are described below. Model input files are provided as described in Appendix A.

4.2 MODFLOW Grid

The active zone of the MODFLOW grid was based on the extent of the graben-fill deposits (Figures 6 and 7). The grid is irregular, with 15 meter by 15 meter cells beneath the tailing basin area, and a maximum cell size of 500 meters by 500 meters. The aspect ratio for adjacent cells was set at 1.5.

4.3 Model Layers

The flow model has 5 layers. Layer 1 of the flow model is active only under the footprint of the tailing basin. Layer 1 is intended to simulate the hydraulic and transport properties of the tailings.

Beyond the limits of the tailing basin, the top of model layer 2 was set equal to ground surface elevation. Digital elevation maps (DEMs) were acquired from the U.S. Geological Survey at the following internet address for the regional ground surface data:

<http://edcftp.cr.usgs.gov/pub/data/DEM/7.5min/>

The ground surface elevation data from the 7.5 minute DEMs were merged and interpolated to the MODFLOW cell centers using the ArcView GIS software; then imported into GMS as a two-dimensional grid. Under the basin footprint, the predevelopment topographic data were used to get an accurate simulation of the tailings volume (Figure 8). Figure 9 shows the thickness of layer 1 (tailings). Figure 10 shows the topography of the top of layer 2 (native soil beneath the tailings and ground surface beyond the limits of the tailing basin).

The model was then divided vertically into five layers to account for the observed heterogeneity and completion depths of wells at the plant site (Figure 11). The model layers were “draped” down from ground surface. In other words, the model layers are not horizontal; instead they mimic the topography of the area (Figure 12).

Data acquired from the Montana Bureau of Mines and Geology (MBMG, 1999) were used to refine estimates of the depth to basement rocks in the graben (see Figure 3). In the site vicinity, layers 2-5 were subdivided based on the completion depths of the site monitoring and production wells (Figure 11). Layers 2-5 were subdivided equally in areas away from the site. The total estimated thickness for layers 2-5 of the flow model over the entire model domain is shown on Figure 13. This grid was interpolated from the data shown on Figure 3.

4.4 Hydraulic Conductivity Distribution

Available hydraulic conductivity and transmissivity data are summarized on Table 1. Regional information provided in the MBMG (1999) database on aquifer transmissivity and hydraulic conductivity

were evaluated to determine if any spatial trends were apparent (Figures 14 and 15). The transmissivity was estimated based on reported specific capacities of the wells in the database. Specific capacity is defined as the pumping rate divided by the drawdown (Q/s), typically expresses as gallons per minute per foot (gpm/ft).

Driscoll (1986, p. 1021) describes an empirical equation relating aquifer transmissivity to the specific capacity of a well completed in the aquifer:

$$Q/s = T/C$$

where:

Q is the yield of the well, gpm,

s is the drawdown in the well, feet,

T is the aquifer transmissivity, gallons per day per foot (gpd/ft), and

C is an empirical constant (for unconfined conditions, $C = 1500$; for confined conditions, $C = 2000$).

By definition, transmissivity is converted to hydraulic conductivity by dividing by the saturated thickness of the aquifer (Freeze and Cherry, 1979, p. 59). However, Heath (1989, p. 61) suggests that the value of transmissivity estimated from specific capacity applies only to that part of the aquifer adjacent to the saturated well screen. This is because during a short-term test the entire thickness of the aquifer does not supply water to the well. For this reason, the hydraulic conductivity of the aquifer was estimated using the length of the saturated well screen, rather than the aquifer saturated thickness. Transmissivity estimates based on specific capacity are low if well losses are significant. The data appear to be consistent with Borduin's (1999) conclusion that the material beneath Silver Bow Creek has a relatively high hydraulic conductivity. The same approach was applied to specific capacity data from the Silver Bow Plant Production Wells (see Table 2).

The following hydraulic conductivity zones were explicitly modeled. Calibrated values for the hydraulic conductivity zones are given below. Model calibration is discussed in the following section. Uniform aquifer properties were assumed over the rest of the model domain. It was assumed that the values assigned to the large areas with unknown properties adequately represent the bulk properties of these rocks and sediments.

- Based on laboratory testing of thin-wall samples, the tailings deposited in the basin form a man-made aquitard. Layer 1 was assigned a uniform horizontal hydraulic conductivity of $2.26\text{E-}2$ m/day and vertical anisotropy of 0.11 (the ratio of vertical to horizontal hydraulic conductivity (K_z/K_h)).
- A zone was placed in Layer 2 based on the results of drilling and aquifer testing to characterize the coarse-grained deposits in the valley fill beneath the tailing basin (shown close-up in Figure 16 and as Zone D on Figure 17). This feature was described in detail in Section 2.2.
- A zone of relatively high permeability (15.2 m/day to 32.1 m/day) was placed in Layers 2 through 5 beneath the alluvial valley of Silver Bow Creek (Figure 17 through 19). This is based on results of regional studies. In Layer 5, this zone was expanded to include the plant production wells and extends south to encompass areas of lower head relative to the regional heads (Zone J of Figure 19). The distribution of hydraulic conductivity data in Layer 5 (Figure 15) was used to set the southern boundary of this zone.
- Layer 2 has a uniform hydraulic conductivity of 7.57 m/day beyond the limits of the zones representing Silver Bow Creek alluvium and the coarse-grained valley fill deposits beneath the tailing basin. This zone was assigned a relatively high value based on the inverse modeling, which is consistent with the results of aquifer testing performed in 1999 (see Appendix N).
- Figures 17 through 19 show a zone that was placed in Layers 2-5 northeast of the plant site to simulate a knob of intrusive igneous rock that crops out in this area (Derkey and Bartholomew, 1988). Data obtained from the MBMG well index show wells completed in this area. If very low hydraulic conductivity values are assigned to this zone, the heads drop to extremely low levels due to simulation of pumping of the area wells. The observations used in model calibration are not sensitive to the hydraulic conductivity of this zone, consequently, it was set to 1.1 m/day and not varied later in the calibration.

4.5 Vertical Conductance

The model input Vcont (vertical leakance between layers, defined as the vertical conductance divided by the area of the model cell) is calculated for each cell by ModIME using the follow formula (McDonald and Harbaugh, 1988, p. 5-13):

$$V_{cont_{i,j,k+1/2}} = \frac{1}{\frac{(\Delta v_k)/2}{K_{zi,j,k}} + \frac{(\Delta v_{k+1})/2}{K_{zi,j,k+1}}}$$

where:

Δv_k is the thickness of the upper layer,

Δv_{k+1} is the thickness of the lower layer,

$K_{zi,j,k}$ is the vertical hydraulic conductivity of the upper layer, and

$K_{zi,j,k+1}$ is the vertical hydraulic conductivity of the lower layer.

Two anisotropy zones were used in Layers 2 through 5, one representing finer-grained, more highly stratified graben-fill deposits and one representing the coarse-grained deposits of Silver Bow Creek (Figures 17 through 19). The calibrated anisotropies of these zones are 0.12 and 0.45, respectively.

4.6 Lateral and Basal Boundary Conditions

The default boundary condition for the margins of the grid in MODFLOW is the no-flow boundary. With the exception of the margins of the Silver Bow Creek alluvial deposits, this default boundary condition was used on the lateral margins of the model and for the base of the model because the intrusive igneous rocks in contact with the graben-fill sequence are believed to act as essentially impermeable boundaries. Borduin (1999) simulated discharge across the Rocker fault (the eastern margin of the graben) but indicated that he had no direct evidence for this and that his model was not highly sensitive to the amount of discharge simulated. Although the extrusive igneous rocks in contact with the graben-fill sequence on the northern margin may transmit water in the interflow zones, this was not included in the flow model because of the distance from the area of interest and the uncertainty associated with the potential flux from these rocks. Underflow into the Silver Bow Creek alluvial deposits from the east and out of these deposits to the west was modeled using the general head boundary package. Heads were assigned as one meter above the top of the stream bed and the conductance was determined based on the cell dimensions and horizontal hydraulic conductivity assigned to the zone representing the Silver Bow Creek alluvium as follows:

$$C = \frac{KA}{L} = \frac{K(L_c L_z)}{\frac{L_r}{2}}$$

where:

C is the conductance assigned to the general head boundary for a particular cell,
 K is the horizontal hydraulic conductivity,
 L_c is the cell width along columns,
 L_z is the layer thickness, and
 L_r is the cell width along rows.

4.7 Streams

Silver Bow Creek and the drainages crossing the graben-fill sequence were simulated using the stream-flow routing package (Prudic, 1989). The advantage of using this package over the river package for simulating the interaction between a stream and aquifer in semi-arid regions such as western Montana is that discharge from the stream to the aquifer is limited to a user-defined value. In other words, if the stream is losing discharge to the aquifer, the model keeps track of the rate of loss and makes the stream cells inactive downstream of the point at which leakage from the stream has exceeded the available discharge. This is crucial for the simulation to have a realistic water budget. In addition, if heads in the aquifer rise above the stream bed in lower reaches of stream, the cells in that area become active and the stream can remove discharge from the aquifer cells. This is an observed condition for the streams at and near the plant, including Sheep Gulch.

The stream in Sheep Gulch, Silver Bow Creek, and several of the drainages on the graben-fill sequence south of Silver Bow Creek were simulated (Figure 20). The area of the drainage basin south of Silver Bow Creek and outside the limits of the graben-fill sequence was determined and stream discharge distributed around the margins of the sequence as follows. It was assumed that up to 70 percent of the average annual precipitation falling on the area outside the graben-fill (0.7 x 12.5 inches per year) would enter streams at the margins of the graben-fill sequence. This discharge was divided equally among the ten stream segments that originate at the margins of the active area of the model south of Silver Bow Creek.

4.8 Recharge

The recharge package was used to simulate infiltration of precipitation falling directly on the graben-fill sequence. Recharge was applied to uppermost active layer (i.e., layer 2 outside the footprint of the tailing basin). Recharge was applied to the tailing basin in the no-action alternative.

4.9 Tailing Basin

Discharge to the tailing basin during the historical loading period was simulated with the general head boundary package (Figure 21). Two conductance zones were used for each portion of the pond: one for areas overlying the coarse-grained deposits in the former stream bed, and one for areas beyond the limits of the former stream bed (see Figure 16). This allowed the model to simulate differential flux from the tailing basin into the materials in Layer 2.

4.10 Wells

The plant production wells were simulated using MODFLOW's well package. The simulated discharge was distributed among the model layers based on the estimated transmissivity of the screened interval in each layer. The production wells are simulated as screened across Layers 2 through 5, with the majority of the water being produced from Layer 5. The pumping rates used in the model for the historical simulation were 400 gpm for Wells 1, 4, and 7; and 100 gpm for Wells 5 and 6 (Rhodia, 1998). The pumping rates used for calibration to observed conditions in November, 1997 were 150 gpm each from Wells 1 and 7. Well locations are shown on Figure 5.

Other wells in the area were identified from the MBMG database (Figure 22). It was assumed that these wells are pumped continuously at 5 percent of the pump capacity indicated in the database.

4.11 Ground Water Seepage into the Beaver Pond

Ground water seepage into the beaver pond north of the tailing basin was simulated using the drain package (Figure 21). Drains in MODFLOW only remove water if the head in the aquifer is above the specified invert elevation; they do not contribute water to the aquifer if the head in the aquifer is below the invert. The invert on the drain was specified as 5312.5 ft MSL to simulate the elevation of the outlet to the beaver pond.

During automated model calibration, the beaver pond was simulated using the general head boundary package. Unlike the drain package, the general head boundary will allow discharge from the boundary cell into the aquifer if the head in the aquifer is lower. This was necessary during automated calibration because of the need for continuity of the simulated discharge to (or from) the beaver pond. The automated model calibration software used in this project must be able to determine a sensitivity (change

in simulated head or discharge caused by a change in a given parameter value). If the head in the aquifer fell below the specified invert elevation during an automated calibration using the drain package, no discharge would be simulated, so no matter how far the head fell below the invert, the simulated discharge would be zero. In other words, the model would become insensitive to the parameter.

5.0 Flow Model Calibration

Model calibration was accomplished with a combination of manual and automated inverse modeling. The goal in setting up parameter zones was to create the simplest model possible in terms of zonation and to avoid undocumented, site-specific features if possible. The calibration results depend in large part on which observations are considered the most important.

5.1 Automated Inverse Modeling

Inverse modeling of ground water flow systems consists of using observations regarding the flow system (primarily hydraulic head and ground water discharge information) to determine optimal values for a set of parameters related to physical properties of the aquifer system. PEST98 is a nonlinear parameter estimation program used to automate the inverse modeling process (Watermark Computing, 1994; 1998). PEST98 uses the Gauss-Marquardt-Levenberg method of nonlinear regression to determine the set of model parameters that minimizes the sum of squared weighted residuals, referred to as the objective function:

$$\Phi = \sum_{i=1}^n ([m_i - s_i] w_i)^2$$

where:

- Φ is the objective function,
- n is the number of observations used in the calibration,
- m_i is the measured value of water level or ground water discharge,
- s_i is the simulated value of water level or ground water discharge, and
- w_i is the weight assigned to the given observation.

The observations used and parameters varied in the model calibration are described below.

5.2 Observations Used in the Model Calibration

Two types of observations were used in the model calibration: measured water levels in wells (heads in meters above mean sea level) and measured or estimated ground water discharge to surface water bodies

(with units of cubic meters per day). In order to use observations with different units, the weights assigned to the observations must account for the difference in units. In addition, the weights reflect the uncertainty associated with the measurement and the modeler's desire to match a particular measurement.

5.2.1 Water Level Measurements

Water level measurements used in the model calibration came from three sources: measurements in Silver Bow Plant wells made in November of 1997, measurements supplied to Barr by Mike Borduin (Borduin, 1999) and measurements from the MBMG database. The largest weights were assigned to measurements from the Silver Bow Plant wells that do not appear to be influenced by localized leakage from site features (e.g., Wells MW97-1 and EPA-4, see Table 3 and Figure 5). The data from Mike Borduin were assigned an intermediate weight, and the data from the MBMG database were assigned the lowest weight because of the uncertainty associated with the timing, location, and elevations of the measuring points.

5.2.2 Discharge Measurements

The primary discharge observation for the flow model calibration was the estimated seepage from the tailing basin: 380 gpm (Barr, 1998b). An additional discharge observation is Silver Bow Creek's gain in discharge from ground water across the graben-fill. Three independent estimates show that this observation has a relatively large uncertainty:

- Borduin (1999) reported measuring gains of 5 cfs and 10 cfs across the model domain in July and August, 1998, respectively.
- Barr (1999, Appendix N) estimated a total gain of 12.7 cfs across the model domain.
- The baseflow in Silver Bow Creek at Opportunity is estimated at 17 cubic feet per second (cfs). The length of Silver Bow Creek simulated by the model is approximately 50 percent of the total length of the stream from Butte to Opportunity. Assuming the gain in discharge is distributed evenly along the length of the creek, the estimated gain for the reach simulated the MODFLOW model domain is 8.5 cfs.

The geometric mean value of these estimates (8.6 cfs) was used as the observed ground water discharge to Silver Bow Creek for the model calibration.

Discharge into the beaver pond and Sheep Gulch in the reach between the flume at SW-4 and German Gulch Road was estimated at 244 gpm (1330 m³/day). For model calibration, this combined flow was divided as shown on Table 3. These estimates are based in part on the depth of flow through the culverts under German Gulch Road and are subject to a large degree of uncertainty.

5.3 Parameters Used in the Model Calibration

With PEST98, parameters can either be variable (allowed to vary within a user-specified range), tied (kept at a constant ratio with a specific variable parameter), or fixed. In the process of calibration, the most sensitive parameters are identified and the more insensitive or highly correlated parameters are fixed.

Aquifer parameters varied in the model calibration included horizontal hydraulic conductivity, vertical anisotropy, and conductance on the general head boundary cells representing the tailing basin. Table 4 summarizes the final values and data sources for the parameters used in the model calibration. Parameter zones are summarized in Section 4.4.

The discharge available to each of the stream segments originating on the margin of the model was treated as a single parameter in the flow model calibration. An upper limit for this parameter value was set at 70 percent of the precipitation falling in the part of the watershed outside the active area of the flow model.

Recharge from precipitation was allowed to vary from 0.3 inches per year to 3.0 inches per year (the value in Borduin's (1999) calibrated flow model).

5.4 Calibration Results

Figure 23 shows the simulated heads in layer 2 of the model in the vicinity of the Silver Bow Plant. The contours compare well with those of the measured heads (Figure 4-11 of the VCP Report (Barr, 1999)). Simulated loss of discharge from Sheep Gulch to layer 2 of the model causes the 5340 contour to extend further north than was observed. This was a common problem in model calibration: the simulated heads

south of the site tend to be higher than observed. In addressing this problem, it was difficult to keep the simulated heads on the north side of the site high enough to produce ground water discharge into the beaver pond and Sheep Gulch.

Figure 24 shows the composition of the objective function (sum of squared weighted residuals) for the calibrated model. Table 3 lists the residuals on flow measurements and site head measurements. The objective function is dominated by residuals on heads measured in Silver Bow Plant wells (groups hi, int, and low on Figure 24). The ground water discharges are underestimated in the calibrated model, but given the uncertainty in the estimated magnitude of these discharges and intended goal of keeping the model as simple as possible, it is necessary to compromise between matching heads and matching discharges.

In earlier calibrations, in which the weights on the discharges were higher, the objective function was dominated by residuals on the discharge to the beaver pond and Sheep Gulch, both of which were more closely simulated than in the final calibration. This is part of the compromise involved in keeping the model as simple as possible while still capturing the important hydrologic features and processes. The calibrated model represents the best fit to the observations without introduction of site-specific features to cause additional discharge into Sheep Gulch and the beaver pond.

Figure 25 shows the simulated heads versus observed heads. The site heads and gradient across the site are matched very well. With the exception of three outliers, the model also matches Borduin's (1999) data well. The outliers may represent zones that are isolated from the regional flow system. The data from the MBMG are not matched as well, however, these data have a large degree of uncertainty as discussed above.

Model parameter sensitivities for a preliminary calibration are shown in Figure 26. The most insensitive parameters were fixed (not variable) in the final calibration. Mass balance summaries for the calibration run and the various forward simulations are presented in Appendix B.

5.5 Particle Tracking with the Calibrated Model

The calibrated flow model was modified to simulate historical pumping rates from the Silver Bow Plant production wells (combined discharge of 1400 gpm) and used to track ground water flow directions to the production wells and from the tailing basin. Backward traces from the production wells in Layer 5

indicate that these wells obtained most of their discharge from the south (Figure 27). The traces do not suggest significant induced recharge from Silver Bow Creek. Forward traces from the tailing basin (Layer 1) indicate that some of this water was drawn into the deepest part of the aquifer by the pumping of the production wells and that some of the water discharges to surface water bodies (Figure 28).

6.0 Arsenic Transport Modeling Methods

Arsenic transport was modeled because of the three chemicals of concern (arsenic, cadmium, and fluoride) arsenic is more mobile than cadmium and more toxic than fluoride. Cadmium adsorption to sediments increases with pH, and above a pH of approximately 7, virtually all cadmium is adsorbed (Moore and Ramamoorthy, 1984, p. 36). The distribution of cadmium in ground water at the Silver Bow Plant reflects its strongly attenuated nature (see Figure 4-13 of the VCP Report (Barr, 1999)).

The three-dimensional transport modeling code MT3DMS was used to model arsenic transport in ground water. Methods for estimation of the arsenic transport parameters and calibration of the transport model are described below.

6.1 Code Selection and Description

The transport code MT3DMS can be used to simulate changes in concentrations of soluble contaminants in ground water caused by advection, dispersion, diffusion, and some basic chemical reactions, with various types of boundary conditions and external sources or sinks. The basic chemical reactions included in MT3DMS are equilibrium-controlled or rate-limited linear or non-linear sorption, and first-order irreversible or reversible kinetic reactions. MT3DMS can accommodate very general spatial discretization schemes and transport boundary conditions, including: 1) confined, unconfined or variably confined/unconfined aquifer layers; 2) inclined model layers and variable cell thickness within the same layer; 3) specified concentration or mass flux boundaries; and 4) the solute transport effects of external hydraulic sources and sinks such as wells, drains, rivers, areal recharge and evapotranspiration. MT3DMS is designed for use with any block-centered finite-difference flow model, such as the U.S. Geological Survey modular finite-difference ground water flow model, MODFLOW, under the assumption of constant fluid density and full saturation.

The partial differential equation describing the fate and transport of contaminants of species k in three-dimensional, transient ground water flow systems can be written as follows (Zheng and Wang, 1998):

$$\frac{\partial(\theta C^k)}{\partial t} = \frac{\partial}{\partial x_i} \left(\theta D_{ij} \frac{\partial C^k}{\partial x_j} \right) - \frac{\partial}{\partial x_i} (\theta v_i C^k) + q_s C_s^k + \sum R_n$$

where:

- θ is the porosity of the subsurface medium, dimensionless;
- C^k is the dissolved concentration of species k , ML^{-3} ;
- t is time, T;
- x_i is the distance along the respective Cartesian coordinate axis, L;
- D_{ij} is the hydrodynamic dispersion coefficient tensor, $\text{L}^2 \text{T}^{-1}$;
- v_i is the seepage or linear pore water velocity; LT^{-1} ; it is related to the specific discharge or Darcy flux (q_i) through the relationship, $v_i = q_i / \theta$;
- q_s is the volumetric flow rate per unit volume of aquifer representing fluid sources and sinks, T^{-1} ;
- C_s^k is the concentration of the source or sink flux for species k , ML^{-3} ;
- R_n is the chemical reaction term, $\text{ML}^{-3} \text{T}^{-1}$.

MT3DMS includes an implicit formulation that is solved with an iterative solver that is based on generalized conjugate gradient (GCG) methods with three preconditioning options and the Lanczos/ORTHOMIN acceleration scheme for non-symmetrical matrices. If the GCG solver is selected, dispersion, sink/source, and reaction terms are solved implicitly without any stability constraints. The GCG solver was used with Jacobi preconditioning in this modeling project. The fully implicit standard finite-difference method was used to solve the advection term. Model input files are provided as described in Appendix A.

6.2 MT3DMS Packages Used

Optional MT3DMS packages used in the simulations described below included: the advection package; the source-sink mixing package for simulation of historical conditions and the closure alternative involving infiltration through unsaturated tailings; and the reaction package for simulation of non-linear sorption of arsenic. The dispersion package was not used (see Section 6.4 for further details).

6.3 Determination of Transport Parameters

A series of batch sorption/desorption tests were performed in which the equilibrium concentration of dissolved arsenic in contact with tailings and three soil types from the Silver Bow Plant were determined for approximately seven to ten starting dissolved arsenic concentrations. In general, the batch sorption/desorption data are consistent with the Freundlich isotherm, in which the mass of a compound adsorbed on the solid phase per unit mass of the solid phase ($\bar{C}$) is related to the concentration in solution at equilibrium (C) by the following equation (Zheng and Wang, 1998):

$$\bar{C} = K_f C^a$$

where:

K_f is the Freundlich constant, with units of (L/• g)^{1/a} and

a is the Freundlich exponent, a dimensionless parameter.

Graphs of all of the Freundlich isotherms determined from the batch testing are shown as blue traces on Figures 29 through 31. Details on the batch sorption testing are presented in Appendix C.

6.4 Transport Model Calibration

The transport model was calibrated manually using a simulation of the period from 1970 through 1999. Water with an arsenic concentration of 0.5 mg/L (based on typical reported concentrations for the pond return water, see Table 4-13) infiltrating at a rate of 387 gpm (based on the calibrated flow model) was simulated for this time period.

Preliminary modeling consisted of using mean values for the Freundlich isotherm coefficients for the tailings, alluvium (assigned to all zones in layers 2 through 5 except those representing coarse-grained deposits), and fluvial deposits associated with the buried channel beneath the tailing basin and with Silver Bow Creek. Arsenic concentrations were underestimated in all cases. The model was relatively insensitive to the effective porosity within reasonable ranges (0.25 to 0.005). The lowest Freundlich coefficient values from any of the batch tests were assumed for each of the materials, but the resulting arsenic concentrations were still too low. A starting concentration of arsenic in the pore water of the tailings of 0.5 mg/L was assumed. The bulk densities of the tailings and alluvium were reduced to 90

percent and 80 percent of the measured values, a slightly lower slope (α) was assumed for the alluvium and the fluvial deposits, and a lower offset (K_f) was assumed for the tailings to yield a reasonable match to observed arsenic concentrations. The red traces on Figures 29 through 31 are the calibrated isotherms. The arsenic transport parameters for the calibrated transport model result in isotherms that are lower than the laboratory-measured values at high dissolved arsenic concentrations, but consistent with the laboratory-measured values at lower dissolved arsenic concentrations.

The dispersion package was not used because the aquifer system has such a high capacity for arsenic sorption that difficulty was encountered simulating arsenic transport into the aquifer as far from the tailing basin as is currently observed. Simulation of dispersion would lower the modeled arsenic concentrations by spreading the mass further than advective transport alone. Since mass is conserved in the simulation, dispersion would not be anticipated to affect the mass flux calculations.

Measured arsenic concentrations above background versus simulated concentrations are listed on Table 5 and plotted in Figure 32. For simplicity, the background arsenic concentration was assumed to be 0.010 mg/L, which is considered a representative value for most areas around the Silver Bow Plant. As discussed in Section 4.3.3 of the VPC Report (Barr, 1999), it appears that the background arsenic concentrations may be spatially variable and exceed the WQB-7 standard for arsenic in the vicinity of Sheep Gulch. If this is the case, the arsenic concentration above background for Wells PW-99-1 and PW-99-3 may represent concentrations to of zero to approximately 0.015 mg/L above background. In addition, arsenic concentrations exceeding WQB-7 in Silver Bow Plant Production Wells RP W-4 and RP W-6 may reflect some natural variability in background concentrations.

Simulated concentrations around 0.001 mg/L to 0.002 mg/L versus measured concentrations at background are not considered significant residuals because the simulated value is a small fraction of the background concentration, and therefore could not be distinguished from background. Three wells are located near sharp fronts in the simulated arsenic plume. Slight variations of the ground water flow direction would cause marked increases/decreases in simulated arsenic concentration at these wells. Thus the fact that the model does not match these observations is reasonable. The model is considered representative of site conditions.

The arsenic concentrations at Wells MW97-3 and PW99-1 (see Figure 5) were considered the most critical to match because these are the furthest downgradient and represent the shallow aquifer system's ability to attenuate arsenic transport and control the rate of mass loading to surface water bodies. Table 6 lists the calibrated transport parameters, the resulting adsorbed arsenic concentration in equilibrium with a

dissolved concentration of 0.5 mg/L, and the retardation factor for a dissolved arsenic concentration of 0.5 mg/L. The retardation factor represents the inverse of the rate of arsenic migration relative to the rate of ground water movement. In other words, arsenic migrates at a rate of 280 to 1490 times slower than ground water due to the effects of sorption by the tailings and aquifer material. Mass balance summaries for the calibration run and the various forward simulations are presented in Appendix D. As described above, these calibrated values are consistent with the laboratory-measured values.

The simulated arsenic concentrations above background under current conditions in model layers 1 through 5 are shown on Figures 33 through 37. Certain aspects of the shape of the arsenic plume are notable. For instance, the split of the plume downstream of the Silver Bow Plant in Figure 34 is caused by simulation of loss of discharge from Sheep Gulch to Layer 2 of the model in this reach. The simulated arsenic concentration in the water discharging from Sheep gulch is zero, consequently an apparent dilution of arsenic concentrations in Layer 2 occurs in this area. This phenomenon of a tributary stream losing discharge to ground water in the vicinity of a larger stream that is gaining ground water discharge has been observed in other settings. In nature, arsenic reaching Sheep Gulch in a gaining reach would be available for reintroduction into the ground water in a losing reach further downstream. This is a limitation of MODFLOW/MT3DMS: the concentration of a given species in a stream can be specified by the user, but is not calculated internally. If the value were specified as greater than zero, it would not change with time and would artificially add mass to the system.

The arsenic mass flux calculation, which is described in more detail below, consisted of adding the mass reaching Sheep Gulch in cells that gain discharge from ground water to the mass reaching the beaver pond and Silver Bow Creek in cells that gain discharge from ground water. Simulating the infiltration of “clean” surface water in the lower reaches of Sheep Gulch has the apparent effect of displacing the arsenic in the ground water, but the mass flux calculation considers all stream cells that gain discharge from ground water, so the total mass flux calculation is accurate.

The shape of the southwestern margin of the plume is also notable (see Figure 34). Simulation of loss of discharge from Sheep Gulch to ground water at the south end of the Silver Bow Plant, combined with infiltration from the tailing basin causes a mounding condition that forces arsenic-bearing ground water along the southwestern margin of the tailing basin to flow to the west. This can also be seen in the particle traces shown on Figure 28. Further to west, the flow direction changes to a northerly direction as the mounding conditions dissipate (see Figure 23). The varying flow direction causes the abrupt angle on the margin of the plume shown on Figure 34.

6.5 Arsenic Mass Loading Estimates for the Current Conditions

The rate of mass flux to Sheep Gulch, the beaver pond, and Silver Bow Creek was estimated by multiplying the simulated rate of ground water discharge from each model cell connected to these surface water bodies times the simulated arsenic concentration in each cell. The flux of arsenic in addition to background to these surface water bodies is estimated to be 10.3 g/day.

The effect of this additional mass loading on the arsenic concentration in Silver Bow Creek was estimated as follows. The estimated average stream discharge rate at the upstream end of the model domain is 21.6 cfs (based on Titan Environmental, 1994). An additional net gain of 3.2 cfs from ground water is estimated to occur between the upstream end of the model domain and the reach of the creek downgradient of the Silver Bow Plant (based on the calibrated flow model simulating typical conditions for the period 1970-1999). The additional arsenic concentration in Silver Bow Creek under current conditions was thus estimated by dividing the rate of additional mass flux into the surface water bodies (10.3 g/day) by the estimated average stream discharge (24.84 cfs or 60,820 m³/day) to yield an additional concentration of 1.7E-4 g/m³ (0.00017 mg/L).

6.6 Forward Simulations

Results of the batch sorption testing and model calibration indicate that a significant mass of arsenic is adsorbed in the native material beneath the tailings as well as in the tailings themselves. A no-action alternative and three remedial alternatives were simulated using the calibrated arsenic transport parameters. These alternatives are described below along with an estimate of arsenic mass flux to Sheep Gulch, the beaver pond, and Silver Bow Creek.

6.6.1 No-action Alternative

The no-action alternative consists of no remedial action beyond that taken for plant dismantling and demolition. The no-action alternative assumed a rate of infiltration of 0.3 inches/year (the regional rate in the calibrated model) with a dissolved arsenic concentration of 0.5 mg/L. Simulation of the no-action alternative indicates that the tailings will only be partially saturated after basin closure (Figure 38). A calculation was performed regarding mass removal from the unsaturated tailings that indicated it would take over 7000 years to desorb the arsenic in this zone at this dissolved concentration. The starting

arsenic concentration in ground water was taken from the historical simulation and the mass sorbed in the aquifer is determined by MT3DMS based on the volume of saturated aquifer material in each cell and the Freundlich isotherm for the cell.

The predicted arsenic distribution in Layer 2 (the layer from which ground water discharges to surface water bodies) at 50 years, 200 years, and 600 years after closure are shown on Figures 39 through 41. The area of high dissolved arsenic concentrations migrates slowly toward Silver Bow Creek as the mass is desorbed from the upgradient side and adsorbed on the downgradient side. The dissolved concentrations downgradient of the tailing basin and the rate of mass loading to the surface water bodies rise at first, then slowly decrease with time. The maximum dissolved concentration also slowly decreases with time. Estimated mass loading to Silver Bow Creek in excess of background for this alternative is summarized on Table 7. Details on the mass flux calculations are presented in sections 6.3 and 6.4.5.

A notable feature on Figure 39 (and all of remedial simulations at 50 years after closure) is the shape of the southwestern margin of the plume. Development of this margin in the historical simulation, which was the starting condition for the remedial alternatives, is discussed in Section 6.4. The simulated effect of closure is to reduce the mounding condition under the tailing basin due to a reduction in the amount of infiltration in the basin footprint. This cuts off the source of arsenic-bearing water. Sheep Gulch is simulated to lose discharge in this reach in the remedial simulations. As described in Section 6.4, simulation of infiltration of water from Sheep Gulch containing no arsenic creates an apparent gap in the plume but does not affect the mass flux calculations. By 200 years after closure, advection of clean, upgradient water through the area covered by the portion of the plume west of the gap has reduced arsenic concentrations below 0.0001 mg/L in this area (Figure 40).

6.6.2 Evapotranspiration Cap Alternative

In the evapotranspiration cap alternative, zero infiltration is assumed over the footprint of the tailing basin. The results from this alternative are nearly identical to the no-action alternative because the calibrated rate of infiltration (0.3 inches per year) resulted in a minor additional mass flux compared to the mass in the system at the start of the simulation. The predicted arsenic distribution in Layer 2 at 50 years, 200 years, and 600 years after closure are shown on Figures 42 through 44. The estimated mass flux to Silver Bow Creek is slightly lower in the capping alternative (Table 7).

6.6.3 Deep Ground Water Interception

The deep ground water interception alternative consisted of simulating capping of the tailing basin (zero infiltration on the tailing basin footprint) and pumping of Silver Bow Plant Production Wells RP W-4 and RP W-6. Maps of the simulated arsenic distribution in Layer 2 at 50 years, 200 years, and 600 years after closure are shown on Figures 45 through 47.

Pumping of the deep wells acts as a gradient control, capturing some of the contaminated ground water that would otherwise discharge to Silver Bow Creek. Because arsenic is so strongly adsorbed, the pump-out system would have to operate for an indefinite period of time to effect significant mass removal. The simulation results indicate that shutting the system down any time in the foreseeable future would result in little difference in future arsenic flux to Silver Bow Creek as compared to the capping alternative.

6.6.4 Shallow Ground Water Interception

The shallow ground water interception alternative consisted of simulating capping of the tailing basin (zero infiltration on the tailing basin footprint) and installation and pumping of a shallow french drain at 250 gpm. Maps of the simulated arsenic distribution in Layer 2 at 50 years, 200 years, 600 years, and 1000 years after closure are shown on Figures 48 through 50.

As with the deep ground water interception alternative, the shallow drain acts as a gradient control. However, because arsenic is so strongly adsorbed, the drain would have to operate for an indefinite period of time to effect significant mass removal. The simulation results indicate that shutting the system down any time in the foreseeable future would result in little difference in future arsenic flux to Silver Bow Creek as compared to the capping alternative.

6.6.5 Arsenic Mass Loading Estimates for the Forward Simulations

Table 7 summarizes the no-action and remedial alternatives in terms of mass loading of arsenic to Sheep Gulch, the beaver pond, and Silver Bow Creek above the rate due to background concentrations in ground water. The additional increase in arsenic concentration this mass loading would cause in Silver Bow Creek is also listed. Details on the calculations of mass flux from ground water are presented in Section 6.5.

In addition to the mass flux from ground water, the mass flux calculations for the deep ground water interception alternative and shallow ground water interception alternative include the effects of discharging treated water to Silver Bow Creek. It was assumed that the pumped water would be treated to 0.01 mg/L arsenic. This value is approximately half of the WQB-7 human health standard for arsenic. Given a pumping rate of 800 gpm for the deep ground water interception alternative, discharge of the effluent would result in a mass loading of 43.6 g/day arsenic. Likewise for the shallow ground water interception alternative, a pumping rate of 250 gpm would result in mass loading of 13.6 g/day of arsenic in the effluent. The effluent discharge rates were added to the estimated average stream discharge in Silver Bow Creek for each of the alternatives in calculating the change in arsenic concentration in the creek.

Table 7 summarizes the combined arsenic loading from ground water and treated water. Based on the analysis, the deep and shallow ground water interception alternatives introduce a greater mass of arsenic to Silver Bow Creek and result in larger increases in arsenic concentration in the creek than the no-action and evapotranspiration cap alternatives.

Assuming a background arsenic concentration of 0.010 mg/L in ground water, the background mass flux of arsenic to Silver Bow Creek for the no-action alternative (unrelated to releases from the Silver Bow Plant) is 320 g/day. The largest simulated mass flux of arsenic to surface water contributed by Silver Bow Plant operations in the no-action alternative is 22.9 g/day at 200 years after site closure, or approximately 7 percent of the background rate of arsenic mass flux to the creek. The calculated impact on Silver Bow Creek for typical creek flows never exceeds 0.0004 mg/L. Addition of this incremental arsenic concentration to the average Silver Bow Creek water quality in this reach (0.0155 mg/L, see the discussion in Section 4.2.4 of the VCP Report (Barr, 1999)), would not exceed the WQB-7 standard for arsenic.

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Table 1
Prior Information on Flow Model Parameters

Parameter	Estimated Value	Source/Comments
Transmissivity of coarse deposits in Silver Bow Creek alluvium in the Silver Bow Area	189,000 gpd/ft to 250,000 gpd/ft	Titan Environmental, 1994, p. 246, well GS-03, converted to hydraulic conductivity by dividing by 10 ft saturated thickness: 98 ft/day to 130 ft/day
Transmissivity of fine-grained deposits in Silver Bow Creek alluvium in Silver Bow Area	2,900 gpd/ft to 42,400 gpd/ft	Titan Environmental, 1994, p. 246, Silver Bow Sludge Site, converted to hydraulic conductivity by dividing by screen length: 1.1 ft/day to 15 ft/day
Transmissivity of coarse deposits in Silver Bow Creek alluvium in the Ramsay Flats area	789,000 gpd/ft	Titan Environmental, 1994, p. 246, well TS-01, converted to hydraulic conductivity by dividing by 10 ft screen length: 410 ft/day
Vertical Hydraulic Conductivity of clayey alluvial soils underlying the tailing basin	4.9E-8 cm/sec (4.2E-5 m/day)	Barr, 1998a, p. 22
Horizontal Hydraulic Conductivity of clayey alluvial soils underlying the tailing basin	1.5E-6 cm/sec (1.3E-3 m/day)	
Transmissivity of coarse-grained valley-fill deposits beneath the tailing basin	3,880 gpd/ft to 5,920 gpd/ft	Barr, 1999, converted to hydraulic conductivity by dividing by 15 ft and 8 ft saturated thickness: 99 ft/day to 35 ft/day, respectively
Vertical Leakage of aquitard on top of coarse-grained valley fill deposits beneath the tailing basin	4.48 day ⁻¹ to 6.71 day ⁻¹	Barr, 1999
Transmissivity of strata penetrated by site production wells	50,000 gpd/ft	Barr, 1998a, p. 23, converted to hydraulic conductivity by dividing by 10 ft saturated thickness: 98 ft/day
	38,500 gpd/ft to 148,000 gpd/ft	Leonard Rice Consulting Engineers, Inc., 1997
Transmissivity of strata penetrated by AsiMI Well ASM3	153,000 gpd/ft	
Transmissivity of the graben-fill deposits	3,000 gpd/ft to 30,000 gpd/ft	
Hydraulic Conductivity of alluvium beneath Silver Bow Creek	50 ft/day (15.2 m/day)	Borduin, 1999
Hydraulic conductivity of alluvium beneath Sand Creek and Sheep Gulch	30 ft/day (9.1 m/day)	
Typical hydraulic conductivity values for graben-fill material	1 ft/day to 10 ft/day (0.305 m/day to 3.05 m/day)	
Range of transmissivity values based on specific capacity of wells in area	170 gpd/ft to 88,000 gpd/ft	Analysis of data obtained from the Montana Bureau of Mines and Geology, 1999
Range of hydraulic conductivity values based on specific capacity of wells in area	0.042 m/day to 890 m/day	

Table 2
Hydraulic Conductivity Estimate Based on On-site Production Wells

Production Well No.	Pumping Rate (gpm)	Drawdown (ft)	Estimated Transmissivity (gpd/ft)	Saturated Thickness* (ft)	Hydraulic Conductivity (ft/day)	Comments
1	375	15	50000	30	223	Estimated saturated thickness
2	500	14	71429	28	341	
2A	500	82	12195	57	29	
3	550	18.5	59459	23	346	
4	350	5.5	127273	27	630	
5	350	46	15217	90	23	Estimated saturated thickness
6	350	1	700000	45	2080	Drawdown estimate is suspect
7	500	84	11905	80	20	

*Length of screen/perforated zones

Table 3
Summary of Observed and Simulated Flows and Heads in Site Monitoring Wells for
the Calibrated Flow Model

Observation	Measured value	Calculated Value	Residual	Weight
Ground Water Discharge to Surface Water Bodies				
Tailing basin (m ³ /day)	2073	2108.78	-35.78	0.072
Sheep Gulch (m ³ /day)	-880	-16.929	-863.07	0
The beaver pond (m ³ /day)	-450	-49.1596	-400.84	0.006
Silver Bow Creek (m ³ /day) (8.6 cfs)	-21060	-13818.5	-7241.5	0.0022
Water Levels in Wells				
Epa1 (m MSL)	1627.05	1626.835	0.215	1.4
MW97-10 (m MSL)	1619.69	1620.774	-1.084	1.4
MW97-11 (m MSL)	1624.689	1624.566	0.123	1.4
MW97-7 (m MSL)	1624.119	1620.762	3.357	1.4
MW97-8 (m MSL)	1622.451	1619.964	2.487	1.4
MW97-9 (m MSL)	1620.1	1619.336	0.764	1.4
RP2a (m MSL)	1622.18	1620.908	1.272	1.4
Epa3 (m MSL)	1619.213	1617.197	2.016	4.8
MW97-3 (m MSL)	1620.07	1619.567	0.503	4.8
MW97-4 (m MSL)	1620.07	1619.609	0.461	4.8
MW97-6 (m MSL)	1623.98	1621.606	2.374	4.8
Epa4 (m MSL)	1615.67	1615.48	0.19	10.6
MW97-1 (m MSL)	1627.387	1629.528	-2.141	10.6
MW97-2 (m MSL)	1627.418	1628.528	-1.110	10.6
MW97-5 (m MSL)	1627.58	1626.714	0.866	10.6
Horizontal Hydraulic Gradients				
Gradient Across the site (unitless) MW97-5 to EPA3	.0055	.0062	-.00007	NA*
Gradient Across the site (unitless) MW97-1 to EPA4	.0074	.0089	-.0015	NA

*Not used explicitly as an observation in the automated flow model calibration.

Table 4
Summary of Calibrated Flow Model Parameters

Parameter Description	Parameter Name	Estimated Value*	Comment
Horizontal hydraulic conductivity (K) of the tailings.	tail	2.26E-02 m/day	16x higher than previous estimates.
Global K for Layer 2.	glob2	7.5683 m/day	
Global K for Layers 3-5.	glb35	0.3048 m/day	
K of the zone representing Silver Bow Creek deposits in Layer 5.	hik5	32.103 m/day	Extended beneath the Silver Bow Plant to encompass the production wells.
Discharge in streams at the margins of the graben-fill.	Strq	3739 m³/day	70% of precipitation on watershed outside margins of graben-fill
Rate of infiltration.	Rch	2.086E-05 m/day	0.3 in/yr (Borduin's (1999) model used 3 in/yr, but rate of stream loss in upper reaches not reported.)
Anisotropy in deposits beneath Silver Bow Creek in Layers 2-5.	Ansbc	0.4502	
Anisotropy of Layers 2-4 beyond the limits of the zone beneath Silver Bow Creek.	Anis	0.1282	
Tied parameters			
Conductance on general head boundary representing the tailing basin.	Ghblo	643.72 m²/day	
	Ghbhi	733.95 m²/day	
Fixed parameters			
K of sediments beneath Silver Bow Creek, Layers 2-4.	sbcr	15.244 m/day	Estimate from Mike Borduin (1999): 50 ft/day (15.2 m/day).
K of coarse-grained deposits in valley fill of former stream bed beneath the tailing basin.	vfill	17.8333 m/day	Mean value from Focused Data Collection (see Appendix N).
K of igneous rocks cropping out northeast of the Silver Bow Plant.	igrx	1.10889 m/day	Raised from preliminary model based on data from the MBMG well database.

