FEASIBILITY OF GROUNDWATER CUTOFF/DIVERSION STUDY

Task 26
of the
Zero-Offsite Water-Discharge Study

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FEASIBILITY OF GROUNDWATER CUTOFF/DIVERSION STUDY

Rocky Flats Plant Site

EXECUTIVE SUMMARY

The Feasibility of Groundwater Cutoff/Diversion Study is one of several studies being conducted for, and in the development of, a Zero-Offsite Water-Discharge Plan for Rocky Flats Plant (RFP) in response to Item C.7 of the Agreement in Principle (AIP) between the Colorado Department of Health (CDH) and the U.S. Department of Energy (DOE). The CDH/DOE Agreement Item C.7 states "Source Reduction and Zero Discharge Study: Conduct a study of all available methods to eliminate Rocky Flats discharges to the environment including surface waters and ground water. This review should include a source reduction review".

The purpose of this study is to assess the feasibility of groundwater cutoff/diversion in the area of the RFP. A literature search was undertaken as a part of the feasibility study. The relevant literature on the geology and hydrology of the RFP was compiled into an annotated bibliography. Hydrogeologic characteristics of the alluvium and bedrock pertinent to the cutoff/diversion alternatives was gathered from various sources. Information was also acquired on the slurry wall method of cutoff trench construction.

Four groundwater cutoff/diversion scenarios were addressed as alternatives. All alternatives for this study were based on simplified, idealized hydrogeologic systems. The total saturated thickness was considered to consist of alluvial material and was regarded as homogeneous, isotropic and infinite in areal extent. The effectiveness of the alternatives was assessed using hand generated flow nets and analytical solutions.

Alternative 1 involved the use of a linear cutoff wall placed west of the Controlled Area. The cutoff wall, 75 feet deep and 8400 feet in length, extended beyond the boundary of the RFP, and

was not sufficient to prevent groundwater from flowing into the Controlled Area. The estimated cost of $6.3 million and the estimated construction time of 1.5 years is the costliest in terms of money and time of the alternatives investigated. Implementation of Alternative 1 would involve substantial impact to surface waters since the trench would intercept streams and ditches.

Alternative 2 involved the use of a curvilinear cutoff wall placed in a horseshoe shape around the west, south and north sides of the Controlled Area of the RFP. The extreme dimensions of the cutoff wall, 18,400 feet in length, and the proximity of the trench to plant operations, substantially lowers the feasibility of this alternative. The cost is estimated at $4.6 million and the construction time is estimated to take 1.1 years. This alternative also represents a significant impact on surface water since the trench would intercept streams and ditches. Although the flownet analysis indicates that the cutoff wall is successful in cutting off groundwater flow to the Controlled Area, there is the possibility that eddies may carry some groundwater back into the Controlled Area.

Alternative 3, the line of pumping wells at the east end of the Controlled Area of the RFP involved the installation of fifteen pumping wells along a north-south line tangent to the East Trenches contaminant plume. The analytical solution indicated that the wells successfully intercepted all groundwater flow leaving the Controlled Area and adjacent contaminated sites. The fifteen wells would pump 17.6 acre-feet of groundwater per year which must be collected and treated. The estimated construction cost is $422,000 and the expected construction time is over 2.1 months.

Alternative 4, pumping wells at individual contaminant plumes, included the installation of a total of twelve pumping wells situated on the downgradient edges of the individual contaminant plumes. An analytical assessment of the flow regime indicated that the wells successfully captured the groundwater flow through each of the contaminant plumes. The total volume pumped per year was 11.7 acre feet. The estimated cost is $346,000 and the expected time to complete construction is about 2.0 months. This alternative ranked first in the evaluation matrix.

Of the four alternatives that were considered in this study of the feasibility of diverting ground water around the RFP and of cutting off groundwater discharge as it left the RFP, Alternative 4, pumping wells at individual contaminant sites, is the recommended alternative.

1.0 INTRODUCTION

The Feasibility of Groundwater Cutoff/Diversion Study is one of several studies being conducted for, and in the development of, a Zero-Offsite Water-Discharge Plan (ASI, 1990) for the RFP in response to Item C.7 of the Agreement in Principle (AIP) between the Colorado Department of Health (CDH) and the U.S. Department of Energy (DOE) (DOE and State of Colorado, 1989). The CDH/DOE Agreement Item C.7 states "Source Reduction and Zero Discharge Study: Conduct a study of all available methods to eliminate Rocky Flats discharges to the environment including surface waters and ground water. This review should include a source reduction review" (DOE, 1989).

1.1 PURPOSE AND SCOPE OF THE STUDY

The purpose of this study is to investigate the feasibility of diverting ground water around the Rocky Flats Plant (RFP) Controlled Area and of cutting off the groundwater flow downgradient as it leaves the RFP Controlled Area (Figure 1) (ASI, 1991b). The analyses of alternative cutoff/diversion scenarios are limited to the Controlled Area and a small part of the Buffer Zone of the RFP where contaminant plumes have been mapped (Figure 2). The cost-effectiveness of selected groundwater cutoff/diversion scenarios is investigated and effectiveness criteria is related to the potential environmental changes as a result of each scenario.

2.0 LITERATURE SEARCH

As a part of the feasibility study a literature search was undertaken to include available reports, drawings, maps and applicable documents from EG&G personnel at the RFP. Data and literature searches also include sources from Federal, State and local agencies for both published and unpublished data and information regarding the groundwater conditions at the RFP. The relevant literature was compiled into an annotated bibliography (Appendix A). The following sources were used.

1. United States Geological Survey
2. National Technical Information Center
3. Rocky Flats Plant Library, Wind Site
4. Colorado Division of Water Resources
5. Colorado Geological Survey
6. Colorado State Oil and Gas Commission
7. Denver Earth Resources Library
8. Rocky Mountain Association of Geologists
9. Petroleum Information Center
10. W.W. Wheeler and Associates
11. Woodward Clyde Consultants
12. Colorado School of Mines, Arthur Lakes Library
13. University of Colorado, Norlin Library

Data and literature was also acquired on selected slurry-cutoff-wall construction techniques and effectiveness based upon similar groundwater environments and applications. This information is used in this study to choose a model upon which to base a slurry wall design for use in feasibility and cost analyses. The sources used for this study are included in the references, and case histories are attached as Appendix B.

3.0 GEOLOGIC/HYDROGEOLOGIC SETTING

The RFP site is located about 15 miles northwest of Denver, Colorado and is situated on a pediment alluvium that dips at approximately one degree to the east. The pediment is dissected by several small streams that flow toward the east the headwaters of the streams are located one or two miles west of the RFP.

3.1 LOCAL GEOLOGIC SETTING

The surficial geology in the RFP area consists of a veneer of Rocky Flats Alluvium, Valley Fill Alluvium and colluvium overlying bedrock (Figure 3). The Rocky Flats Alluvium developed during Nebraskan or Aftonian time in the Pleistocene. It consists of poorly sorted, unconsolidated deposits of gravel (granules to cobbles and boulders) with clay, silt, and sand matrices.

The colluvium is a poorly sorted mixture of topsoil, weathered bedrock, and reworked Rocky Flats Alluvium and is comprised of silty clay and clayey silt with some gravel. The Valley Fill Alluvium is a poorly sorted mixture of reworked Rocky Flats Alluvium, colluvium, and weathered bedrock found in drainages throughout the area.

The Arapahoe Formation lies beneath the alluvium and colluvium. This Upper Cretaceous unit consists mainly of claystones and silty claystones. Significant sandstone intervals occur within the claystone. The Arapahoe Formation is up to 250 feet in thickness in the RFP area (EG&G, 1990). The sandstones are discontinuous fluvial deposits, consequently they are not present beneath all of the RFP. There are at least six mappable sandstone intervals in the Arapahoe Formation in the RFP area. The thicknesses and vertical separations of the sandstone intervals are given in Table 1.

Table 1

Arapahoe Sandstones: Thickness and Vertical Separation

Sandstone	Thickness	Vertical Separation between Sandstone
		Depending on Sandstone Thickness
Sandstone #1	0' - 27.2'	35' - 40'
Sandstone #2	0' - 10'	15' - 23'
Sandstone #3	0' - 16'	7' - 18'
Sandstone #4	0' - 15'	2' - 8'
Sandstone #5	0' - 9'+	92' - 98'
Basal Sandstone(s)	14'- 37'	

Source: EG&G, 1991b

The Upper Laramie Formation occurs stratigraphically below the Arapahoe Formation and subcrops below the alluvial material in the west part of the RFP area just beyond the West Spray Field (Figure 2). It consists of primarily of relatively impermeable claystones.

3.2 LOCAL HYDROGEOLOGIC SETTING

The Rocky Flats site is located within a ground water recharge area. The saturated material in this recharge area exhibits a strong vertical hydraulic gradient. Recharge to the alluvium and the bedrock occurs as a result of precipitation, overland flow, lateral flow, and seepage from streams, ditches, and ponds. In the western portion of the RFP the depth to water in the alluvium and shallow bedrock materials is 50 to 70 feet (ft.) below the surface, and tends to become shallower to the east. In the stream drainages, seeps are common at the base of the Rocky Flats Alluvium where individual Arapahoe Formation sandstones crop out. The claystones of the Arapahoe Formation have a low hydraulic conductivity, on the order of 1×10^{-7} to 1×10^{-8} centimeters per second (cm/s) (EG&G, 1991b), effectively constraining much of the flow within the water table aquifer to the alluvial material above the alluvial/bedrock discontinuity. Only where the uppermost Arapahoe sandstone subcrops does bedrock form a part of the water table aquifer.

The geologic and geohydrologic characteristics of the alluvial and bedrock aquifers in the vicinity of the RFP as described in a limited number of publications are compiled and presented in Table 2.