*Note: the number of significant figures are those used by PEST98. Accuracies are not implied to exceed two significant figures.

Table 5

Summary of Observed and Simulated Arsenic Concentration Above Background
in Site Monitoring Wells for the Calibrated Transport Model

Well	Measured (mg/L)	Simulated (mg/L)	Residual (mg/L)	Comment
EPA1	0	0.0012	-0.0012	Background assumed to be 0.010 mg/L
EPA3	0	0.0	0.0	
EPA4	0	0.0	0.0	
MW97-1	0	0.0	0.0	
MW97-2	0	0.0	0.0	
MW97-3	0.032	0.038	-0.006	
MW97-4	0.036	0.012	0.024	
MW97-5	0	0.0	0.0	
MW97-6	0	0.0	0.0	
MW97-7	0.109	0.0	NA	Other Source
MW97-8	0.038	0.0001	NA	Other Source
MW97-9	0.071	0.0006	0.070	Near sharp front
MW97-10	0.022	0.068	-0.046	Near sharp front
MW97-11	0.005	0.006	-0.001	
RP W-1	0	0.0003	-0.0003	Near background
RP W-4	0.012	0.002	0.0118	
RP W-5	0	0.0003	-0.0003	Near background
RP W-6	0.023	0.002	0.021	
RP W-7	0	0.0	0.0	
PW99-1	0.034	0.007	0.027	
PW99-3	0.048	158.5	-110.5	Near sharp front

Note: Wells MW 97-7 and MW 97-9 are located near arsenic sources other than the tailing basin, so are not expected to be matched with this model.

Table 6
Calibrated Arsenic Transport Parameters

Material Type	$K_f (L/\bullet g)^a$	a	$\bar{C} (\bullet g/g)$ for $C=0.5$ mg/L	Retardation Factor (R) for $C=0.5$ mg/L
Tailings	1.13E-01	0.631	8.1	1490
Fluvial Deposits	8.01E-04	1.5977	16.4	610
Alluvial Deposits	7.05E-04	1.5039	5.7	280

Table 7
Simulated Arsenic Mass Loading Above Background to Silver Bow Creek

Elapsed Time	No-action Alternative		Evapotranspiration Cap Alternative		Deep Ground Water Interception Alternative		Shallow Ground Water Interception Alternative	
(years)	Additional As flux to surface water* (g/day)	Increase in As Concentration in Silver Bow Creek (mg/L)	Additional As flux to surface water (g/day)	Increase in As Concentration in Silver Bow Creek (mg/L)	Additional As flux to surface water (g/day)□	Increase in As Concentration in Silver Bow Creek (mg/L)	Additional As flux to surface water (g/day)□	Increase in As Concentration in Silver Bow Creek (mg/L)
50	17.6	0.00029	17.4	0.00029	43.7	0.00069	27.5	0.00044
100	20.8	0.00034	20.6	0.00034	43.7	0.00069	30.1	0.00049
200	22.9	0.00038	22.6	0.00037	43.8	0.00069	34.1	0.00055
300	22.5	0.00037	22.1	0.00036	43.7	0.00069	35.7	0.00058
400	20.3	0.00033	19.8	0.00033	43.7	0.00069	27.4	0.00044
500	14.9	0.00025	13.8	0.00023	43.7	0.00069	23.7	0.00038
600	11.6	0.00019	10.9	0.00018	43.7	0.00069	21.1	0.00034

*Includes the beaver pond , Sheep Gulch, and Silver Bow Creek

□Includes the effect of discharging treated water with an arsenic concentration of 0.01 mg/L.

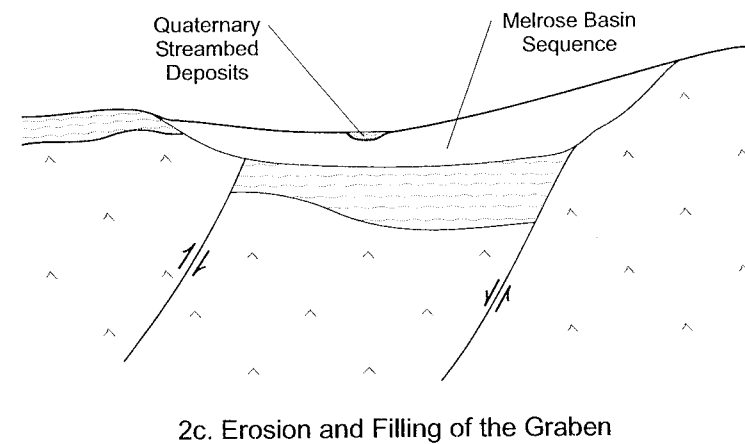
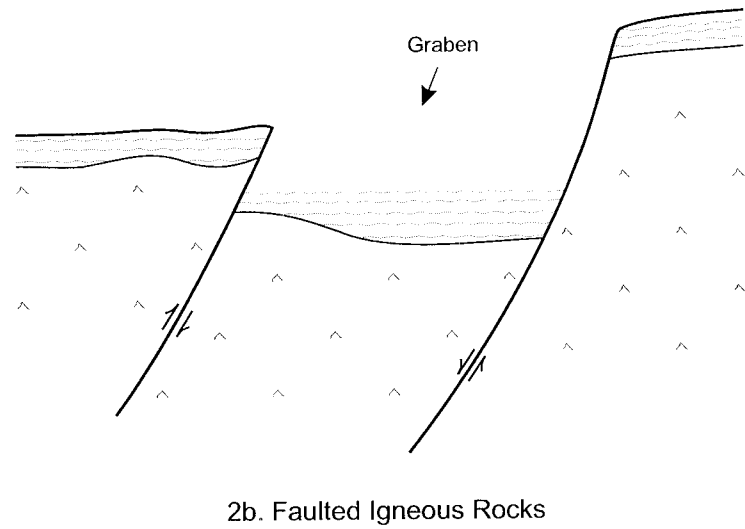
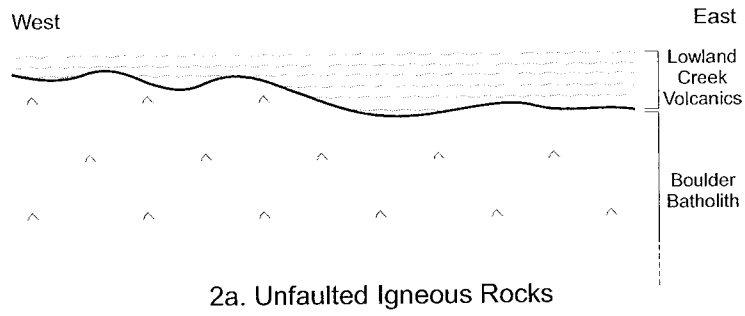
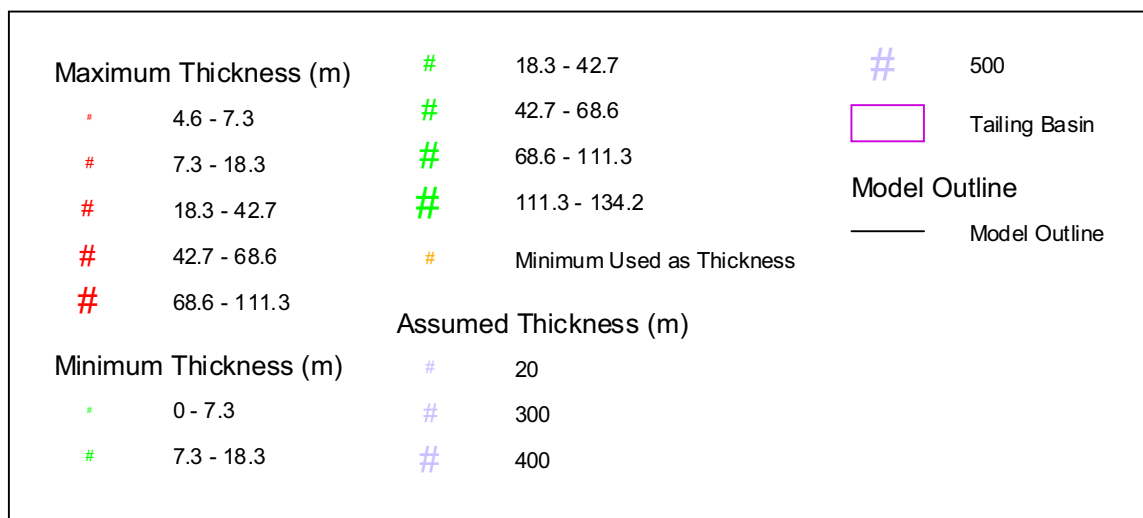


Figure 2

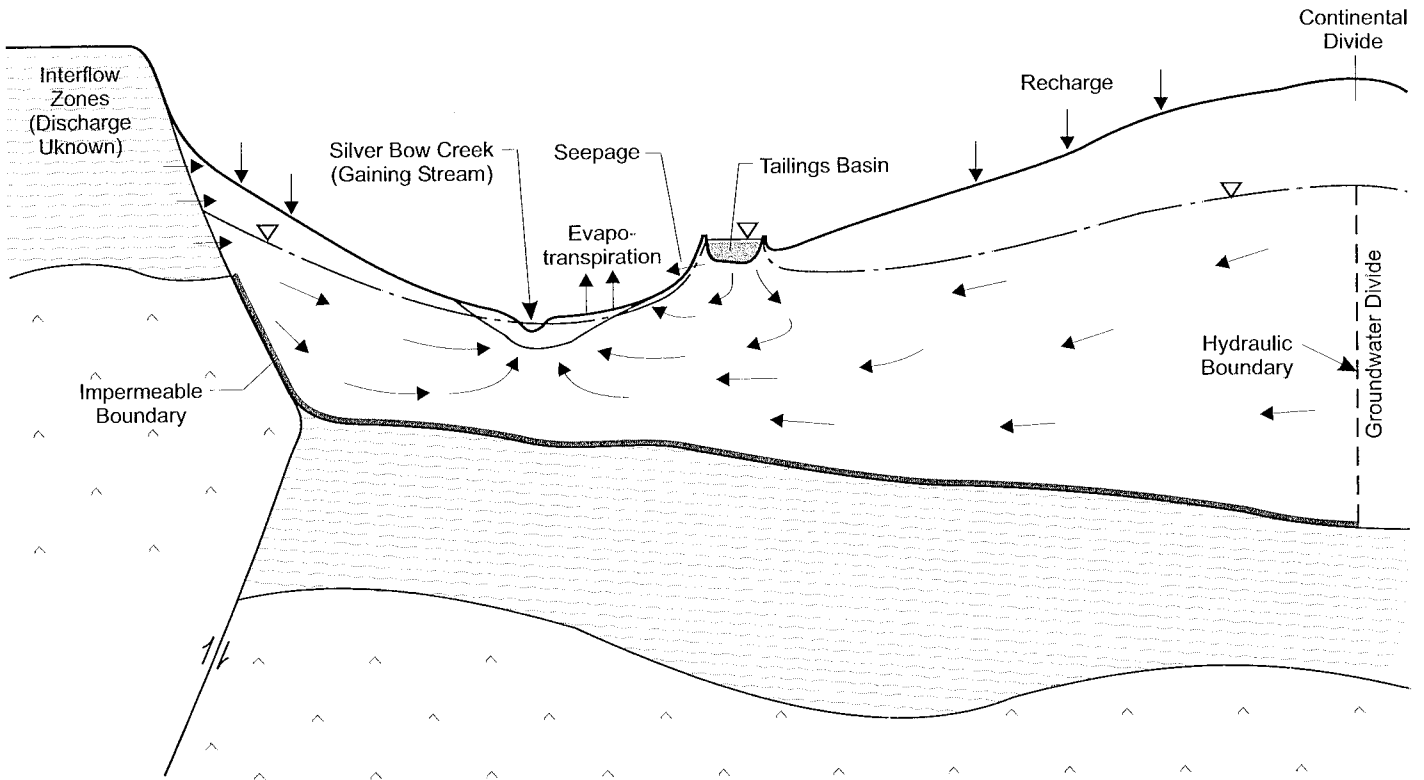
SCHEMATIC CROSS-SECTIONS SHOWING
DEVELOPMENT OF THE REGIONAL GEOLOGY



Barr: Arcview3.1 FI\AV\p\26\46\04\gis\project\demapr, Layout: thidnessdata.qld, Fri Jun 11 16:59:41 1999

NORTHWEST

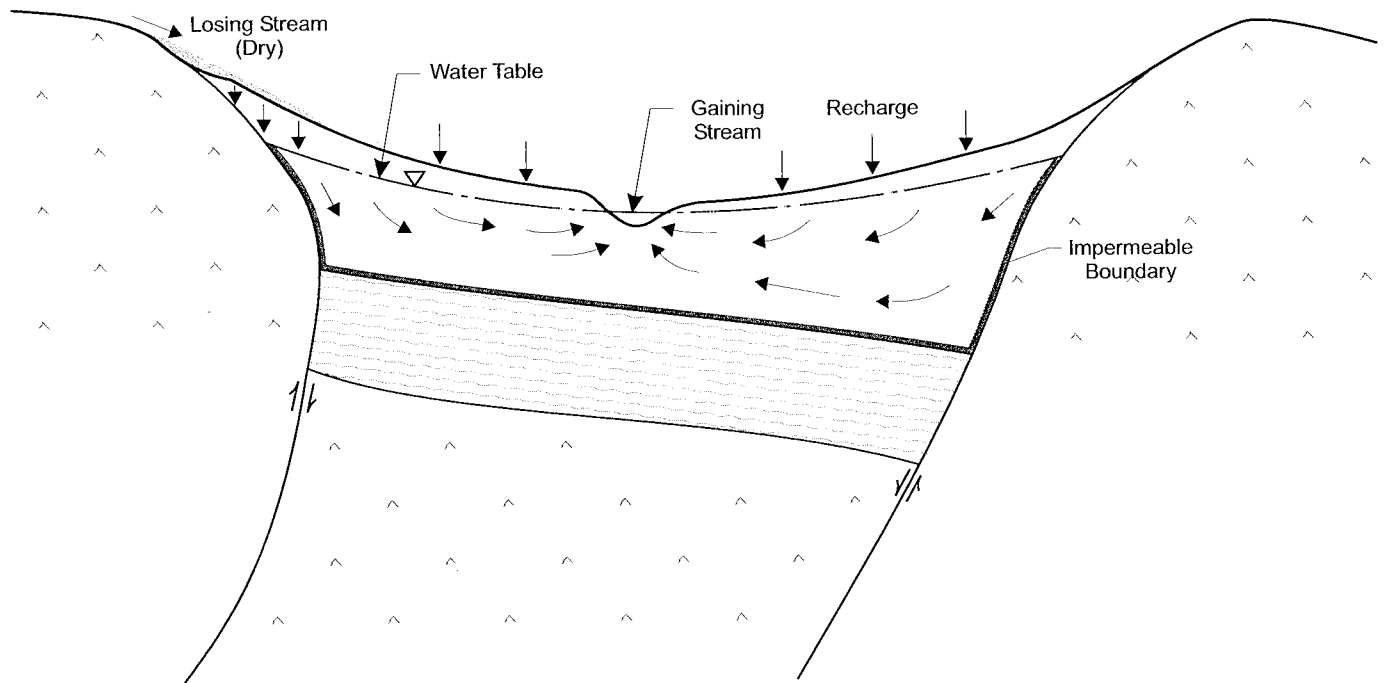
SOUTHEAST



NOT TO SCALE

SOUTHWEST

NORTHEAST



NOT TO SCALE

Figure 4

CONCEPTUAL HYDROGEOLOGIC CROSS-SECTIONS

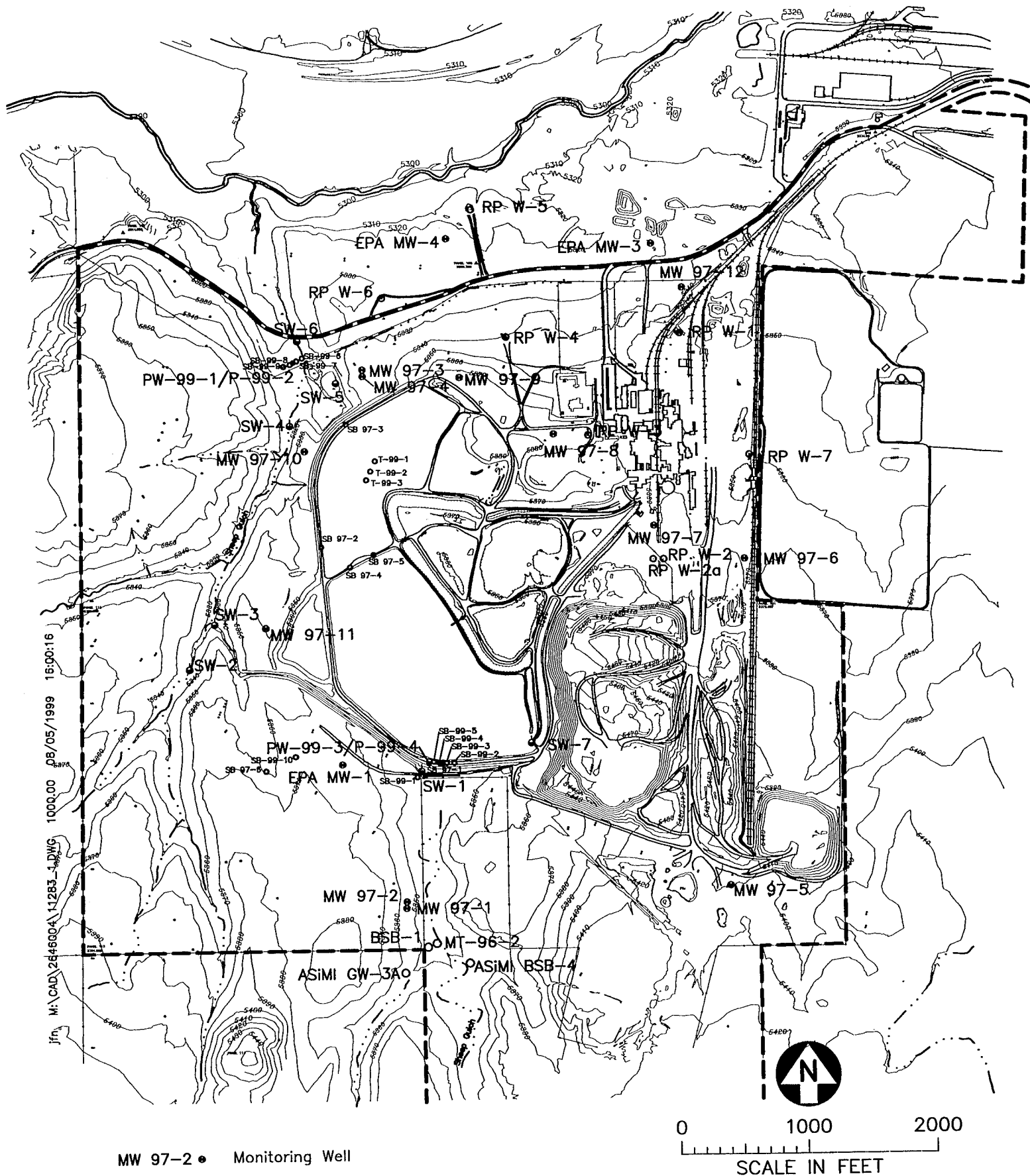
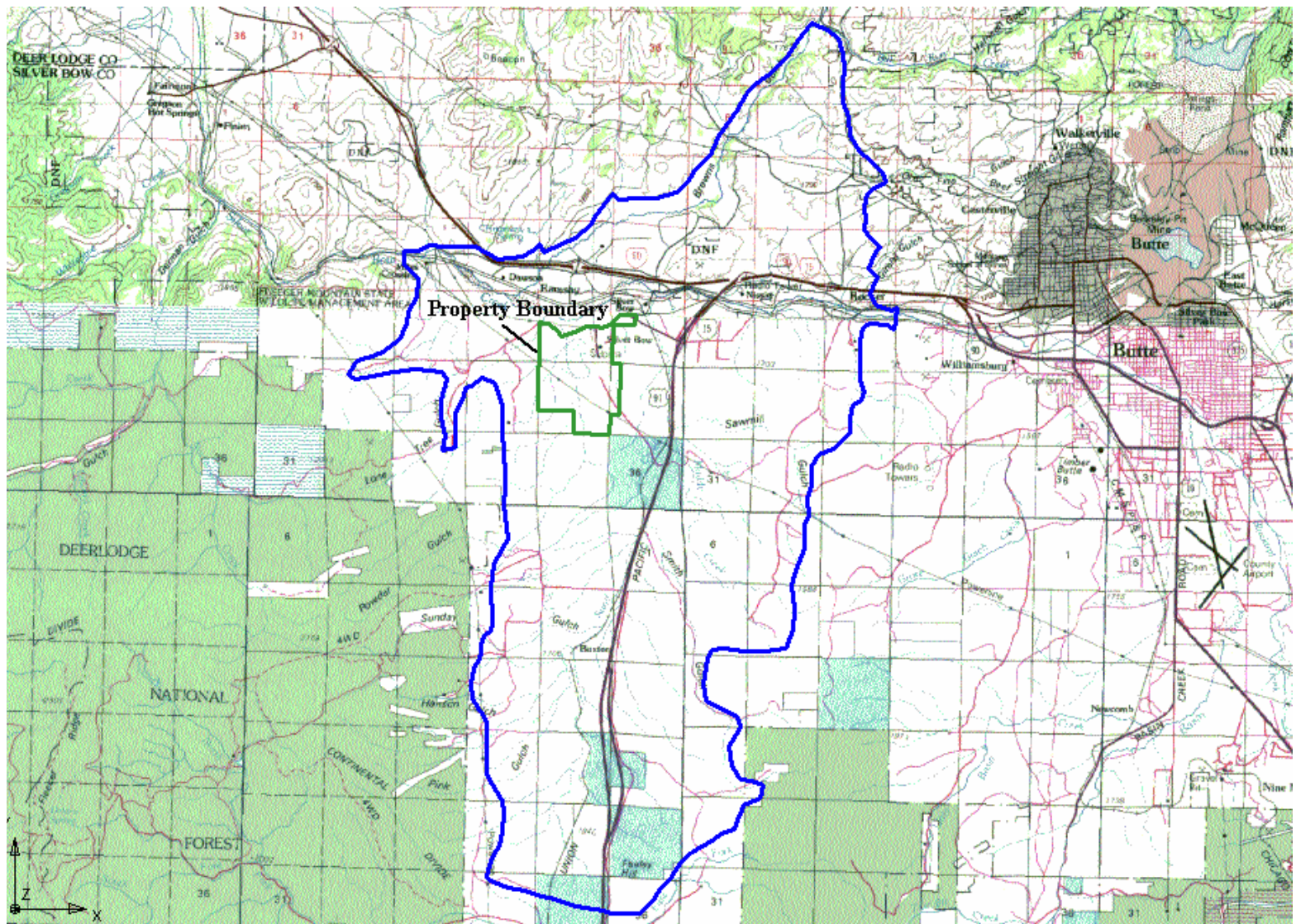


Figure 5

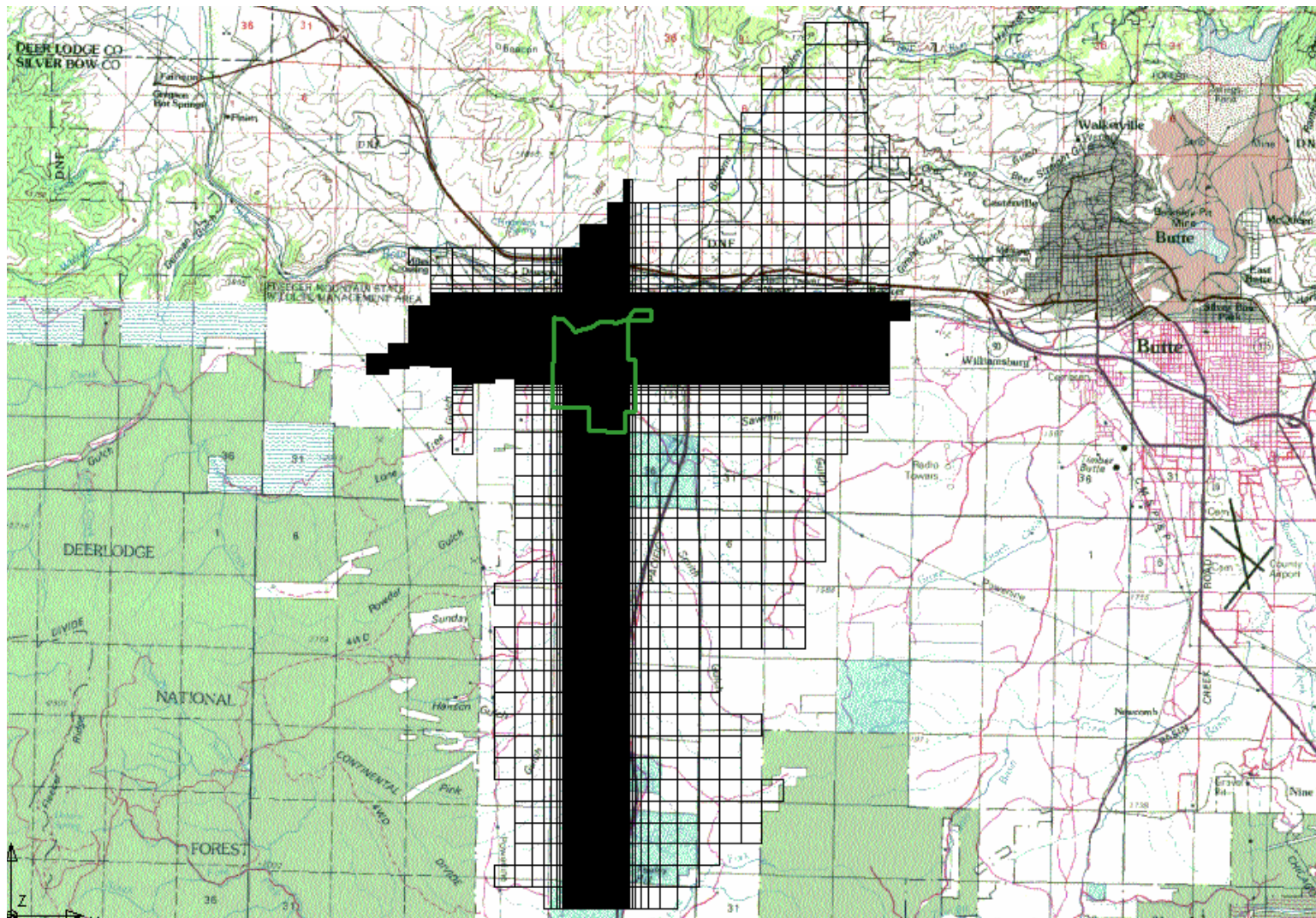
GROUNDWATER AND SURFACE WATER MONITORING LOCATIONS

Rhodia, Inc., Silver Bow, Montana



Note: Y-axis oriented due north, length of segment Z-X is 1 mile

Figure 6
Extent of the MODFLOW Groundwater Flow Model



Note: Y-axis oriented due north, length of segment Z-X is 1 mile

Figure 7

Active Cells in Layers 2 through 5 the MODFLOW Finite-difference Grid

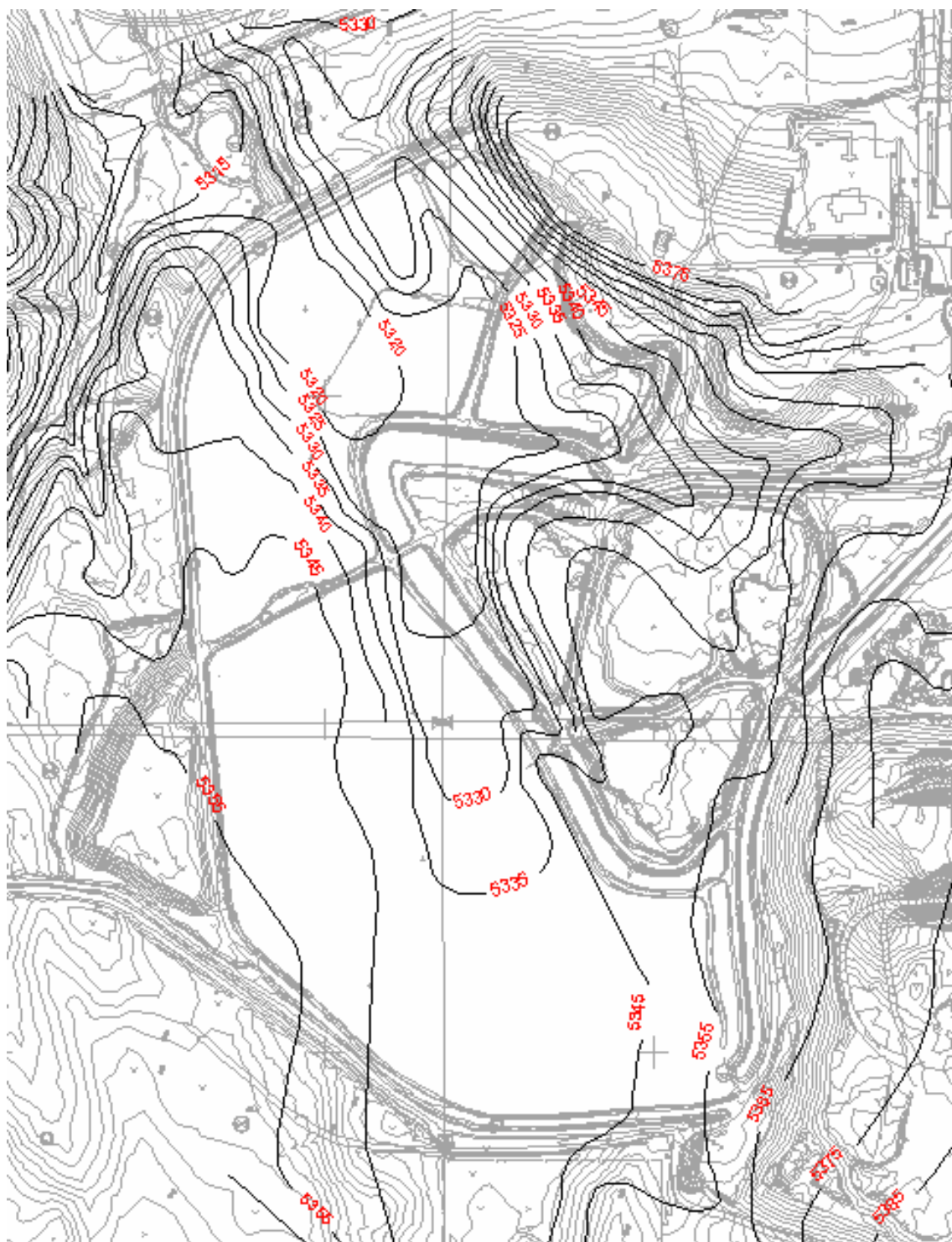


Figure 8
Predevelopment Topography Beneath the Tailings Basin

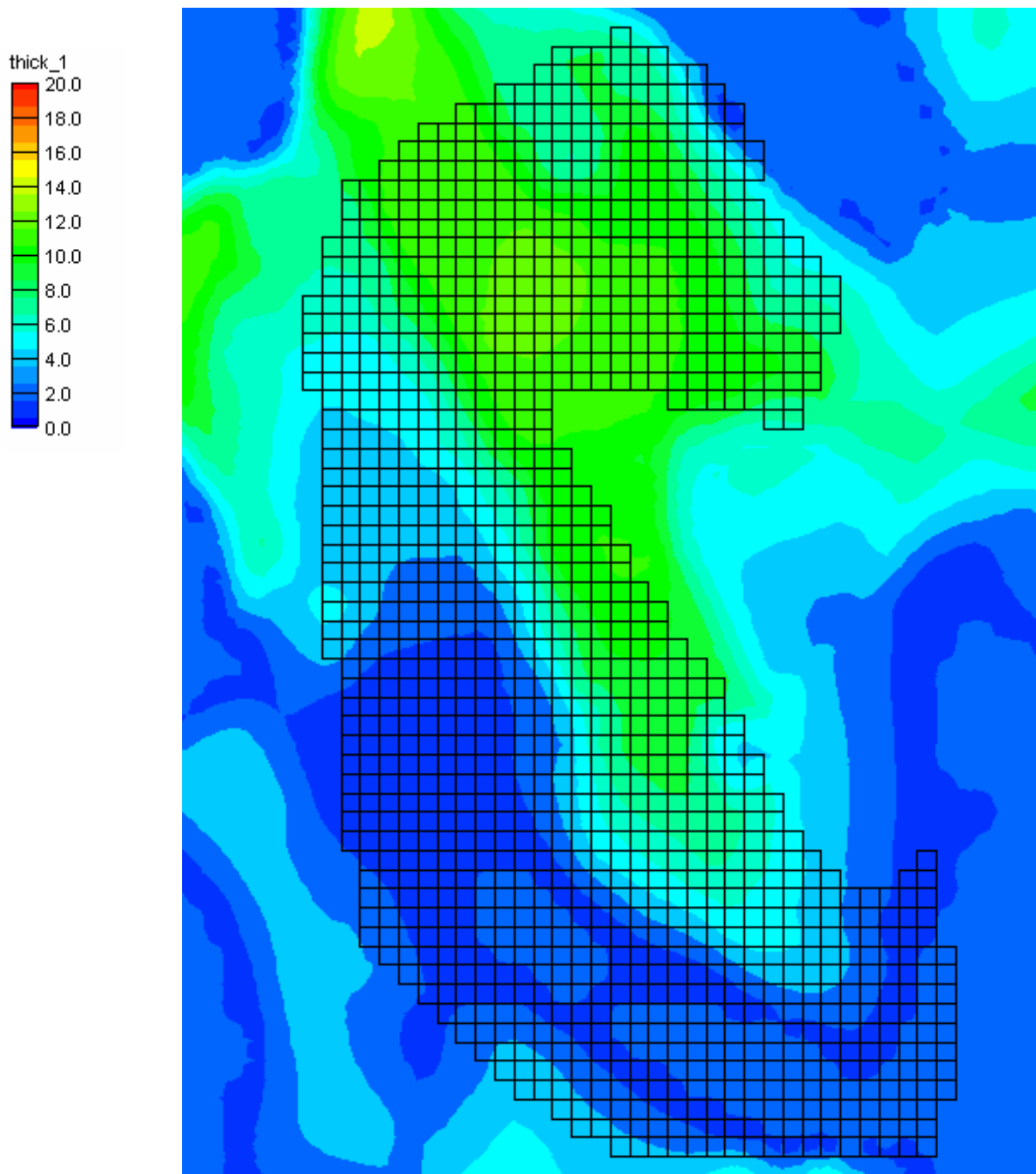


Figure 9

Thickness in meters and Extent of Active Cells in Layer 1 of the Flow Model

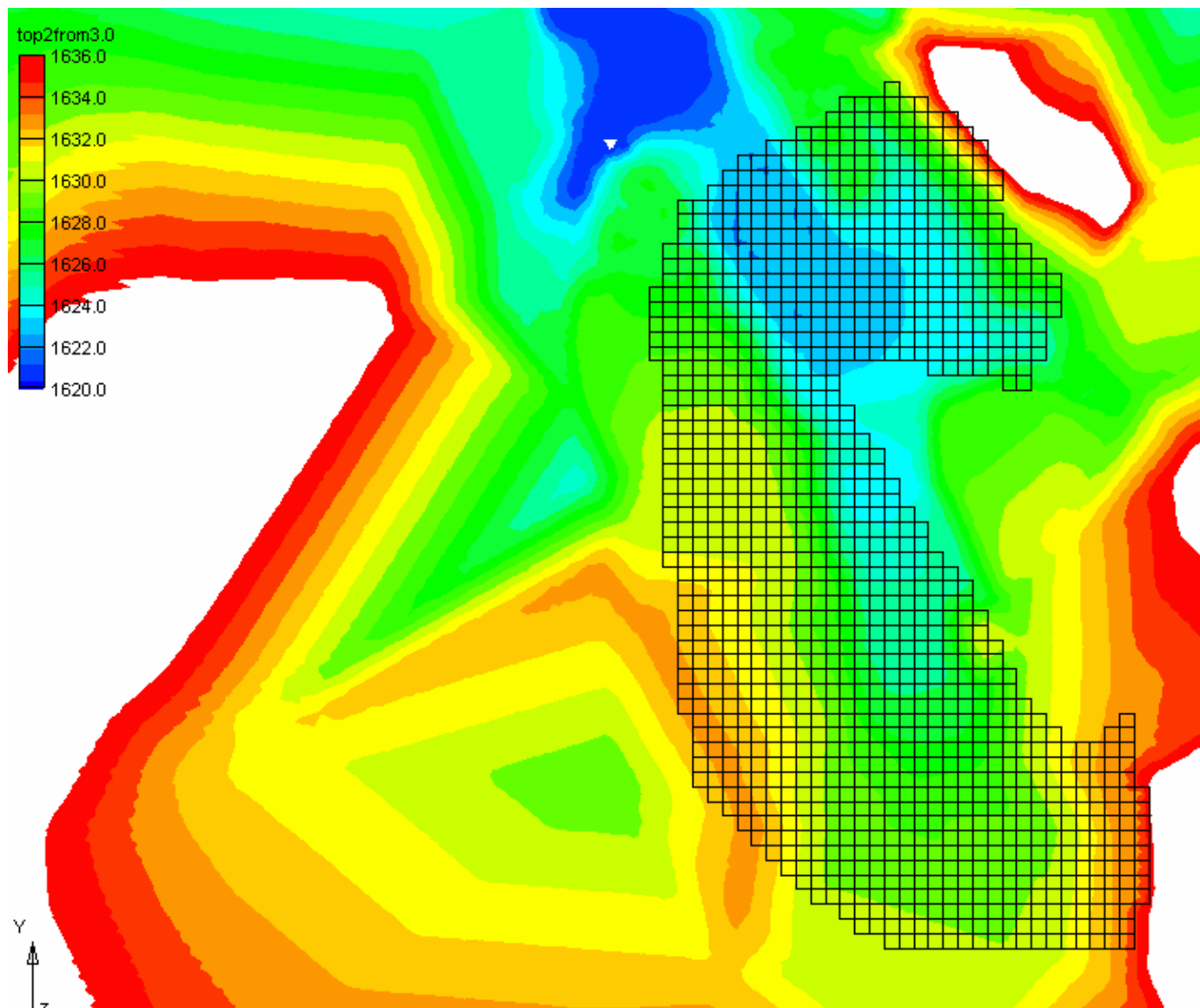


Figure 10
Elevation of the Top of Layer 2 in the Site Vicinity (m MSL)