Table 2

Comparison of Hydraulic Properties

Source	Formation	Hydraulic Conductivity (cm/s)
Ground Water Assessment Plan Addendum - Draft EG&G, 1990	Valley Fill	9×10^{-5}
	Alluvium	5.3×10^{-4} - 2.1×10^{-5}
	Bedrock	5.4×10^{-7} - 4×10^{-8}
Hydrogeological Characterization of the Rocky Flats Plant, Hydro-Search, 1985.	Alluvium	1×10^{-3}
	Arapahoe Sandstone	4×10^{-5}
	Arapahoe Claystone	3×10^{-7}
Section E Groundwater Protection, Rockwell International, 1986.	Rocky Flats Alluvium	7×10^{-5}
	Walnut Creek Alluvium	3×10^{-5}
	Woman Creek Alluvium	3×10^{-3}
	Arapahoe Sandstone	2×10^{-6}
	Weathered Arapahoe Claystone	5×10^{-7}
	Unweathered Arapahoe Claystone	1×10^{-7}
	Qal (Valley Fill)	2×10^{-4}
Draft Final Groundwater Protection and Monitoring Plan, EG&G, 1991.	Rocky Flats Alluvium Arapahoe Sandstone #1	6×10^{-5}
	Arapahoe Sandstones #3, 4, 5	10^{-6}
	Basal Arapahoe Sandstone	10^{-6}
	Arapahoe Claystone (Weathered & Unweathered)	10^{-7} - 10^{-8}
RCRA Part B Permit Application Rockwell International, 1988a.	Rocky Flats Alluvium	7×10^{-5}
	Valley Fill	3×10^{-3}
	Arapahoe Formation	2×10^{-6} - 1×10^{-7}
Hydrology Of A Nuclear-Processing Plant Site Hurr, 1976.	Rocky Flats Alluvium	1×10^{-2}
	Valley Fill	NA
	Arapahoe Formation	1×10^{-4}
RCRA Post Closure Care Permit Application Rockwell International, 1988b.	Rocky Flats Alluvium	9×10^{-6} - 4×10^{-8}
	Valley Fill	5×10^{-6}
	Arapahoe Formation	NA

4.0 CUTOFF/DIVERSION ANALYSES

The analyses of groundwater cutoff/diversion scenarios include the feasibility of shallow (alluvial aquifer) cutoff trenches and/or interceptor wells to control groundwater flow in support of zero-offsite groundwater discharge. The area of study includes the Controlled Area and areas of soil and groundwater contamination adjacent to the Controlled Area at the RFP.

4.1 APPROACH

The computer program DREAM (Bonn and Rounds, 1990) and hand-generated flow nets were used in the analyses to simulate the groundwater flow system. In keeping with the scope of work and the limitations inherent in analytical solutions, a simplified, idealized model of the hydrogeologic system was used. The alluvial aquifer characteristics were considered homogeneous and isotropic. There are wide variations in reported hydraulic conductivities as presented in Table 2. For the purpose of this study a hydraulic conductivity value of $6x10E^{-05}$ for the Rocky Flats Alluvium (Table 2) was used. The alluvial hydraulic gradient is reported to vary between 0.02 and 0.05 ft/ft. (Hurr, 1976). For this study an alluvial hydraulic gradient of 0.03 ft/ft. was used. The direction of groundwater flow was assumed to be due east.

The saturated thickness of the alluvial system was used in the diversion/cutoff alternatives presented in this study; the basis for this condition is related in the description of each alternative. The four alternatives investigated as a result of this study are:

Diversion of groundwater entering the RFP site.

Alternative 1 A cutoff trench through the alluvium to the underlying Cretaceous Upper Laramie Formation west of the West Spray Field; and

Alternative 2 A cutoff trench through the alluvium to the underlying Arapahoe Claystones around the Controlled Area and selected areas of the buffer zone adjacent to the Controlled Area.

Interception of groundwater leaving the RFP site.

Alternative 3 Pumping wells along the east side of the Controlled area; and

Alternative 4 Pumping wells at the individual contaminant plumes.

4.1.1 Diversion of Groundwater

In the groundwater diversion alternatives (Alternatives 1 and 2), groundwater is prevented from entering the plant site with the use of cutoff trenches. The construction of cutoff trenches involves the excavation of pervious material to the depth just beyond which a low permeability layer or aquitard is encountered. The trench is then backfilled with a low permeability material, which acts as a barrier to groundwater flow.

The slurry-wall method of construction involves the use of a slurry which consists of a suspension of hydrated bentonite in water. The purpose of the slurry is to prevent collapse of the trench walls during construction by forming a filter cake along the walls of the excavation and exerting static head pressure on the sides of the trench. The filter cake also affects the permeability of the trench walls, reducing infiltration of fluids. The backfill material, usually a mixture of site soil and bentonite slurry, is placed in the trench displacing the slurry. Construction of the entire length of the trench proceeds in this manner, with the backfill displacing the slurry as the trench is advanced with earth-moving equipment. For trenches up to 50 feet deep, a backhoe is used, between 50 and 80 feet a dragline is used and anything deeper requires the use of a clamshell. Slurry wall construction has been used for trenches over 390 feet deep (Calabrese and Kostecki, 1989). The width of the trench varies, usually between two and five feet. Case histories of specific designs are included as Appendix B.

Historically the cutoff trench has been considered a temporary measure to reduce groundwater flow into an area that is under construction. More recently cutoff trenches have been used in

areas of contamination both as a temporary measure to reduce contaminant migration until a permanent solution can be devised, and as a permanent barrier to contaminant migration.

Ideally the cutoff wall acts as an impermeable barrier to flow. Generally, however, the cutoff wall merely reduces the rate of flow to a level which is acceptable or manageable. Leakage through the wall can occur as a result of, among other things, improper seating of the cutoff in the basal low permeability material, cracking of the wall after construction, and formation of pockets during the backfilling process. Disintegration of the wall can also occur as a result of chemical attack, such as the affect of organic compounds on bentonite. However, the development of specially treated bentonite can reduce the severity of this problem (Calabrese and Kostecki, 1989). It is also noted that a design specific to contaminant migration involves the use of a soil barrier and a synthetic membrane. A granular material within the membrane acts as a leak collection and extraction system if a contaminant passes into the membrane (Calabrese and Kostecki, 1989).

For the purposes of this study the cutoff wall is assumed to be impermeable.

4.1.1.1 Linear Cutoff Trench West of Spray Field (Alternative 1)

In this alternative a cutoff trench is emplaced west of the West Spray Field (Figure 4) extending north-south. Its purpose is to cut/off and divert ground water before it enters the RFP.

Conditions and Assumptions: Immediately west of the West Spray Field the Rocky Flats Alluvium averages 75 feet in thickness, based on alluvial thicknesses noted in well logs related to wells 51-86 and 52-86 of 78.5 feet and 72 feet respectively (EG&G, 1990). The claystones of the Cretaceous Upper Laramie Formation underlie the Rocky Flats Alluvium in this area. The Upper Laramie Formation is believed to be relatively impermeable (Hurr, 1976, EG&G, 1990) and, therefore, it is a suitable base for the cutoff trench. The backfill material is assumed to be an impermeable mixture of the excavated soil and bentonite.

Model: A linear cutoff trench is emplaced by slurry wall method immediately west of the West Spray Field (Figure 4). The trench extends north-south 8400 feet. The alluvial material will be modeled to extend the length of the cutoff wall and is assumed to be homogeneous and isotropic. The excavation is assumed to penetrate the claystone of the Laramie Formation and is, therefore, in excess of 75 feet deep. A design width of three feet is based on information set forth in a summary of costs of remedial technologies (Yang, et al., 1987) included as Appendix C.

Analysis: A flow net was drawn to assess the effectiveness of the linear cutoff trench in diverting groundwater flow around the Controlled Area of the RFP (Figure 4). The following observations were made:

- The cutoff wall does not succeed in preventing groundwater flow from entering the Controlled Area of the RFP.
- The cutoff wall, at 8400 feet in length, extends beyond the plant boundaries; and
- The cutoff wall intercepts Rock Creek, Woman Creek and the Upper Church and McCay Ditches.

4.1.1.2 Curvilinear Cutoff Trench (Alternative 2)

In this alternative, a cutoff trench is emplaced adjacent to the Controlled Area forming a horseshoe shape and encircling the west, south and north sides of the Controlled Area of the RFP (Figure 5). Its purpose is to cutoff and divert groundwater before it enters the Controlled Area. The West Spray Field is outside of the cutoff trench, and, is therefore not included in this scenario. It is noted however, that the curvilinear wall could be extended to include the spray field.

Conditions and Assumptions: The thickness of the alluvium surrounding the Controlled Zone varies. Information presented in well logs related to wells 45-86, 56-86, 58-86, 70-86, 42-87, 60-87, 39-89BR and 51-89BR indicate alluvial thicknesses of 49.7', 9', 3', 7', 6.1', 27', 22.9' and 30' respectively (EG&G, 1990). The claystones of the Cretaceous Arapahoe Formation are

assumed to underlie the alluvium. The claystones are relatively impermeable with a hydraulic conductivity of 1×10^{-7} to 1×10^{-8} cm/s (EG&G, 1991b) and, therefore, should be a suitable base in which to found the cutoff trench. The backfill material is assumed to be an impermeable mixture of the excavated soil and bentonite.

Model: A curvilinear cutoff trench is emplaced by slurry wall method immediately west of the Controlled Area and extends symmetrically north and south of the Controlled Area. The length of the cutoff trench is approximately 18,400 feet. The alluvial material is modeled with an average thickness of 25 feet. The trench wall is three feet thick. The three foot thickness is based on information set forth in the summary of costs of remedial technologies (Yang, et al., 1987) included as Appendix C.

Analysis: A flow net was drawn to assess the effectiveness of the curvilinear cutoff trench in diverting groundwater flow around the Controlled Area of the RFP (Figure 5). The following observations were made:

(1) The flow net demonstrates that the cutoff wall diverts groundwater flow around the Controlled Area, however, there is a potential for eddying of groundwater into the site from the east;

(2) The cutoff trench does impact the groundwater regime of a large area surrounding the RFP; and

(3) The cutoff trench intercepts the Upper Church and McCay Ditches, and Woman Creek.