SOUTH

NORTH

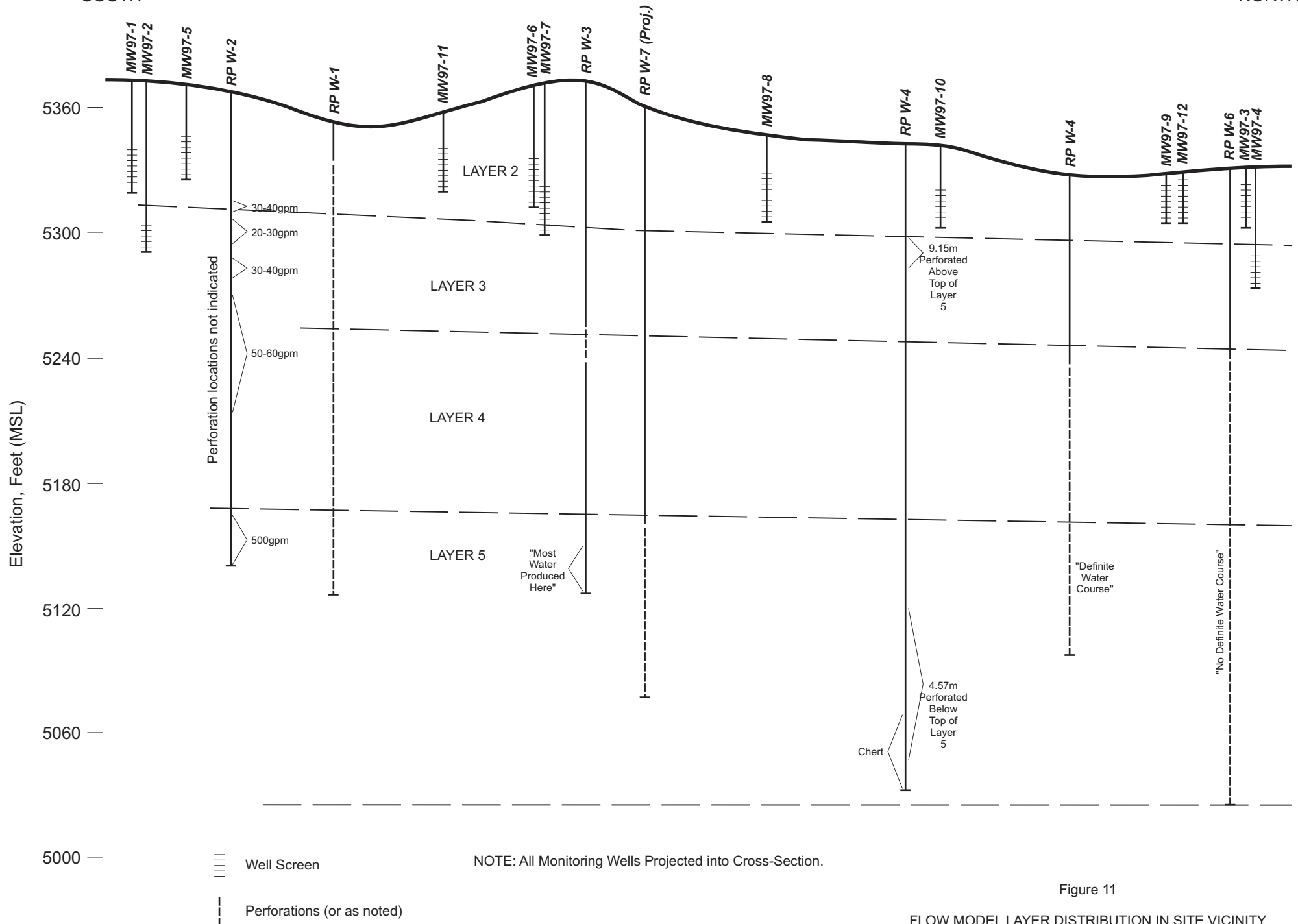


Figure 11

FLOW MODEL LAYER DISTRIBUTION IN SITE VICINITY

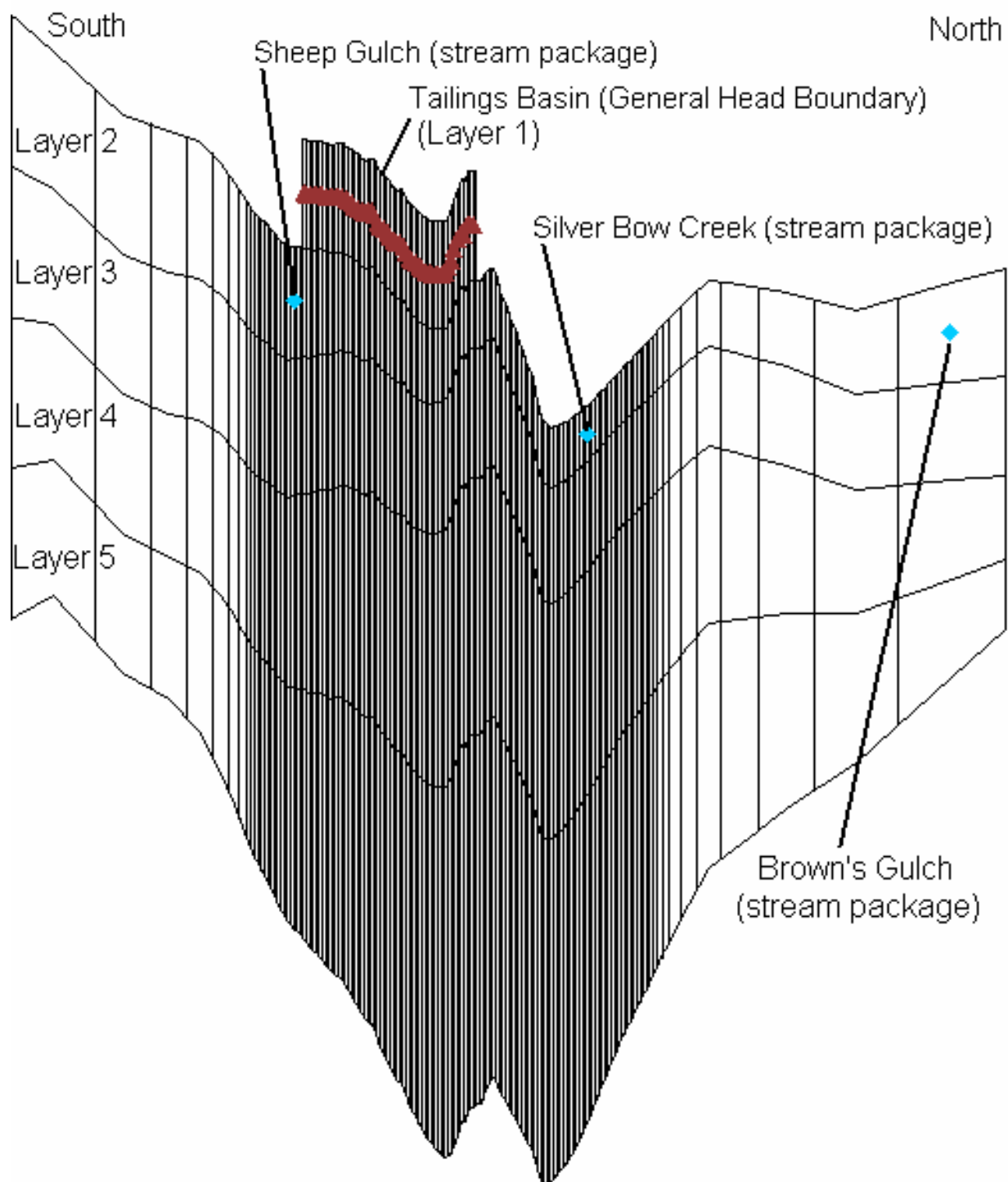


Figure 12
Cross-section of Part of the MODFLOW Grid Along Column 49

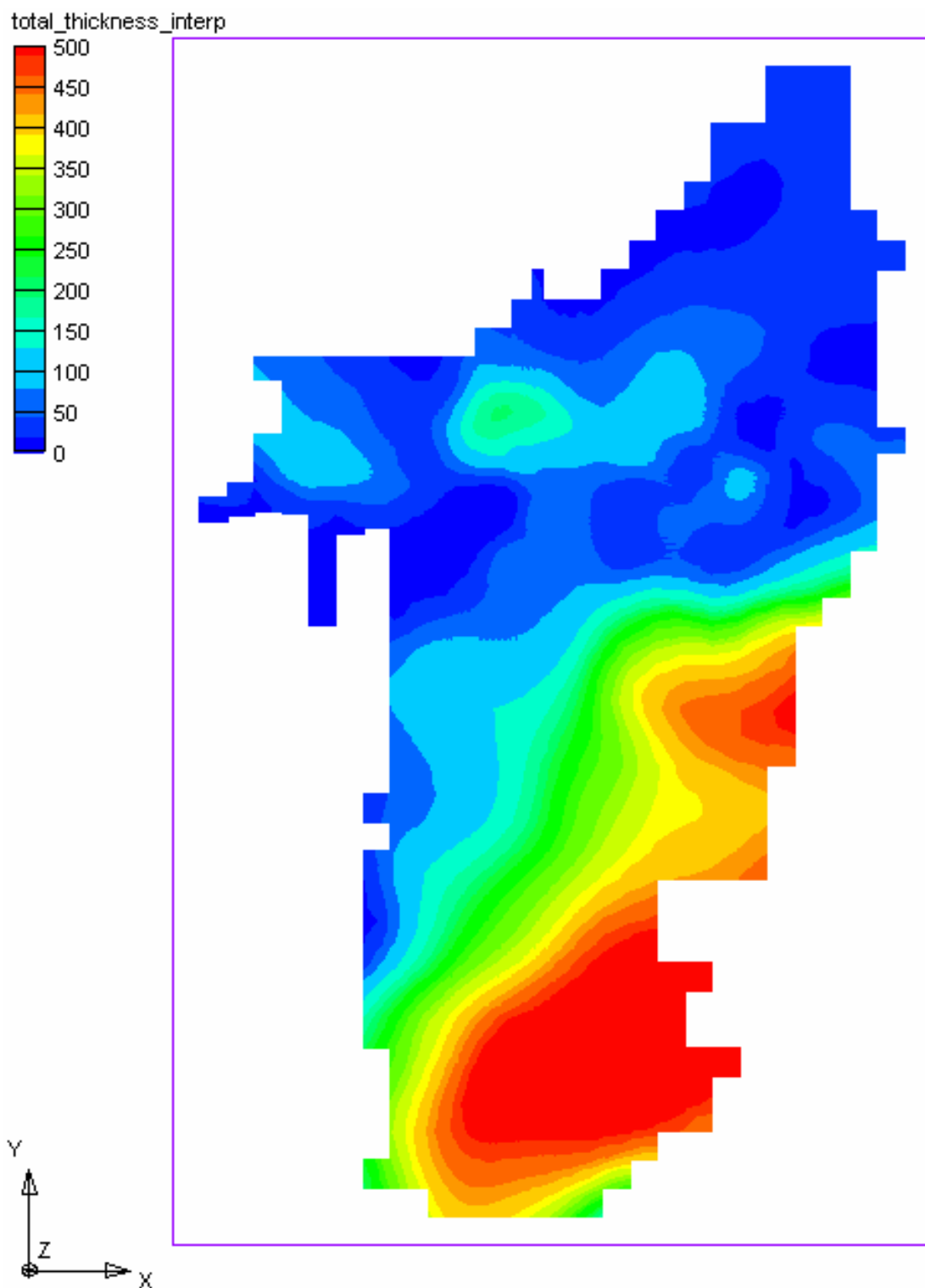


Figure 13

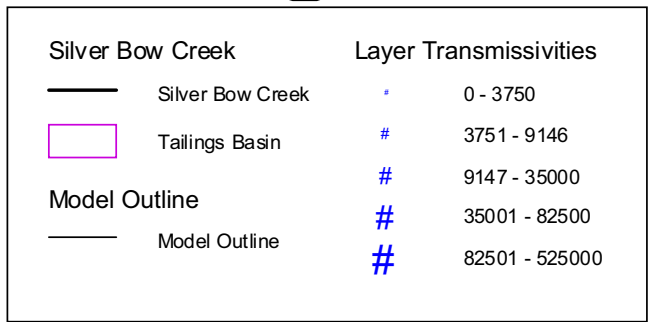
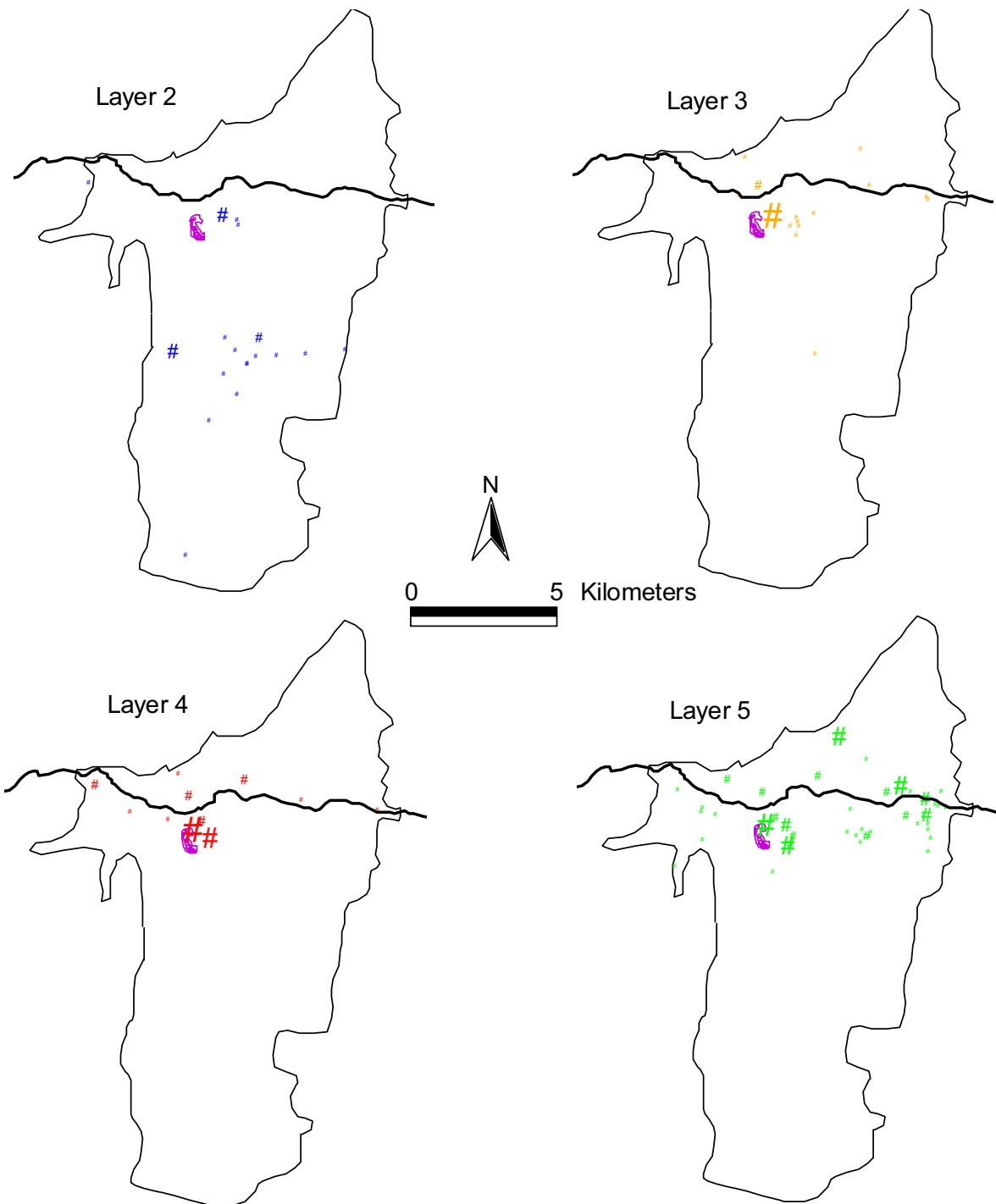


Figure 14
Distribution of Transmissivity Data by Layer
(gal/day/ft)

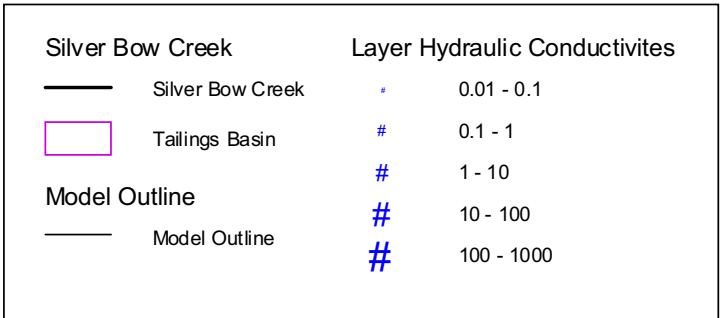
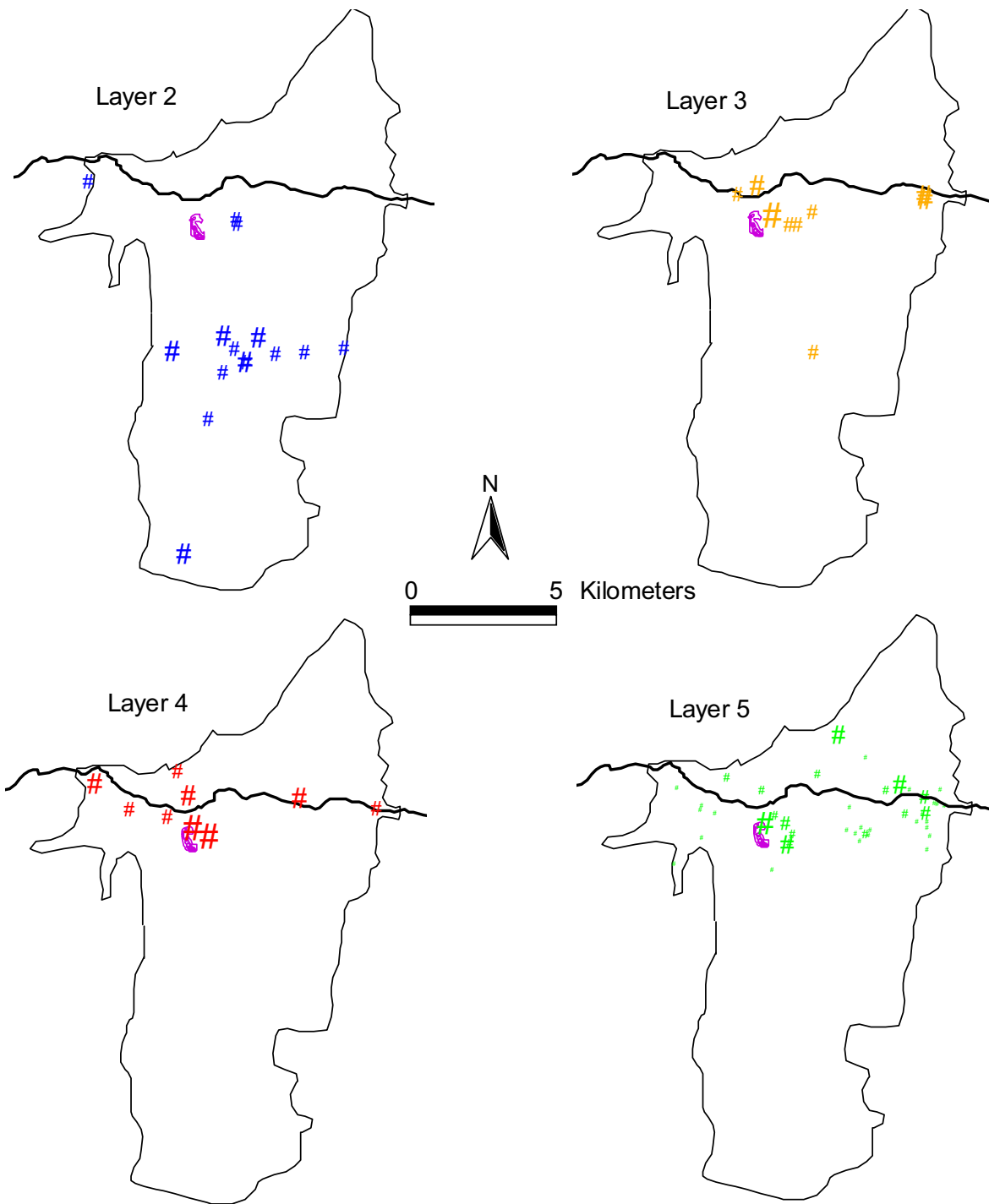
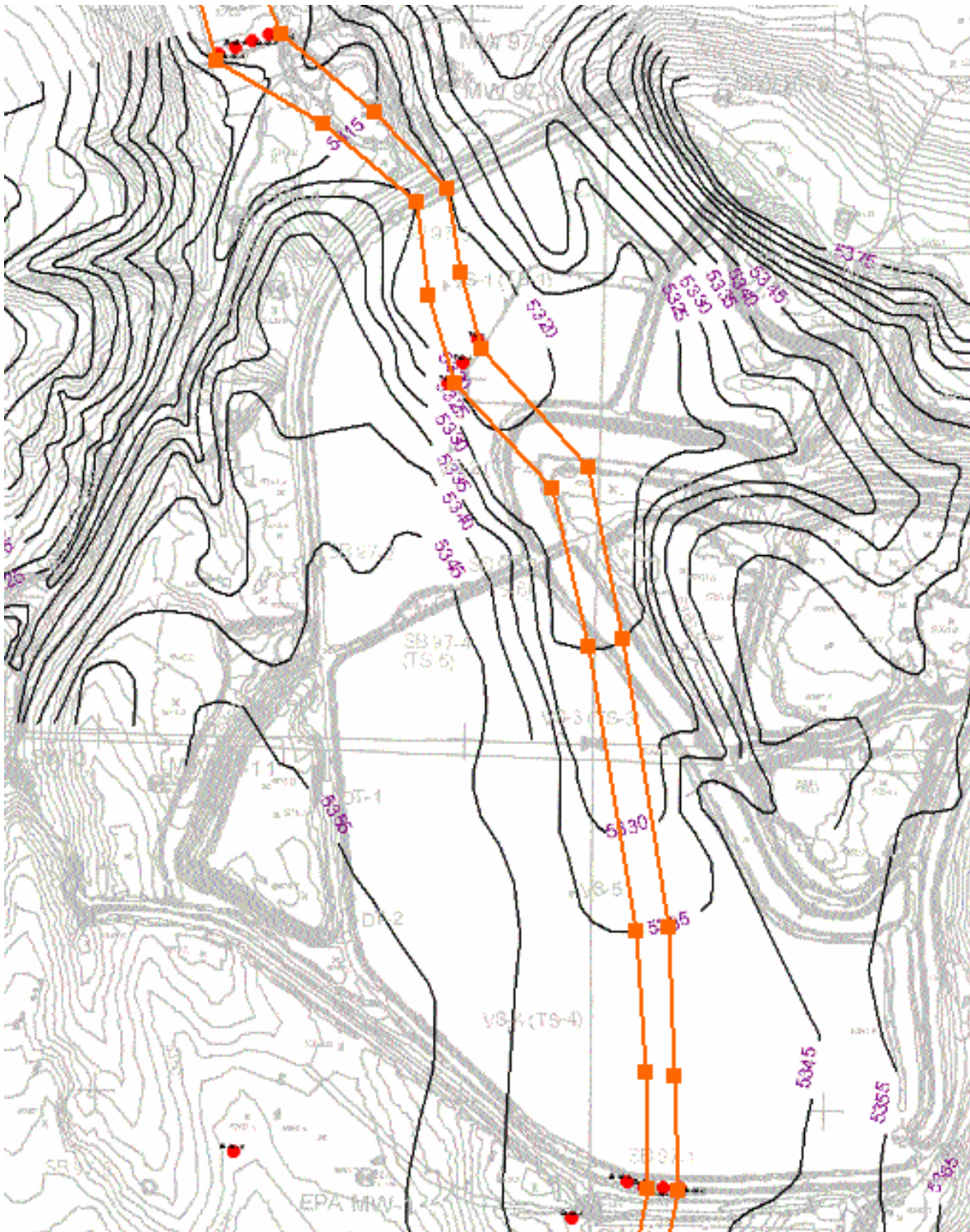
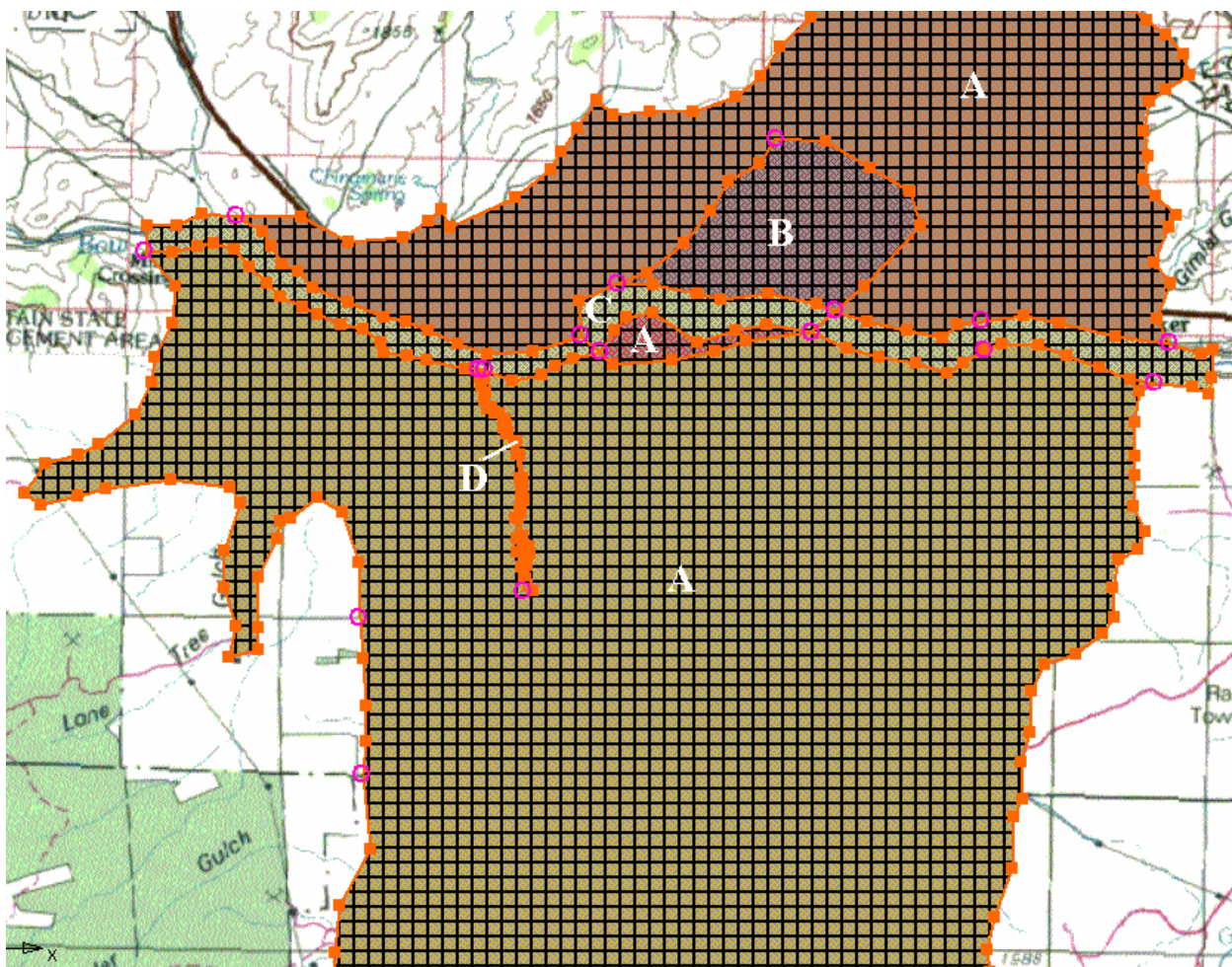


Figure 15
Distribution of Hydraulic Conductivity Data
by Layer (m/day)



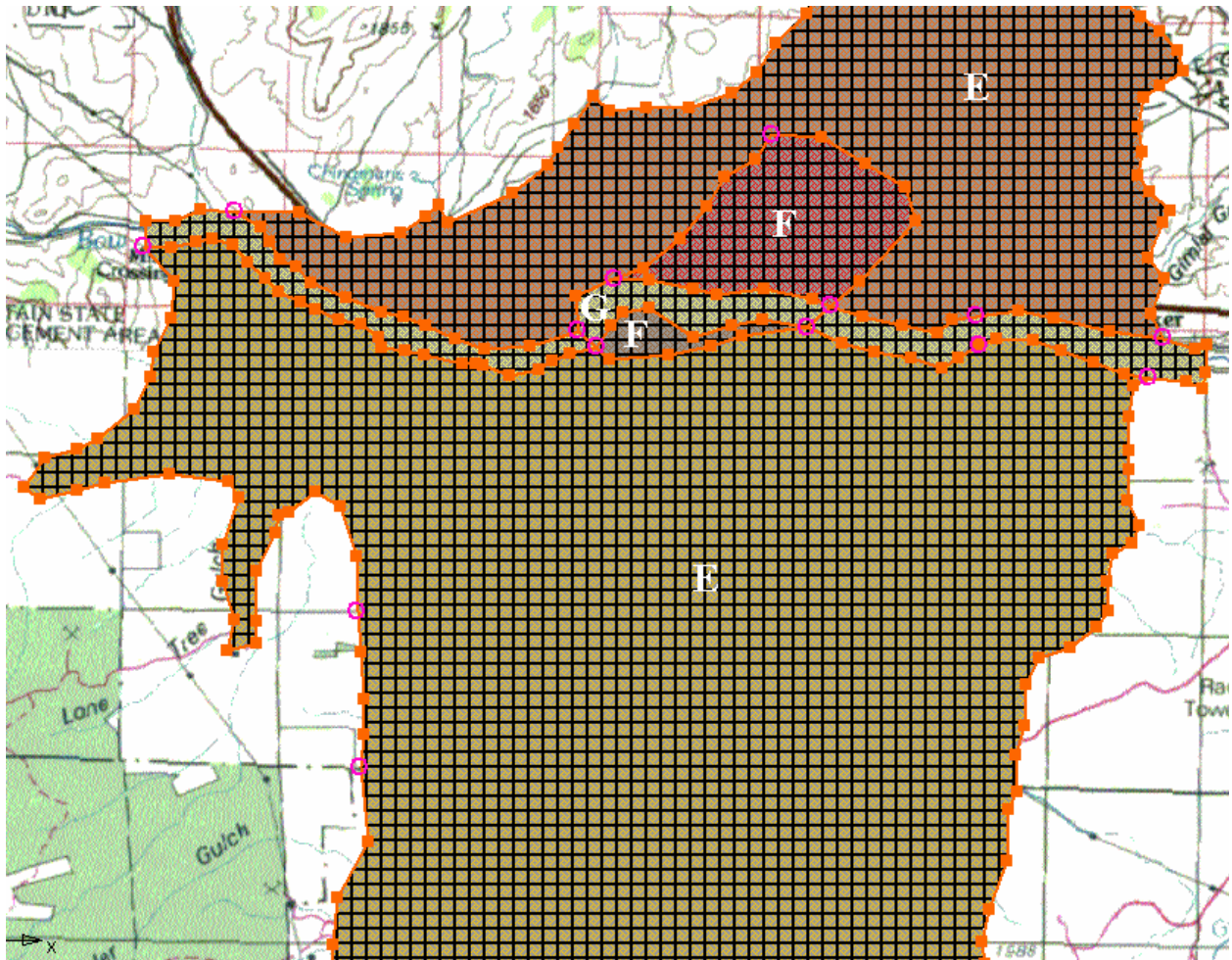


Values Used in the Flow Models

Zone	Parameter	Calibrated Model
Zone A	Hydraulic Conductivity	7.57 m/day
	Vertical Anisotropy	0.128
Zone B	Hydraulic Conductivity	1.11 m/day
	Vertical Anisotropy	0.128
Zone C	Hydraulic Conductivity	15.2 m/day
	Vertical Anisotropy	0.450
Zone D	Hydraulic Conductivity	17.8 m/day
	Vertical Anisotropy	0.450

Figure 17

Hydraulic Conductivity/Vertical Anisotropy Zones in Layer 2

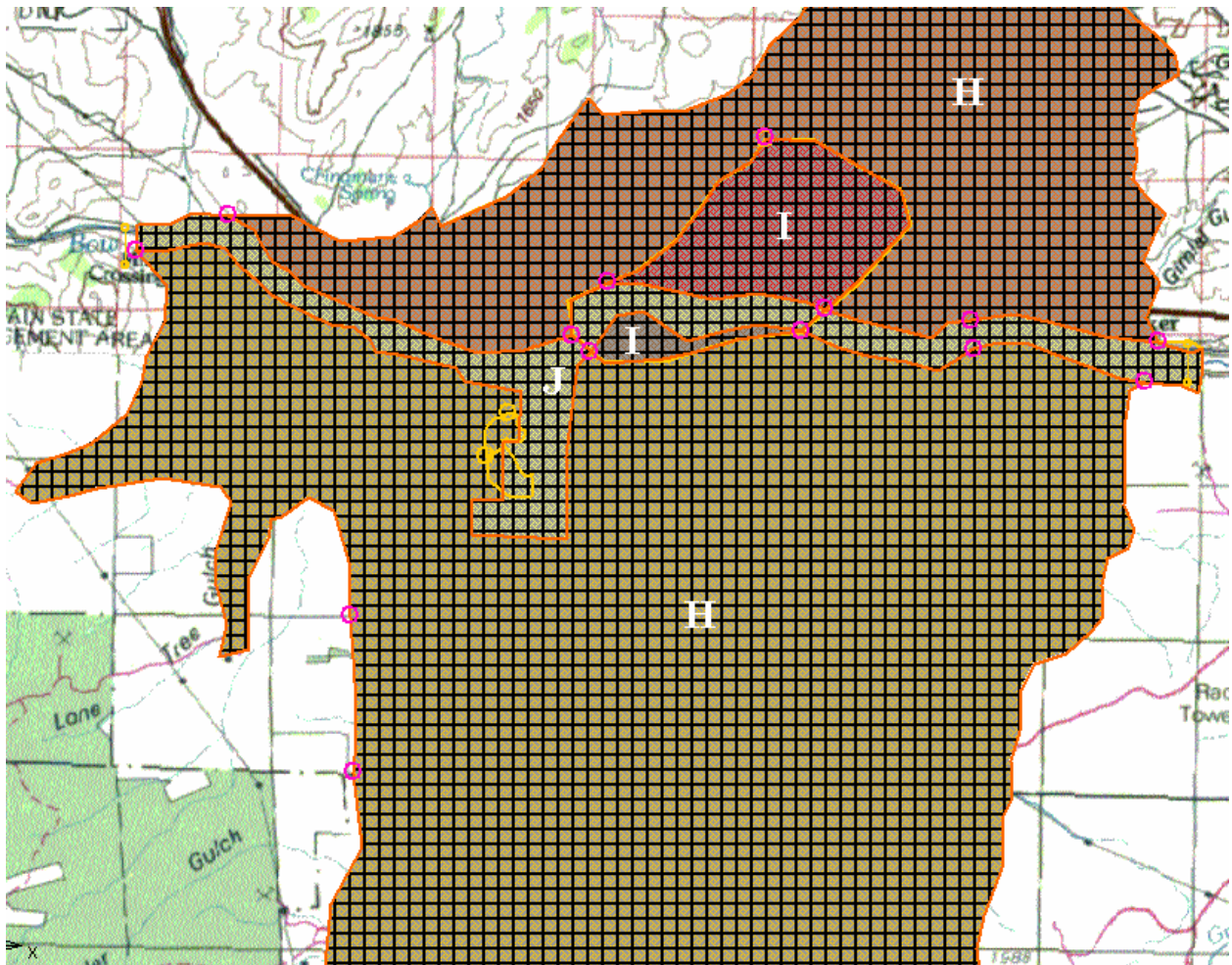


Values Used in the Flow Models

Zone	Parameter	Calibrated Model
Zone E	Hydraulic Conductivity	0.305 m/day
	Vertical Anisotropy	0.128
Zone F	Hydraulic Conductivity	1.11 m/day
	Vertical Anisotropy	0.128
Zone G	Hydraulic Conductivity	15.2 m/day
	Vertical Anisotropy	0.450

Figure 18

Hydraulic Conductivity/Vertical Anisotropy Zones in Layers 3 and 4



Values Used in the Flow Models

Zone	Parameter	Calibrated Model
Zone H	Hydraulic Conductivity	0.305 m/day
	Vertical Anisotropy	0.128
Zone I	Hydraulic Conductivity	1.11 m/day
	Vertical Anisotropy	0.128
Zone J	Hydraulic Conductivity	32.1 m/day
	Vertical Anisotropy	0.450

Figure 19
Hydraulic Conductivity/Vertical Anisotropy Zones in Layer 5

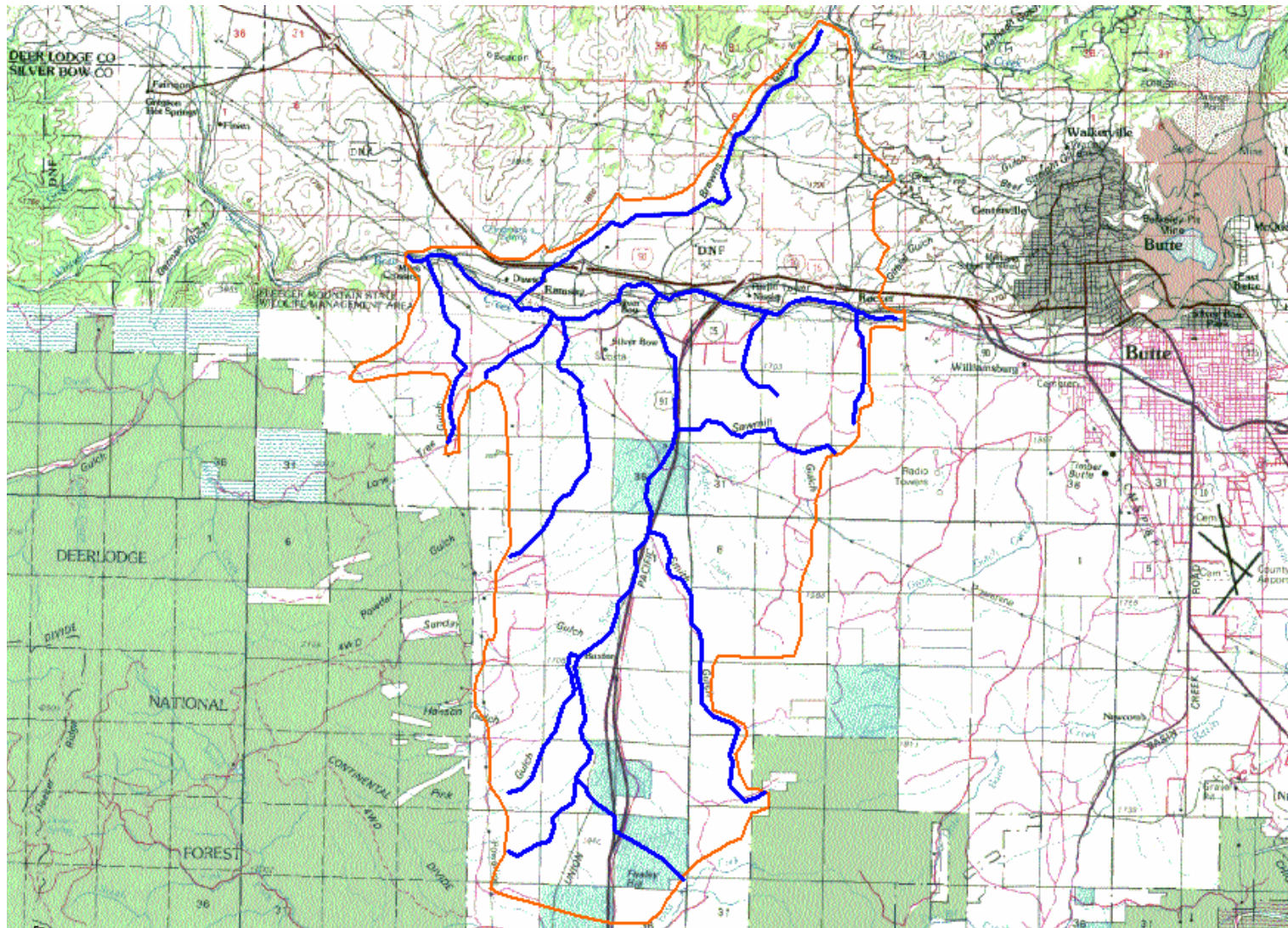


Figure 20
Streams Simulated in the MODFLOW Model

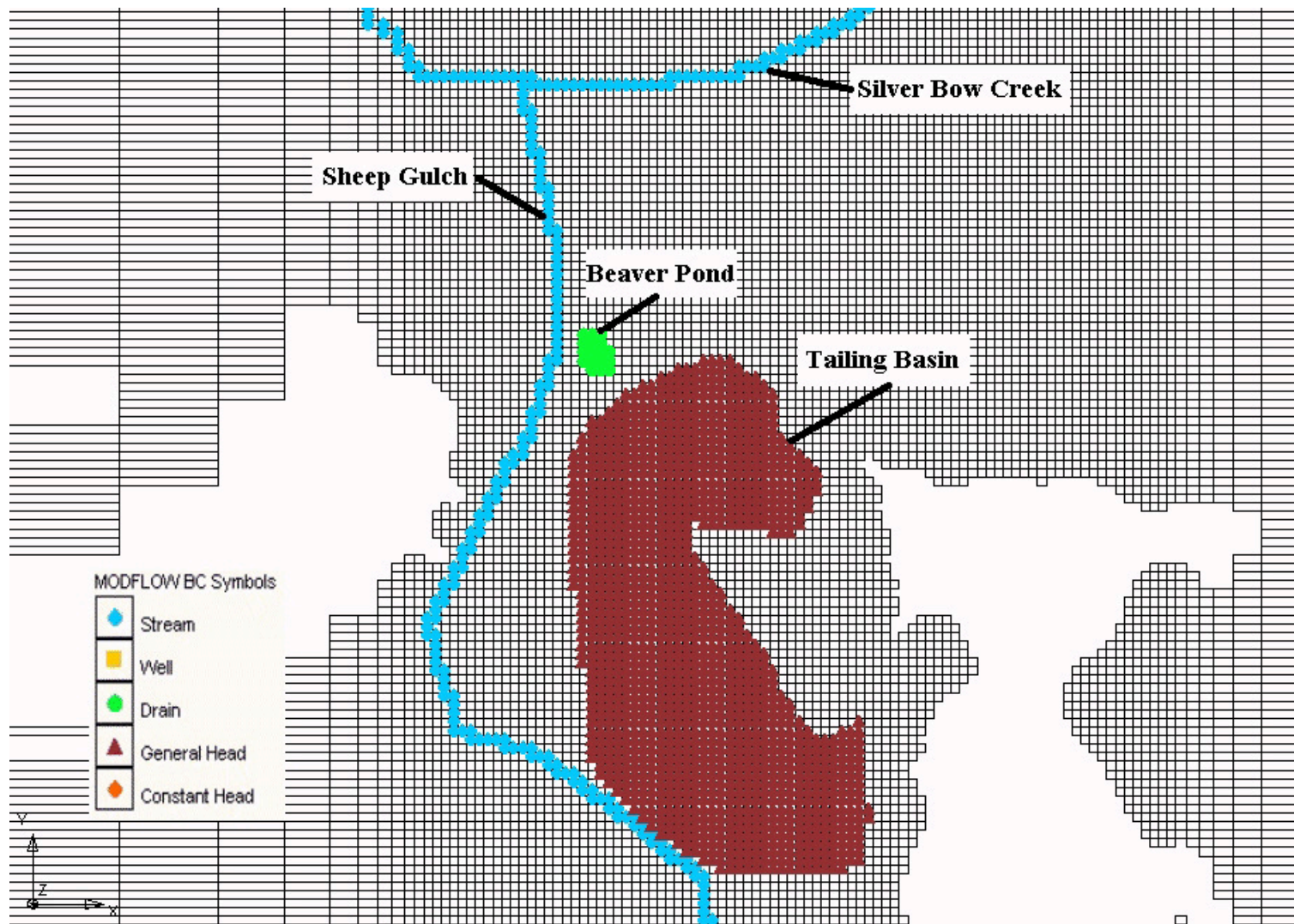


Figure 21

General Head Boundaries and Drains Simulated in the MODFLOW Model

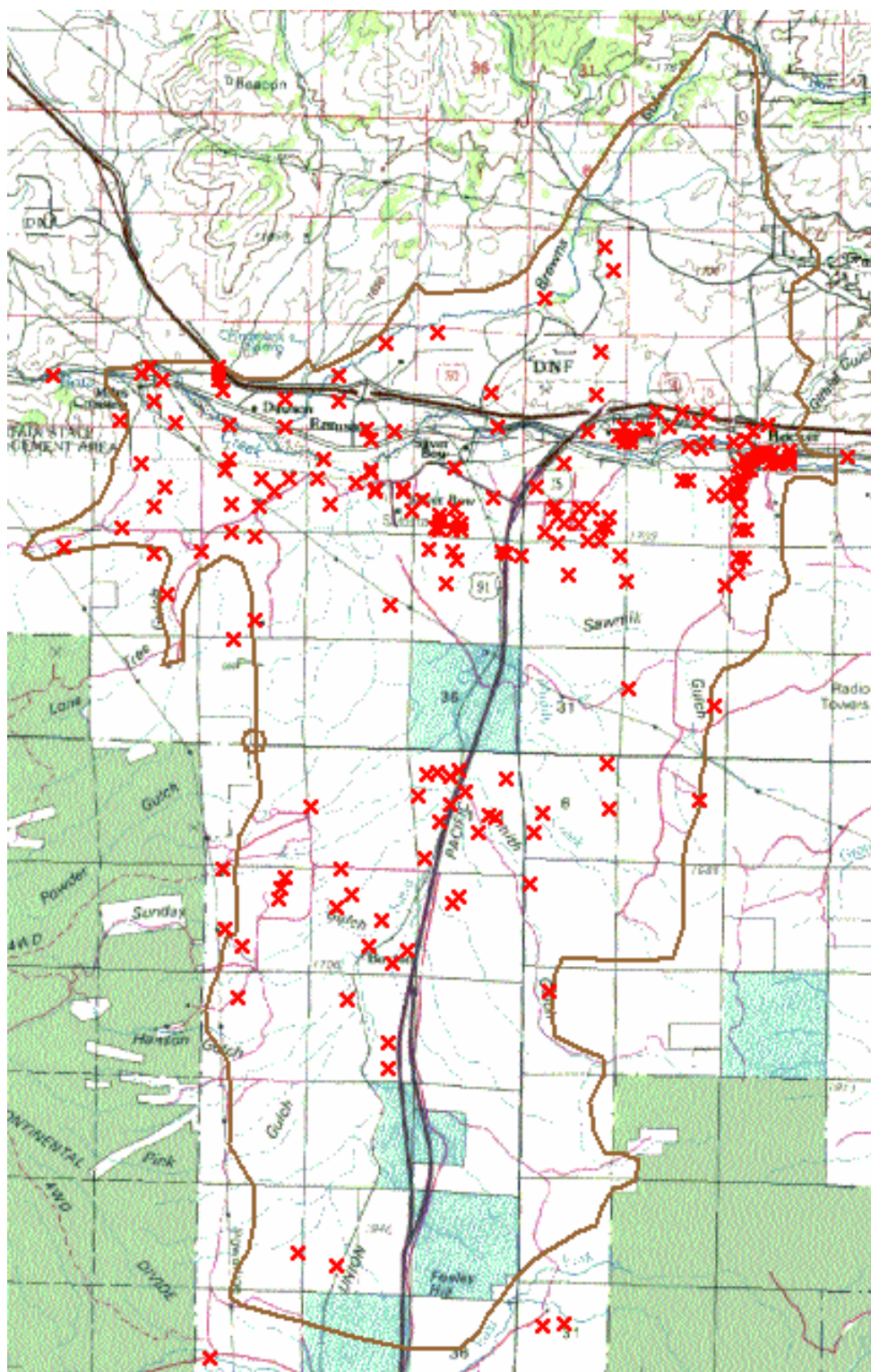


Figure 22
Distribution of Pumping Wells from the MBMG Database

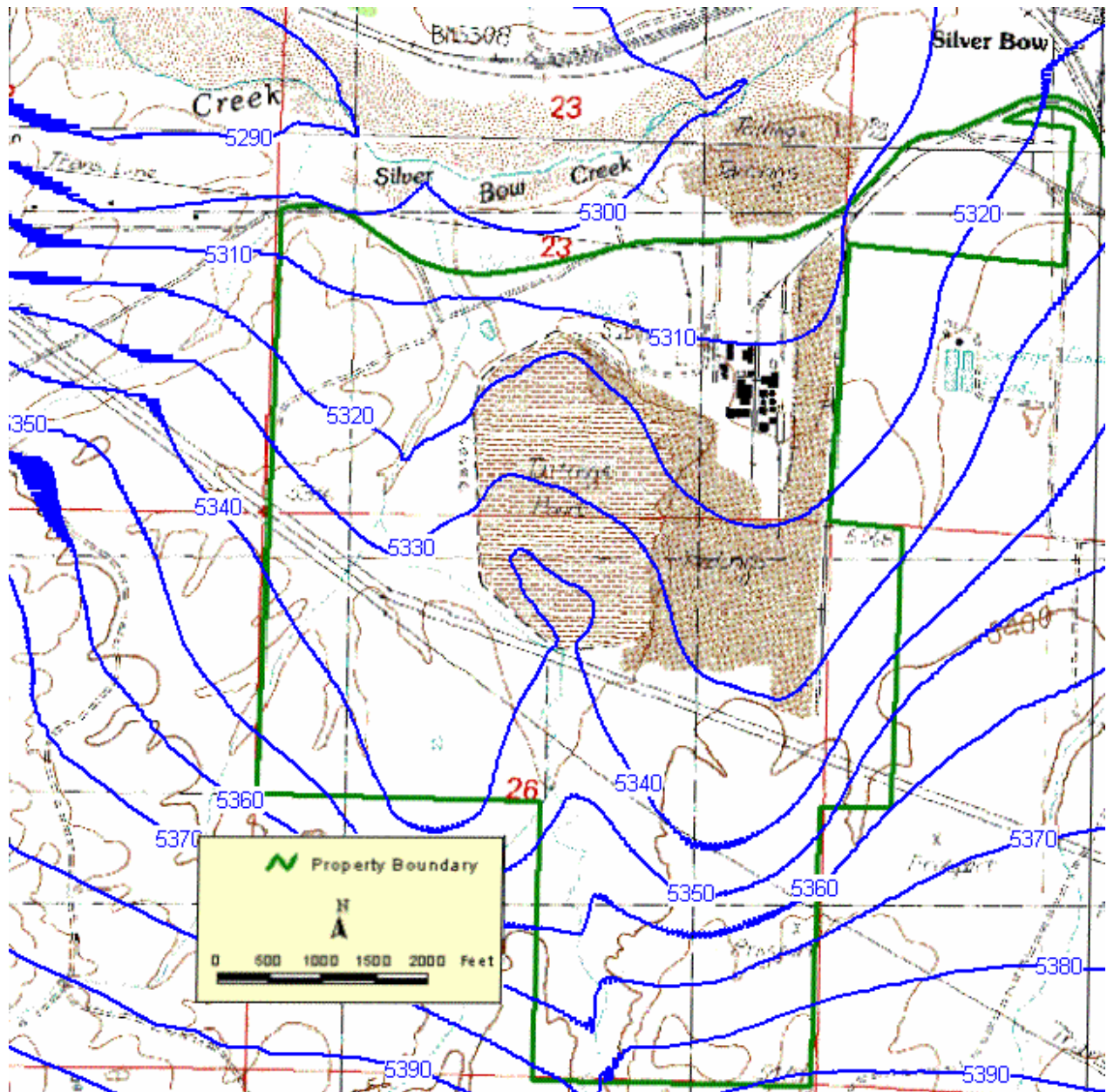


Figure 23
Simulated Water Levels in Layer 2 of the Calibrated Model (ft MSL)