4.1.2 Interception of Groundwater

Pumping wells are used in these alternatives (Alternatives 3 and 4) to remove groundwater after it has flowed through the Controlled Area and associated contaminant plumes. The pumping wells were considered to be fully penetrating. The computer program DREAM was used to

simulate the flow field under steady state conditions. The assumptions DREAM uses are that the aquifer is homogeneous, isotropic, confined, of uniform thickness, and of infinite areal extent. It is noted that this study bases interpretations on these same assumptions and conditions, with the exception of the type of aquifer. Although DREAM uses analytical solutions based on conditions in a confined aquifer and the scenarios involve an unconfined aquifer, the steady state condition essentially eliminates significant differences in the shape of the drawdown curve after a long pumping time (Lohman, 1979).

4.1.3 Pumping Wells Along East Side of Controlled Area (Alternative 3)

For this alternative, pumping wells are installed east of the Controlled Area along a line running north-south tangent to the downgradient tail of the East Trenches contaminant plume (Figure 6). The purpose of the wells is to intercept all groundwater which flows through the Controlled Area and related identified contaminant plumes.

Conditions and Assumptions: A saturated thickness of 50 feet was used for this scenario. This reflects the average thickness of the Rocky Flats Alluvium along the line of pumping wells and worst-case water levels. These thicknesses are based on the average thickness of alluvial material (EG&G, 1990) at wells 32-87 and 41-86, with thicknesses of 46.2 feet and 44.5 feet, respectively. Based on the geometry of the Arapahoe Formation sandstone bodies (EG&G, 1990), no contamination is expected to be present in the sandstones along the line of pumping wells. The Arapahoe Sandstone No. 1 is not known to be present at any point beneath the line of pumping wells. There is believed to be no opportunity for the sandstone to pick up additional contaminants through subcrops east of the well field. There may be a potential for Sandstone No. 3 to become contaminated near 881 Hillside, however, analyses have not indicated contamination (EG&G,1990). Additionally, a collector trench is currently being installed at the 881 Hillside site to intercept contaminant migration. Sandstone Nos. 2, 4 and 5 are not believed to be exposed to contaminants within the Rocky Flats area. Therefore, the Arapahoe Formation sandstones are not included in the saturated thickness for this scenario.

Model: Fifteen pumping wells were installed at regularly spaced intervals along a line extending from Walnut Creek to Woman Creek and tangent to the east edge of the East Trenches contaminant plume (Figure 6). The wells are spaced at 250-foot intervals and are fully penetrating. An effective porosity of 0.1 and pumping rate of 140 cubic feet per day (0.73 gpm) is assumed.

Analysis: The computer programs DREAM and Surfer (Golden Software, 1987) were used to analyze the flow system and to contour the stream lines. The following observations were made:

(1) The fifteen pumping wells capture all flow lines through the Controlled area and the related contaminant plumes;

(2) The total volume pumped in one year is 17.6 acre-feet; and

(3) Drawdown in each well is approximately 20 feet.

4.1.4 Pumping Wells at Individual Contaminant Plumes (Alternative 4)

In this alternative, pumping wells are installed on the downgradient side of each of the identified contaminant plumes (Figure 7). The purpose of the wells is to intercept all groundwater which flows through the individual sites of identified contamination.

Conditions and Assumptions: A saturated alliumum thickness of 50 feet is used for this alternative. Although the alluvial thickness varies considerably at the individual sites, the constraints of the program used to calculate drawdown and produce streamlines include constant thickness; therefore, a maximum alluvial thickness is used. All other assumptions made for Alternative 3, regarding the Arapahoe sandstones, are used in this alternative. In addition, the 881 Hillside plume is omitted from this alternative since the contaminant plume will be controlled by the installation of a collector trench,which is currently being constructed.

Model: Twelve pumping wells are situated on the downgradient sides of the four identified contaminant plumes (Figure 7). The wells are located downgradient of each of the identified contaminant plumes. The wells are fully penetrating. An effective porosity of 0.1 is assumed. A pumping rate of 140 cubic feet per day (0.73 gpm) is assumed.

Analysis: The computer program DREAM was used to analyze the flow system and the Surfer program was used to contour the stream lines. The following observations were made:

(1) The twelve pumping wells capture all streamlines flowing through the individual contaminant plumes;

(2) The total volume pumped in one year is 11.7 acre-feet; and

(3) Drawdown in each well is approximately 20 feet.

5.0 RELATIVE COSTS

The cost figures used in this report are provisional construction cost estimates only and should be considered accordingly. Detailed construction costs were beyond the scope of this project. Operation and maintenance are not included in the estimates. Additionally, the collection and treatment costs of contaminated water, the detection and disposal of contaminated soils and the rerouting/diversions of waterways are not considered in the costs of the alternatives.

5.1 CUTOFF WALLS

The factors affecting cost of the cutoff wall construction are primarily wall material, bentonite-soil-cement walls the most expensive, soil-bentonite mixtures as median priced and a local clay source as the least expensive. The depth of the trench is the next most important factor affecting cost. Another contributing factor is the occurrence of boulders in the soil. The type of subsurface materials encountered has a large impact on excavation cost. Actual and estimated costs (Appendix C) were used to estimate costs associated with the construction of the cutoff trench by slurry wall method. The costs for soil-bentonite walls ranges from $4.50 to $8.05 per square foot. However, when boulders are occasionally encountered during excavation, the cost increases significantly, to $10 and more per square foot. Square footage is the product of the height and the length of the wall.

5.1.1 Linear Cutoff Wall (Alternative 1)

Dimensions of the linear cutoff wall are 8400 feet long and 75 feet deep. This gives a square footage of 630,000. Using an average cost of $10 per square foot for a bentonite-soil mixture backfill and a trench depth of 75 feet (Appendix C), the estimated cost is $6.3 million. However, it should be noted that many factors could arise during construction that could amplify the cost by as much as three times the original estimate. Those factors may include the need to test each

excavated scoop with an organic vapor analyzer and removal of the contaminated soil to a disposal site which could triple construction costs.

Based on a daily excavation rate of 80 cubic yards and a 230 day work year, construction of the wall is estimated to take 1.5 years.

5.1.2 Curvilinear Cutoff Wall (Alternative 2)

Dimensions of the curvilinear cutoff wall are 18,400 feet long and 25 feet deep. This represents a an area of 460,000 square feet. Using an average cost of $10 per square foot for a bentonite-soil mixture for the backfill and a trench depth of 25 feet (Appendix C), the estimated cost is $4.6 million. Again, the cost could be tripled if contaminated soils are encountered or if the soils must be continuously screened for contaminants and the contaminated soil requires off-site disposal.

Construction of the wall is estimated to take 1.1 years.

5.2 PUMPING WELLS

The factors affecting construction costs include the number of wells, completion depth, pumps and interwell pipe. Formulas from a FORTRAN computer program COST were used to calculate the cost of wells, pumps and interwell pipe as well as construction time. A description of calculation factors for the computer program COST is included as Appendix D.

5.2.1 Pumping Wells Along the East Side of the Controlled Area (Alternative 3)

In this alternative fifteen wells were installed along the east side of the Controlled Area. The cost of these wells, pumps and the interwell pipe is $422,000.

The time required for construction of the well field is 2.1 months.

5.2.2. Pumping Wells at Individual Contaminant Plumes (Alternative 4)

In this alternative twelve wells were installed down gradient of each contaminant plume. The cost of these wells, pumps, and the interwell pipe is $346,000.

The estimated time for completion of construction is 2.0 months.

6.0 RECOMMENDED ALTERNATIVE

A scenario evaluation matrix utilizing eleven evaluation criteria and weighing factors follows. The weighting factors are on a scale of one (least significance) to 10 (greatest significance). The scores of each alternative reflect the relative desirability. General descriptive comments relative to each factor and score are discussed below. Within the alternative evaluation system are weighting factors that influence the overall zero-discharge study. These factors were selected by a committee consisting of cognizant DOE and EG&G personnel, headed by Russell A. Applehans. The matrix used to evaluate and weigh the four scenarios is given in Table 3. It is noted that the diversion trenches are assumed to be impermeable and that all contaminated water is contained within the capture zones of the pumping wells.

Controlled Discharge - Discharge is controlled well by two of the four alternatives. Alternative 1 does not fully control discharge, as groundwater flows into the Controlled Area. Alternative 2 may produce eddies in the groundwater on the east ends of the cutoff wall allowing a minimal amount of flow into the Controlled Area.

Waste Generation - Waste generation is associated primarily with Alternatives 3 and 4. The pumping wells generate waste in the form of contaminated water, which must be treated. Alternative 3, with 15 pumping wells, generates 2100 cubic feet of waste water daily, whereas Alternative 4, with only ten pumping wells, generates 1680 cubic feet of waste water daily. Alternatives 1 and 2 may generate waste in the form of contaminated soil that is excavated during construction of the trench. Contaminated soil will require disposal.

Risk - Alternative 2, the curvilinear diversion trench, represents the least risk in that ground water is diverted from the site, essentially eliminating the potential for migration of the identified contaminant plumes. Alternative 1, the linear diversion

trench, represents the greatest risk since it allows ground water to flow back into the Controlled Area and through the sites of contamination, potentially contaminating drinking water downgradient. Pumping wells, Alternatives 3 and 4, also carry a risk since both generate waste which may be involved in accidental spillage. Possible equipment failure resulting in down time also represents a risk for Alternatives 3 and 4 by allowing contaminants to migrate offsite.

Cost - Alternative 4 represents a distinct cost advantage. Considering the extreme dimensions of the diversion trenches construction of the trenches is more costly than the installation of the pumping wells. Since Alternative 4 calls for three wells less than Alternative 3, it will cost less. However, treatment of the pumped water is not included in this cost comparison, nor are operation and maintenance for any of the four alternatives.

Design and Construction Schedule - Alternative 4 is based on a simple design and construction should be completed quickly. The design of the pumping wells is based on a homogeneous system and the wells are shallow (50 feet). Construction of the diversion trenches will require extensive planning, particularly due to the extreme dimensions. The depth of the linear trench at 75 feet and the lengths of both trenches, over 8000 feet, will require long periods of time for construction.

Flexibility - Flexibility is not applicable to any of the alternatives.

Water Rights - All alternatives represent a large impact on water rights both for surface and ground water. However, Alternatives 1 and 2 represent the greatest impact, altering the groundwater flow regime for a large area around the Rocky Flats Plant. The linear diversion trench may cut off flow in Woman and Rock Creeks and the curvilinear diversion trench may cut off flow in Walnut and Woman Creeks. In addition both alternatives may affect the McCay and Upper

TABLE 3
EVALUATION MATRIX

EVALUATION FACTORS*	WEIGHTING FACTOR	SCENARIO 1 LINEAR CUTOFF WALL		SCENARIO 2 CURVILINEAR CUTOFF WALL		SCENARIO 3 EAST SIDE PUMPING WELLS		SCENARIO 4 PLUME SITE PUMPING WELLS	
		S	W	S	W	S	W	S	W
CONTROLLED DISCHARGE	10	1	10	3	30	5	50	5	50
WASTE GENERATION	7	4	28	4	28	1	7	2	14
RISKS	8	1	8	5	40	2	16	3	24
COST	6	1	6	2	12	4	24	5	30
DESIGN AND CONSTRUCTION SCHEDULE	6	1	6	1	6	4	24	5	30
FLEXIBILITY	8	3	24	3	24	3	24	3	24
WATER RIGHTS	5	1	5	1	5	5	25	3	15
AIR EMISSIONS	10	3	30	3	30	3	30	3	30
WETLANDS/T&E SPECIES	10	1	10	1	10	2	20	3	30
IHSS (SWMU)	10	3	30	3	30	3	30	3	30
PUBLIC ACCEPTABILITY	8	3	24	3	24	1	8	1	8
TOTALS			181		239		258		285
RANK			**4**		**3**		**2**		**1**

S = SCORE; W = WEIGHTED SCORE = SCORE x WEIGHTING FACTOR

* Defined on the following pages

Church Ditches. Alternative 3 will probably impact both Walnut Creek and Woman Creek, but will not entirely cutoff the flow. Alternative 4 will have the least impact on both surface and ground water.

Air Emissions - None of the four scenarios represent significant risk with regard to emissions. Air will be affected during the construction phase of the alternatives. Although the construction time for the cutoff trench is expected to take a considerable amount of time, the affect on air emissions should not be significant. There is the potential in Alternatives 3 and 4, however, for emitting pollutants to the environment due to storage in open ponds and/or air stripping of contaminated water.

Wetland/T & E - All of these alternatives have some impacts in this regard. To varying degrees each alternative will reduce surface water flow in various portions of the streams at the RFP. The linear diversion trench will affect into Rock and Woman Creeks and the curvilinear diversion trench will cutoff flow into Walnut and Woman Creeks. Reduced or negligible flow in the streams may impact wetlands.

IHSS/SWMU - None of the four scenarios have any impacts.

Public Acceptability - Although all four scenarios impact water rights, Alternative 2 represents a plan which may be appealing in its simplicity of purpose. It diverts groundwater away from the Controlled Area, thereby avoiding the possibility of carrying contaminants downgradient toward the public. It may also be more appealing than the other scenarios because it requires no maintenance and will not generate waste (assuming the excavated soil is not contaminated) that may be subject to spillage, endangering both human health as might the pumping wells.

Based on the above criteria, the alternative that ranked the highest for the cutoff/diversion of groundwater was Alternative 4, pumping wells at individual contaminant plumes.

7.0 SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

All alternatives for this groundwater cutoff/diversion study were based on simplified, idealized hydrogeologic systems. The total saturated thickness was considered to consist of alluvial material and was regarded as homogenous, isotropic and infinite in areal extent.

Alternative 1 involved the use of a linear cutoff wall placed just west of the West Spray Field. The wall at 75 feet deep passed through the alluvial material into the Laramie Formation claystones. The feasibility of constructing the linear cutoff wall is low. The length of 8400 feet, which surpassed the confines of the RFP site, was not sufficient to prevent groundwater from flowing back into the Controlled Area. The estimated cost of $6.3 million and the estimated construction time of 1.5 years is the costliest in terms of money and time of the alternatives investigated. The evaluation matrix score of 181 was the lowest. Implementation of alternative 1 would require rerouting of the upper reaches of Woman and Rock Creeks and the diversion of the McCay and Upper Church Ditches. It would also require the construction of the cutoff wall outside the plant boundaries.

Alternative 2 involved the use of a curvilinear cutoff wall placed in a horseshoe shape around the west, south and north sides of the Controlled Area, omitting the West Spray Field from groundwater diversion. The wall at a depth of 25 feet extended through the alluvial material into the claystones of the Arapahoe Formation. The extreme dimensions of the cutoff wall substantially lowers the feasibility of constructing this alternative. A length of 18,400 feet and the position of the trench in relation to the daily activities at the RFP may mean construction is impractical. The cost is estimated at $4.6 million and the construction time is estimated to take 1.1 years. In addition, the cutoff wall intercepts the Upper Church and McCay Ditches and, therefore, would require the diversion of these ditches. The wall also would require the rerouting of Woman Creek. Although the flownet indicates that the wall is successful in cutting off groundwater flow into the Controlled Area of the RFP, there is the possibility that eddies may

carry some groundwater west, back into the Controlled Area. The evaluation matrix ranking of this alternative was third.

Alternative 3, the line of pumping wells at the east end of the Controlled Area of the RFP included the installation of fifteen pumping wells along a north-south line tangent to the East Trenches contaminant plume. The wells penetrated an alluvial thickness of 50 feet and successfully intercepted all groundwater flow leaving the site. The fifteen wells pump 17.6 acre-feet of contaminated water per year which must be collected and treated. The estimated construction cost is $422,000 and the expected construction time is 2.1 months. This alternative ranked second in the evaluation matrix.

Alternative 4, pumping wells at individual contaminant plumes, included the installation of a total of twelve pumping wells situated on the downgradient edges of the individual contaminant plumes. The wells were assumed to fully penetrate the alluvial material. An analytical assessment of the flow regime indicated that the wells successfully captured only the flow through each of the contaminant plumes. Other flow, presumably uncontaminated, was allowed to flow through the RFP Controlled Area and off site. The total volume pumped per year was 11.7 acre feet. The estimated cost is $346,000 and the expected time to complete construction is 2.0 months. This alternative ranked first in the evaluation matrix.

Of the four alternatives that were considered in this study of the feasibility of diverting ground water around the RFP and of cutting off groundwater discharge as it left the RFP, Alternative 4, pumping wells at individual contaminant sites, is recommended.

8.0 ACKNOWLEDGMENTS

This study was conducted under the general supervision of Mr. Michael G. Waltermire, P.E., Project Manager, Advanced Sciences, Inc. (ASI). Work involving this project task was under the technical management of Dr. James R. Kunkel, P.E., P.H., ASI Principal Scientist. Darrel Dunn, Ph.D., provided technical assistance and report review. The draft of this report was also reviewed by Mike Rengel, P.E. This report was written by Ms. Rose M. Zeiler, Senior Hydrogeologist, with assistance from Dawn Tschanz, Engineer. Mr. Nick Massaro, ASI Staff Member, assisted in the preparation of this report. Project Engineer R.A. Applehans, of EG&G's Facilities Engineering, Plant Civil-Structural Engineering (FE/PCSE)Project Engineer, provided a responsive review of this report.

This report was prepared and submitted in partial fulfillment of the Zero-Offsite Water-Discharge Study being conducted by ASI on behalf of EG&G's Rocky Flats, Inc.

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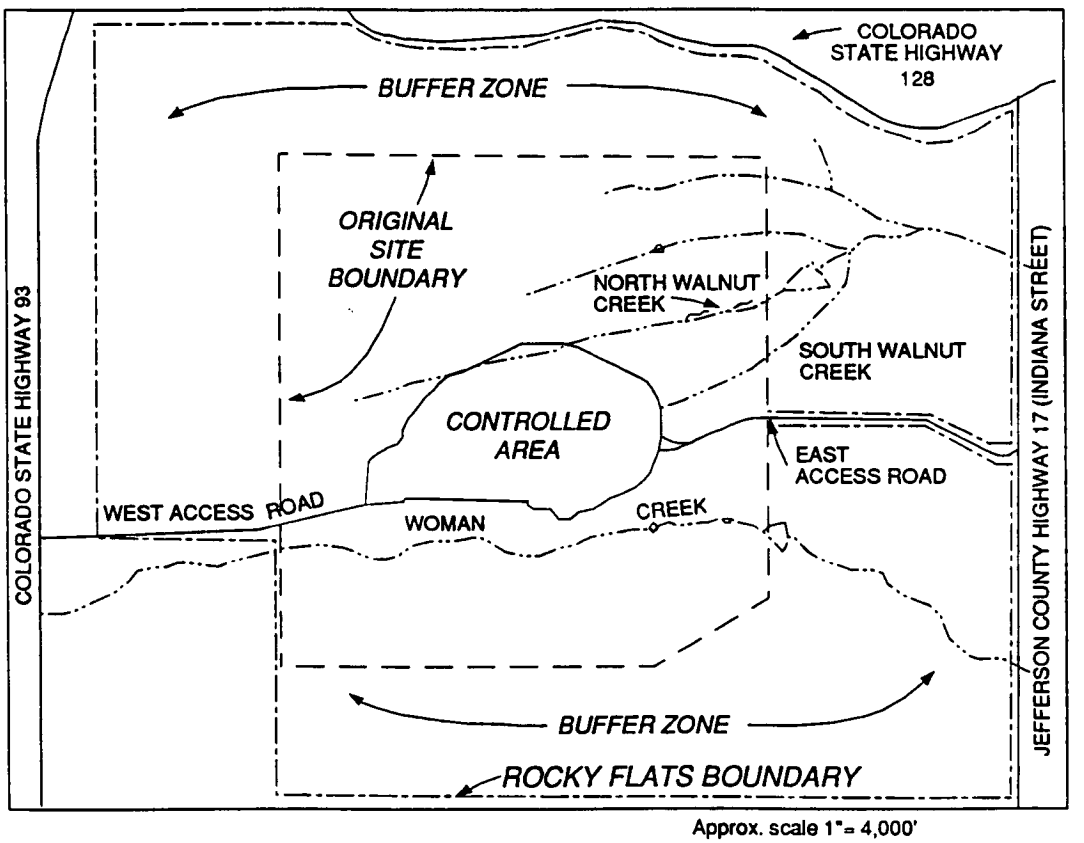
FIGURES