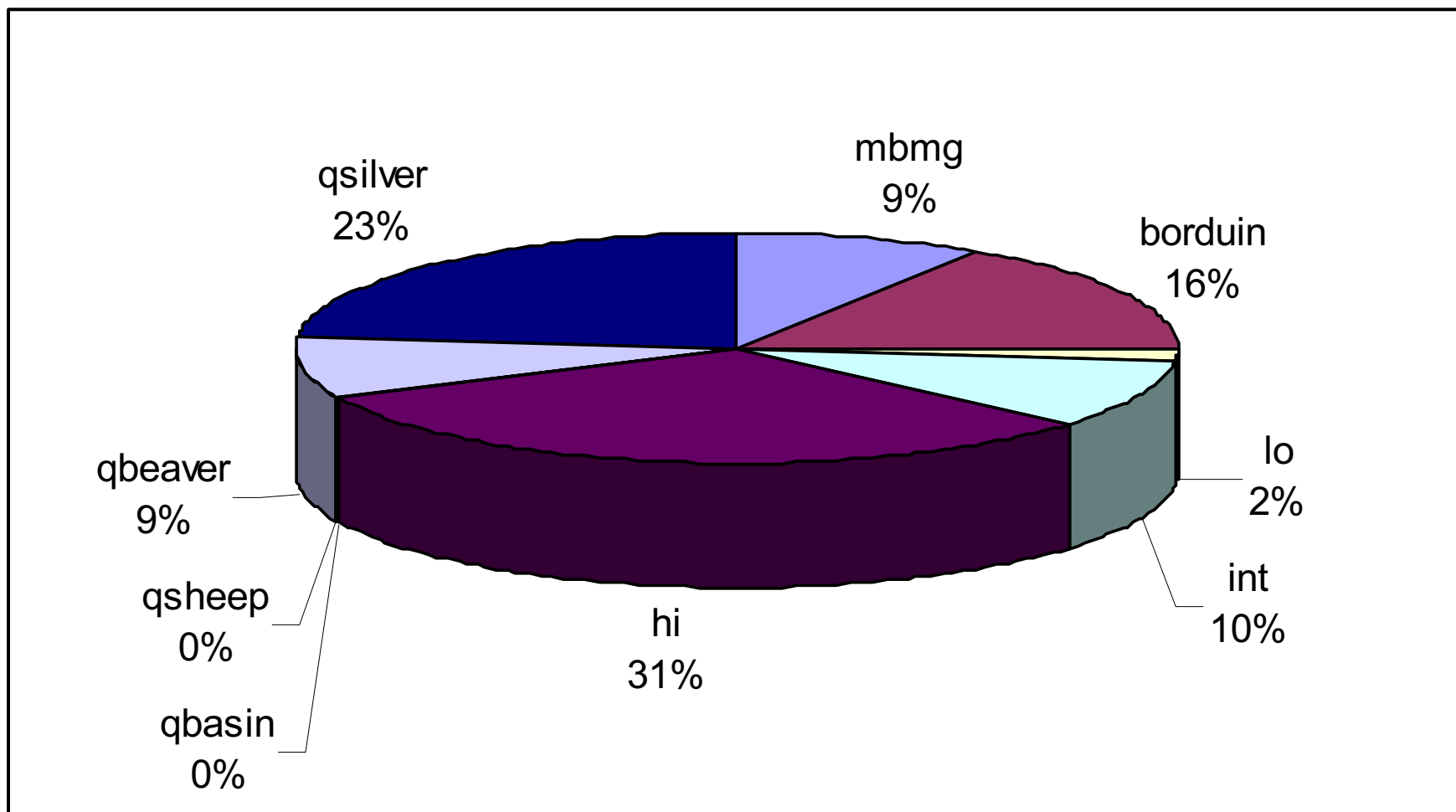


Figure 24
Composition of the Objective Function for the Calibrated Model

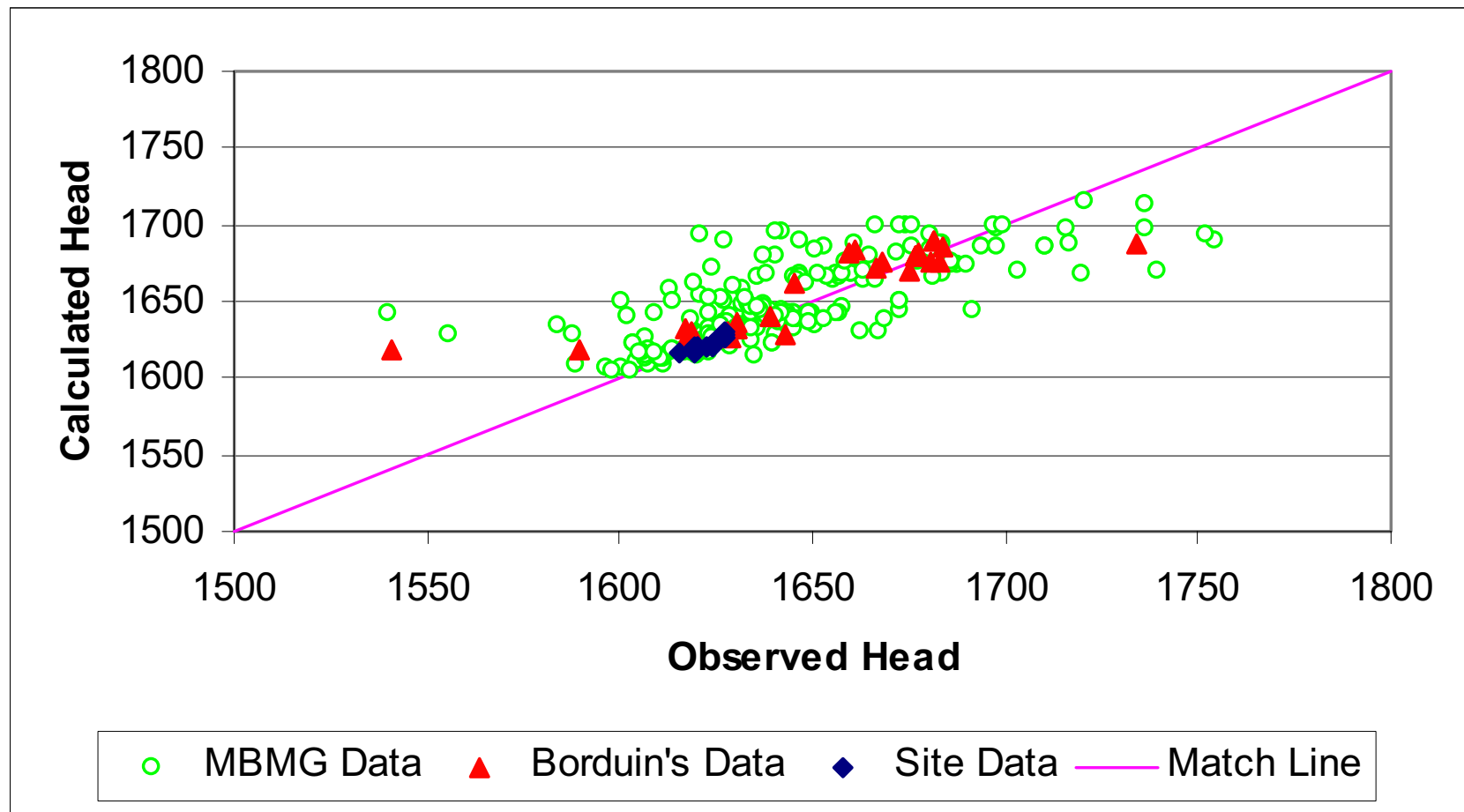


Figure 25
Hydraulic Head Calibration Results (m MSL)

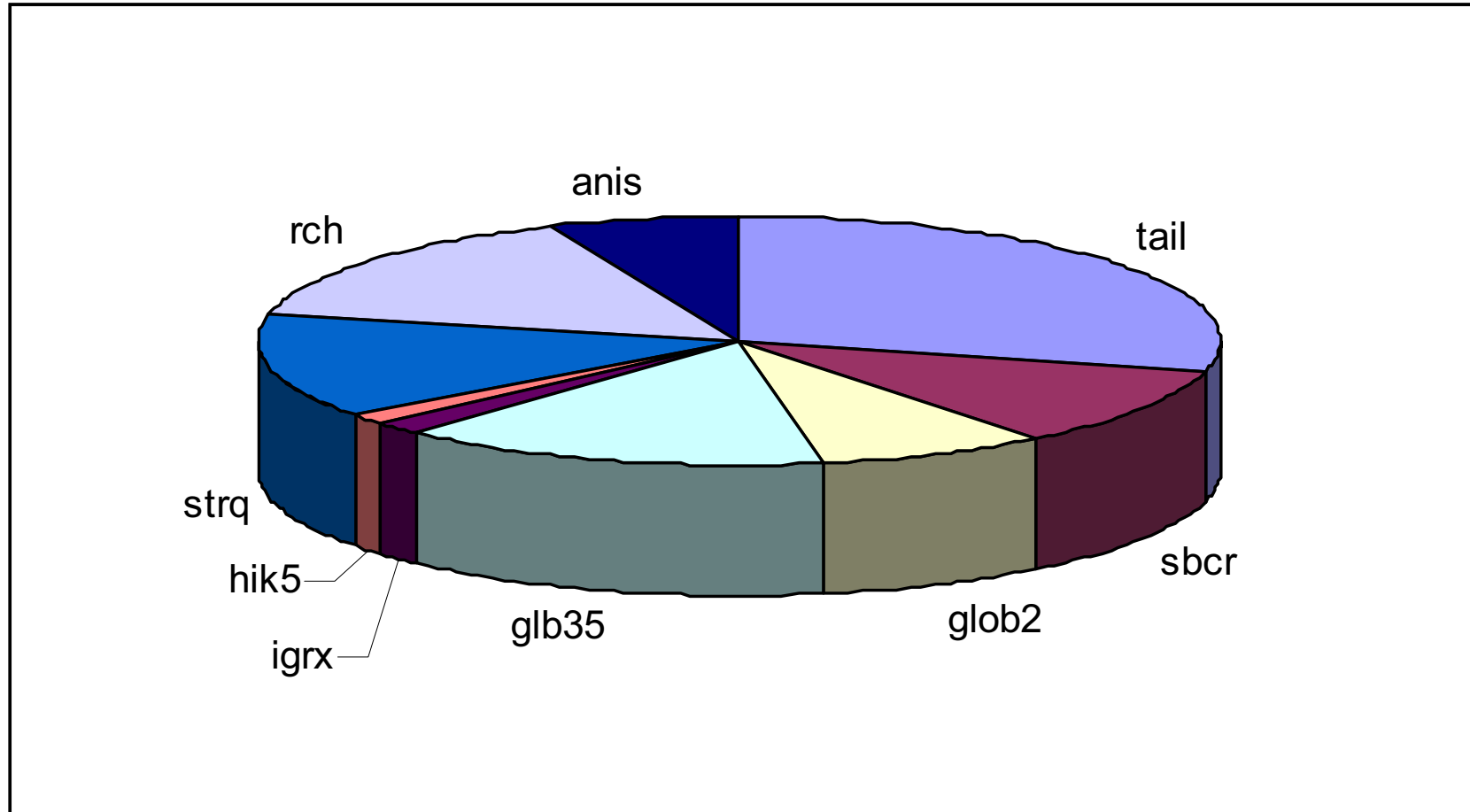


Figure 26
Distribution of Parameter Sensitivities for a Preliminary Calibration

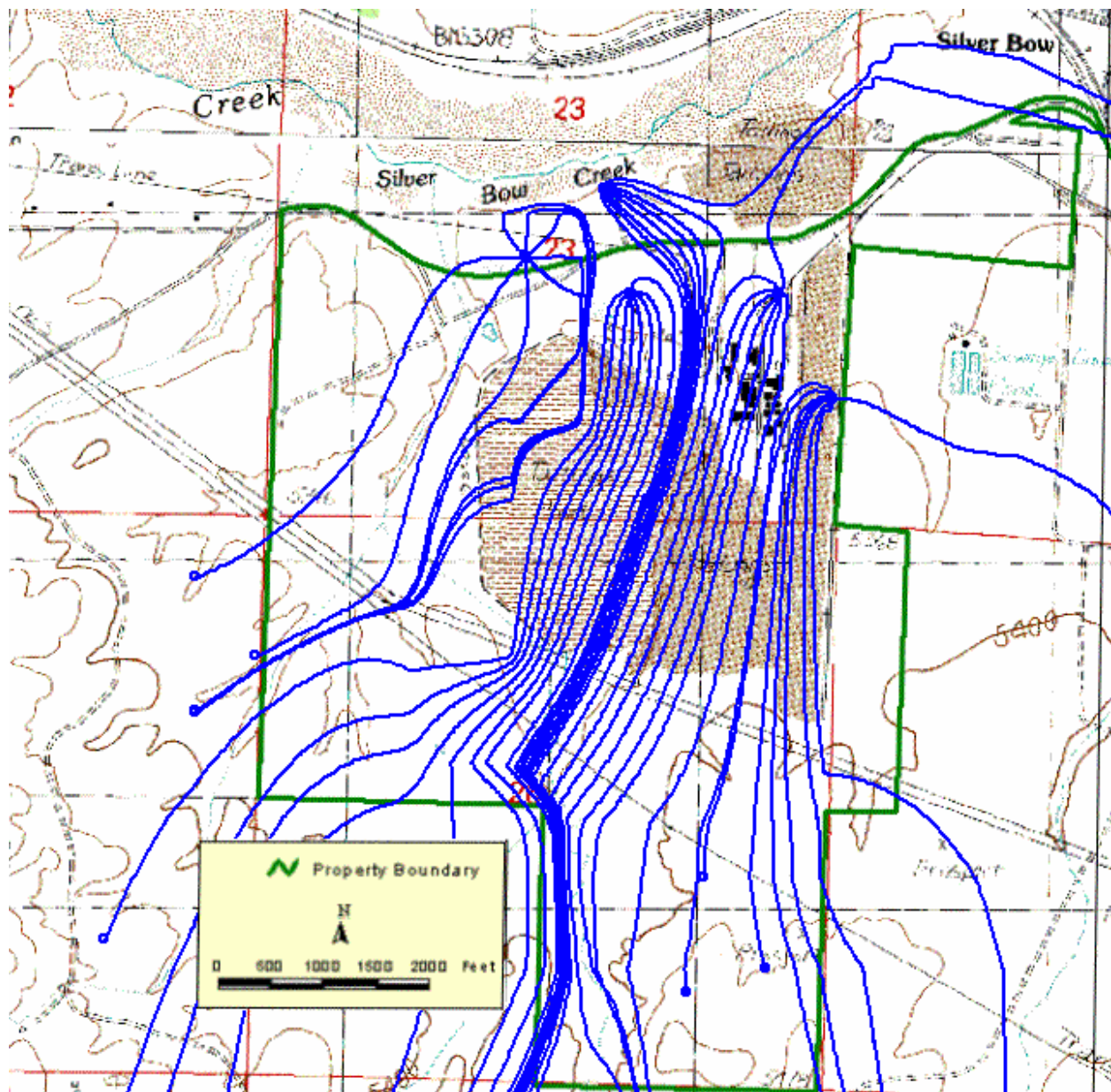
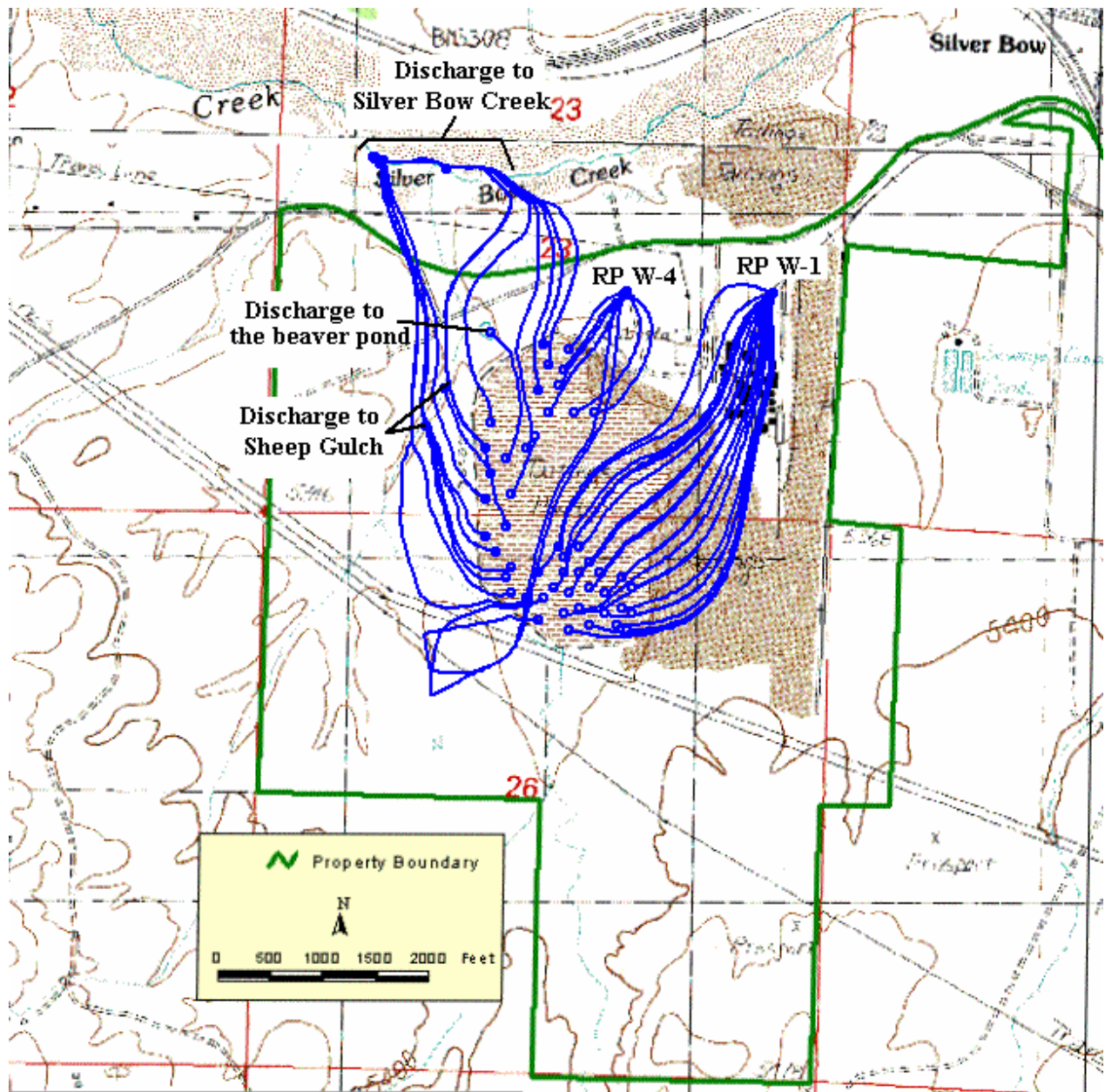


Figure 27

Capture Zones for the Silver Bow Plant Production Wells (Backward Traces in Model Layer 5)



Note: Wells RP W-1 and RP W-4 withdraw water primarily from Layer 5 of the model.

Figure 28

Forward Traces from the Tailing Basin (Layer 1) in the Historical Loading Scenario

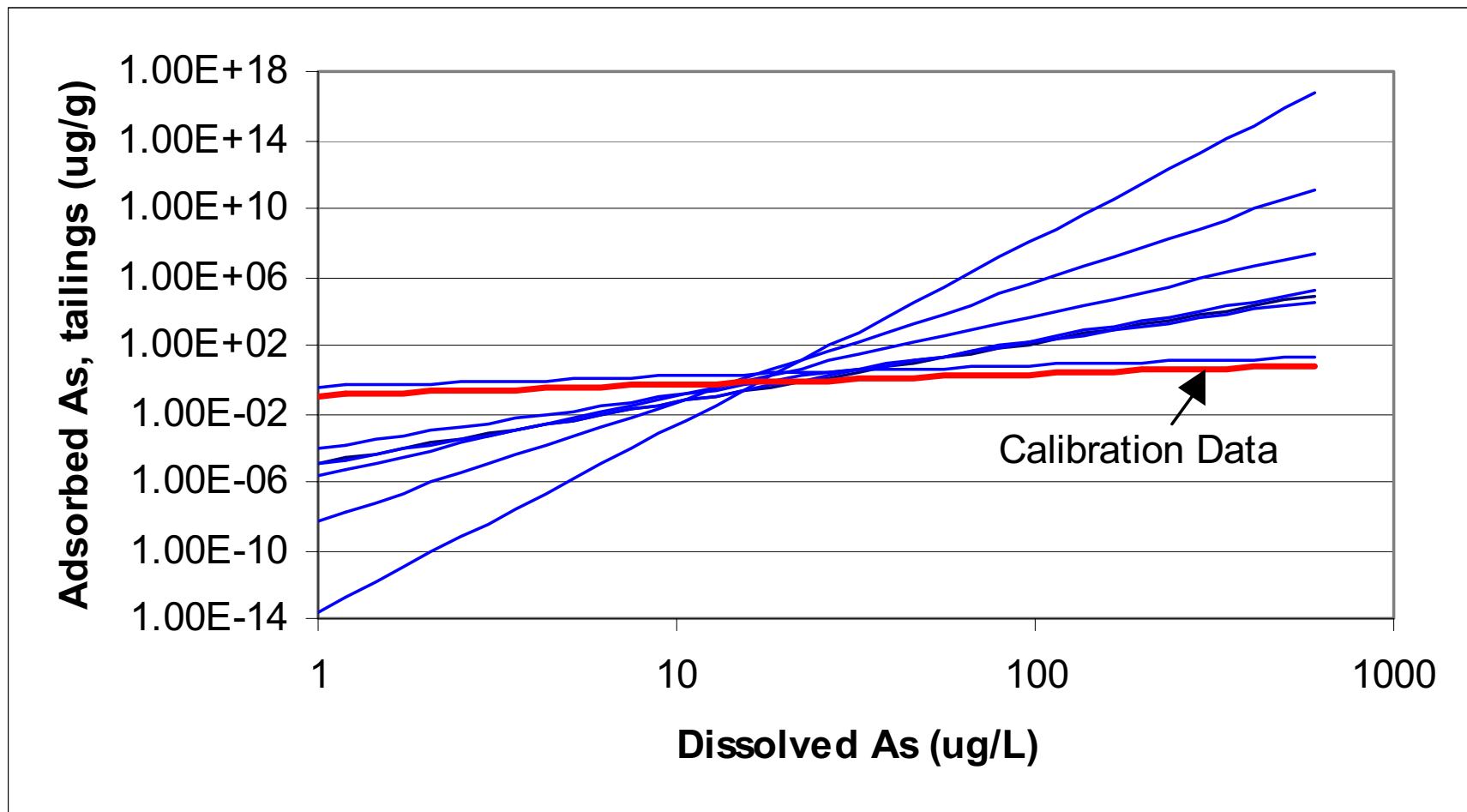


Figure 29
Freundlich Isotherms for the Tailings Material

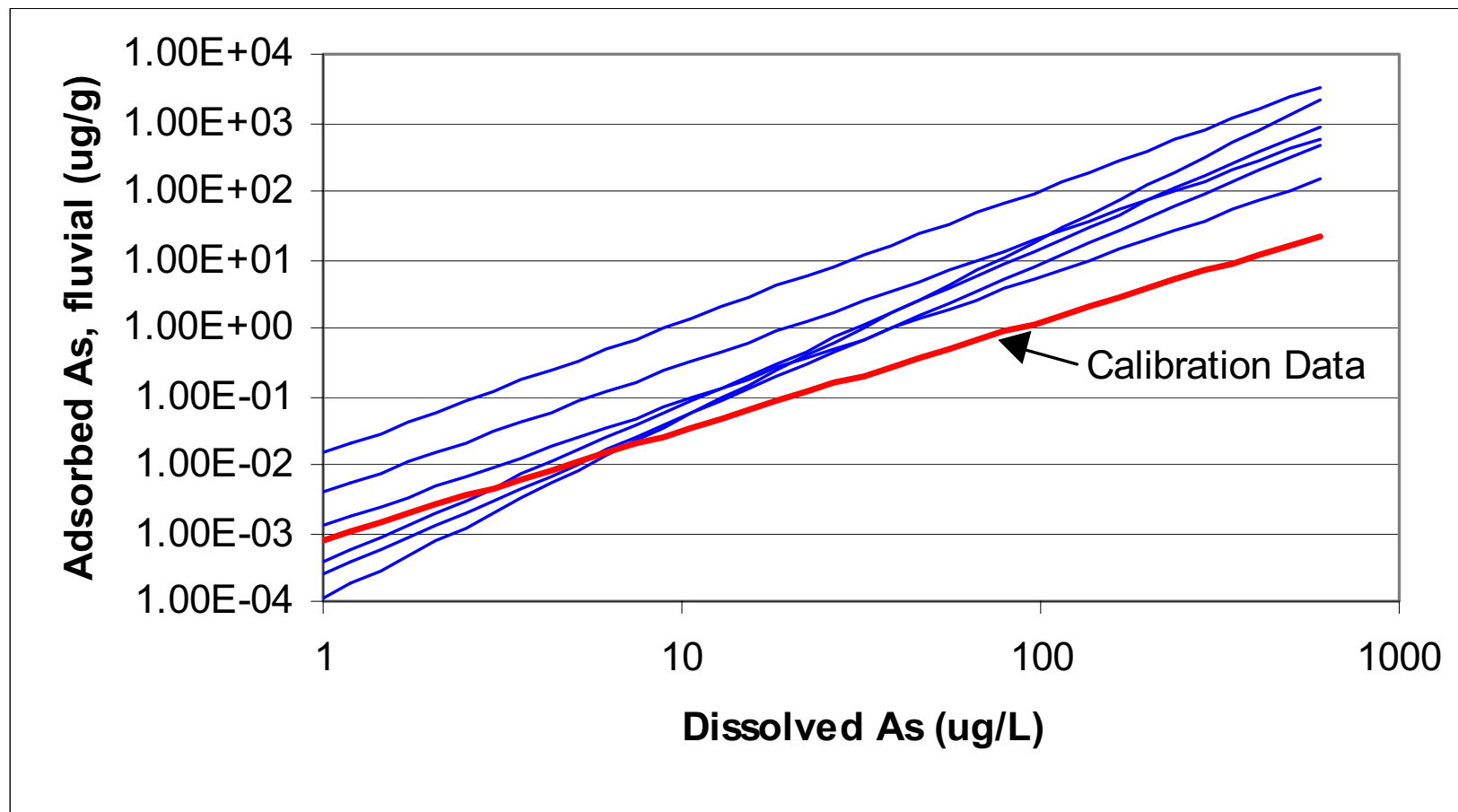


Figure 30
Freundlich Isotherms for the Fluvial Material

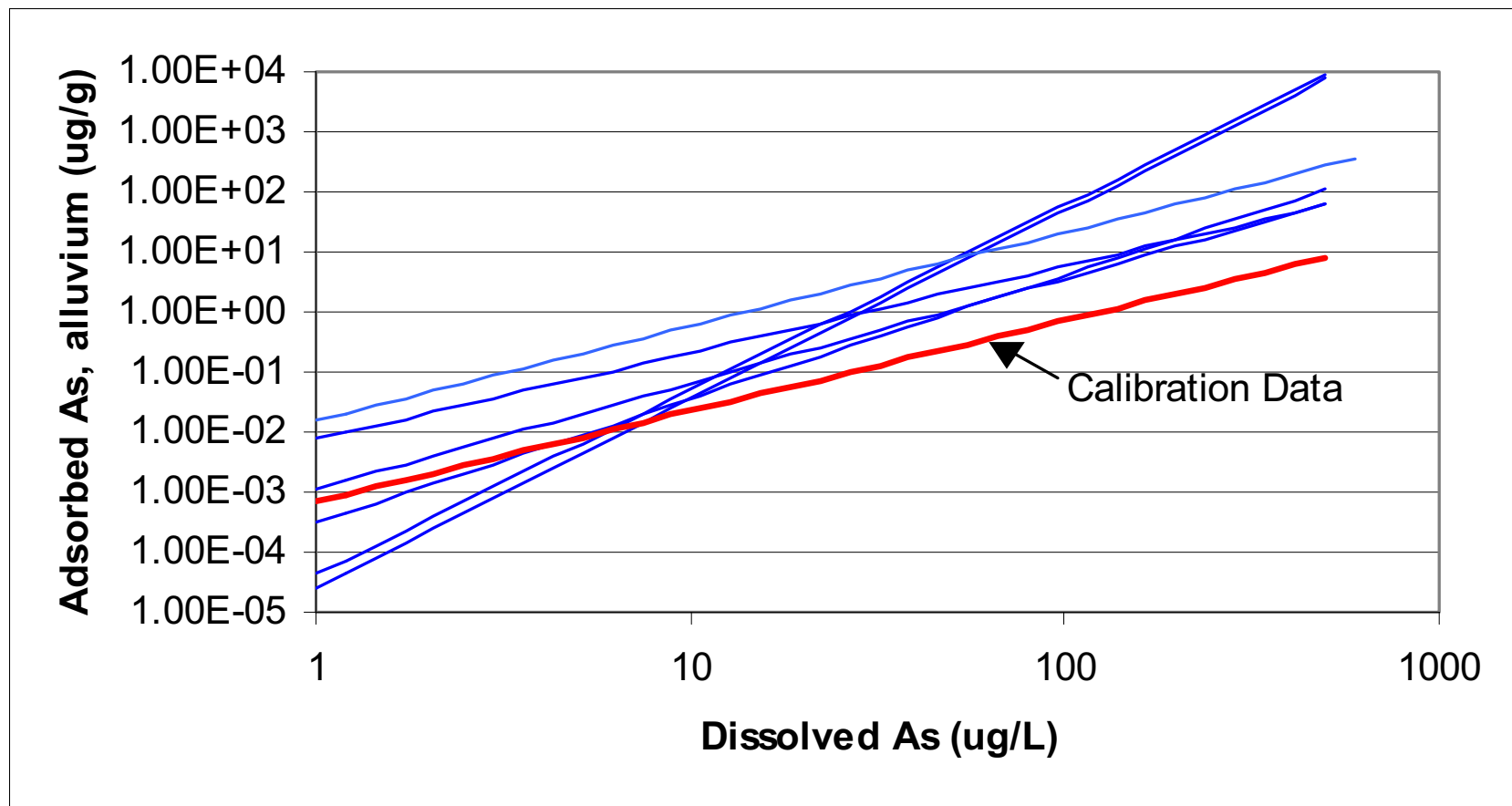


Figure 31
Freundlich Isotherms for the Alluvial Material

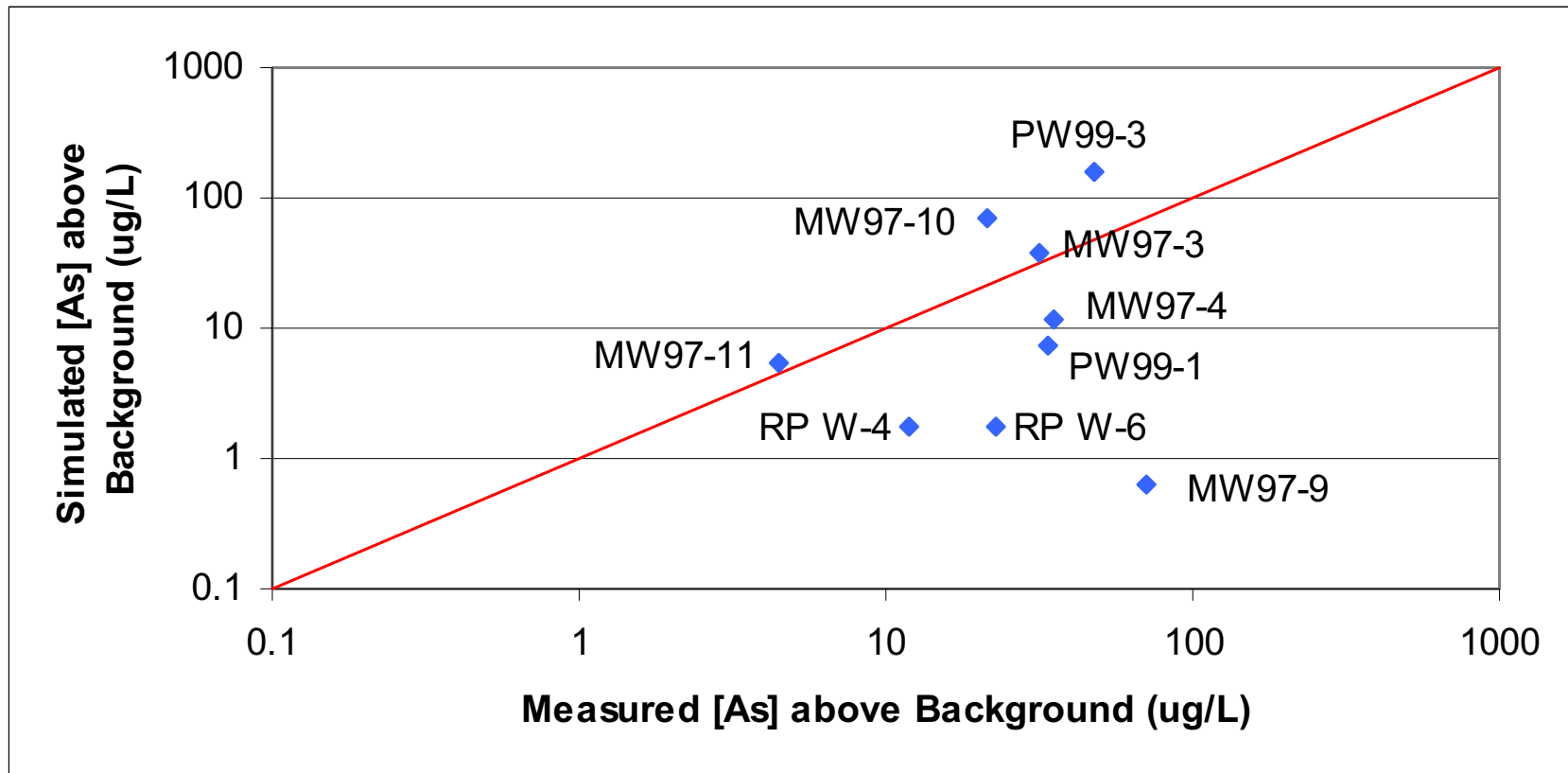


Figure 32
Measured Versus Simulated Arsenic Concentration from the Calibrated Transport Model

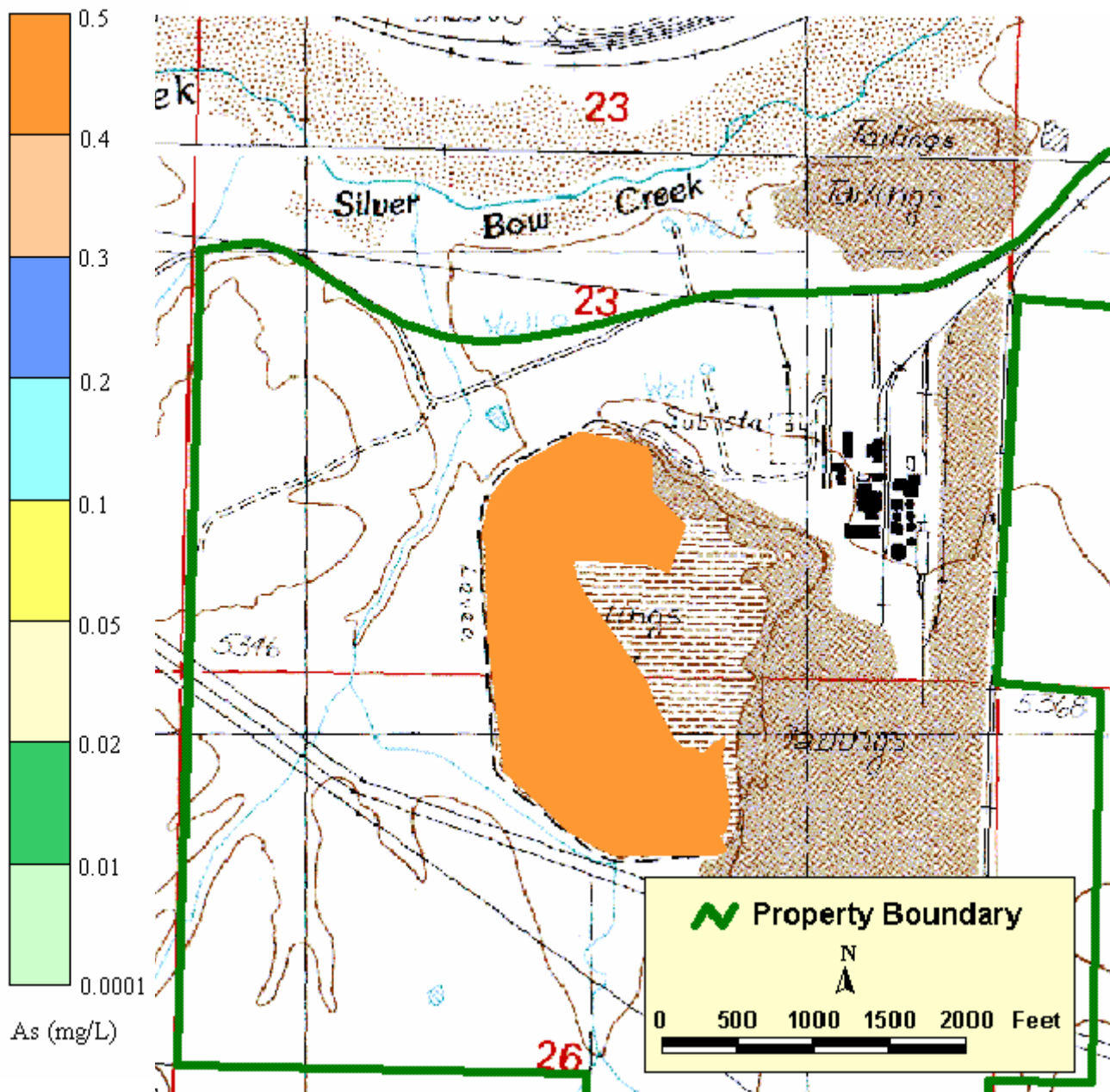


Figure 33

Simulated Arsenic Concentrations Above Background in Layer 1 as of 1999 (Tailings)