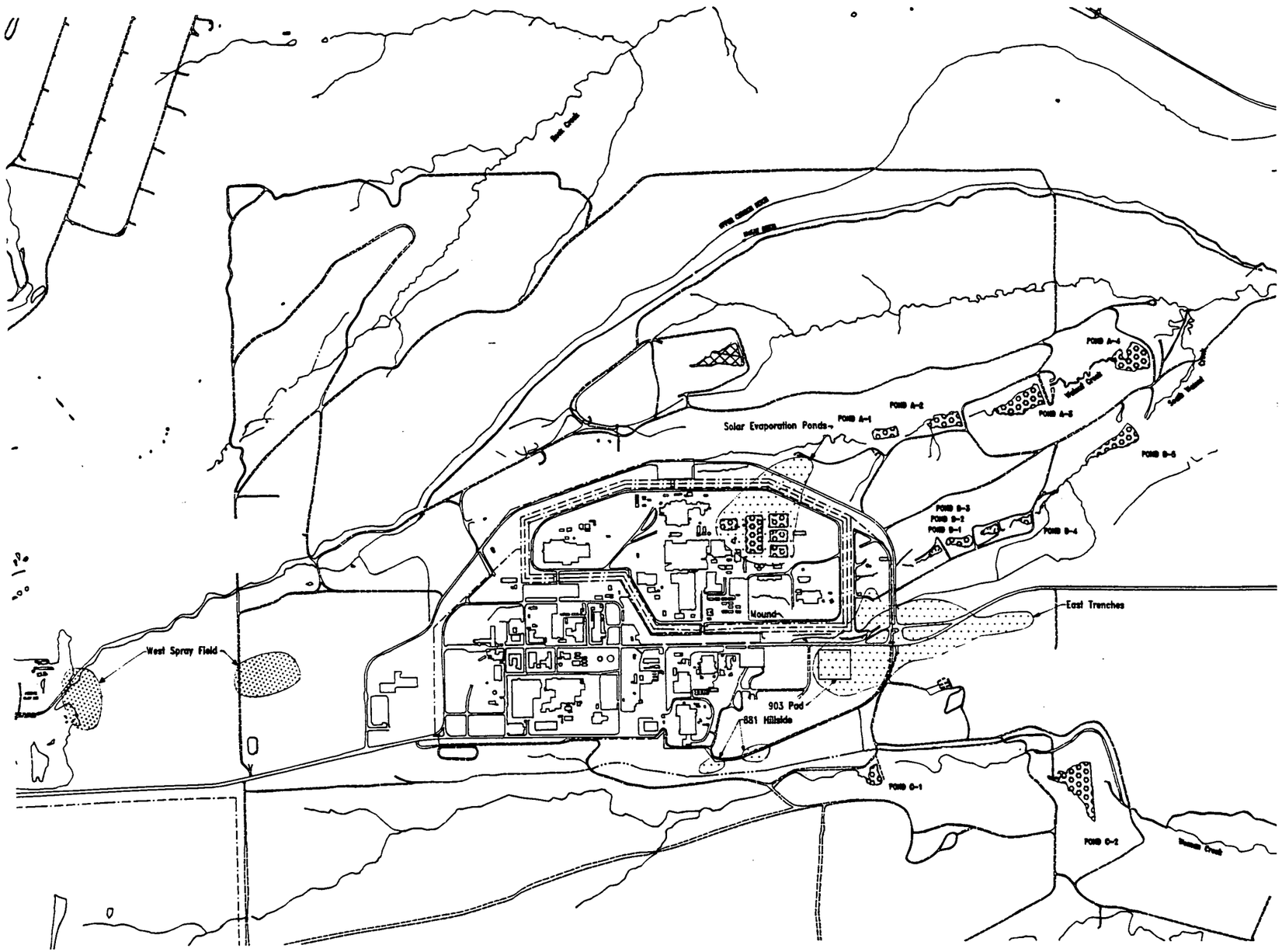


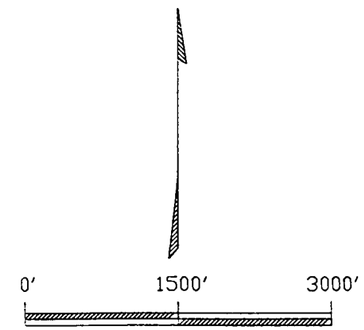
LOCATION MAP

FEASIBILITY OF GROUNDWATER CUTOFF/DIVERSION STUDY

Proj. No. 208.0126

Figure 1





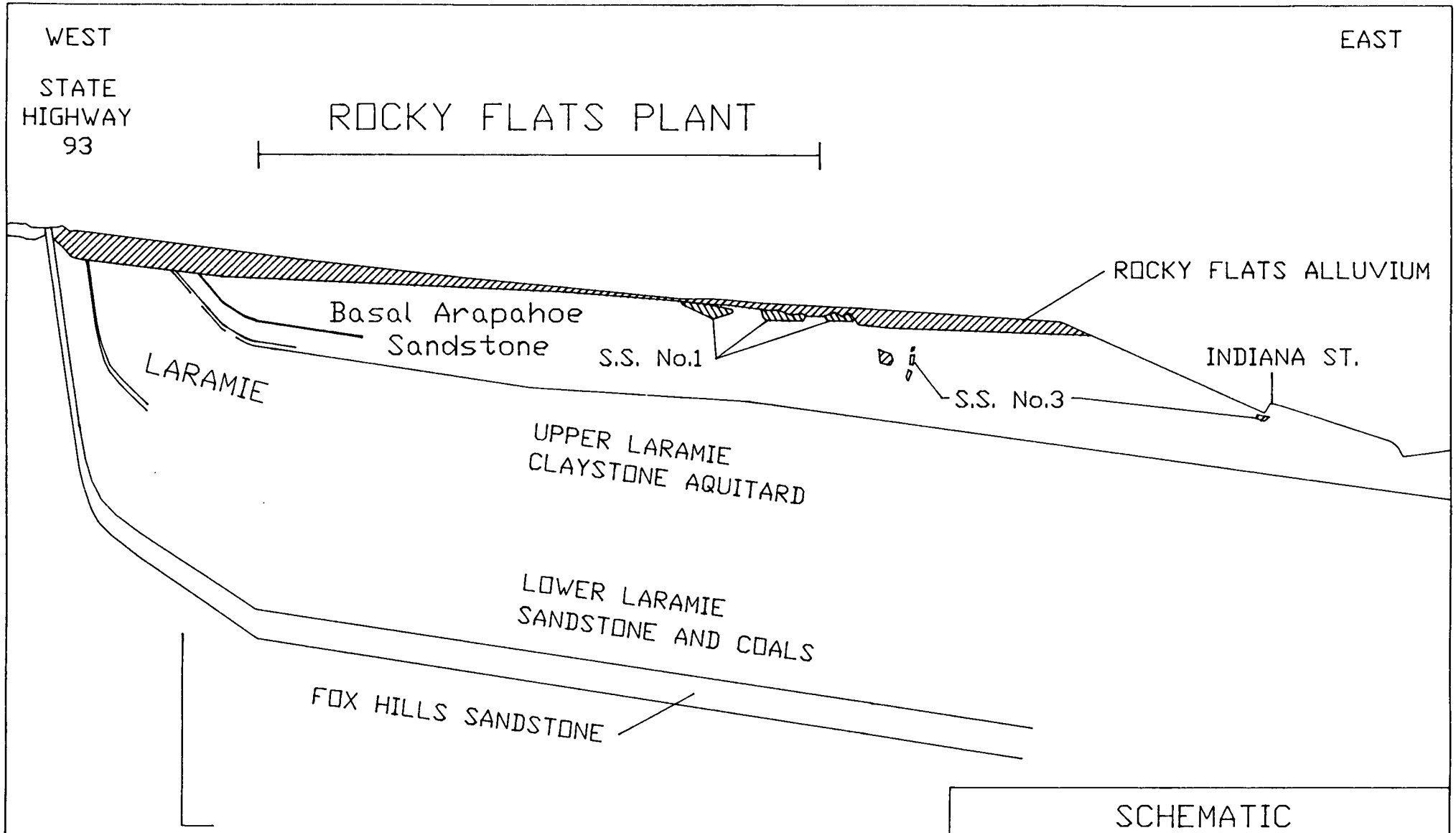
SCALE: 1" = 1500'

CONTAMINANT PLUME

POSSIBLE CONTAMINANT PLUME

SOURCE: EG&G, 1991a

LOCATION OF CONTAMINANT PLUMES		
FEASIBILITY OF GROUNDWATER CUTOFF/DIVERSION STUDY		
ZERO-OFFSITE WATER DISCHARGE		
	PROJECT: 208.0126	FIGURE 2
	DATE: MAY 1991	