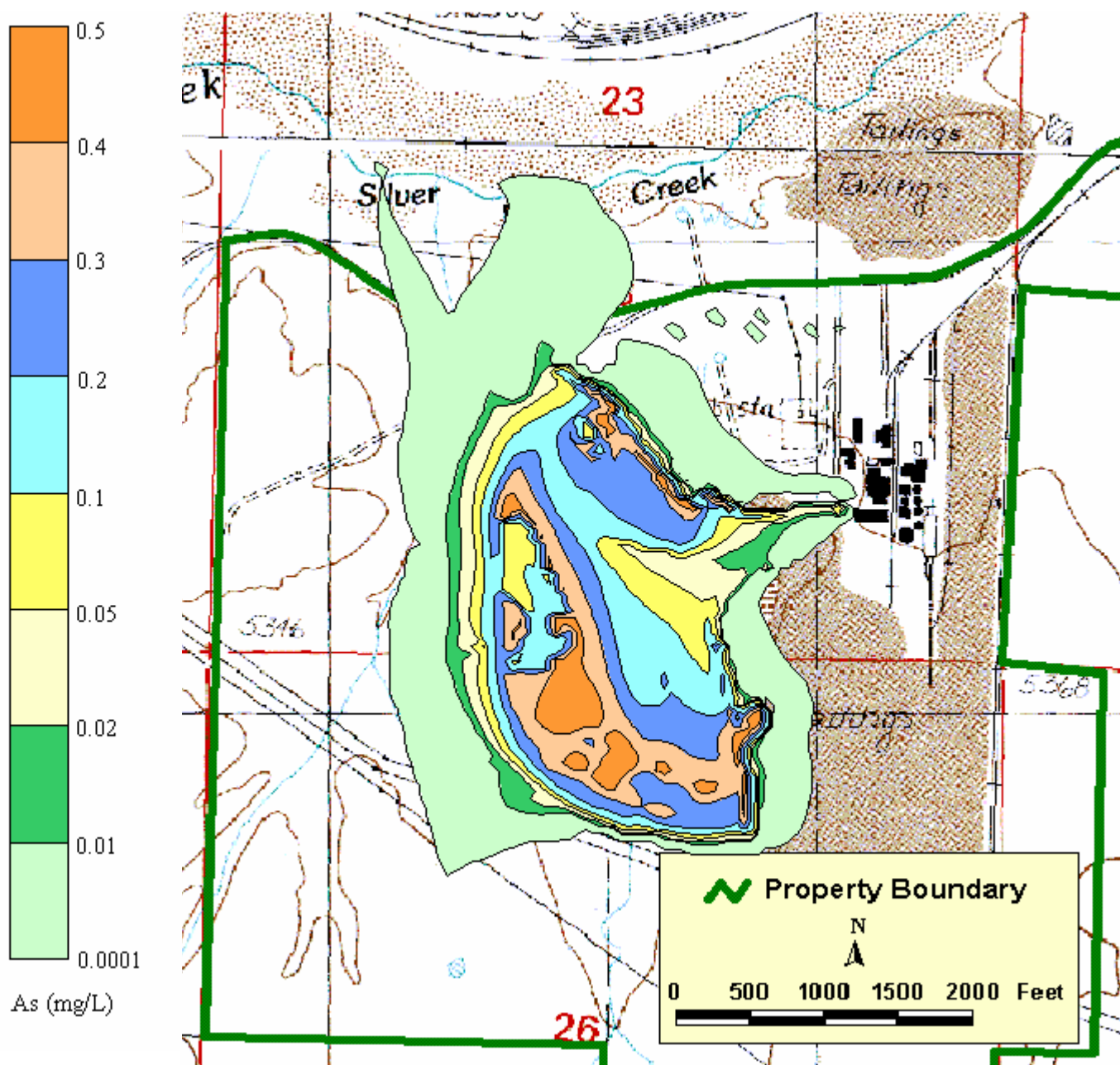


Figure 34
 Simulated Arsenic Concentrations Above Background in Layer 2 as of 1999

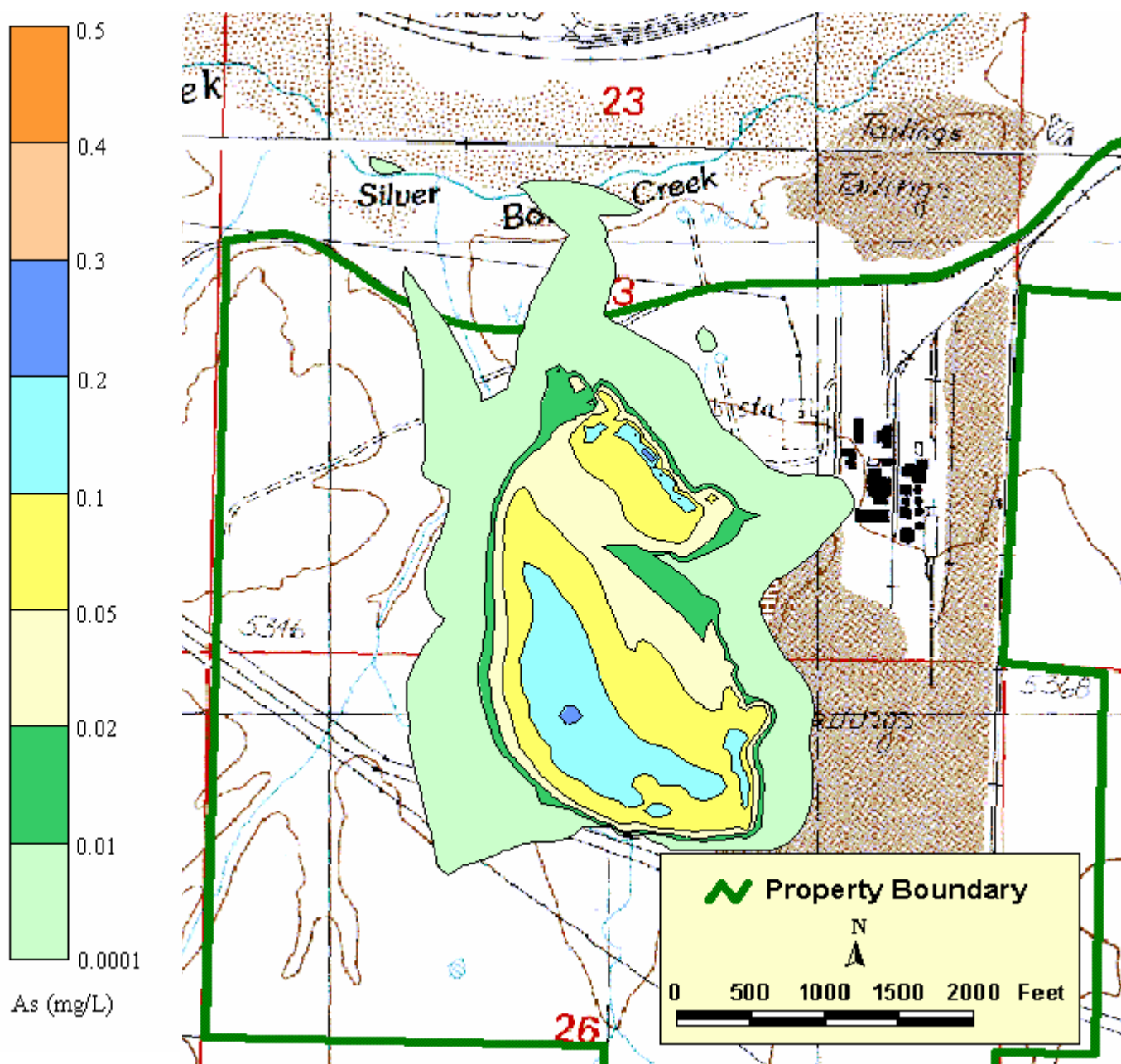


Figure 35
Simulated Arsenic Concentrations Above Background in Layer 3 as of 1999

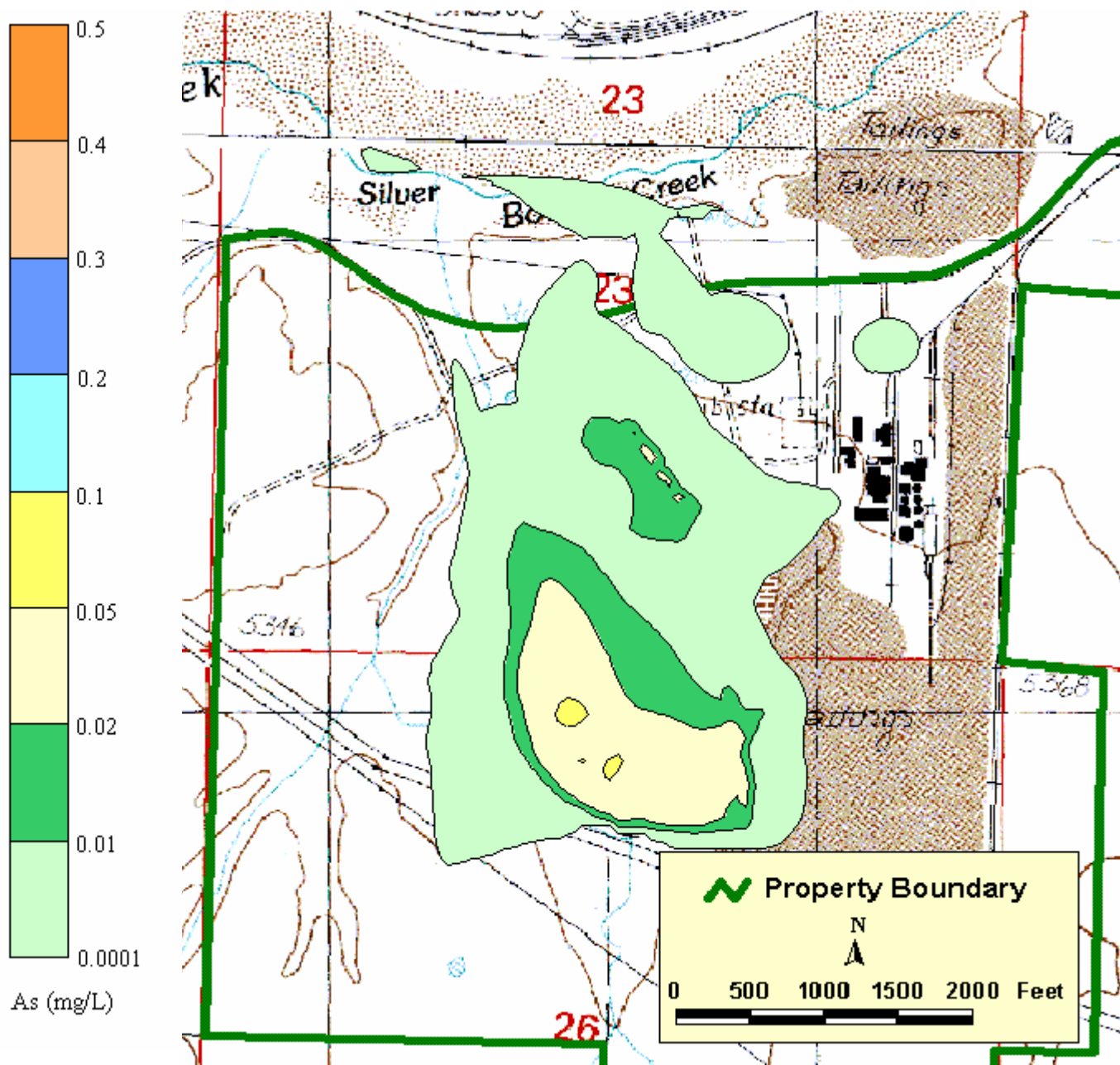


Figure 36

Simulated Arsenic Concentrations Above Background in Layer 4 as of 1999

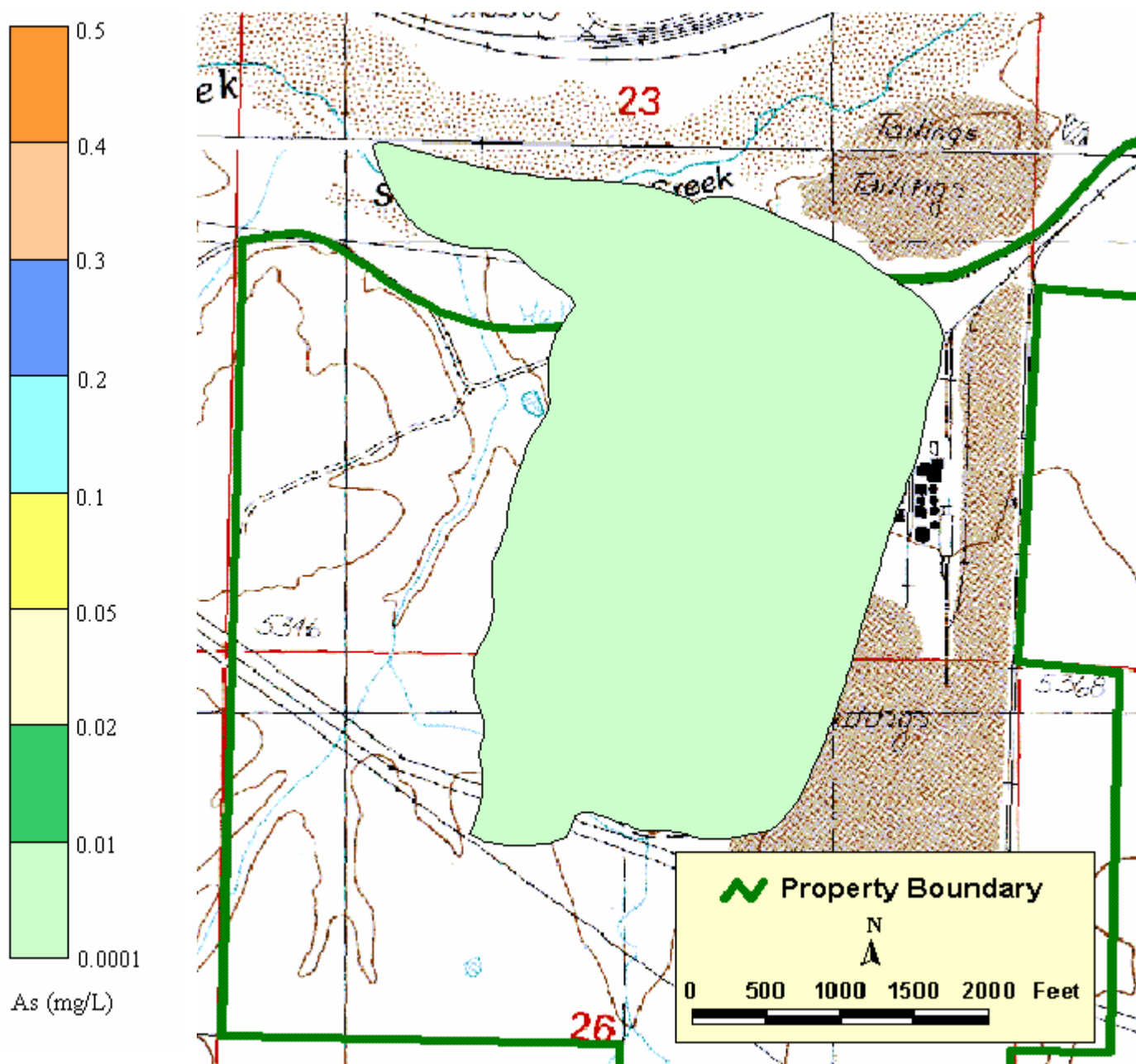


Figure 37
Simulated Arsenic Concentrations Above Background in Layer 5 as of 1999

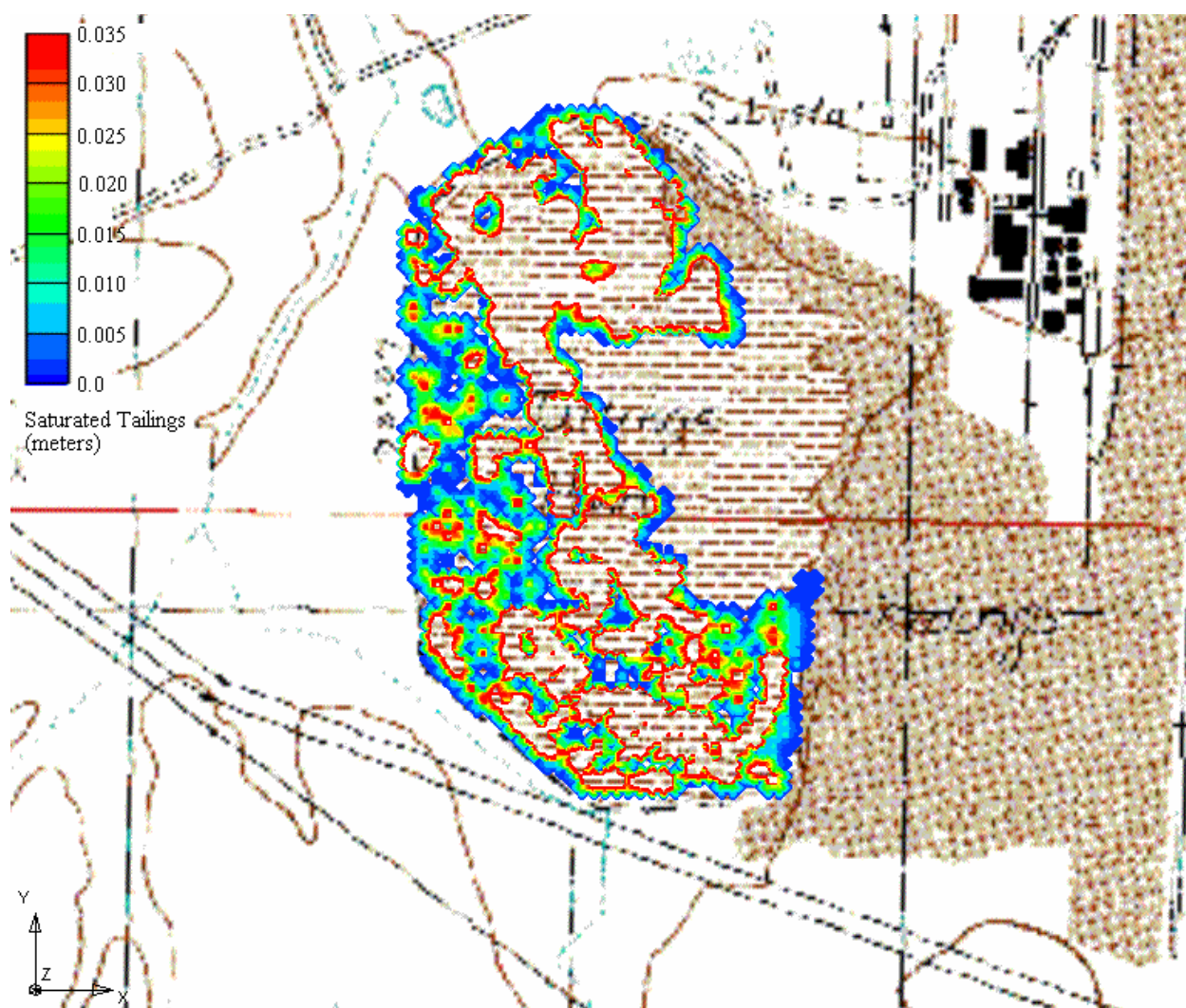


Figure 38
Simulated Saturated Thickness of the Tailings in the No-Action Alternative

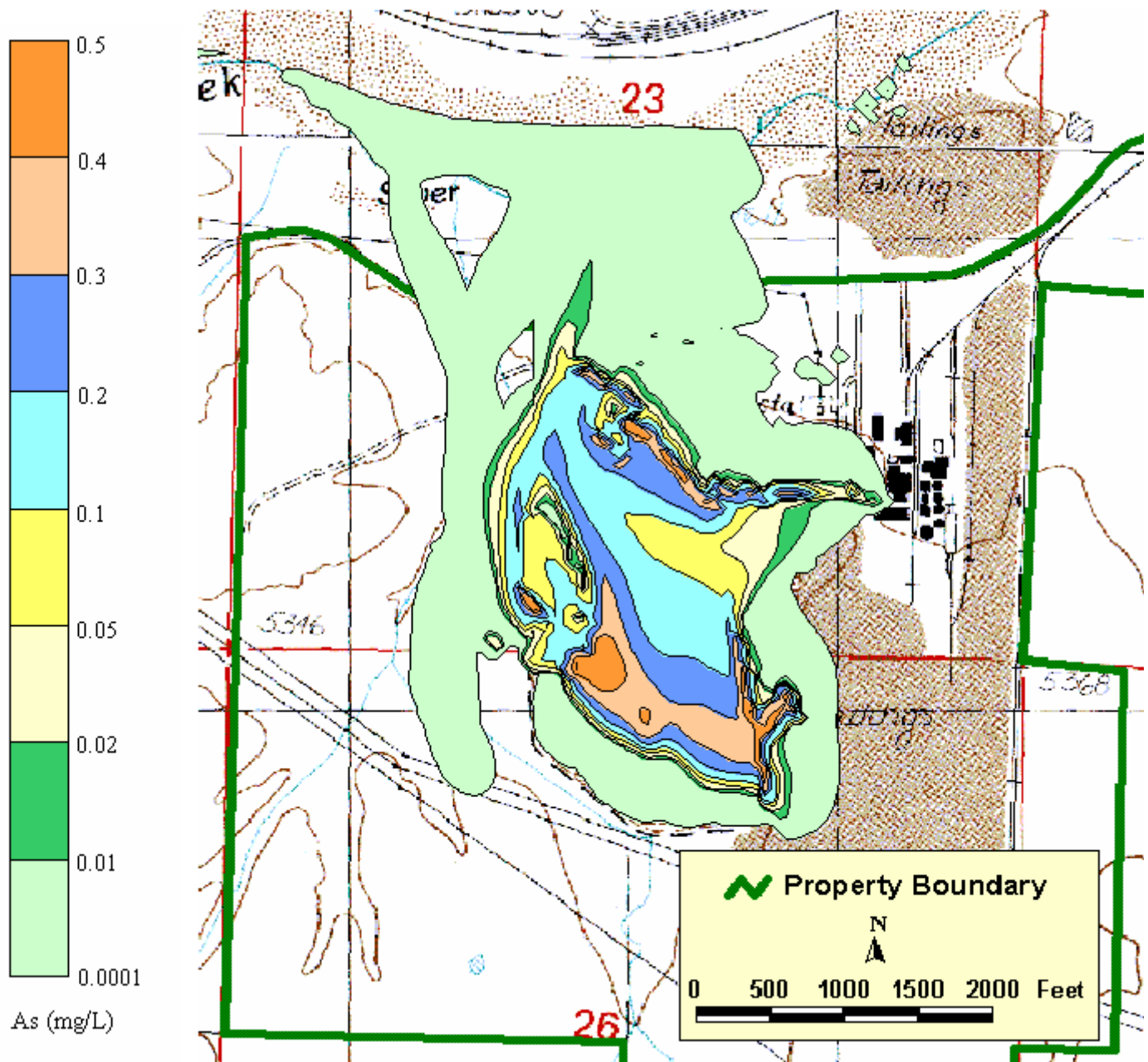


Figure 39

Simulated Arsenic Concentration Above Background in Layer 2 at 50 Years After Closure for the No-action Alternative

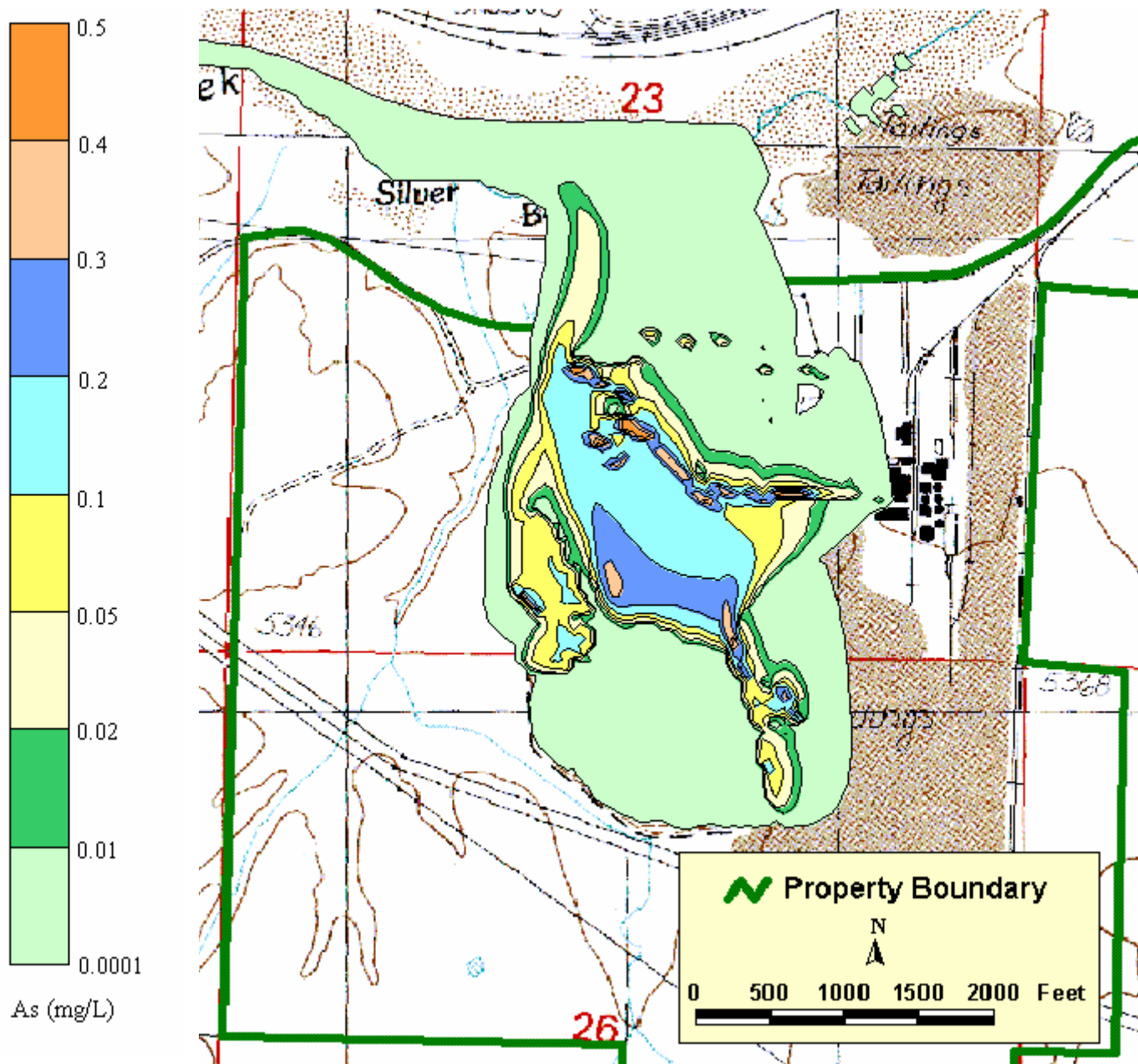


Figure 40

Simulated Arsenic Concentration Above Background in Layer 2 at 200 Years After Closure for the No-action Alternative

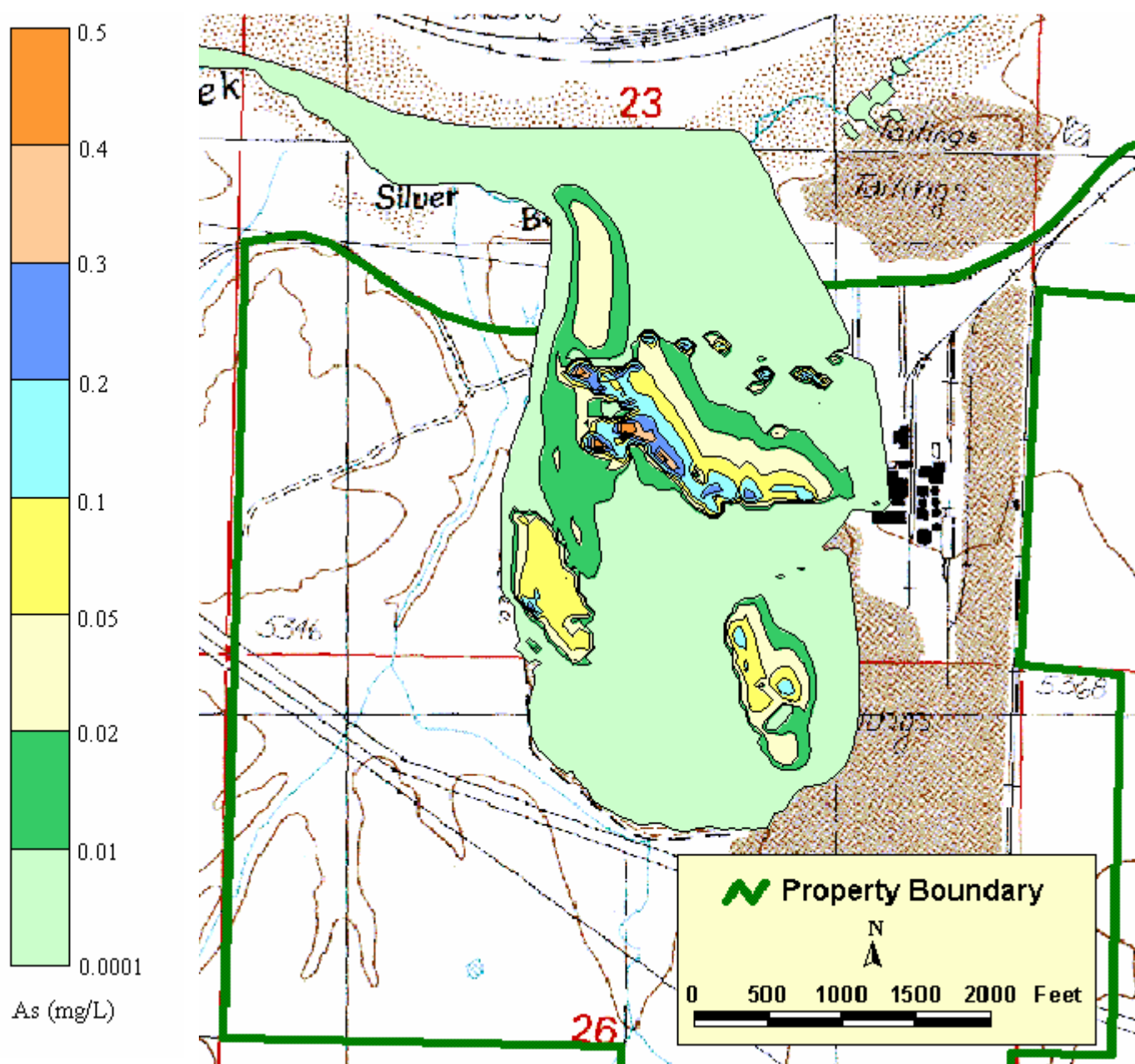


Figure 41

Simulated Arsenic Concentration Above Background in Layer 2 at 600 Years After Closure for the No-action Alternative

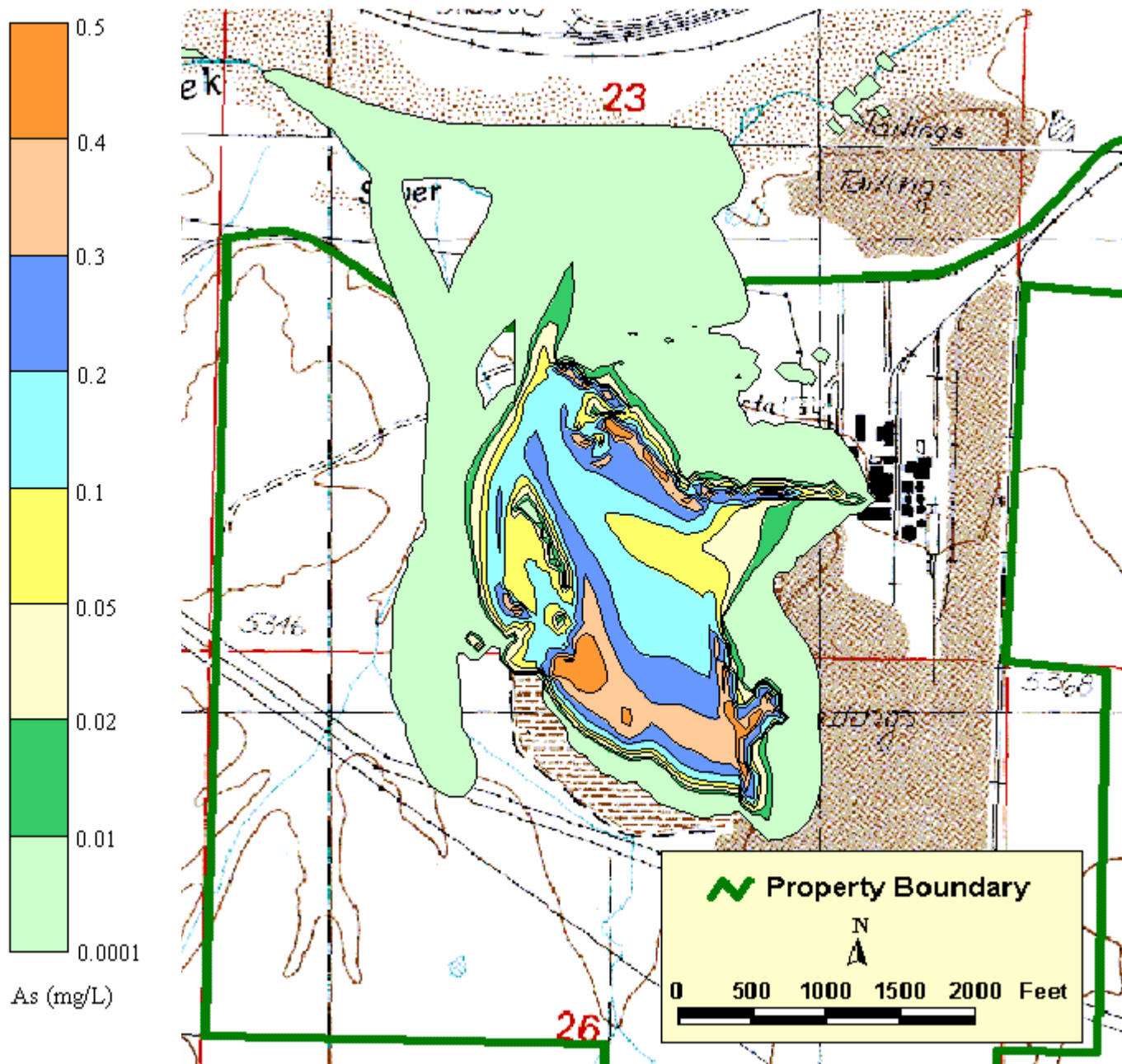


Figure 42

Simulated Arsenic Concentration Above Background in Layer 2 at 50 Years After Closure for the Evapotranspiration Cap Alternative

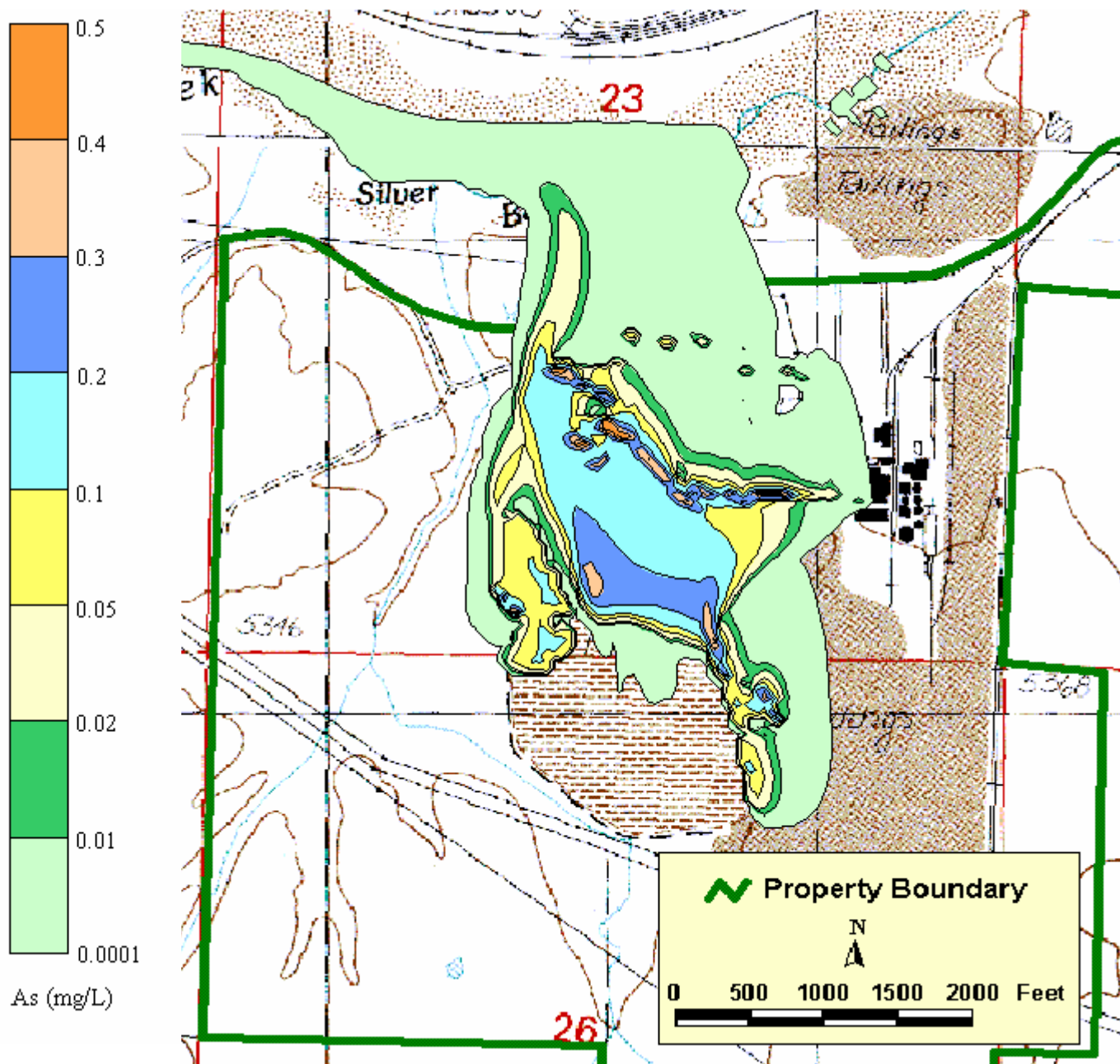


Figure 43
Simulated Arsenic Concentration Above Background in Layer 2 at 200 Years After Closure for the
Evapotranspiration Cap Alternative

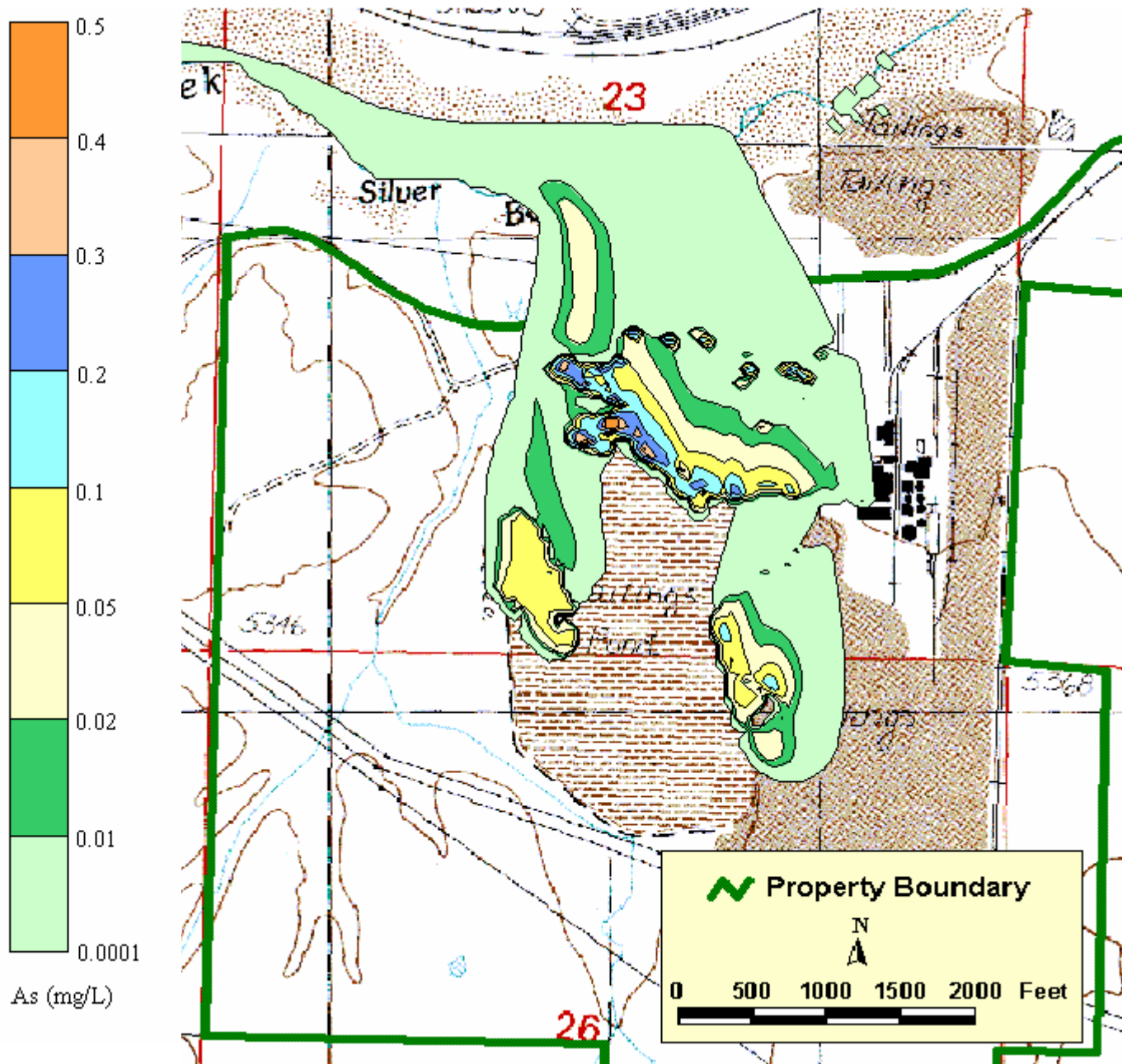


Figure 44
 Simulated Arsenic Concentration Above Background in Layer 2 at 600 Years After Closure for the
 Evapotranspiration Cap Alternative

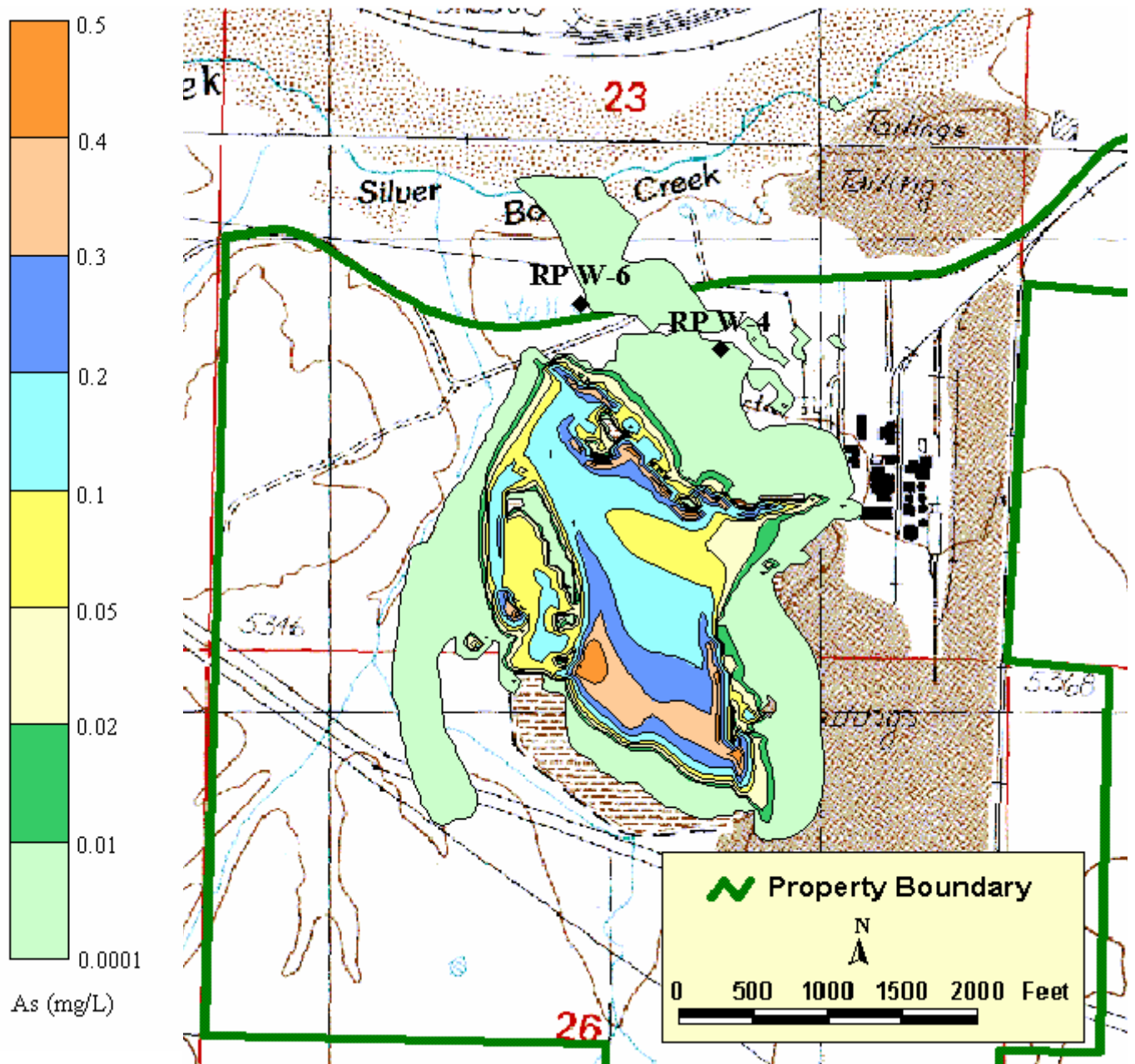


Figure 45

Simulated Arsenic Concentration Above Background in Layer 2 at 50 Years After Closure for the Deep Ground Water Interception Alternative

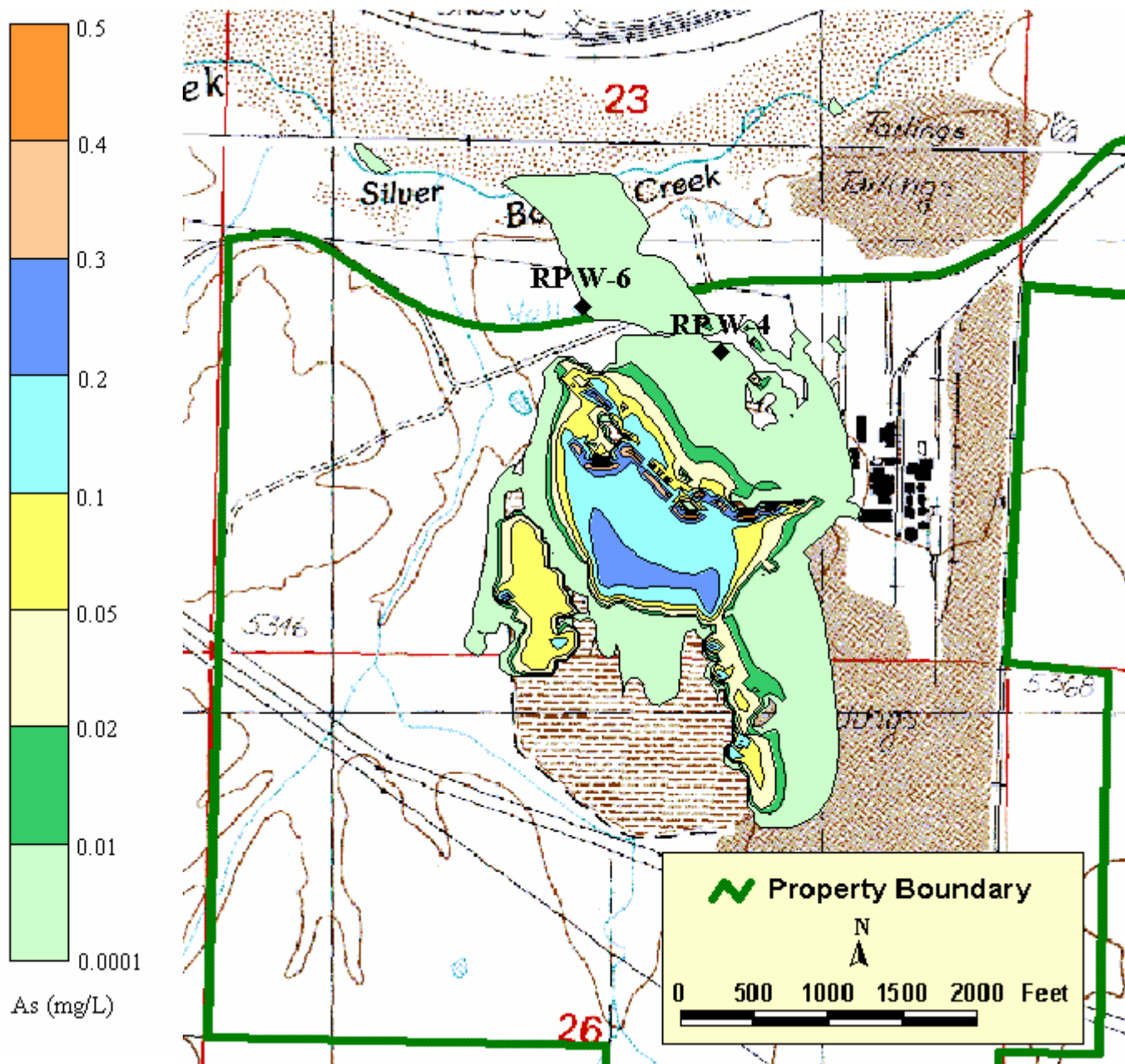


Figure 46

Simulated Arsenic Concentration Above Background in Layer 2 at 200 Years After Closure for the Deep Ground Water Interception Alternative

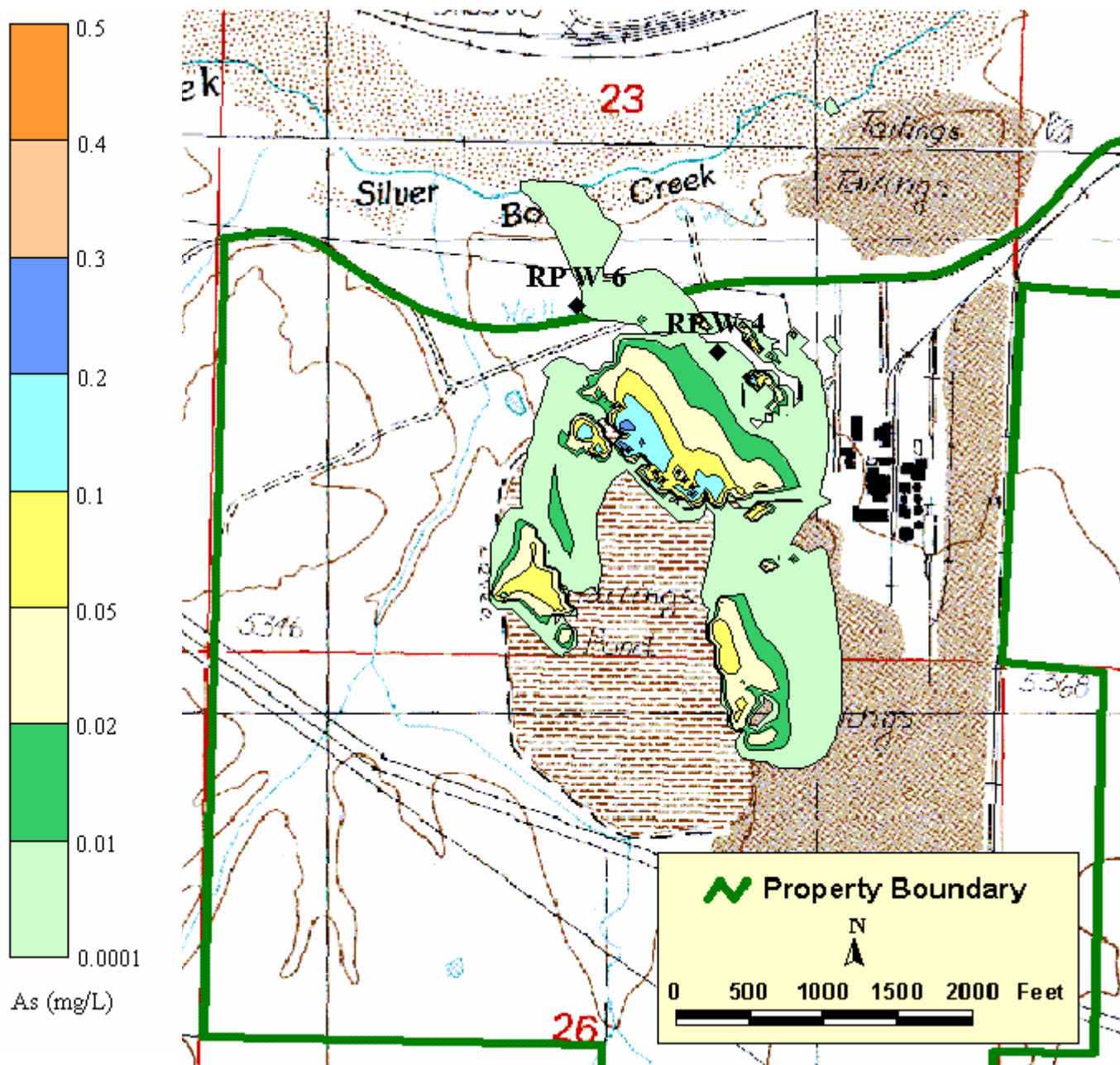


Figure 47

Simulated Arsenic Concentration Above Background in Layer 2 at 600 Years After Closure for the Deep Ground Water Interception Alternative

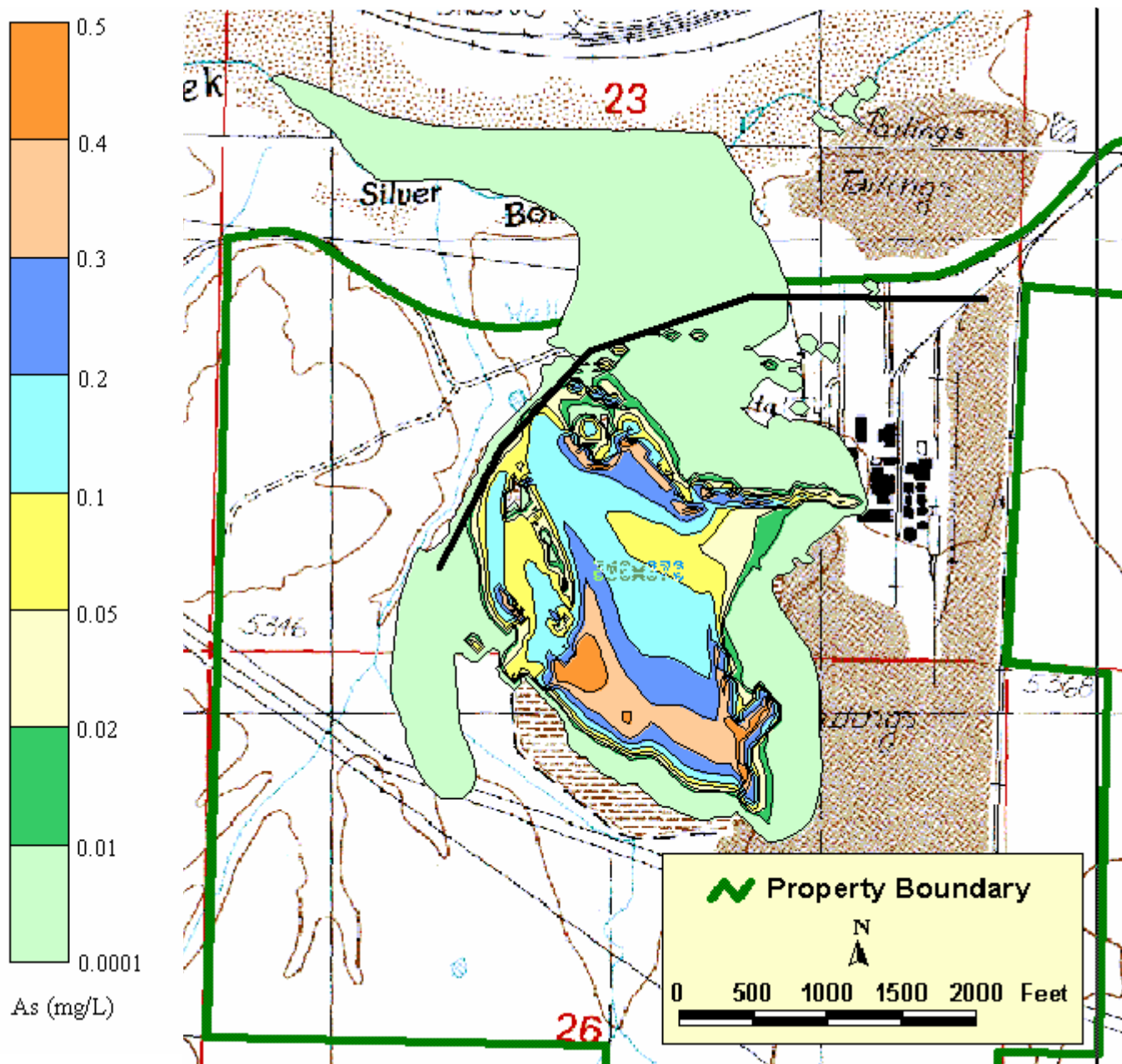


Figure 48

Simulated Arsenic Concentration Above Background in Layer 2 at 50 Years After Closure for the Shallow Ground Water Interception Alternative

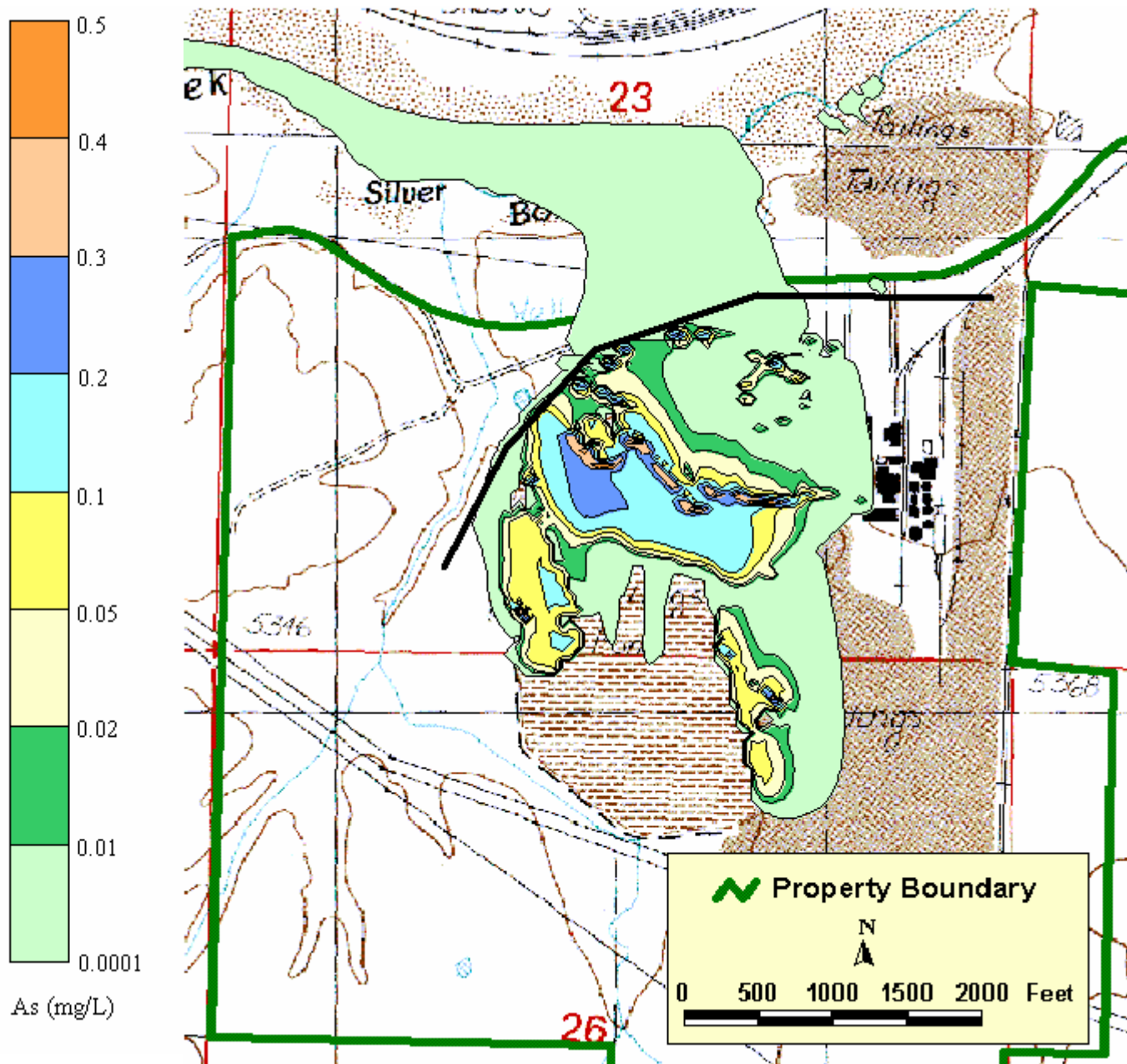


Figure 49

Simulated Arsenic Concentration Above Background in Layer 2 at 300 Years After Closure for the Shallow Ground Water Interception Alternative

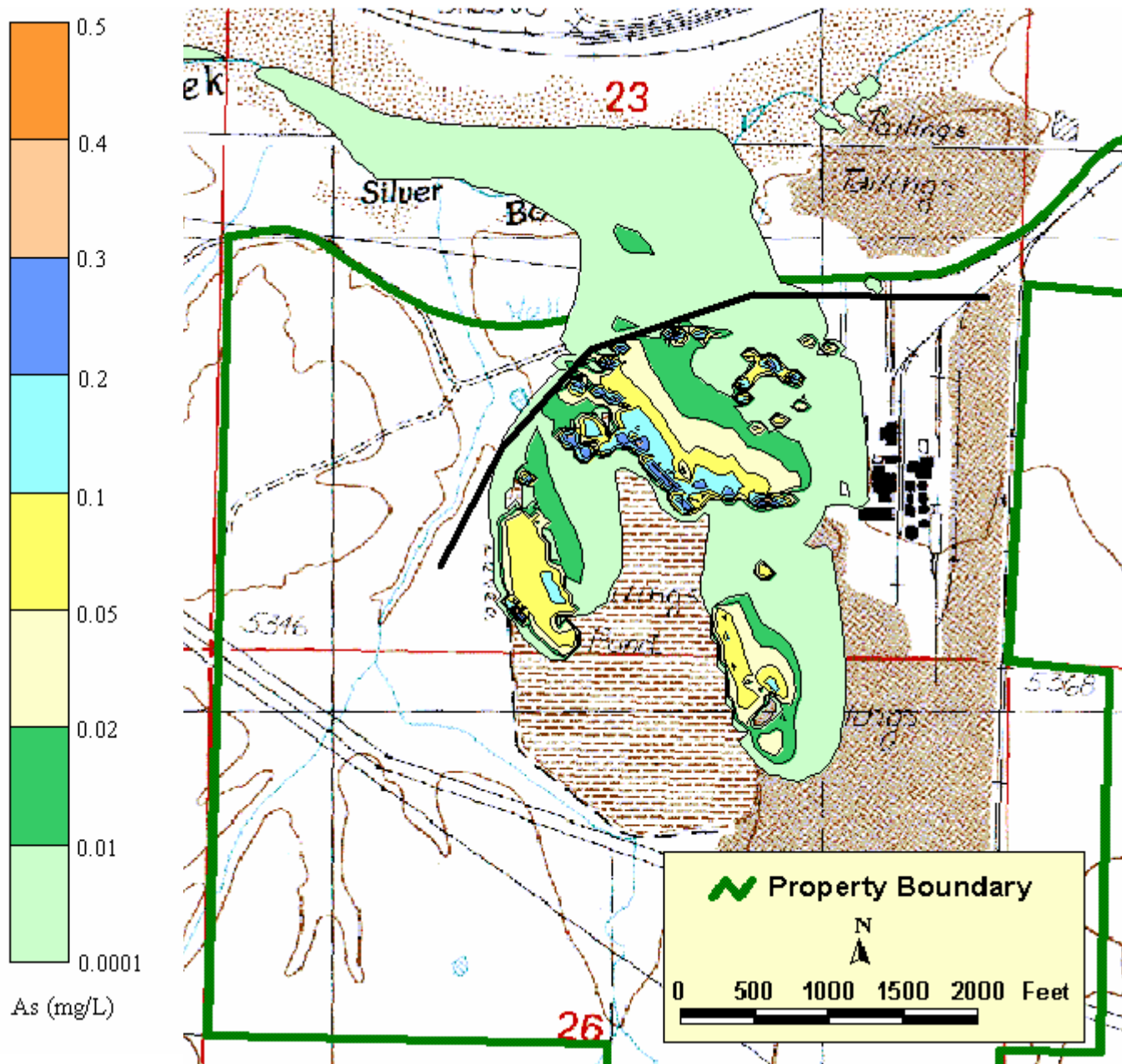


Figure 50

Simulated Arsenic Concentration Above Background in Layer 2 at 600 Years After Closure for the Shallow Ground Water Interception Alternative

Appendices

Appendix A

Appendix A

Source Code, Executable Files, and Model Input and Output Files Used in the MODFLOW/MT3D Modeling of Tailing Basin Closure

The attached compact disc (CD) contains the following:

- the source listing showing the modifications made to MODFLOW as described in Section 4.1;
- MODFLOW and MT3DMS executables used to perform the simulations for this project; and
- The model input files and output files for the various flow and transport scenarios.

The folder names and contents for the CD are as follows:

Folder Name	Description of Contents
CD	Root directory for the following folders.
EXEC	MODFLOW and MT3DMS executables and associated files, modified BCF package source code listings.
CALIB	MODFLOW input and output files for the steady-state flow model used in the automated calibration.
HIST	MODFLOW and MT3DMS files for conditions representative of the historical loading period (1970-1999)
NO_ACT	MODFLOW and MT3DMS files for the no-action alternative.
CAP	MODFLOW and MT3DMS files for the evapotranspiration cap alternative.
DEEP	MODFLOW and MT3DMS files for the deep groundwater interception alternative.
SHALLOW	MODFLOW and MT3DMS files for the shallow groundwater interception alternative.

The modifications to the BCF input file are described in Section 4.1 of this appendix. File BCF5.FOR is the source file associated with MODFLOW-96 and file BCF2.FOR is the source file associated with MODFLOW/mt, the version distributed with MT3DMS. The modification occurs on line 956 in BCF2.FOR and line 1071 in BCF5.FOR.

The executables must be run in a MS-DOS environment or an MS-DOS window in Windows 95, 98 or NT. The path established for MS-DOS should include the folder containing the executables (x:\cd\exec, where x is the drive name where the contents of the CD are located or to which the contents of the CD have been copied).

The calibration runs were made using MODFLOW-96. To execute MODFLOW-96, type TARGET at the DOS prompt. The code will prompt the user for a name file; type BOB6.NAM to execute the calibration run.

All other MODFLOW runs were made using MODFLOW/mt. To execute MODFLOW/mt, type MODFWET2 <filename at the DOS prompt, where *filename* is one of the following:

HISTORY.FIL	for the historical, loading scenario (1970-1999)
ONBASIN.FIL	for the no-action alternative
FORWARD.FIL	for the capping alternative
PUMP46.FIL	for the deep groundwater interception alternative
PERIMETR.FIL	for the shallow groundwater interception alternative

to execute MT3DMS, type MT3DMS < *filename* at the DOS prompt, where *filename* is one of the following:

GCGSTRT.FIL	for the historical, loading scenario (1970-1999)
GCGONBAS.FIL	for the no-action alternative
CGCFORW.FIL	for the capping alternative
CGCPUMP.FIL	for the deep groundwater interception alternative
CGCPERIM.FIL	for the shallow groundwater interception alternative

The executable files were compiled using a Lahey Fortran 90 compiler. The unformatted output files can be read using any compatible utilities.

Appendix B

Appendix B

Mass Balance Summaries for the Groundwater Flow Simulations

This appendix contains the mass balance summaries from MODFLOW for the flow models. The models run included:

- The calibration run simulating conditions in November, 1997 (Table B-1);
- The historical run simulating typical conditions for plant operation (1970-1999) (Table B-2);
- The no-action alternative simulating basin closure with regional infiltration on the basin footprint (Table B-3);
- The evapotranspiration cap alternative simulating basin closure with zero infiltration on the basin footprint (Table B-4);
- The deep groundwater interception alternative simulating basin closure with zero infiltration on the basin footprint and pumping of Wells RP W-4 and RP W-6 (Table B-5);
- The shallow groundwater interception alternative simulating basin closure with zero infiltration on the basin footprint and pumping from a shallow drain located on the downgradient perimeter of the tailing basin (Table B-6);

Table B-1
Calibrated Model

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 1 IN STRESS PERIOD 1					
CUMULATIVE VOLUMES		L**3	RATES FOR THIS TIME STEP		L**3/T
IN:			IN:		
---			---		
STORAGE =	0.0000		STORAGE =	0.0000	
CONSTANT HEAD =	0.0000		CONSTANT HEAD =	0.0000	
WELLS =	0.0000		WELLS =	0.0000	
RECHARGE =	0.26952E+08		RECHARGE =	2545.1	
ET =	0.0000		ET =	0.0000	
STREAM LEAKAGE =	0.12325E+10		STREAM LEAKAGE =	0.11639E+06	
HEAD DEP BOUNDS =	0.22861E+08		HEAD DEP BOUNDS =	2158.7	
TOTAL IN =	0.12823E+10		TOTAL IN =	0.12109E+06	
OUT:			OUT:		
---			---		
STORAGE =	0.0000		STORAGE =	0.0000	
CONSTANT HEAD =	0.0000		CONSTANT HEAD =	0.0000	
WELLS =	0.32875E+08		WELLS =	3104.3	
RECHARGE =	0.0000		RECHARGE =	0.0000	
ET =	0.48442E+08		ET =	4574.3	
STREAM LEAKAGE =	0.11956E+10		STREAM LEAKAGE =	0.11290E+06	
HEAD DEP BOUNDS =	0.56039E+07		HEAD DEP BOUNDS =	529.17	
TOTAL OUT =	0.12826E+10		TOTAL OUT =	0.12111E+06	
IN - OUT =	-0.21798E+06		IN - OUT =	-20.570	
PERCENT DISCREPANCY =	-0.02		PERCENT DISCREPANCY =	-0.02	
TIME SUMMARY AT END OF TIME STEP 1 IN STRESS PERIOD 1					
	SECONDS	MINUTES	HOURS	DAYS	YEARS
TIME STEP LENGTH	0.914976E+09	0.152496E+08	254160.	10590.0	28.9938
STRESS PERIOD TIME	0.914976E+09	0.152496E+08	254160.	10590.0	28.9938
TOTAL SIMULATION TIME	0.914976E+09	0.152496E+08	254160.	10590.0	28.9938

Table B-2
Historical Simulation

"
"
"

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 1 IN STRESS PERIOD 1

CUMULATIVE VOLUMES		L**3	RATES FOR THIS TIME STEP		L**3/T
-----			-----		
IN:			IN:		
---			---		
STORAGE =	0.0000		STORAGE =	0.0000	
CONSTANT HEAD =	0.0000		CONSTANT HEAD =	0.0000	
WELLS =	0.0000		WELLS =	0.0000	
DRAINS =	0.0000		DRAINS =	0.0000	
RECHARGE =	0.26952E+08		RECHARGE =	2545.1	
ET =	0.0000		ET =	0.0000	
STREAM LEAKAGE =	0.12459E+10		STREAM LEAKAGE =	0.11765E+06	
HEAD DEP BOUNDS =	0.22798E+08		HEAD DEP BOUNDS =	2152.8	
TOTAL IN =	0.12957E+10		TOTAL IN =	0.12235E+06	
OUT:			OUT:		
----			----		
STORAGE =	0.0000		STORAGE =	0.0000	
CONSTANT HEAD =	0.0000		CONSTANT HEAD =	0.0000	
WELLS =	0.96406E+08		WELLS =	9103.5	
DRAINS =	0.18155E+07		DRAINS =	171.43	
RECHARGE =	0.0000		RECHARGE =	0.0000	
ET =	0.48055E+08		ET =	4537.7	
STREAM LEAKAGE =	0.11467E+10		STREAM LEAKAGE =	0.10828E+06	
HEAD DEP BOUNDS =	0.45599E+07		HEAD DEP BOUNDS =	430.58	
TOTAL OUT =	0.12976E+10		TOTAL OUT =	0.12253E+06	
IN - OUT =	-0.18605E+07		IN - OUT =	-175.69	
PERCENT DISCREPANCY =	-0.14		PERCENT DISCREPANCY =	-0.14	

TIME SUMMARY AT END OF TIME STEP 1 IN STRESS PERIOD 1

	SECONDS	MINUTES	HOURS	DAYS	YEARS
-----	-----	-----	-----	-----	-----
TIME STEP LENGTH	0.914976E+09	0.152496E+08	254160.	10590.0	28.9938
STRESS PERIOD TIME	0.914976E+09	0.152496E+08	254160.	10590.0	28.9938
TOTAL SIMULATION TIME	0.914976E+09	0.152496E+08	254160.	10590.0	28.9938

Table B-3
No-action Alternative

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 1 IN STRESS PERIOD 1					
CUMULATIVE VOLUMES		L**3	RATES FOR THIS TIME STEP		L**3/T
IN:			IN:		
---			---		
STORAGE =	0.0000		STORAGE =	0.0000	
CONSTANT HEAD =	0.0000		CONSTANT HEAD =	0.0000	
WELLS =	0.0000		WELLS =	0.0000	
DRAINS =	0.0000		DRAINS =	0.0000	
RECHARGE =	0.27018E+08		RECHARGE =	2551.3	
ET =	0.0000		ET =	0.0000	
STREAM LEAKAGE =	0.12410E+10		STREAM LEAKAGE =	0.11719E+06	
HEAD DEP BOUNDS =	0.0000		HEAD DEP BOUNDS =	0.0000	
TOTAL IN =	0.12680E+10		TOTAL IN =	0.11974E+06	
OUT:			OUT:		
----			----		
STORAGE =	0.0000		STORAGE =	0.0000	
CONSTANT HEAD =	0.0000		CONSTANT HEAD =	0.0000	
WELLS =	0.15543E+08		WELLS =	1467.7	
DRAINS =	0.15680E+07		DRAINS =	148.06	
RECHARGE =	0.0000		RECHARGE =	0.0000	
ET =	0.48313E+08		ET =	4562.1	
STREAM LEAKAGE =	0.11980E+10		STREAM LEAKAGE =	0.11313E+06	
HEAD DEP BOUNDS =	0.46006E+07		HEAD DEP BOUNDS =	434.42	
TOTAL OUT =	0.12681E+10		TOTAL OUT =	0.11974E+06	
IN - OUT =	-45312.		IN - OUT =	-4.2656	
PERCENT DISCREPANCY =		0.00	PERCENT DISCREPANCY =		0.00

TIME SUMMARY AT END OF TIME STEP 1 IN STRESS PERIOD 1					
	SECONDS	MINUTES	HOURS	DAYS	YEARS
TIME STEP LENGTH	0.914976E+09	0.152496E+08	254160.	10590.0	28.9938
STRESS PERIOD TIME	0.914976E+09	0.152496E+08	254160.	10590.0	28.9938
TOTAL SIMULATION TIME	0.914976E+09	0.152496E+08	254160.	10590.0	28.9938

Table B-4
Capping Scenario

"

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 1 IN STRESS PERIOD 1					
CUMULATIVE VOLUMES		L**3	RATES FOR THIS TIME STEP		L**3/T
IN:			IN:		
---			---		
STORAGE =	0.0000		STORAGE =	0.0000	
CONSTANT HEAD =	0.0000		CONSTANT HEAD =	0.0000	
WELLS =	0.0000		WELLS =	0.0000	
DRAINS =	0.0000		DRAINS =	0.0000	
RECHARGE =	0.26952E+08		RECHARGE =	2545.1	
ET =	0.0000		ET =	0.0000	
STREAM LEAKAGE =	0.12410E+10		STREAM LEAKAGE =	0.11719E+06	
HEAD DEP BOUNDS =	0.0000		HEAD DEP BOUNDS =	0.0000	
TOTAL IN =	0.12680E+10		TOTAL IN =	0.11973E+06	
OUT:			OUT:		
----			----		
STORAGE =	0.0000		STORAGE =	0.0000	
CONSTANT HEAD =	0.0000		CONSTANT HEAD =	0.0000	
WELLS =	0.15543E+08		WELLS =	1467.7	
DRAINS =	0.15606E+07		DRAINS =	147.36	
RECHARGE =	0.0000		RECHARGE =	0.0000	
ET =	0.48324E+08		ET =	4563.2	
STREAM LEAKAGE =	0.11980E+10		STREAM LEAKAGE =	0.11313E+06	
HEAD DEP BOUNDS =	0.46003E+07		HEAD DEP BOUNDS =	434.40	
TOTAL OUT =	0.12681E+10		TOTAL OUT =	0.11974E+06	
IN - OUT =	-70656.		IN - OUT =	-6.6797	
PERCENT DISCREPANCY =		-0.01	PERCENT DISCREPANCY =		-0.01

TIME SUMMARY AT END OF TIME STEP 1 IN STRESS PERIOD 1					
	SECONDS	MINUTES	HOURS	DAYS	YEARS
TIME STEP LENGTH	0.914976E+09	0.152496E+08	254160.	10590.0	28.9938
STRESS PERIOD TIME	0.914976E+09	0.152496E+08	254160.	10590.0	28.9938
TOTAL SIMULATION TIME	0.914976E+09	0.152496E+08	254160.	10590.0	28.9938

Table B-5
Deep Groundwater Interception

"

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 1 IN STRESS PERIOD 1					
CUMULATIVE VOLUMES		L**3	RATES FOR THIS TIME STEP		L**3/T
IN:			IN:		
---			---		
STORAGE =	0.0000		STORAGE =	0.0000	
CONSTANT HEAD =	0.0000		CONSTANT HEAD =	0.0000	
WELLS =	0.0000		WELLS =	0.0000	
DRAINS =	0.0000		DRAINS =	0.0000	
RECHARGE =	0.26952E+08		RECHARGE =	2545.1	
ET =	0.0000		ET =	0.0000	
STREAM LEAKAGE =	0.12504E+10		STREAM LEAKAGE =	0.11807E+06	
HEAD DEP BOUNDS =	0.0000		HEAD DEP BOUNDS =	0.0000	
TOTAL IN =	0.12773E+10		TOTAL IN =	0.12062E+06	
OUT:			OUT:		
---			---		
STORAGE =	0.0000		STORAGE =	0.0000	
CONSTANT HEAD =	0.0000		CONSTANT HEAD =	0.0000	
WELLS =	0.61757E+08		WELLS =	5831.7	
DRAINS =	0.13048E+06		DRAINS =	12.321	
RECHARGE =	0.0000		RECHARGE =	0.0000	
ET =	0.48001E+08		ET =	4532.6	
STREAM LEAKAGE =	0.11637E+10		STREAM LEAKAGE =	0.10989E+06	
HEAD DEP BOUNDS =	0.45690E+07		HEAD DEP BOUNDS =	431.44	
TOTAL OUT =	0.12781E+10		TOTAL OUT =	0.12069E+06	
IN - OUT =	-0.81958E+06		IN - OUT =	-77.398	
PERCENT DISCREPANCY =	-0.06		PERCENT DISCREPANCY =	-0.06	

TIME SUMMARY AT END OF TIME STEP 1 IN STRESS PERIOD 1					
	SECONDS	MINUTES	HOURS	DAYS	YEARS
TIME STEP LENGTH	0.914976E+09	0.152496E+08	254160.	10590.0	28.9938
STRESS PERIOD TIME	0.914976E+09	0.152496E+08	254160.	10590.0	28.9938
TOTAL SIMULATION TIME	0.914976E+09	0.152496E+08	254160.	10590.0	28.9938

Table B-6

Shallow Groundwater Interception

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 1 IN STRESS PERIOD 1					
CUMULATIVE VOLUMES		L**3		RATES FOR THIS TIME STEP	
				L**3/T	
IN:				IN:	
---				---	
STORAGE =	0.0000			STORAGE =	0.0000
CONSTANT HEAD =	0.0000			CONSTANT HEAD =	0.0000
WELLS =	0.0000			WELLS =	0.0000
DRAINS =	0.0000			DRAINS =	0.0000
RECHARGE =	0.26952E+08			RECHARGE =	2545.1
ET =	0.0000			ET =	0.0000
STREAM LEAKAGE =	0.12486E+10			STREAM LEAKAGE =	0.11791E+06
HEAD DEP BOUNDS =	0.0000			HEAD DEP BOUNDS =	0.0000
TOTAL IN =	0.12756E+10			TOTAL IN =	0.12045E+06
OUT:				OUT:	
----				----	
STORAGE =	0.0000			STORAGE =	0.0000
CONSTANT HEAD =	0.0000			CONSTANT HEAD =	0.0000
WELLS =	0.15543E+08			WELLS =	1467.7
DRAINS =	0.13092E+08			DRAINS =	1236.2
RECHARGE =	0.0000			RECHARGE =	0.0000
ET =	0.48208E+08			ET =	4552.2
STREAM LEAKAGE =	0.11943E+10			STREAM LEAKAGE =	0.11278E+06
HEAD DEP BOUNDS =	0.45924E+07			HEAD DEP BOUNDS =	433.65
TOTAL OUT =	0.12758E+10			TOTAL OUT =	0.12047E+06
IN - OUT =	-0.15949E+06			IN - OUT =	-15.063
PERCENT DISCREPANCY =		-0.01		PERCENT DISCREPANCY =	-0.01
TIME SUMMARY AT END OF TIME STEP 1 IN STRESS PERIOD 1					
	SECONDS	MINUTES	HOURS	DAYS	YEARS
TIME STEP LENGTH	0.914976E+09	0.152496E+08	254160.	10590.0	28.9938
STRESS PERIOD TIME	0.914976E+09	0.152496E+08	254160.	10590.0	28.9938
TOTAL SIMULATION TIME	0.914976E+09	0.152496E+08	254160.	10590.0	28.9938

Appendix C

Appendix C

Arsenic Batch Sorption Experiments

on Soils Found at the Silver Bow Plant, Montana

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Purpose and Scope

Batch adsorption and desorption experiments were performed using four types of soils found at the Silver Bow facility in order to characterize the soils' ability to adsorb (take up from water) and desorb (release into water) arsenic. The primary purpose for performing these batch experiments is to quantify the attenuation characteristics of dissolved arsenic through the construction of isotherms (relating equilibrium arsenic concentration to quantity of arsenic adsorbed by the solid), whose constants are used in computer solute transport modeling.

Arsenic is typically found in two valence states in natural waters - +3 (arsenite, or As(III)) and +5 (arsenate, or As(V)). Both of these valence conditions hydrolyze to form anionic species in pH ranges typical of surface and groundwater (@ pH of 5 to 9). Studies by Frost and Griffin (1977), Gulens et al. (1979), and Jain et al. (1999) indicate that there may be differences in the sorption characteristics of As(III) and As(V), especially at pH's above 7. At the Silver Bow facility, speciation data suggest that either As(III) or As(V) can be the dominant valence, depending upon which well the sample is collected from. Because both valence species are present and because previous research has indicated a potential difference in the sorptive characteristics of As(III) and As(V), separate batch experiments were performed using arsenite and arsenate.

In natural water, As(III) and As(V) hydrolyze to form negatively charged species. The degree of negative charge is dependent upon the pH. The negative charge causes the hydrolyzed arsenic species to be attracted to positively charged surfaces, typically in the form of iron, aluminum, and manganese sesquioxide coatings on silt and clay particles. These sesquioxides (particularly amorphous iron hydroxide) have positively charged surfaces that are pH dependent – at pH's below the pH of the isoelectric point (pH_{iep}) the surfaces are positively charged and attract negatively charged dissolved species. Studies of the pH dependency of arsenic adsorption have been performed by Anderson et al. (1976), Frost and Griffin (1977), Jones et al. (1978), Gupta and Chen, (1978), Wuolo (1986), and Jain et al. (1999). Consequently, batch experiments were included to evaluate the pH effects of adsorption within expected pH ranges.

The soil itself is an important variable in adsorption. Factors such as the distribution of fine-grained sediment, quantity of pH buffering constituents, and percentage of iron hydroxide can all play a role in the characteristics of arsenic adsorption. For example, Jenne (1977) indicates that finer-grained soil has a higher capacity for adsorbing trace metals because of the larger surface area per unit volume that these materials have. Batch experiments were performed using four types of soil materials encountered at the Silver Bow facility: tailings material; fine-grained "slack-water" deposits; alluvium; and material collected from the fluvial channel underneath the tailings basin.

Finally, studies have suggested that arsenic adsorption may not be a reversible process – i.e., the affinity for adsorption may be greater than the affinity for desorption (Frost and Griffin, 1977; Schindler, 1981). This phenomenon would have important ramifications at the Silver Bow facility because if it were shown to be the case at the facility, two different isotherms would be necessary – one to represent adsorption and another to represent desorption. Furthermore, if the sorption process were shown to not be reversible, this would tend to indicate that arsenic, once adsorbed, might become immobile and no longer a source of dissolved arsenic.

Overview of Batch Experiment Procedures

The batch adsorption experiments were performed in accordance with ASTM D 4319-93, *Standard Test Method for Distribution Ratios by the Short-Term Batch Method*, except for some noted situations that the ASTM method was not applicable or appropriate. Additional procedures that were employed by Wuolo (1986) were also incorporated into the experiments. Detailed procedures for certain aspects of the batch experiment are included as standard operating procedures at end of this document.

The following steps were used:

1. Representative soil samples were collected at the Silver Bow facility for use in the experiments. These samples were maintained in a sealed, intact state until used in the experiments.
2. The general major ion characteristics of the groundwater upgradient of the tailings pond and the tailings pond water were estimated from the available water-quality data. Piper and plots were employed to ascertain which samples seemed most representative of these two water types.
3. Synthetic groundwater and synthetic tailings water were constructed in the laboratory. These waters were made by dissolving reagent-grade compounds into double-dionized water to approximate the major ion chemistry and ionic strength of the natural waters. The pH of these waters could be modified by titration with NaOH or HCL solution. The arsenic concentration could be controlled by spiking with a solution of arsenic with a known concentration. Synthetic waters were used, rather than natural waters collected from the facility because the arsenic concentration could be controlled with synthetic waters and questions regarding preservation of potentially large volumes of water could be avoided.
4. Soil samples were weighed and placed in 50 ml polypropylene centrifuge bottles.
5. Synthetic water (40 ml), adjusted to the target pH, was added and the sealed bottle was placed in a Wrist-Action® shaker for 15 minutes. The bottle was centrifuged at @ 1,000 g for 5 minutes, and the water was decanted. This procedure was performed 3 times to “condition” the soil with the water, as per ASTM standard requirements. A fourth aliquot of synthetic water was added to the soil and shaken for 24 hours to equilibrate the water with the soil.
6. The tube was centrifuged for 5 minutes at 1,000 g and the supernatant was poured into a graduated cylinder. Additional synthetic water was added, as necessary, to make a 40 ml volume. The pH and Eh of the water were measured and recorded. If the pH required adjustment to the target pH, NaOH or HCL (0.1 or 1 N) was added and allowed to equilibrate. The water was then returned to the sample bottle that contained the soil sample. If spiking with a arsenic solution was called for, this was now performed and the bottle was sealed.