SOURCE: EG&G, 1991b

REG28

SCHEMATIC

GEOLOGIC CROSS-SECTION OF SITE

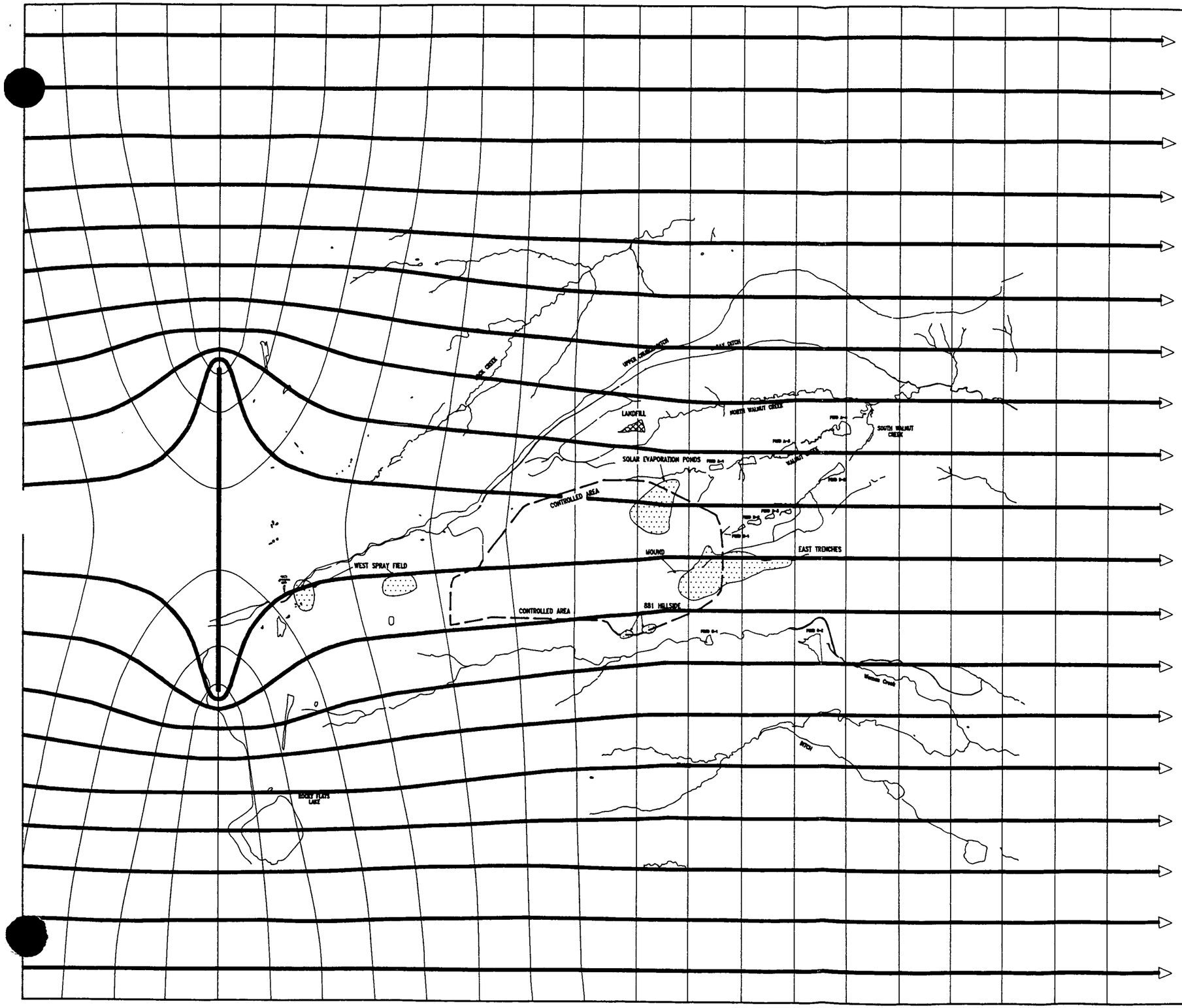
FEASIBILITY OF GROUNDWATER CUTOFF/DIVERSION STUDY

ZERO-OFFSITE WATER DISCHARGE

PROJECT: 208.0126

DATE: MAY 1991

FIGURE 3



BENTONITE-SOIL MIXTURE CUTOFF WALL

8400 FEET LONG X 75 FEET DEEP X 3 FEET WIDE

ESTIMATED COST: 6.3 MILLION

ESTIMATED CONSTRUCTION TIME: 1.5 YEARS

0′ 2500′ 5000′

SCALE: 1″ = 2500′

EQUIPOTENTIAL LINE

FLOWLINES: DIRECTION OF FLOW FROM WEST TO EAST

CUTOFF WALL

CONTAMINANT PLUME

POSSIBLE CONTMINANT PLUME

ALTERNATIVE 1 FLOW NET

(LINEAR CUTOFF TRENCH)

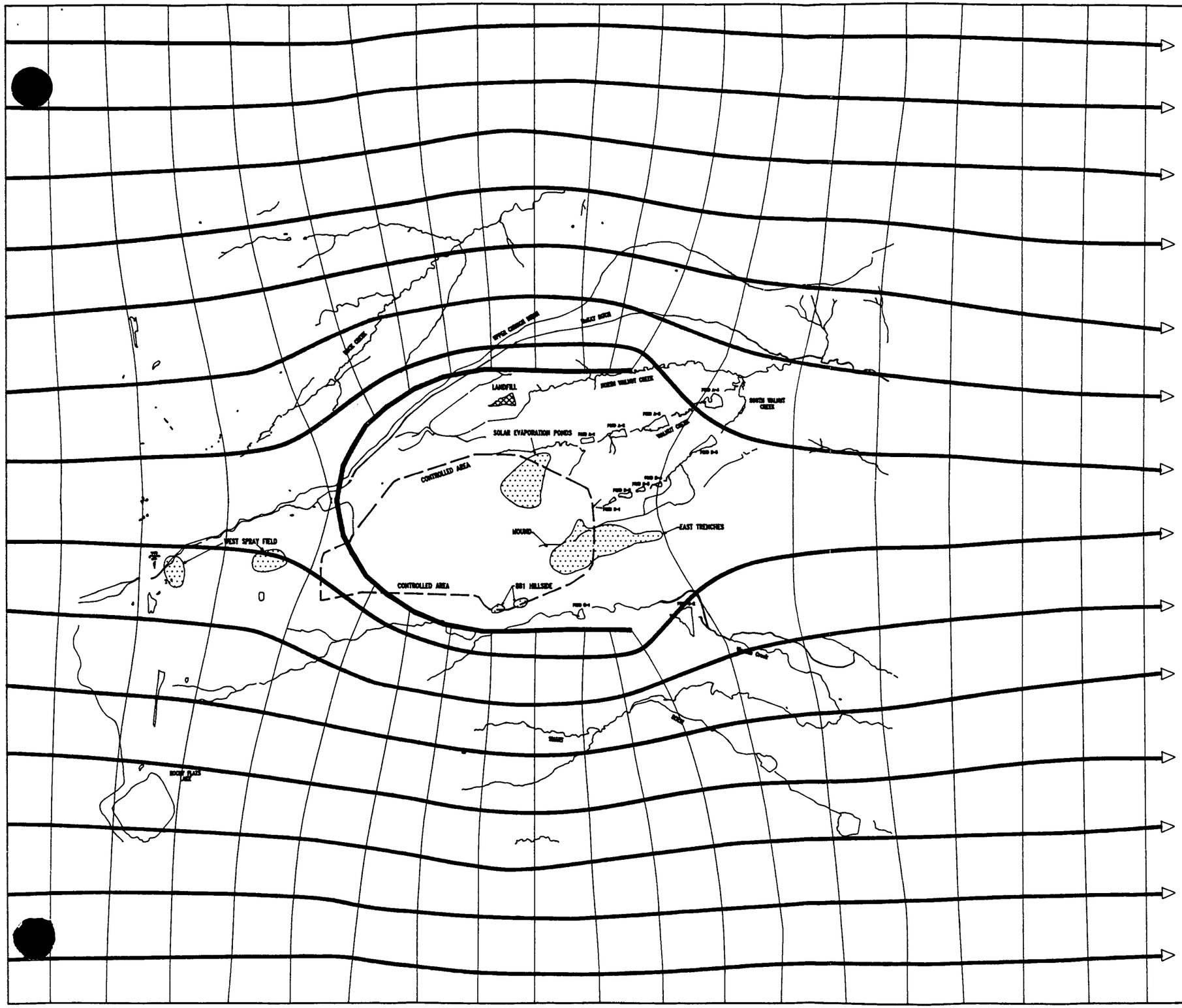
FEASIBILITY OF GROUNDWATER CUTOFF/DIVERSION STUDY

ZERO-OFFSITE WATER DISCHARGE

PROJECT: 208.0126

DATE: AUGUST 1991

FIGURE 4



BENTONITE-SOIL MIXTURE CUTOFF WALL

18400 FEET LONG X 25 FEET DEEP X 3 FEET WIDE

ESTIMATED COST: 4.6 MILLION

ESTIMATED CONSTRUCTION TIME: 1.1 YEARS

0′ 2500′ 5000′

SCALE: 1″ = 2500′

EQUIPOTENTIAL LINE

FLOWLINES: DIRECTION OF FLOW FROM WEST TO EAST

CUTOFF WALL

CONTAMINANT PLUME

POSSIBLE CONTAMINANT PLUME

ALTERNATIVE 2 FLOW NET

(CURVILINEAR CUTOFF TRENCH)