7. The bottle was placed in the Wrist-Action® shaker and agitated for at least 3 hours each day during the course of contact. In most cases, the contact time was approximately 7 days but 3 days and 14 days were also used in some instances in order to evaluate the effects of contact time on results, as per the requirements of ASTM D 4319. Bottles were not shaken during the final 24 hours of contact time, per the requirements of ASTM D 4319.
8. At the end of the contact period, each bottle was centrifuged for 20 minutes at 1,600 g. Eh and pH measurements were made on the supernatant while it was still in the bottle. The supernatant was then filtered through an 0.45 µm filter and placed into a glass jar with nitric acid preservative for analysis by the laboratory. Analyses were performed by Braun Intertec laboratory for total arsenic.
9. Immediately after decantation and sampling of the supernatant, 40 ml synthetic water (tailings or groundwater), adjusted for the target pH, was added to the bottle containing the soil sample. This constituted the beginning of the desorption phase of the batch experiment. The target contact time for each sample was the same as the adsorption (spiked) experiment's contact time. The bottle was placed in the Wrist-Action® shaker and agitated for at least 3 hours each day during the course of contact.
10. At the end of the contact period, each bottle was centrifuged for 20 minutes at 1,600 g. Eh and pH measurements were made on the supernatant while it was still in the bottle. The supernatant was then filtered through an 0.45 µm filter and placed into a glass jar with nitric acid preservative for analysis by the laboratory. Analyses were performed by Braun Intertec laboratory for total arsenic. The soil sample was then discarded.

Batch Experiment Procedures

Soil Sample Preparation

Soil samples used in the batch experiments were collected by a split-spoon sampler in a hollow-stem auger boreholes T-99-1, T-99-2 and T-99-3, augured through the dike of the tailings basin, through the tailings, through alluvial channel deposits that pre-dated the pond, and into alluvium that is typical of much of the sediments in the area. Four samples were used: (1) silty clay to clayey silt **tailings** material from near the bottom of the tailings basin at a depth of 44.2-44.5 feet in boring T-99-2; (2) slightly organic, clayey silt “**slack-water**” deposits that underlie tailings in boring T-99-3 at a depth of 44-46 feet; (3) **fluvially** deposited channel deposits (gravelly sand) that underlie slack-water deposits in boring T-99-2 at a depth of 56-58 feet; and (4) silty sand to sandy silt **alluvium** that underlies the tailings basin and channel deposits from boring T-99-1 at a depth of 64-65 feet. Soil samples were stored in glass jars immediately after sampling and remained in this state until used for batch experiments (approximately 30 days between sampling and use).

A portion of each sample was sent to Energy Laboratories of Billings, Montana for total arsenic analyses (3050 digestion) and ASTM D 3987 Leaching. The following results were obtained:

Soil Type	Arsenic leached ($\mu\text{g/g}$ soil)	Total Arsenic ($\mu\text{g/g}$ soil)	pH
Tailings	0.03	79	8.3
Slack Water	0.04	5	8.4
Fluvial	0.02	<5	7.9
Alluvium	0.02	<5	8.1

The tailings sample has substantially more total arsenic than the other soil types. The slack water deposits, which are natural soils situated directly below the tailings, have a relatively low total arsenic concentration but the highest leachable arsenic concentration. This would suggest that the slack water deposits are a repository for arsenic in an adsorbed form.

Samples were removed from the jars and placed in new plastic dinnerware containers. The samples were homogenized by stirring. From these containers, 40 g samples were removed, weighed, and placed in 50 ml polypropylene centrifuge bottles manufactured by Corning. Samples could not be split using a riffle splitter because of they were cohesive and generally moist. For sand and gravel materials (e.g., fluvial deposits and alluvium), pebble and larger sizes were excluded from the sample because they have an unrepresentatively small surface area to weight ratio.

Soil samples are sometimes air dried, oven dried, or freeze dried before being weighed and used in batch experiments (e.g. Wuolo (1986)). None of these methods were employed for fear of causing chemical and physical changes to the sample. Latent pore water from the sample would generally be displaced and

removed through the conditioning process. Pre-treatment of samples with hydrogen peroxide is also a common procedure (e.g., Wuolo, 1986) to remove organic material from the sample before conducting the batch experiments. Since organic material is an inherent part of some of the soil materials, the removal of organic material was not performed because it would result in a non-representative condition.

Each time a liquid was added to the sample bottle that contain a soil sample, the bottle was shaken vigorously to disaggregate the soil (all of which are unconsolidated deposits). This disaggregation was typically necessary after centrifuging the sample. Disaggregation ensured that the entire surface area of the soil grains were in good contact with the fluid.

Synthetic Water Preparation

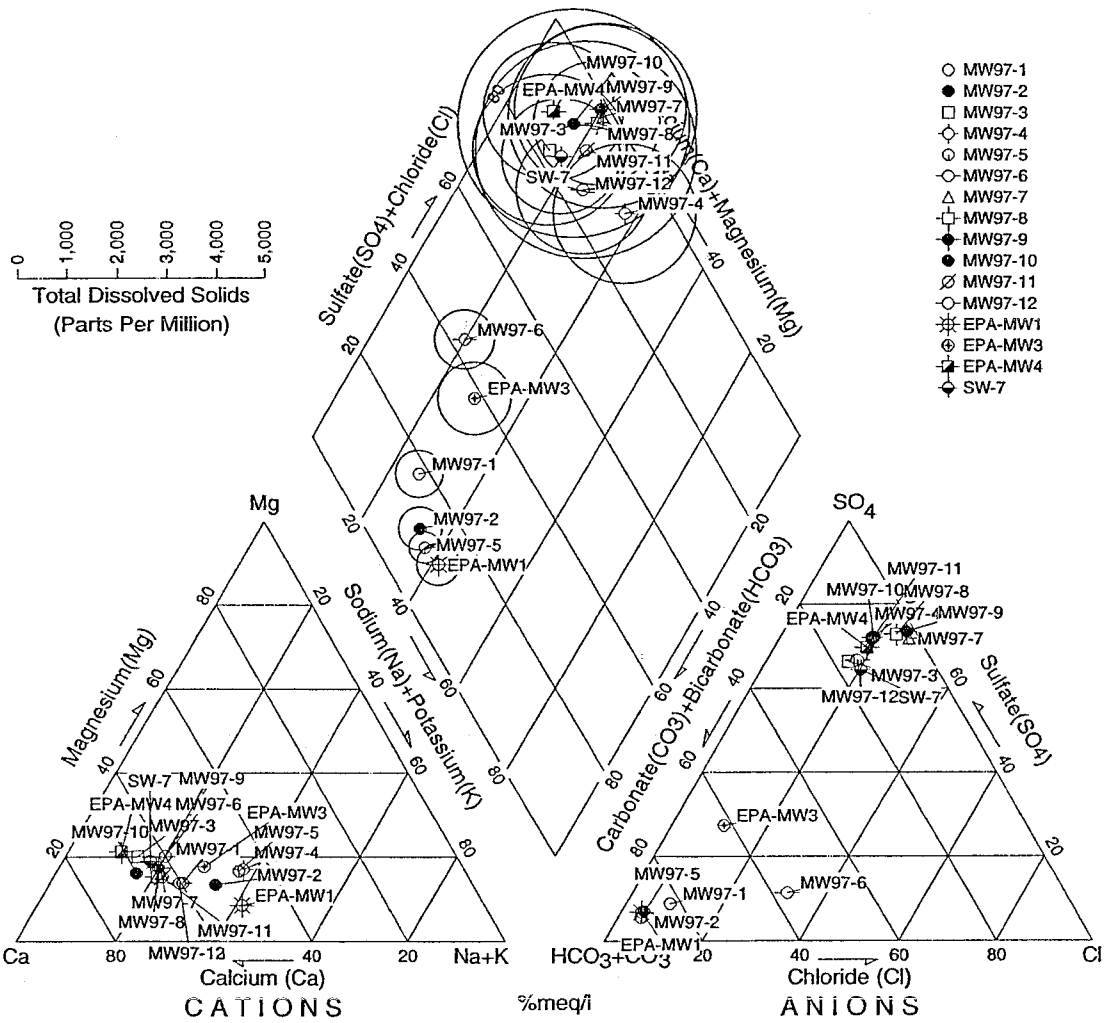
Two water types were identified from a perusal of the major ion concentrations of samples collected from the tailings basin and from monitoring wells: groundwater and tailings water. Near the tailings basin, there appears to be a mixture of the two waters. For these experiments, we wanted to look at sorption in the presence of tailings water and sorption in the presence of upgradient groundwater (which would eventually flush through the tailings pond area).

Synthetic groundwater and synthetic tailings water were created in the laboratory. These waters were made by dissolving reagent-grade compounds into double-dionized water to approximate the major ion chemistry and ionic strength of the natural waters. The pH of these waters could be modified by titration with NaOH or HCL solution. The arsenic concentration could then be controlled by spiking with a solution of arsenic with a known concentration. Synthetic waters were used, rather than natural waters collected from the facility because the arsenic concentration could be controlled with synthetic waters and questions regarding preservation of potentially large volumes of water could be avoided.

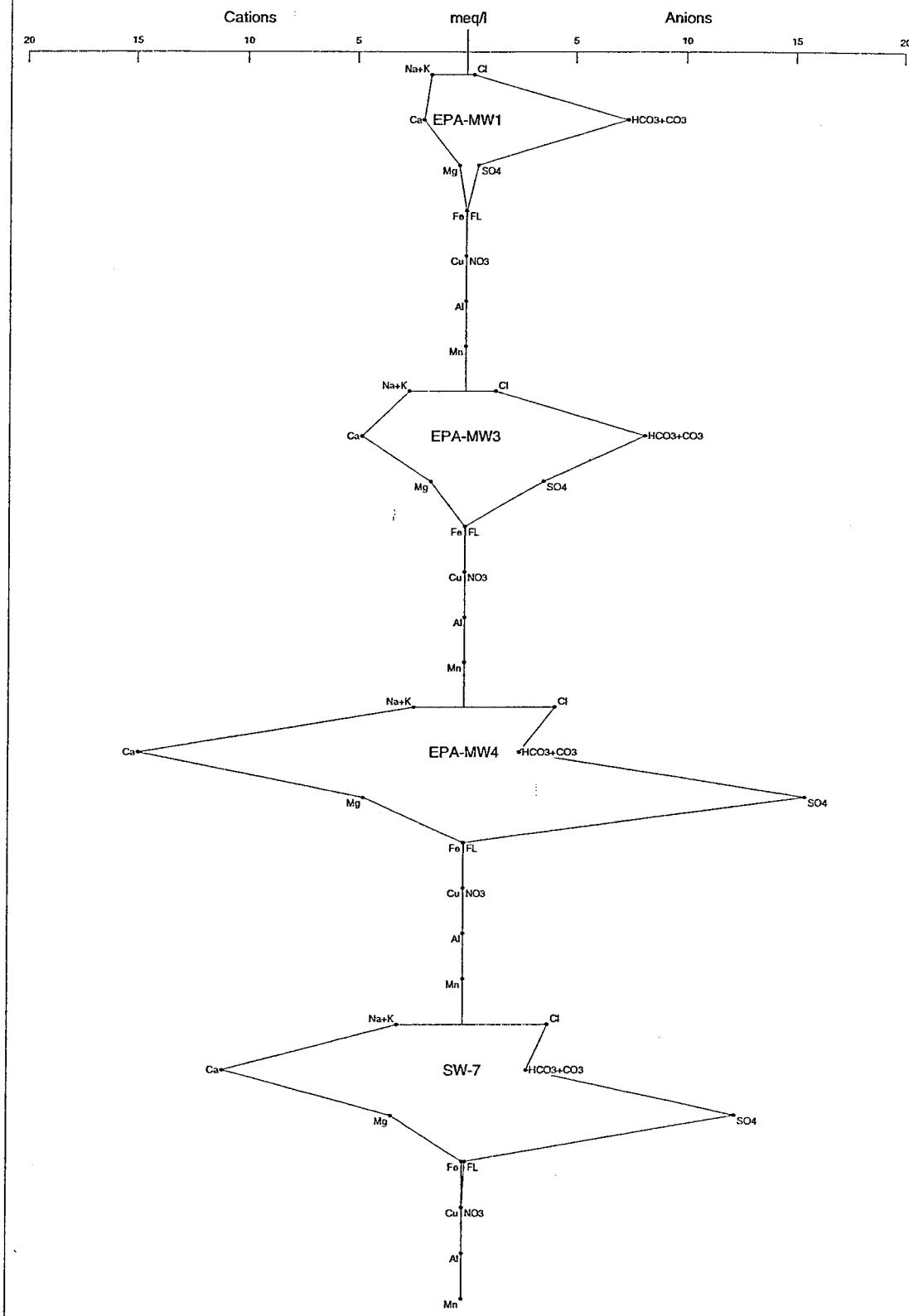
The general major ion characteristics of the groundwater upgradient of the tailings pond and the tailings pond water were estimated from the available water-quality data. Piper and and Stiff plots were employed to ascertain which samples seemed most representative of these two water types. These plots are attached. The synthetic waters have the following major ion compositions:

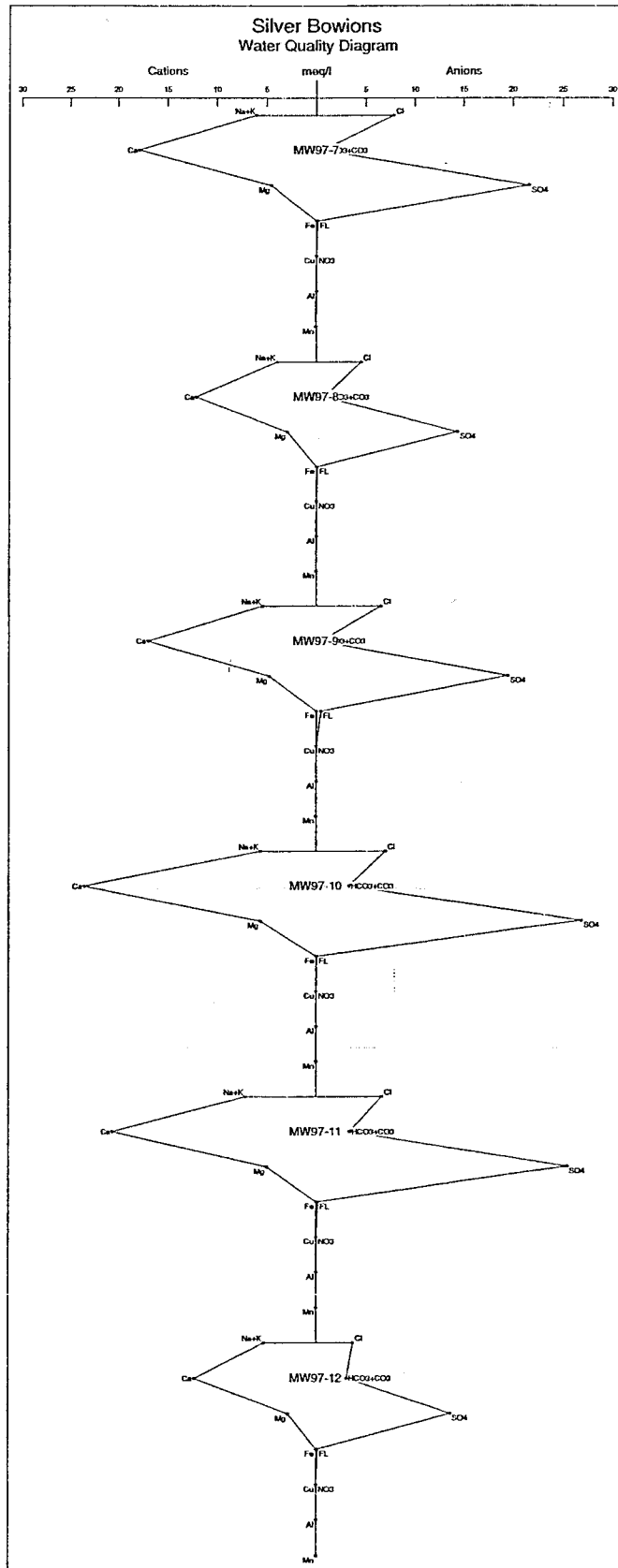
Ion	Synthetic Groundwater	Synthetic Tailings Water
Calcium	114 mg/L	480 mg/L
Sodium	19.5 mg/L	5.7 mg/L
Potassium	7 mg/L	19.5 mg/L
Magnesium	16 mg/L	72 mg/L
Carbonate+Bicarbonate (as CO ₃)	180 mg/L	180 mg/L
Sulfate	63 mg/L	1,152 mg/L
Chloride	25 mg/L	27 mg/L

Silver Bowions Water Quality Diagram

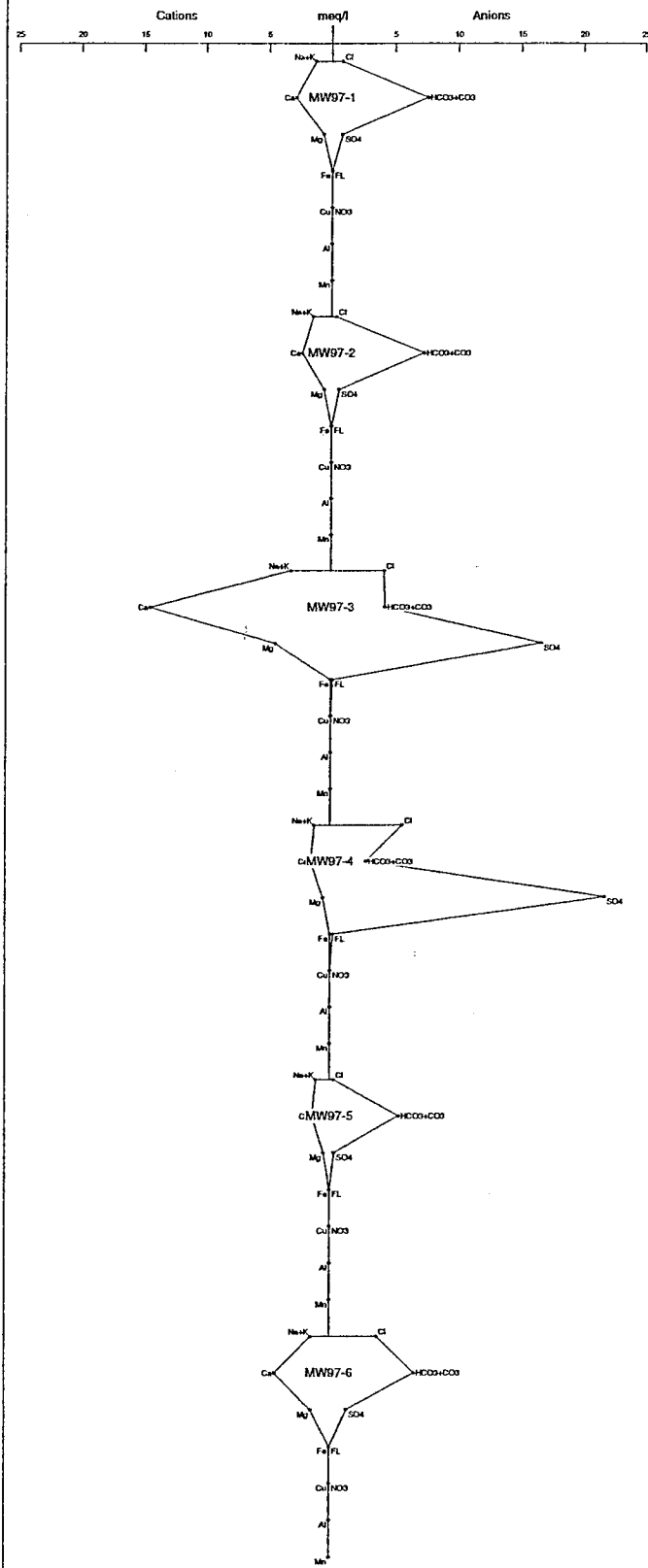


Silver Bowions Water Quality Diagram





Silver Bowions Water Quality Diagram



The synthetic water were created in 2 liter batches for immediate use by: (1) weighing out on a knife-edge balance high-purity reagent-grade powdered compounds in quantities to formulate the desired major ion concentrations; (2) adding compounds to 2 liters of double-dionized water ($18.2 \mu\text{mho/cm}$); (3) stirring with a magnetic stirrer and adding small quantities of 1 N HCl to reduce the pH and dissolve the constituents; and (4) adding small quantities of 1 N NaOH to increase the pH to @ 7. If synthetic water needed to be of a different pH for a particular experiment, the pH was further modified by titrating with NaOH or HCl. Synthetic water was kept at room temperature (@ 20°C).

Soil-Water Conditioning and Equilibration

The soil samples must undergo a “conditioning” process prior to the adsorption batch experiments, as required by ASTM D 4319. The conditioning process consisted of the following procedure:

1. 40 ml of the appropriate synthetic water (groundwater or tailings water, depending upon the experiment) at the target pH was added to the sample bottle that contained the soil sample.
2. The bottle was screwed shut and shaken to disaggregate the soil sample completely.
3. The bottle was shaken in a Wrist-Action® shaker for 15 minutes at moderate speed.
4. The bottle was centrifuged for 5 minutes at 1,000 g.
5. The water was decanted and discarded.¹
6. Steps 1 through 5 were repeated twice more.

The purposes of the conditioning process are: (1) to displace any free water that is associated with the sample, such as pore water; (2) to remove very loosely bound arsenic that might skew the batch experiment results; and (3) to approximate an equilibrium between the synthetic water and the soil sample.

The equilibration process begins by repeating steps 1 and 2 a fourth time. The bottle is placed in the Wrist-Action® shaker but is shaken for 24 hours. The sample is allowed to sit for 15 minutes before centrifuging for 5 minutes at 1,000 g. After centrifuging the sample, the water is decanted into a graduated cylinder and the pH is adjusted, as necessary, to approximate the target pH. The water sample size is reduced to 39.5 ml. If the water sample is not 39.5 ml, minor amounts of synthetic water are added to bring to volume to 39.5 ml. The pH and Eh are measured and recorded. The sample is then returned to the bottle and awaits spiking with an arsenic solution.

Arsenic Spiking

Arsenite (As(III)) or arsenate (As(V)) was used to spike the equilibrated synthetic water for batch adsorption experiments. One liter concentrated solutions of arsenite (1,000 mg/L As(III)) were made by adding 1,733 mg of powdered, reagent-grade sodium m-arsenite (NaAsO_2) to 1 liter of double-dionized water at 20°C . One liter concentrated solutions of arsenate (1,000 mg/L As(V)) were made by adding 4,160 mg of powdered, reagent-grade sodium arsenate ($\text{Na}_2\text{HAsO}_4 \cdot 7\text{H}_2\text{O}$) to 1 liter of double-dionized

¹ Selected decant water was filtered and analyzed for arsenic to evaluate how much arsenic was being removed from the soil sample in this process.

water at 20°C. These solutions were stirred magnetically for 20 minutes or until all visible powder was dissolved.

The concentrated arsenite and arsenate solutions were used to make diluted solutions for spiking. The target initial concentrations for arsenite or arsenate in the 40 ml synthetic water solution were 0 µg/L, 10 µg/L, 50 µg/L, 100 µg/L, 250 µg/L, and 500 µg/L. 5 ml of spiking solution were added to the 39.5 ml of equilibrated synthetic water to attain a 40 ml volume with the requisite concentration. Thus, dilutions of the spiking concentrates were necessary so that 0.5 ml of the diluted solution, when added to 39.5 ml of synthetic water, would result in the target initial concentration.

Diluted spiking aliquots for each target concentration were made in 250 ml batches from the concentrate as follows:

desired test As concentration	10 ug/L	50 ug/L	100 ug/L	250 ug/L	500 ug/L
quantity of 40 mg/L As concentrate to be diluted in distilled water to make a ¼ liter volume	5 ml of 40 mg/L As solution added to 245 ml of distilled water	25 ml of 40 mg/L As solution added to 225 ml of distilled water	50 ml of 40 mg/L As solution added to 200 ml of distilled water	125 ml of 40 mg/L As solution added to 125 ml of distilled water	0 (a 0.5 ml aliquot of 40 mg/L solution is used directly)

A 1-ml glass pipette was used to deliver the spike to the sample bottle. The bottle was immediately closed and shaken to disaggregate the sample.

Additional batch experiments were employed using alluvium and tailing with synthetic tailings water and initial spiked arsenate concentrations of 10,000 ug/L, 100,000 ug/L, and 500,000 ug/L. These experiments were performed after the results of the experiments with the original spiking concentrations were evaluated. The reason for performing these experiments was that the adsorption capacity of the materials were found to be much higher than expected and the equilibrium concentration with a beginning spike of 500 ug/L arsenate was lower than historical concentrations of arsenic in the tailings pond.

Contact Period and Sampling for Batch Adsorption Experiments

Samples were placed on the Wrist-Action® shaker in groups of 16 and shaken for at least 3 hours each day during the contact period – except they were not shaken during the final 24 hours before sampling, as required by ASTM D 4319.

Most samples were shaken for a period of seven days. This contact time was selected because a previous batch experiment study of arsenic using similar soils (Wuol, 1986) found that concentrations in solution stabilized before seven days. Some experiments were duplicated for contact times of three days and 14 days, as required by ASTM D 4319 in order to verify that a quasi-steady-state condition was attained.

At the end of the contact period, sample bottles were centrifuged at 1,600 g for 20 minutes, as outlined in ASTM D 4319. The sample bottle tops were removed and pH-Eh measurements were taken in the bottle, taking care to not disturb the soil. The supernatant was then placed in a new disposable filtration system

and filtered under vacuum through an 0.45 μm filter. The filtered sample was then placed in a glass vial that contained nitric acid preservative. The vial, with preservative, were provided by the laboratory (Braun Intertec). The samples were then delivered to the laboratory for arsenic analysis by induced plasma methods.

Desorption Batch Experiments

Immediately after sampling for the adsorption phase of the batch experiment, 40 ml of unspiked synthetic water (at the appropriate pH) was added to the sample bottle that contained the soil sample. The cap was secured and the contact period began, with shaking identical to the adsorption phase. At the end of the desorption contact period (which was of similar length to the adsorption contact period), the sample was centrifuged and sampled in a manner identical to the adsorption phase. The sample bottle and soil sample were then discarded.

Miscellaneous Experiments

A small number of miscellaneous batch experiments were performed to evaluate experiment methodology and quality of the data. Some of these experiments are part of the ASTM D 4319 protocol.

Evaluation of Effects of Contact Time

As previously discussed, contact times of 3 days and 14 days were employed in addition to the contact time of 7 days for some experiments. Adsorption and desorption experiments with these contact times were performed for all four soil types at initial As(V) concentrations of 50 $\mu\text{g/L}$. Contact times other than 7 days were not employed for other concentrations or for As(III).

Evaluation of Sorptive Characteristics of Sample Bottle

Adsorption and desorption batch experiments were performed using 40 ml of synthetic groundwater (target pH of 7) spiked with 10, 50, 250, and 500 $\mu\text{g/L}$ As(V) and no soil sample. The purpose of these experiments was to evaluate how much arsenic sorption might be attributable to the interior surface of the polypropylene centrifuge bottle that was used in these experiments.

Removal of Arsenic by the Conditioning Process

One of the purposes of the conditioning process is to remove pre-existing arsenic that is loosely “attached” or poorly adsorbed on the soil surfaces or is in the interstitial pore spaces. If this arsenic is not removed, the experimental results might be difficult to interpret. We wanted to evaluate how much, if any, arsenic is removed from the soil by the conditioning process required by ASTM D 4319. For each of the four soil types, the conditioning water supernatant was filtered and analyzed for arsenic.

Batch Experiment Results

The results of the batch experiments are summarized in Table 1. These results were used primarily to compute Freundlich isotherms. The Freundlich isotherm represents a model for the equilibrium sorption between a solute (in this case, As(III) and As(V)) and the soil. In order to construct these isotherms, the mass of the solute that is sorbed onto the soil must be calculated.

Overview of Isotherms

An isotherm (simply meaning “at equal temperature”) relates the mass of a constituent that is adsorbed on a solid (usually expressed in mass adsorbed per unit mass of soil) with the concentration of the constituent in solution. Equilibrium is assumed (this assumption can be tested to a certain extent by performing batch experiments with differing contact times).

There are two common types of isotherms – Freundlich isotherms and Langmuir Isotherms. The Freundlich isotherm is represented by the equation (Huggenberger et al., 1972; Rubin and Mercer, 1981):

$$\hat{C} = K_f C^a$$

where: $\hat{C}$: mass of metal adsorbed per unit mass of the sediment
 C : concentration of metal in solution
 K_f and a are constants

The above equation in log-log form is a linear expression:

$$\log \hat{C} = \log K_f + a \log C$$

Linear regression can be used to fit a straight line to the data in log-log form and obtain the constants K_f and a .

The Freundlich isotherm has the advantage of being relatively insensitive to erroneous data but it does not provide for a maximum value of $\hat{C}$ (mass of adsorbed metal per unit weight of soil). The result is an expression that predicts infinite adsorption at infinite concentration – a situation that does not take place, as detailed studies of adsorption at high concentrations has shown (e.g., Anderson et al, 1976). However, for low concentrations, in which the maximum sorption capacity of the soil is not approached, Freundlich isotherms are applicable.

Many researchers have advocated the use of the Langmuir isotherm in representing adsorption data because the Langmuir isotherm has a maximum. Accounting for a maximum sorption capacity is

advantageous in situations where the sorptive nature of the soil-solute is to be characterized over a wide range of concentrations. The Langmuir isotherm is expressed by the following equation (Forstner and Wittmann, 1979; Rubin and mercer, 1981):

$$C/\hat{C} = 1/(AB) + C/A$$

where: C and $\hat{C}$ have the same meaning as in the Freundlich equation

A and B are constants

The Langmuir expression is a polynomial which passes through the origin and allows for a maximum adsorption value. It can be thought of as consisting of a linear portion at very low concentrations, a log-log linear portion over mid-range concentrations, and a binomial portion at high concentrations. At mid concentrations, the Langmuir isotherm and the Freundlich isotherm are approximately the same.

The equilibrium concentration ranges used in this study are relatively low – corresponding to the mid-range zone in the Langmuir isotherm. This concentration range was chosen because it best represents the observed concentrations at the Silver Bow facility (i.e. very high arsenic concentrations in groundwater have not been observed). It made no sense to spend resources defining the sorption maximum for concentration conditions that will never be attained. Thus, resources were directed toward defining the sorption conditions at expected concentrations. Within these ranges, the Freundlich isotherm is a better tool and it was used to model the sorptive behavior in this study.

Calculating Mass Adsorbed and Desorbed

The mass adsorbed by the soil sample is assumed to be the difference in between the initial mass of the solute and the final mass of the solute. For example, if 50 $\mu\text{g/L}$ As(V) is the initial concentration, the total initial mass of As(V) in solution is 50 $\mu\text{g/L}$ x 0.04 L, or 2 μg . If the final As(V) concentration is 20 $\mu\text{g/L}$, then (50 $\mu\text{g/L}$ – 20 $\mu\text{g/L}$) x 0.04 L, or 1.2 μg of As(V) was adsorbed by the 40 g soil sample. Thus, the amount of As(V) adsorbed per gram of soil is 1.2 $\mu\text{g}/40$ g, or 0.03 $\mu\text{g/g}$. The equilibrium concentration of As(V) that corresponds to 0.03 $\mu\text{g/g}$ As(V) adsorption is 20 $\mu\text{g/L}$.

The above calculation actually represents the amount of As(V) that is adsorbed *in addition* to any As(V) that may already be on the soil when it was sampled. Preconditioning likely will remove some of this latent arsenic but some likely remains. Therefore, the mass of As(V) adsorbed per unit mass of soil is likely a lower-end estimate because the mass of arsenic already adsorbed onto the soil surfaces is not accounted for. This will result in a conservative estimate of the soil's ability to sorb arsenic.

The desorption phase of the batch experiments involves equilibrating the soil (containing the sorbed arsenic) with synthetic water that does not have an initial concentration of arsenic. Generally, arsenic will desorb in response to the concentration gradient between the solid phase and the dissolved phase until a new equilibrium concentration is attained. These data provide information on the reversibility of the sorption reaction and can be used to construct desorption Freundlich isotherms.

As with the adsorption calculations, the desorption calculation assumes that the mass of arsenic remaining on the solid is the difference between the amount desorbed (in solution) and the amount that was assumed to be adsorbed from the first part of the experiment. Because the soils used in this study contain arsenic (most likely in a sorbed form), the actual mass of arsenic in the solid phase is likely greater than the amount calculated from the spiking. Therefore, the mass of arsenic desorbed per unit mass of soil is likely an upper-end estimate because the mass of arsenic already adsorbed onto the soil surfaces is not accounted for. This will result in a conservative estimate of the soil's ability to retain adsorbed arsenic (in other words, it will tend to overestimate the amount of arsenic desorbed per mass adsorbed). For example, an adsorption batch experiment with 0 µg/L arsenic in the original spike should result in a final arsenic concentration at the end of the adsorption experiment of 0µg/L; however, the concentration will likely be something greater than zero. This would be due to the desorption of pre-existing arsenic in the solid.

Evaluating Sorptive Characteristics of Sample Bottle

Glass sample bottles were not used for the batch experiments because dissolved arsenic is suspected to have an affinity to adsorb onto the surface of the glass container. For this reason, fresh spiking concentrates and dilutions were prepared immediately before spiking and were discarded after one day. Polypropylene bottles manufactured by Corning were selected as batch experiment sampling bottles because they held a sufficient volume (50 ml), could be accommodated by the centrifuge, and were shown in a previous study (Wuolo, 1986) to be relatively unreactive with arsenite and arsenate.

Four adsorption and desorption experiments were performed using synthetic groundwater, As(V) spikes (10, 50, 250, and 500 µg/L) and contact times of approximately 7 days to evaluate the sorptive characteristics of the sampling bottles. The results are as follows:

Adsorption (7 day Contact)		Desorption (7 day Contact)	
Initial As(V) Conc. (µg/L)	Final As(V) Conc. (µg/L)	Initial As(V) Conc. (µg/L)	Final As(V) Conc. (µg/L)
10	10	0	<0.50
50	46	0	<0.50
250	230	0	0.70
500	470	0	0.70

The results suggest that the interior surface of the sampling bottle adsorbs approximately 8 % of the As(V) at various concentrations. This adsorbed As(V) does not appear to reversibly desorb because the concentrations at the end of the desorption phase of the experiment were either non-detectable or at very low concentrations.

Evaluating Arsenic Removal During Conditioning Process

ASTM D 4319 requires that the soil sample undergo a "conditioning" process with the water that will be used in the experiments. This involves three contact periods of 15 minutes, followed by centrifuging and discarding of the supernatant. Total analyses of the soil samples, following digestion and analyses of

eluant in the ASTM leach procedure indicate that there is arsenic present in the soil samples. The 40 ml supernatant from selected conditioning procedures was analyzed for arsenic to evaluate how much, if any, pre-existing arsenic was removed by this procedure. The results are as follows:

Soil Type	1st Conditioning	2rd Conditioning	3rd Conditioning	Total Removed ($\mu\text{g/g}$)
Alluvium	7.1 $\mu\text{g/L}$	5.9 $\mu\text{g/L}$	5.5 $\mu\text{g/L}$	0.074
Fluvial	6.4 $\mu\text{g/L}$	6.2 $\mu\text{g/L}$	4 $\mu\text{g/L}$	0.0664
Tailings	9.1 $\mu\text{g/L}$	8.8 $\mu\text{g/L}$	9.9 $\mu\text{g/L}$	0.1112
Slack Water	30 $\mu\text{g/L}$	29 $\mu\text{g/L}$	30 $\mu\text{g/L}$	0.356

The concentration of arsenic in each of the three conditionings for each soil type is very similar. Except for the slack-water deposit, the total arsenic removed on a μg arsenic per gram soil basis for each conditioning is very similar to the leaching values reported by Energy Laboratories using ASTM Method D 3987 (i.e. one-third of the total removed in the above table). The slack-water deposit yields considerably more arsenic than what was reported to be leached using ASTM D 3987.

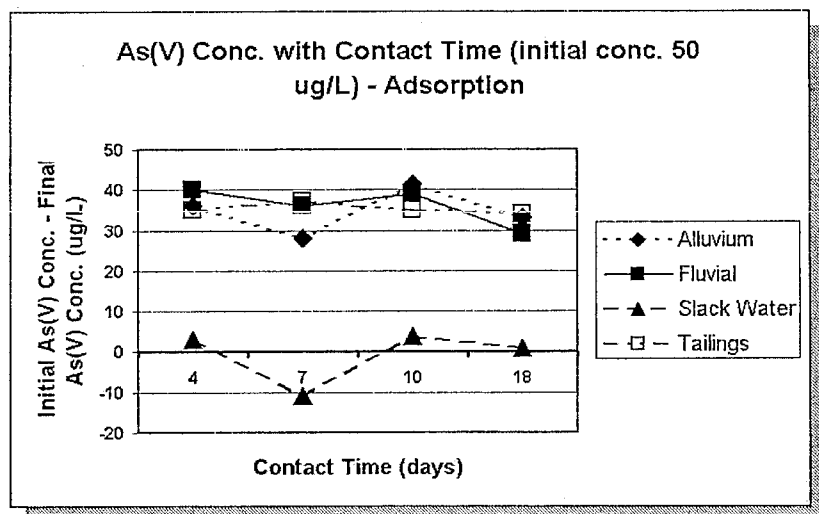
The presence of arsenic in the conditioning water indicates that desorbable arsenic is present on all four soil types – especially in the slack-water deposit (which had the largest total arsenic concentration when digested and analyzed). The uniformity of the concentration between conditionings suggests that an equilibrium concentration is reached rather quickly.

Evaluating Effect of Contact Time on Sorption

ASTM D 4319 suggests that duplicate experiments should be performed on selected samples using different contact times, ranging from 3 days to about 14 days. For this study, a contact time of roughly 7 days was selected for most experiments because previous studies of arsenic adsorption using similar soil materials have demonstrated that 7 days should be sufficient to reach an equilibrium condition (e.g., Wuolo, 1986). Contact times of 3 days, 10 days, and 18 days were also performed for all four soil types using 50 $\mu\text{g/L}$ As(V) as the initial spike. Desorption of these soil samples used identical contact times.

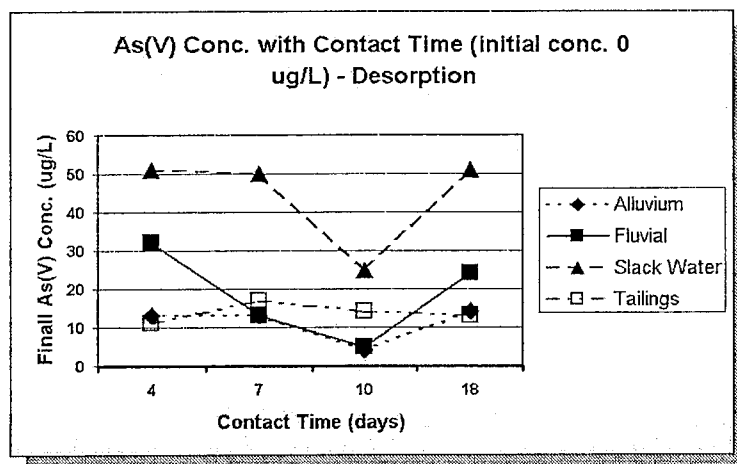
The change in concentration with contact time for the adsorption phase is shown on Figure 1.

Concentrations of As(V) do not change very much between 3 days and 18 days, suggesting that an apparent equilibrium condition was reached before day 3 of the contact period. The equilibrium concentration for alluvium, fluvial deposits, and tailings are generally about the same, showing a reduction in the concentration of between 30 and 40 $\mu\text{g/L}$ – a result that is consistent with the concentrations found in the conditioning samples. This



suggests that adsorption equilibration happens very quickly – perhaps within 15 minutes. The results depicted in Figure 1 indicate that there is almost no reduction in initial concentration of As(V) in the presence of the slack-water deposits.

The contact time during the desorption phase of the batch experiments generally show a similar trend, as depicted in Figure 2. There is a little bit more “noise” in the data but the same general trends that are observed with the adsorption data seem to apply to the desorption data.



Evaluating the Effect of pH on Adsorption

The pH of the water has been shown to be an important factor in arsenic adsorption for reason explained in the Introduction. Anderson et al. (1976), Gulens et al., (1979), and Goddard and Wuolo (1986) have shown that maximum adsorption and minimum desorption takes place near the pH of the isoelectric point (pH_{iep}) of the sorbing medium. The pH_{iep} for hydrous iron oxides has been reported to be between 6 and 9 (Drever, 1982). Frost and Griffin (1977) reported maximum adsorption of As(V) in the more acidic region of 5.0 for kaolinite and montmorillonite. Similarly, acidic pH's for maximum adsorption of As(V) by bauxite have been reported by Gupta and Chen (1978).

The pH of groundwater and tailings water at the Silver Bow site is generally in the 7.0 to 8.0 range – the optimum range for arsenic adsorption by iron hydroxide coatings in the aquifer materials. In order to examine the effect of pH on adsorption of both As(III) and As(V), batch experiments were performed for adsorption and desorption in which the initial pH of the liquid was adjusted (through titration with NaOH or HCl) to attain values of 5.5 and 8.5 immediately prior to commencement of the contact period. The pH of the conditioning and equilibration water were likewise adjusted. Most of the experiments in this study used a target pH of 7.0.

The results were not as expected because all four soil materials appear to be very strong pH buffers. In cases where pH values of the solution were adjusted to about 5.5 and 8.5, the final pH was almost always between 7.0 and 8.0. It is the final pH that dictates the equilibrium condition; therefore the final pH is the value that must differ in order to evaluate the effects of varying pH on adsorption and desorption.

The only conclusion that can be drawn from these experiments is that the soils strongly buffer pH in the 7.0 to 8.0 range and that substantially lower pH values are not likely to be encountered. Higher pH values are less of an issue because: (1) iron hydroxide at higher pH values is stable; (2) the negative charge of

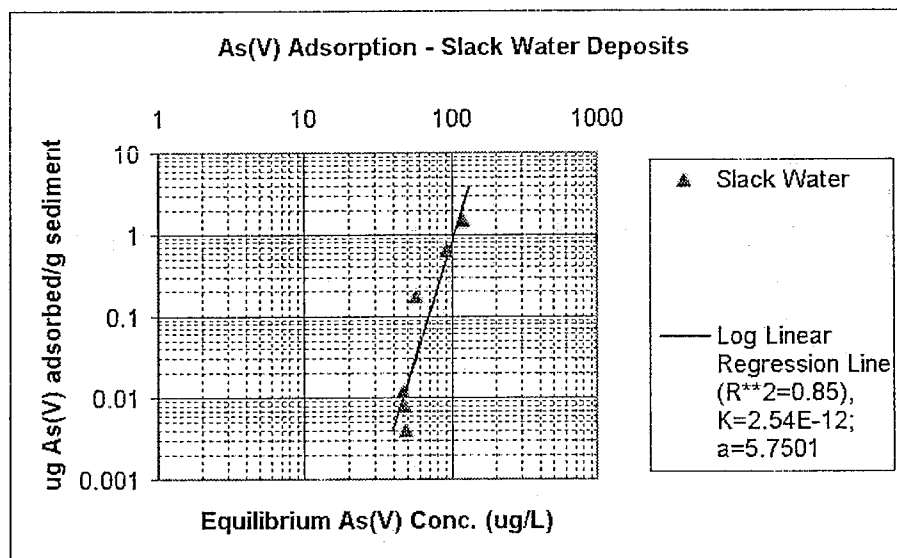
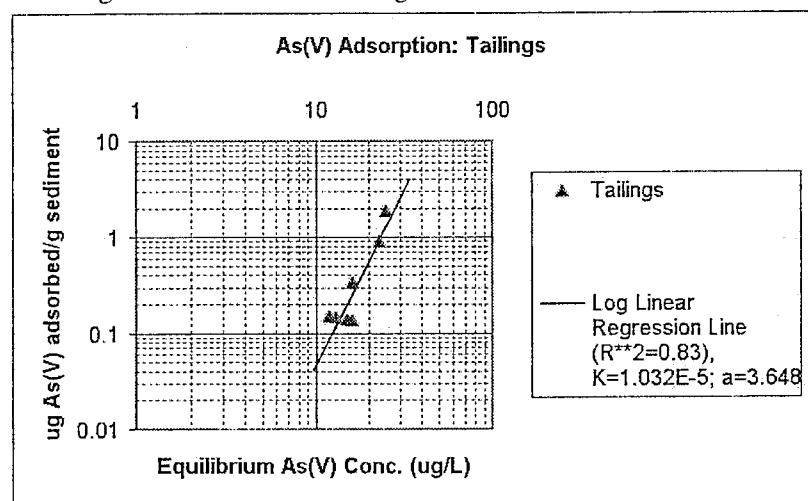
the hydrolyzed arsenic species is greater at higher pH's, resulting in a greater affinity for positively charged surfaces; and (3) the positive charge of iron hydroxide coatings is stable at pH's above the pH_{iep} . If pH's below @ 6.0 become prevalent, additional sorption studies may be warranted.