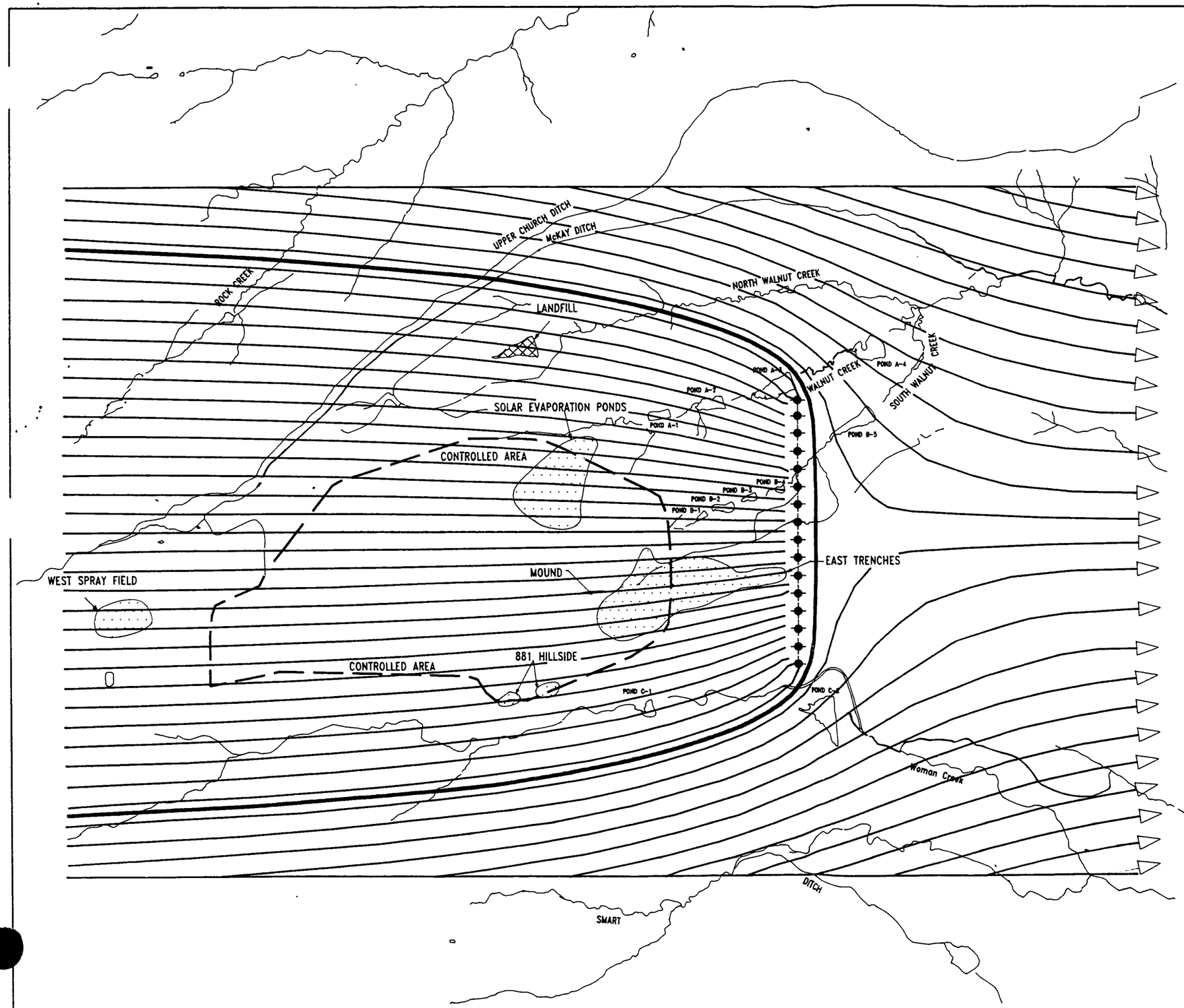
FEASIBILITY OF GROUNDWATER CUTOFF/DIVERSION STUDY

ZERO-OFFSITE WATER DISCHARGE

PROJECT: 208.0126

DATE: AUGUST 1991

FIGURE 5



FIFTEEN PUMPING WELLS

17.6 ACRE-FEET PER YEAR

ESTIMATED COST: $ 422,000

ESTIMATED CONSTRUCTION TIME: 2.1 MONTHS

0′ 1500′ 3000′

SCALE: 1″ = 1500′

PUMPING WELL

STREAMLINES: FLOW FROM WEST TO EAST

CAPTURE ZONES

CONTAMINANT PLUME

POSSIBLE CONTAMINANT PLUME

ALTERNATIVE 3 STREAMLINES

PUMPING WELLS ALONG EAST SIDE OF RFP

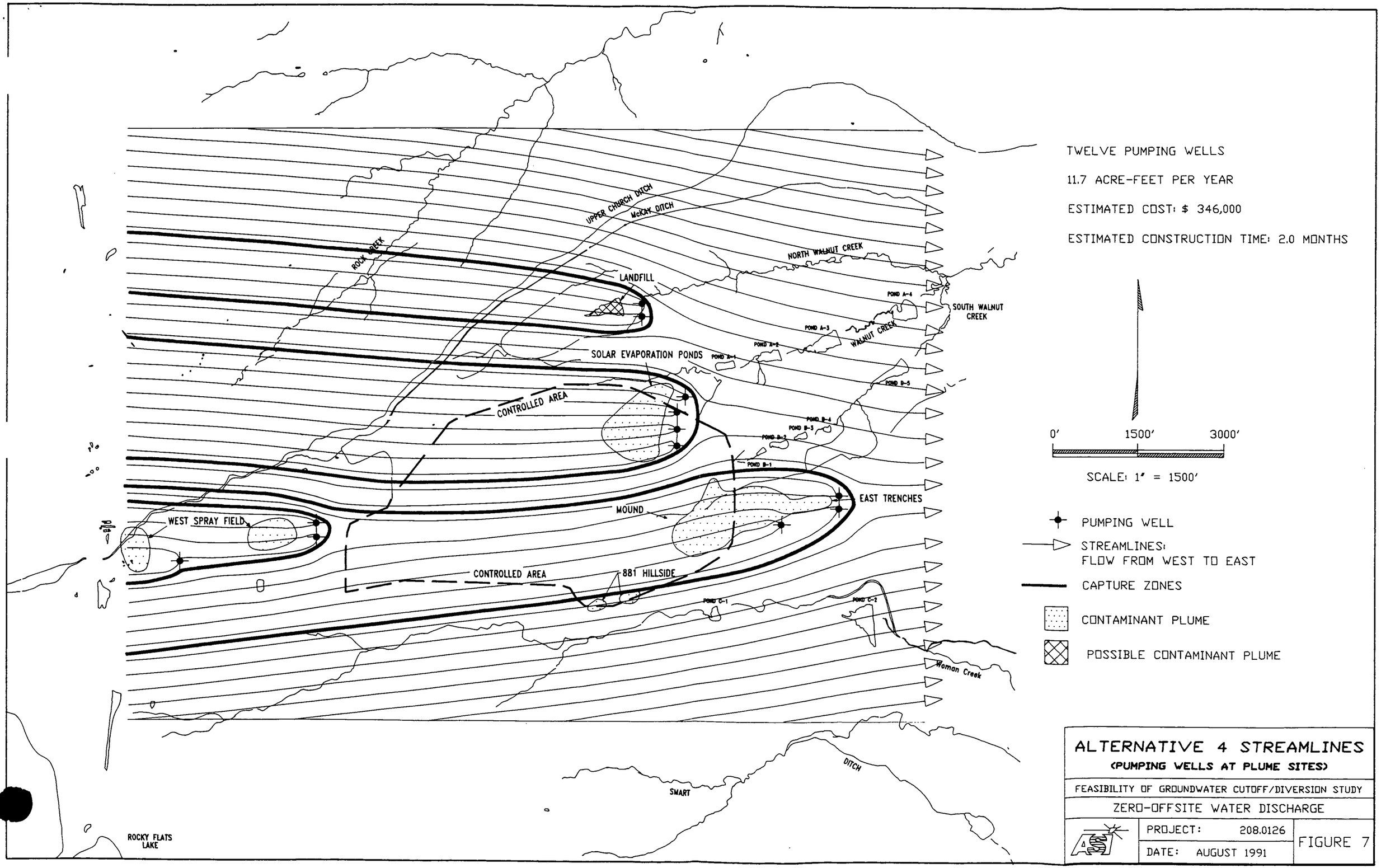
FEASIBILITY OF GROUNDWATER CUTOFF/DIVERSION STUDY

ZERO-OFFSITE WATER DISCHARGE

PROJECT: 208.0126

DATE: AUGUST 1991

FIGURE 6



ALTERNATIVE 4 STREAMLINES
(PUMPING WELLS AT PLUME SITES)

FEASIBILITY OF GROUNDWATER CUTOFF/DIVERSION STUDY

ZERO-OFFSITE WATER DISCHARGE

PROJECT: 208.0126

DATE: AUGUST 1991

FIGURE 7

A

APPENDIX A
ANNOTATED BIBLIOGRAPHY

ANNOTATED BIBLIOGRAPHY

ON THE GEOLOGY AND HYDROGEOLOGY

OF THE ROCKY FLATS PLANT

AND VICINITY

SOURCES FOR REFERENCED MATERIALS

USGS (U.S. Geological Survey)

- Library
  Denver Federal Center
  2nd. Avenue, Bldg. 20
  2nd. Floor, Room 2002
  Denver, Colorado 80225
  (303) 236-1000
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- Public Inquiries Office
  169 Federal Building
  1961 Stout Street, 1st. Floor
  Denver, Colorado 80294
  (303) 866-4169

NTIS (National Technical Information Center)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

RFP (Rocky Flats Plant Library, Wind Site)
P.O. Box 464
RCRA Building 250
Golden, Colorado 80402
(303) 966-7041

CO Div. of Water Res. (Colorado State Division of Water Resources)
Department of Natural Resources
1313 Sherman Street, Room 823
Denver, Colorado 80203
(303) 866-3587

CO Geol. Srv. (Colorado State Geological Survey)
Department of Natural Resources
1313 Sherman Street, Room 715
Denver, Colorado 80203
(303) 866-2611
CO O&G Comm. (Colorado State Oil and Gas Commission)
Department of Natural Resources
1580 Logan Street, Suite 380
Denver, Colorado 80203
(303) 894-2100

Denver Earth Resources Library
1531 Stout Street, Suite 200
Denver, Colorado
Kay Waller, Manager
(303) 825-5614

RMAG (Rocky Mountain Association of Geologists)
1531 Stout Street, Suite 210
Denver, Colorado 80202
(303) 573-8621

PIC (Petroleum Information Center)
518 17th Street, Suite 600
Denver, Colorado 80201
(303) 825-2299

W.W. Wheeler and Associates
3700 South Inca Street
Englewood, Colorado 80110
(303) 761-4130

Woodward Clyde Consultants
Stanford Place 3
4582 South Ulster Street Parkway
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Denver, Colorado
(303) 694-2770

CSM (Colorado School of Mines)
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coal beds and mine in the area. Indicates area discussed should be classed as coal land and contains minable coal at moderate depth. Amount of coal approximated at 30 million, more or less, tons of coal; however, to better ascertain the amount it is recommended in report that several core holes be bored to establish the thickness.