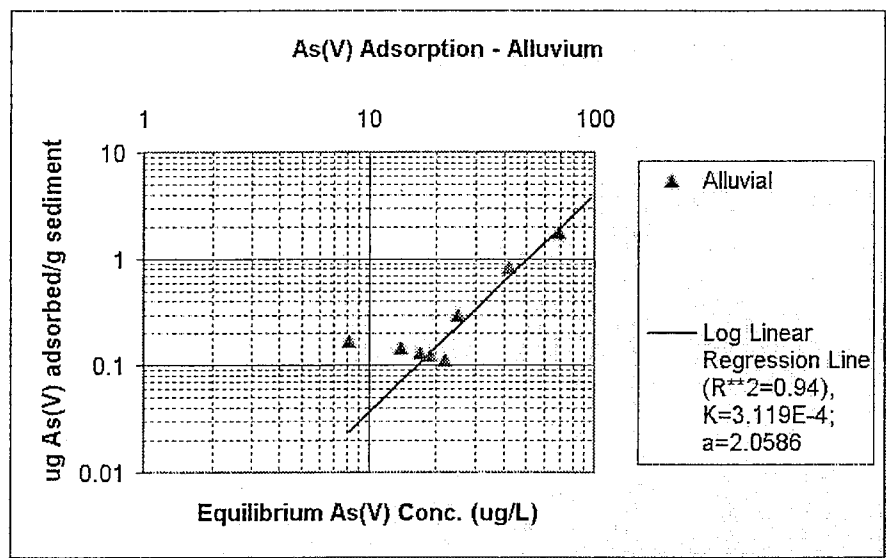
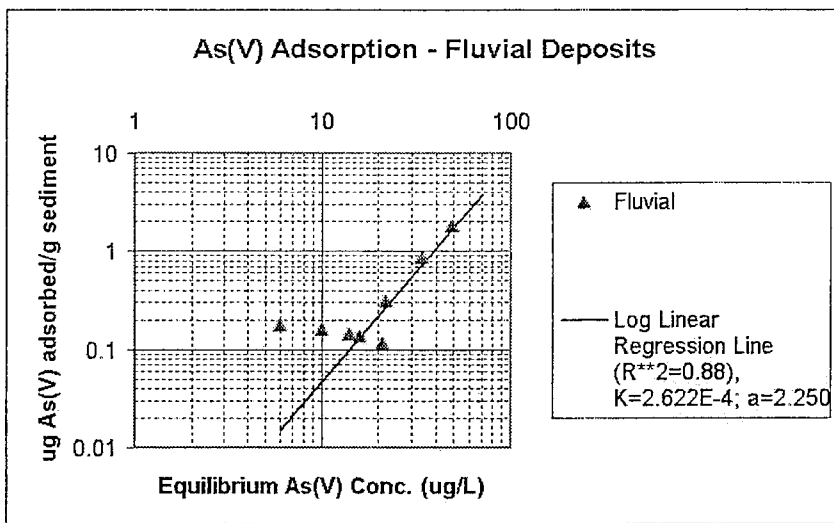
Sorption-Equilibrium Concentration Relationships

Equilibrium concentrations of As(III) and As(V) as a function of the mass of arsenic adsorbed are the principal results of this study. As previously discussed, these data are plotted in log-log format and fitted to a log-log line that represents the Freundlich isotherm. Within this sphere of equilibrium concentrations, there were several factors that might affect sorption that were examined. These factors include: (1) soil type; (2) arsenic valence state (i.e. +3 or +5); and ionic strength of the water (represented by two kinds of water -- groundwater of lower ionic strength and tailings water of higher ionic strength).

Arsenate Adsorption with Synthetic Groundwater

The following plots depict the results of arsenate equilibrium adsorption in groundwater with the four soil types. Linear regression analysis was performed on the data to obtain the Freundlich constants K_f and a . R^2 is the "goodness of fit" of the regression line.

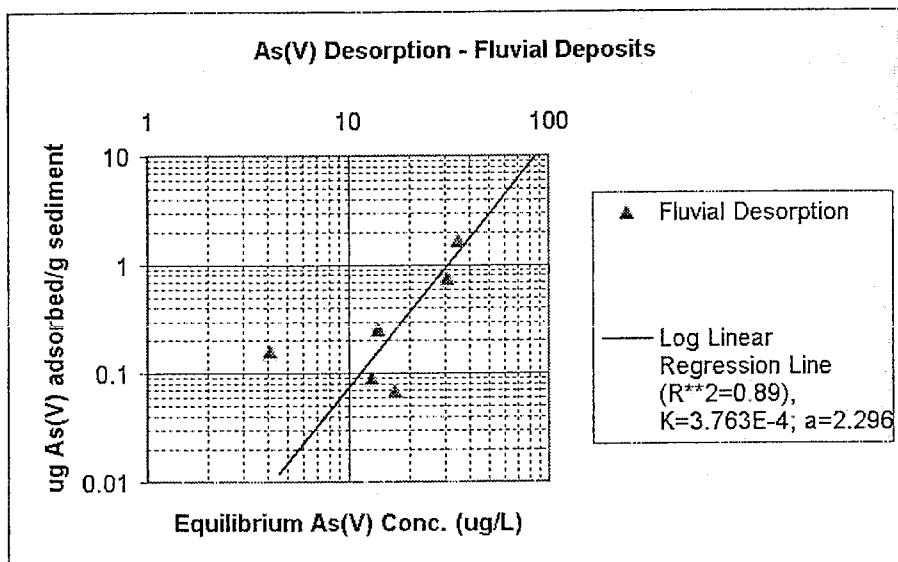
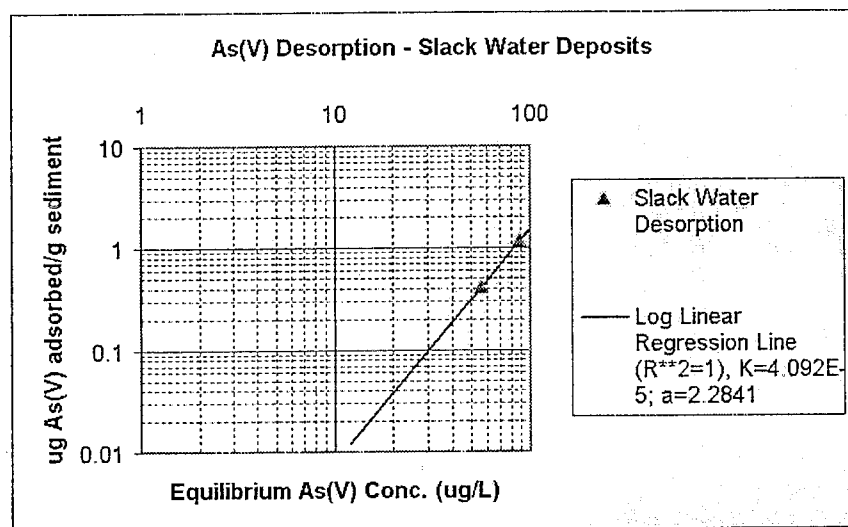
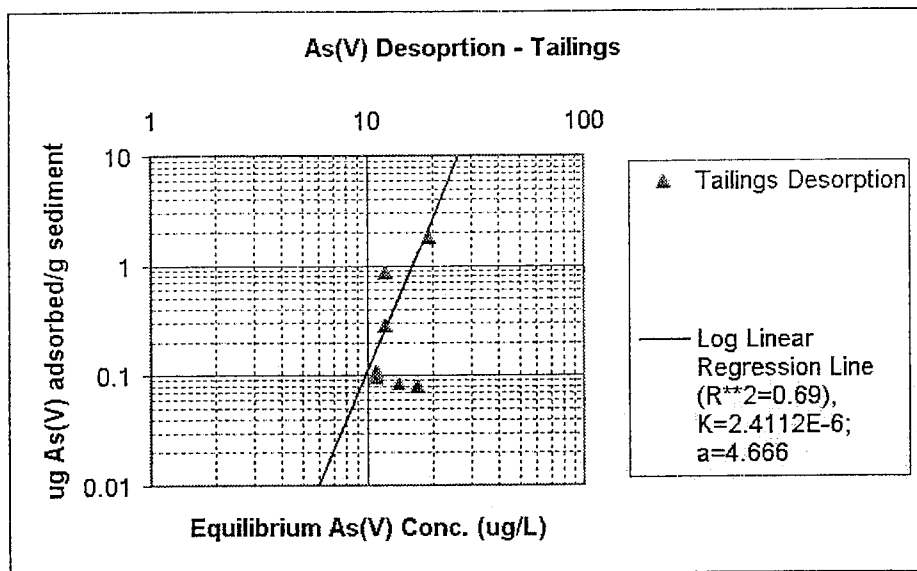


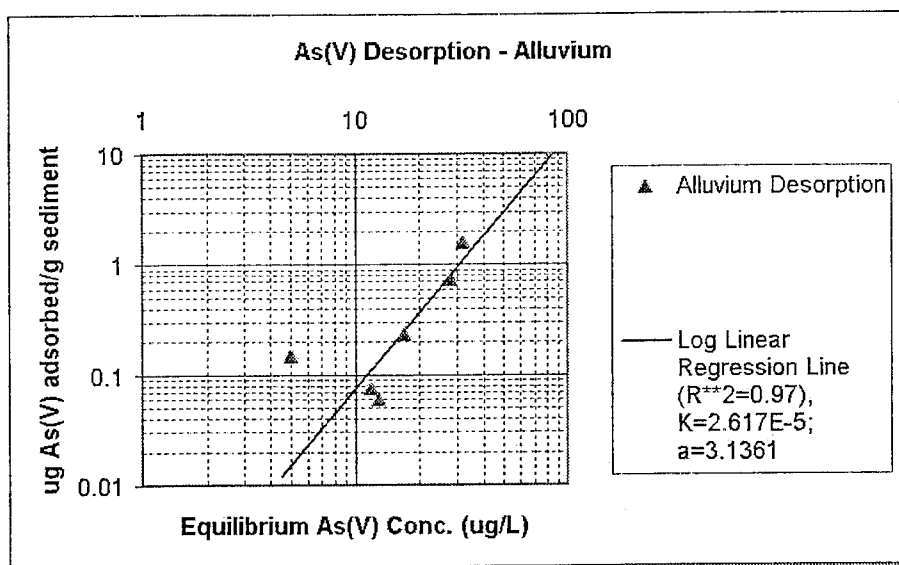


The steeper line (i.e. the higher value of a) indicates a higher capacity to adsorb arsenate and to maintain an equilibrium concentration. The slack-water deposits display the steepest slope, indicating the highest As(V) adsorption capacity. However, the equilibrium concentration at which sorption takes place is generally higher than for the other deposits. Tailings material has the next highest sorption capacity. Tailings and slack-water deposits likely have high adsorption capacities because they have a higher proportion of fine-grained sediment and thus, more surface area. Alluvium and fluvial deposits display nearly identical As(V) adsorption behavior.

Arsenate Desorption with Synthetic Groundwater

The following plots depict the results of arsenate equilibrium desorption in groundwater with the four soil types. Linear regression analysis was performed on the data to obtain the Freundlich constants K_f and a . R is the “goodness of fit” of the regression line. The mass left on the soil surface was assumed to be the mass adsorbed minus the mass in solution (i.e. the presence of pre-existing arsenic was not accounted for).

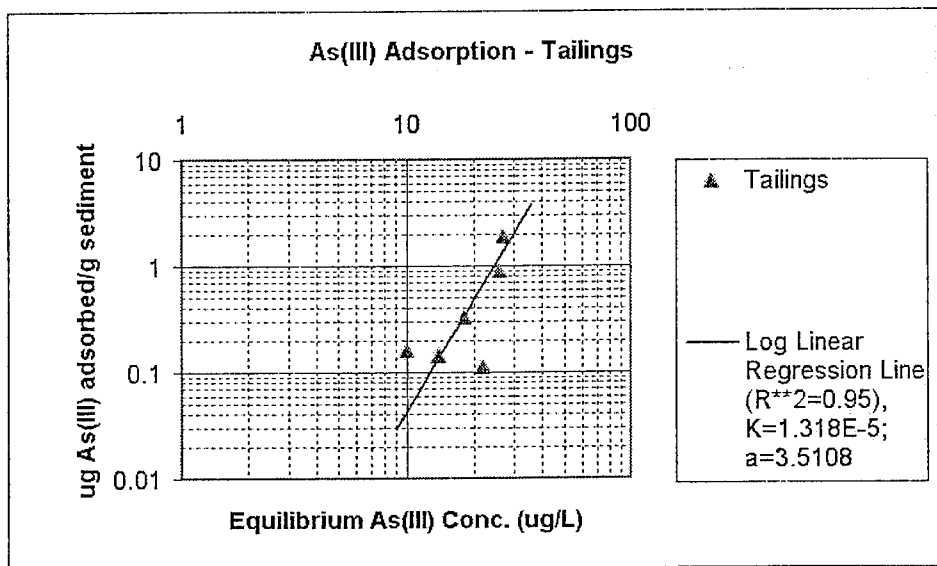


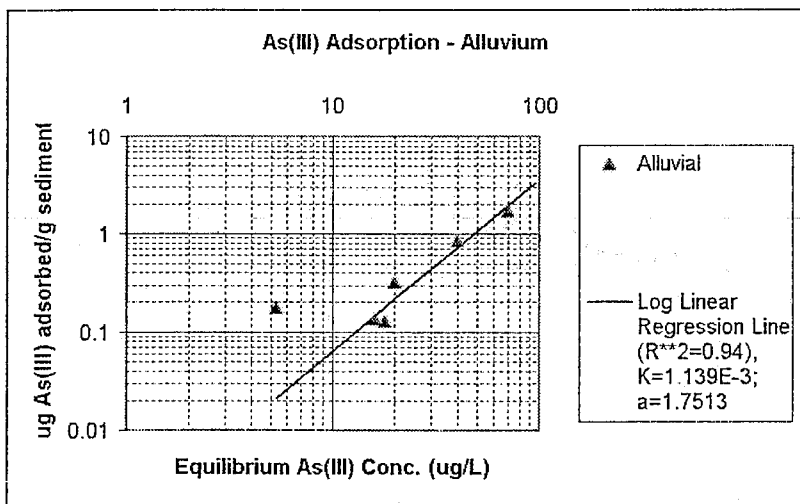
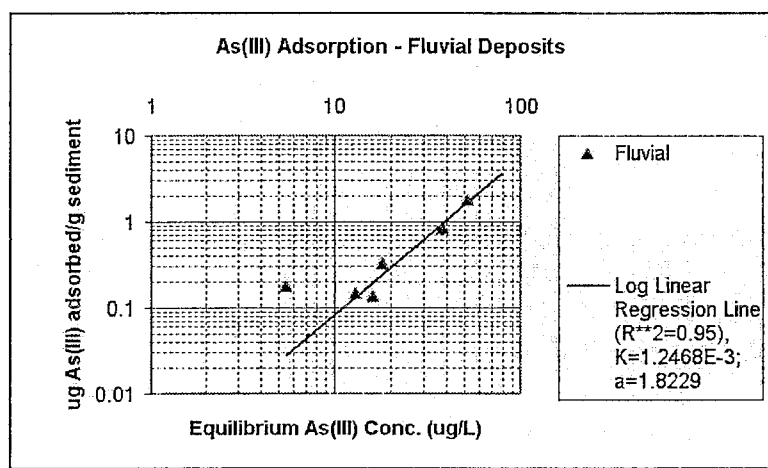
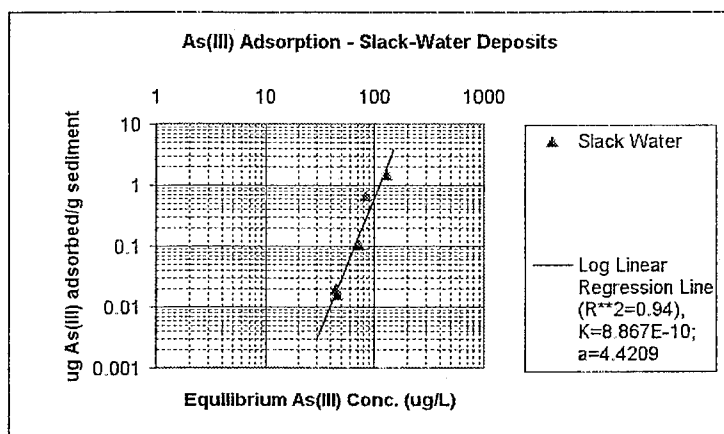


With the exception of the slack-water deposits, the desorption of As(V) is very similar to the adsorption of As(V). This similarity is indicative of a reversible, equilibrium process. It is likely that the slack-water adsorption curve is in error as only two data points are available (the other data predicts negative sorption – i.e. the final equilibrium concentration was higher than the initial spike, likely because of the substantial arsenic content of the slack-water deposits).

Arsenite Adsorption with Synthetic Groundwater

The following plots depict the results of arsenite equilibrium desorption in groundwater with the four soil types. Linear regression analysis was performed on the data to obtain the Freundlich constants K_f and a . R is the “goodness of fit” of the regression line. The mass left on the soil surface was assumed to be the mass adsorbed minus the mass in solution (i.e. the presence of pre-existing arsenic was not accounted for).

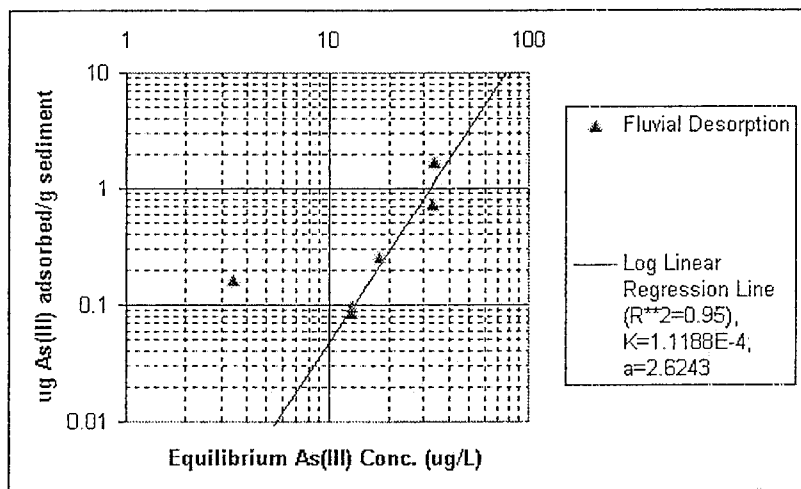
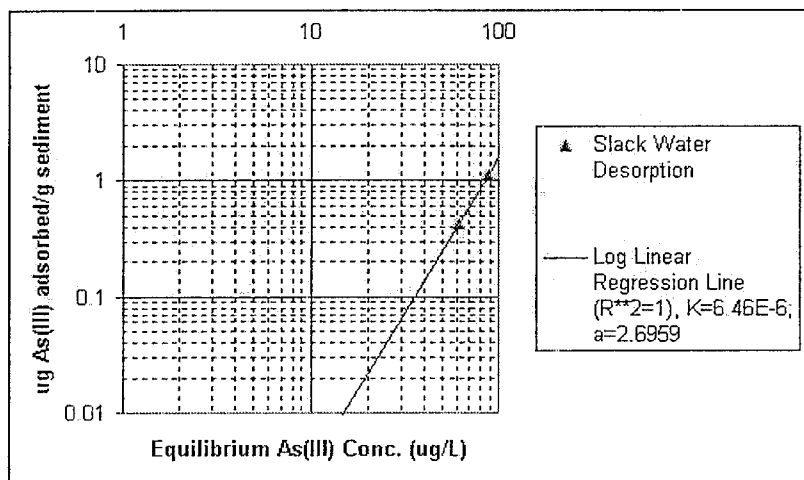
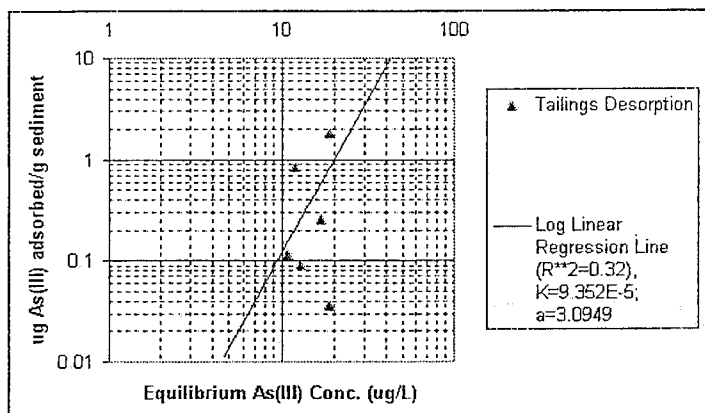


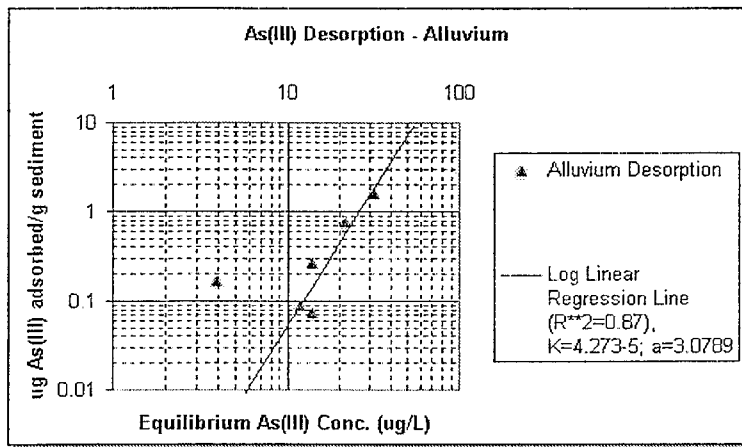


For the most part, the adsorption characteristics of arsenite for the four soil media were similar to that of arsenate. These results seem to suggest that the valence state of arsenic in the pH and redox range of these experiments does not meaningfully affect the adsorption characteristics of arsenic.

Arsenite Desorption with Synthetic Groundwater

The following plots depict the results of arsenite equilibrium desorption in groundwater with the four soil types. Linear regression analysis was performed on the data to obtain the Freundlich constants K_f and a . R^2 is the “goodness of fit” of the regression line. The mass left on the soil surface was assumed to be the mass adsorbed minus the mass in solution (i.e. the presence of pre-existing arsenic was not accounted for).

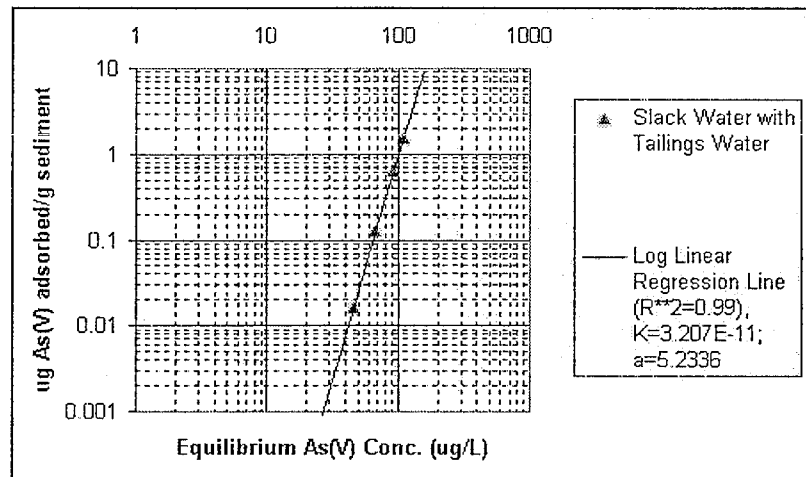
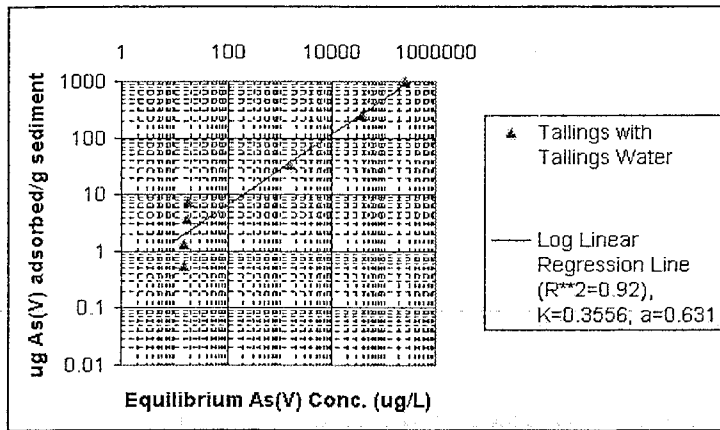


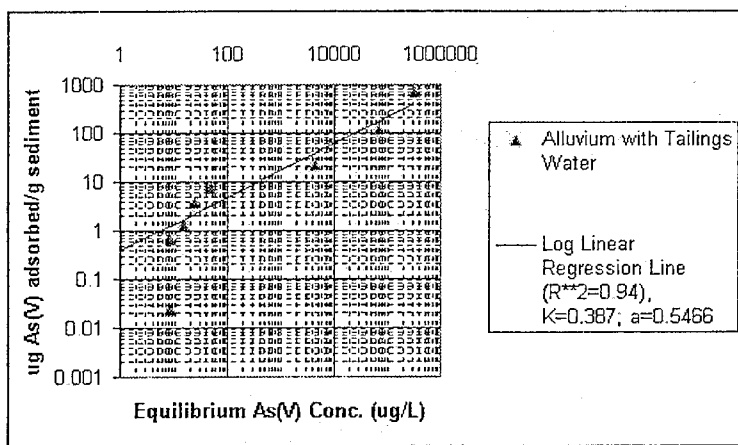
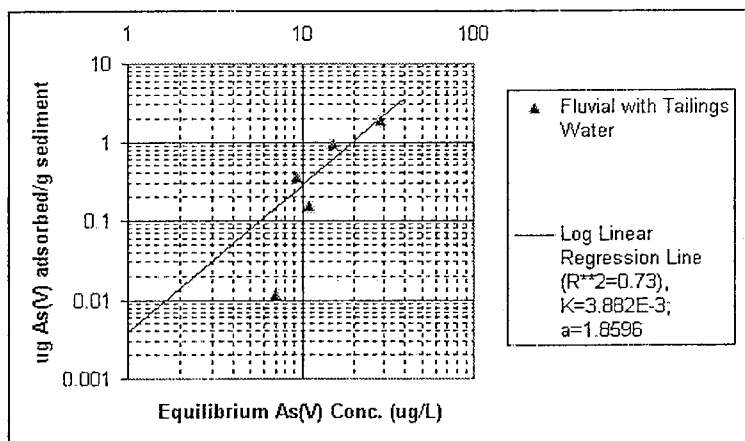


The desorption of As(III) is very similar to the adsorption of As(III). This similarity is indicative of a reversible, equilibrium process.

Arsenate Adsorption with Synthetic Tailings Water

The following plots depict the results of arsenate equilibrium adsorption in tailings water with the four soil types. The main difference between the synthetic groundwater and the synthetic tailings water is that the tailings water has higher ionic strength. Linear regression analysis was performed on the data to obtain the Freundlich constants K_f and a . R is the “goodness of fit” of the regression line.

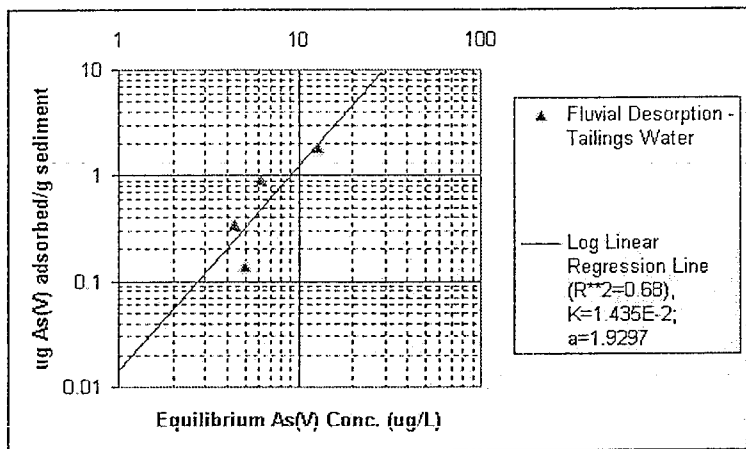
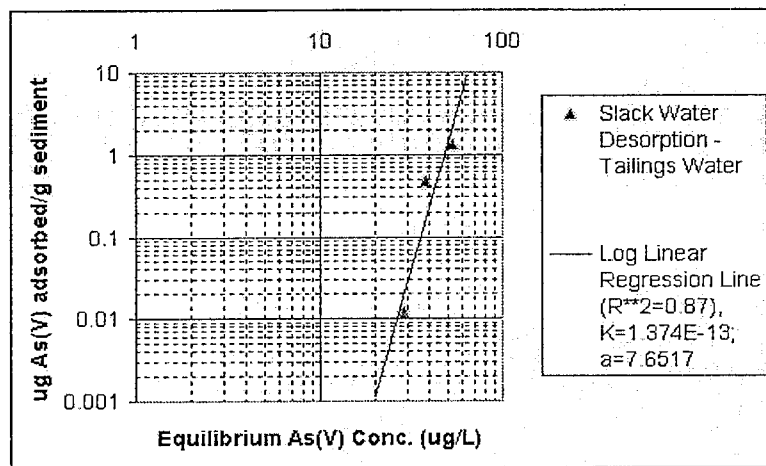
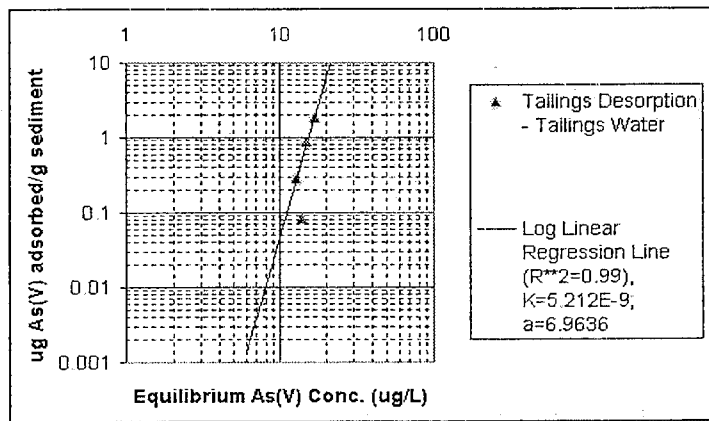


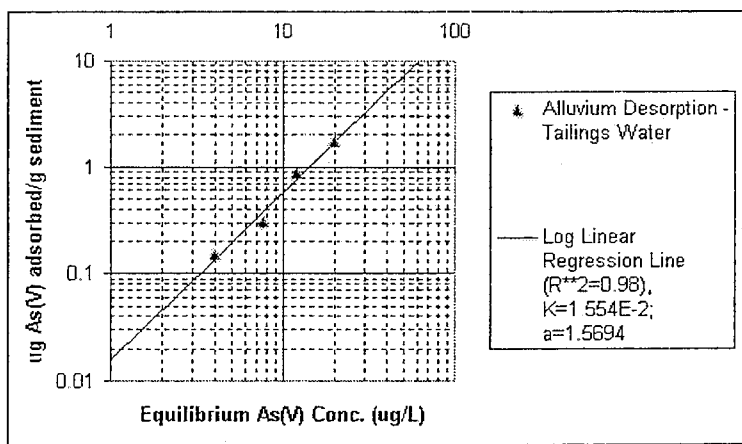


For the most part, the effects of the higher ionic strength in the synthetic tailings water did not impart an adsorption of arsenate that was markedly different from that of the groundwater. However, the effects of three higher equilibrium concentrations of arsenate (imparted by much higher initial spike values) did flatten out the Freundlich line. In other words, at higher concentrations, somewhat less arsenate would be adsorbed than at lower concentrations. Surprisingly, the data still fits a Freundlich model better than a Langmuir model – even at the higher concentrations, there did not seem to be any indication that an adsorption maximum was being reached. This results indicates that both the tailings material and the alluvium have very high capacities for adsorbing arsenic.

Arsenate Desorption with Synthetic Tailings Water

The following plots depict the results of arsenate equilibrium desorption in tailings water with the four soil types. Desorption data for the three high initial concentration spikes (10,000, 100,000, and 500,000 ug/L) were not collected. Linear regression analysis was performed on the data to obtain the Freundlich constants K_f and a . R is the “goodness of fit” of the regression line. The mass left on the soil surface was assumed to be the mass adsorbed minus the mass in solution (i.e. the presence of pre-existing arsenic was not accounted for).





Summary of Data Analyses

The following table summarizes the analyses of the data in there various forms in order to give a range of Freundlich parameters for use in solute-transport modeling.

Material	Species	Water	Test Type	K	a
Alluvium	As(III)	Groundwater	Adsorption	1.14E-03	1.7513
Alluvium	As(III)	Groundwater	Desorption	4.27E-05	3.0789
Alluvium	As(V)	Groundwater	Adsorption	3.12E-04	2.0586
Alluvium	As(V)	Groundwater	Desorption	2.62E-05	3.1362
Alluvium	As(V)	Tailings Water	Adsorption	7.60E-03	1.4428
Alluvium	As(V)	Tailings Water	Desorption	1.55E-02	1.5694
Fluvial	As(III)	Groundwater	Adsorption	1.25E-03	1.8229
Fluvial	As(III)	Groundwater	Desorption	1.12E-04	2.6243
Fluvial	As(V)	Groundwater	Adsorption	2.62E-04	2.25
Fluvial	As(V)	Groundwater	Desorption	3.76E-04	2.296
Fluvial	As(V)	Tailings Water	Adsorption	3.88E-03	1.8596
Fluvial	As(V)	Tailings Water	Desorption	1.43E-02	1.9297
Slack Water	As(III)	Groundwater	Adsorption	8.87E-10	4.4209
Slack Water	As(III)	Groundwater	Desorption	6.46E-06	2.6959
Slack Water	As(V)	Groundwater	Adsorption	2.54E-12	5.7501
Slack Water	As(V)	Groundwater	Desorption	4.10E-05	2.2841
Slack Water	As(V)	Tailings Water	Adsorption	3.21E-11	5.2336
Slack Water	As(V)	Tailings Water	Desorption	1.37E-13	7.6517
Tailings	As(III)	Groundwater	Adsorption	1.32E-05	3.5108
Tailings	As(III)	Groundwater	Desorption	9.35E-05	3.0949
Tailings	As(V)	Groundwater	Adsorption	1.03E-05	3.648
Tailings	As(V)	Groundwater	Desorption	2.41E-06	4.666
Tailings	As(V)	Tailings Water	Adsorption	2.52E-14	10.897
Tailings	As(V)	Tailings Water	Desorption	5.21E-09	6.9636

Material	Species	Water	Test Type	K	a
Alluvium	all	Groundwater	all	1.41E-04	2.5039
Fluvial	all	Groundwater	all	5.39E-04	2.0977
Tailings	all	Groundwater	all	1.21E-05	3.6036
Slack Water	all	Groundwater	all	4.59E-14	6.8285
Alluvium	all	Tailings Water	all	2.87E-02	1.1233
Fluvial	all	Tailings Water	all	2.09E-01	0.3445
Tailings	all	Tailings Water	all	2.98E-14	10.523
Slack Water	all	Tailings Water	all	3.69E-09	3.9514

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Appendix D

Appendix D

Mass Balance Summaries for the Groundwater Flow Simulations

This appendix contains the mass balance summaries from MT3DMS for the arsenic transport models. The models run included:

- The calibration run simulating arsenic loading during typical conditions for plant operation (1970-1999) (Table D-1);
- The no-action alternative simulating basin closure with regional infiltration on the basin footprint (Table D-2);
- The evapotranspiration cap alternative simulating basin closure with zero infiltration on the basin footprint (Table D-3);
- The deep groundwater interception alternative simulating basin closure with zero infiltration on the basin footprint and pumping of Wells RP W-4 and RP W-6 (Table D-4);
- The shallow groundwater interception alternative simulating basin closure with zero infiltration on the basin footprint and pumping from a shallow drain located on the downgradient perimeter of the tailing basin (Table D-5);

Table D-1

Historical Simulation (1970-1999)

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TRANSPORT STEP NO. 553

TOTAL ELAPSED TIME SINCE BEGINNING OF SIMULATION = 10590.00 day

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CUMMULATIVE MASS BUDGETS AT END OF TRANSPORT STEP 553, TIME STEP 1, STRESS PERIOD 1

	IN	OUT
CONSTANT CONCENTRATION:	0.0000000	0.0000000
CONSTANT HEAD:	0.0000000	0.0000000
WELLS:	0.0000000	-0.1682350E+08
DRAINS:	0.0000000	-0.4533638E+08
RIVERS:	0.0000000	-4102027.
HEAD-DEPENDENT BOUNDARY:	0.1138425E+11	0.0000000
RECHARGE:	0.0000000	0.0000000
EVAPOTRANSPIRATION:	0.0000000	0.0000000
DECAY OR BIODEGRADATION:	0.0000000	0.0000000
MASS STORAGE (SOLUTE):	53544.64	-0.1072789E+09
MASS STORAGE (SORBED):	0.8005126E+08	-0.1131743E+11
[TOTAL]:	0.1146435E+11 mg	-0.1149097E+11 mg
NET (IN - OUT):	-0.2661376E+08	
DISCREPANCY (PERCENT):	-0.2318745	

Table D-2

No-action Alternative

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TRANSPORT STEP NO. 4417

TOTAL ELAPSED TIME SINCE BEGINNING OF SIMULATION = 219150.0 day

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CUMMULATIVE MASS BUDGETS AT END OF TRANSPORT STEP 4417, TIME STEP 1, STRESS PERIOD 1

	IN	OUT
CONSTANT CONCENTRATION:	0.0000000	0.0000000
CONSTANT HEAD:	0.0000000	0.0000000
WELLS:	0.0000000	-1101889.
DRAINS:	0.0000000	-0.1035199E+10
RIVERS:	0.0000000	-0.3136444E+10
HEAD-DEPENDENT BOUNDARY:	0.0000000	-25.97182
RECHARGE:	0.3459223E+09	0.0000000
EVAPOTRANSPIRATION:	0.0000000	0.0000000
DECAY OR BIODEGRADATION:	0.0000000	0.0000000
MASS STORAGE (SOLUTE):	0.1118937E+09	-0.9762244E+08
MASS STORAGE (SORBED):	0.1307627E+11	-0.9316126E+10
[TOTAL]:	0.1353408E+11 mg	-0.1358649E+11 mg
NET (IN - OUT):	-0.5241037E+08	
DISCREPANCY (PERCENT):	-0.3864990	

Table D-3
Evapotranspiration Cap

TRANSPORT STEP NO. 4414			
TOTAL ELAPSED TIME SINCE BEGINNING OF SIMULATION = 219150.0 day			
CUMMULATIVE MASS BUDGETS AT END OF TRANSPORT STEP 4414, TIME STEP 1, STRESS PERIOD 1			
	IN		OUT
CONSTANT CONCENTRATION:	0.0000000		0.0000000
CONSTANT HEAD:	0.0000000		0.0000000
WELLS:	0.0000000		-1089782.
DRAINS:	0.0000000		-0.9761096E+09
RIVERS:	0.0000000		-0.3094663E+10
HEAD-DEPENDENT BOUNDARY:	0.0000000		-26.59816
RECHARGE:	0.0000000		0.0000000
EVAPOTRANSPIRATION:	0.0000000		0.0000000
DECAY OR BIODEGRADATION:	0.0000000		0.0000000
MASS STORAGE (SOLUTE):	0.1132912E+09		-0.9612850E+08
MASS STORAGE (SORBED):	0.1312581E+11		-0.9127080E+10
[TOTAL]:	0.1323910E+11 mg		-0.1329507E+11 mg
NET (IN - OUT): -0.5596979E+08			
DISCREPANCY (PERCENT): -0.4218695			

Table D-4
Deep Groundwater Interception

TRANSPORT STEP NO. 4414			
TOTAL ELAPSED TIME SINCE BEGINNING OF SIMULATION = 219150.0 day			
CUMMULATIVE MASS BUDGETS AT END OF TRANSPORT STEP 4414, TIME STEP 1, STRESS PERIOD 1			
	IN		OUT
CONSTANT CONCENTRATION:	0.0000000		0.0000000
CONSTANT HEAD:	0.0000000		0.0000000
WELLS:	0.0000000		-0.4213903E+10
DRAINS:	0.0000000		-1447009.
RIVERS:	0.0000000		-0.2850785E+08
HEAD-DEPENDENT BOUNDARY:	0.0000000		0.0000000
RECHARGE:	0.0000000		0.0000000
EVAPOTRANSPIRATION:	0.0000000		0.0000000
DECAY OR BIODEGRADATION:	0.0000000		0.0000000
MASS STORAGE (SOLUTE):	0.1182957E+09		-0.9403816E+08
MASS STORAGE (SORBED):	0.1283974E+11		-0.8690254E+10
[TOTAL]:	0.1295803E+11 mg		-0.1302815E+11 mg
NET (IN - OUT): -0.7011738E+08			
DISCREPANCY (PERCENT): -0.5396513			

Table D-5
Shallow Groundwater Interception

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TRANSPORT STEP NO. 4414

TOTAL ELAPSED TIME SINCE BEGINNING OF SIMULATION = 219150.0 day
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CUMMULATIVE MASS BUDGETS AT END OF TRANSPORT STEP 4414, TIME STEP 1, STRESS PERIOD 1

	IN	OUT
CONSTANT CONCENTRATION:	0.0000000	0.0000000
CONSTANT HEAD:	0.0000000	0.0000000
WELLS:	0.0000000	-970262.3
DRAINS:	0.0000000	-0.2119486E+10
RIVERS:	0.0000000	-0.2541278E+10
HEAD-DEPENDENT BOUNDARY:	0.0000000	0.0000000
RECHARGE:	0.0000000	0.0000000
EVAPOTRANSPIRATION:	0.0000000	0.0000000
DECAY OR BIODEGRADATION:	0.0000000	0.0000000
MASS STORAGE (SOLUTE):	0.1099669E+09	-0.8156085E+08
MASS STORAGE (SORBED):	0.1235654E+11	-0.7746902E+10
[TOTAL]:	0.1246651E+11 mg	-0.1249020E+11 mg
NET (IN - OUT):	-0.2368922E+08	
DISCREPANCY (PERCENT):	-0.1898425	