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Covington, G., 1966, Stratigraphy and Sedimentary Structures in the Fox Hills Sandstone, Golden Area, Colorado, Mountain Geologist, vol. 3, no. 4, p. 161-169. Source: USGS Library G(200) M864, not avail. for purchase.

Study of two sections of the Upper Cretaceous Fox Hills sandstone near Golden. Includes descriptions of stratigraphy and sedimentary structures.

Dames and Moore, 1981, Final Report, Geologic and Seismologic Investigations for Rocky Flats Plant for U.S. Department of Energy, Volume I , Text 244 p., Job No. 10805-041-14, DOE Contract No. DE-AC04-80AL10890. Source: RFP and USGS Libraries, NTIS, Order# DE83006257, Price Codes-PC A13/MF A01.

Report on a comprehensive geologic and seismologic investigation of the Plant and vicinity. Describes the regional geologic setting and the state of seismic activity for the Golden Fault, the graben, and the Plant. Documents historic research and current field and laboratory data pertaining to the 1882 earthquake.

Dames and Moore, 1981, Final Report, Geologic and Seismologic Investigations for Rocky Flats Plant for U.S. Department of Energy, Volume II , Appendices 455 p., Job No. 10805-041-14, DOE Contract No. DE-AC04-80AL10890. Source: RFP and USGS Libraries, NTIS, Order# DE83006258, Price Codes-PC A24/MF A01.

Results of a seismic refraction study of the Ralston Reservoir area including soil stratigraphic investigations, unit descriptions, an analysis of geodetic data, experimental model, seismological evaluation, a seismicity survey of the northern Golden Fault, historical data for the 1882 earthquake, and a dendrochronology study.

Dames and Moore, 1981, Final Report, Geologic and Seismologic Investigations for Rocky Flats Plant for U.S. Department of Energy, Volume III, Plates 207 p., Job No. 10805-041-14, DOE Contract No. DE-AC04-80AL10890. Source: RFP and USGS Libraries, NTIS, Order# DE83006309, Price Codes-PC A10/MF A01.

Contains geologic maps and cross sections for areas surrounding the Rocky Flats Plant.

Davis, T.L., 1976, Rocky Flats Reflection Seismic Project: In Final EIS to ERDA 1545-D, Rocky Flats Plant Site, Golden, Jefferson County, Colorado, April 1980, vol. 2 of 3, fig. 16. Source: RFP Library.

Results of investigation to determine the possible existence of faults at Rocky Flats. Interpreted 15 miles of seismic reflection data in the general vicinity of Rocky Flats and Eggleston Reservoir north of Highway 128. Three conclusions were drawn: two distinct but associated fault systems exist, a basement controlled graben area to the north and associated penecontemporaneous growth faulting exists in this graben area; the Plant is located on the stable, upthrown, horst block south of the graben area; and no faults exist within the immediate area of the Plant. Includes tectonic, structure contour, and seismic maps, stratigraphic column, synthetic seismogram, and seismic data.

Davis, T.L., and Young, T.K., 1977, Seismic Investigation of the Colorado Front Range Zone of Flank Deformation Immediately North of Golden, Colorado, Rocky Mtn. Assoc. of Geol., 1977 Symposium. Source: USGS Library G(271) R59f, not avail.

for purchase.

Interpretation of 40 miles of reflection seismic data in conjunction with surface maps and well data. Includes zone of flank deformation and seismic investigation.

Dobrovolny, E., and Gard, L.M., 1953, Report on the Geology of the Relocation Alignment Between Marshall, Colorado and the Rocky Flats Atomic Energy Commission Plant, State Highway No. 93, USGS Open-File Rpt. 53-400. Source: USGS Library (200) R290, Distribution.

Reports on the geology of the Pierre shale, Fox Hills sandstone, Laramie Formation, and late Tertiary or early Pleistocene deposits. Includes a geological column compiled from sections measured on and adjacent to the center-line of the proposed relocation.

EG&G, 1990, Draft Ground-Water Assessment Plan Addendum, U.S. Department of Energy, Rocky Flats Plant, Golden, Colorado. Source: ASI Library.

Responds to specific issues raised by the Colorado Department of Health (CDH) concerning inadequacies in the Rocky Flats Ground Water Assessment Plan. Additional information includes description of the current monitoring activities and data evaluation procedures, proposed changes in monitoring activities or data evaluation procedures, description of the data management plans, discussion of the schedules for monitoring, analysis, and data validation and reporting.

EG&G, 1990, Geological Characterization Report, Draft, U.S. D.O.E.-Rocky Flats Plant, Golden, Colorado. Source: ASI Library.

Includes text, maps, and cross-sections that detail the stratigraphic and structural setting of the RFP. The report also includes a model of the depositional setting during the period that the Arapahoe Formation was being deposited. The appendices include Table 1, listing all wells, their location, sands, and grain size analyses (Appendix A), rolled maps and cross-sections (Appendix B), annotated bibliography (Appendix C), graphs of grain size analyses (Appendix D), and a report describing the reprocessing of Colorado School of Mines seismic data (Appendix E).

EG&G, 1990, Groundwater Monitoring Plan for the Rocky Flats Sanitary Treatment Plant Sludge Drying Beds, Draft Final, RFP, Golden, Colorado. Source: ASI Library.

Provides a system for arresting potential impacts of the existing sludge drying beds in the groundwater resources of the area. This plan includes site history, geological/hydrologic setting, geological/hydrologic characterization plan, and groundwater monitoring plan.

EG&G, 1990, Groundwater Protection and Monitoring Program Plan, Draft, RFP, Golden, Colorado. Source: ASI Library.

Summarizes the hydrogeology of the site, major aquifers, movement of groundwater, potential sources of groundwater pollution, and uses of groundwater in the RFP. Includes a review of the monitoring program which describes the number of wells, sampling method, sampling frequency, analyses performed, and a summary of these analyses. This document also presents an analysis of the requirements contained in both Federal and State regulations. DOE Orders, and the Inter-Agency and other agreements, and evaluates their impact on the RFP groundwater program. Improvements are then presented so that the groundwater program may better comply with the regulatory requirements or the technical intent of the program.

ERDA, 1980, Final Environmental Impact Statement, Rocky Flats Plant Site, Golden, Jefferson County, Colorado, DOE/EIS-0064 (ERDA 1545-D), volume 1 of 3, p. 2-16 to 2-56. Source: RFP Library.

Discusses the geology and seismology of the Rocky Flats Plant including the physiography and geomorphology and geologic history, stratigraphy, soils, mineral resources, regional tectonic setting, history of seismographic stations in Colorado, 1882 earthquake, and the hydrology of the surface-water, aquifers, and infiltrating ground-water.

Emmons, S.F., Cross, W., and Eldridge, G.H., 1896, Geology of the Denver Basin in Colorado, USGS Monograph 27, 556 p. Source: USGS Library R(200)c, not avail. for purchase.

Report on the region between Golden and Boulder discusses physiography, historical geology, structural geology, hydrography, paleontology, and coal regions. Includes sections on the post-Laramie and Tertiary geology and the Arapahoe and Denver Formations.

Engineering-Science, Inc., 1975, A Supplementary Report to an Engineering Study for Water Control and Recycle Concerning the Recovery of Nitrate Laden Ground-Water, Contract AT(29-2)-3413. Source: RFP Library.

Evaluation and recommendations concerning problem of nitrate salts which are being transported from the area of the 207 Solar Evaporation Ponds into North Walnut Creek. Report includes problem description, problem analysis, 3 control alternatives and recommendations. Study of the groundwater contamination in the area of the Solar Evaporation Ponds was used to determine what must be accomplished to solve the contamination problem. Included are test hole locations, nitrate concentrations, location and depths of permeable lens, areas of significant nitrate concentration, proposed location of collection trenches, and a series of plans and profiles.

Greengard, T.C., 1984, History and Status of RCRA Ground Water Monitoring Program: Rockwell International Internal Letter. Source: RFP Library.

Letter discusses the groundwater monitoring program. The RCRA monitoring wells are stated as the ones down gradient from the solar ponds, about 17 are listed for monitoring purposes. States when sampling occurred and what was found as a result. Well samples were analyzed for the RCRA parameters in 1982 and 1983 and for the EPA drinking water parameters in 1984.

Gude, J.A. III, 1950, Clay Minerals of the Laramie Formation, Golden, Colorado, Identified by X-Ray Diffraction, American Association of Petroleum Geologists Bulletin, vol. 34, no. 8, p. 1699-1717. Source: USGS Library G(200) Am3.

Study of the mineralogical and lithological distribution and association of clay minerals by the X-ray diffraction powder method. A complete section across the Upper Cretaceous Laramie Formation was mapped, measured, and sampled in detail.

Hall, D.C., and Johnson, C.J., 1979, Drinking-Water Quality and Variations in Water Levels in the Fractured Crystalline-Rock Aquifer, West Central Jefferson County, USGS Water Resource Investigation No. PB-80 128 580 (WRI 79-94), 57 p. Source: USGS Library (200)WRI, NTIS Distribution.

Analysis of water-quality data from 26 wells located in small urbanized areas between Golden and the Arapahoe National Forest. Most of the wells are located between Evergreen and Conifer. Twenty-one wells contained excessive concentrations of major chemicals, bacteria, trace elements, or radiochemicals.

Hall, D.C., Hillier, D.C., Cain, D.C., and Boyd, E.L., 1980, Water Resources of Boulder County, Colorado, CO Geological Survey Bulletin 42, 97 p., 19 figs., 23 tables, 1 pl. Source: USGS Library, CO Geol. Survey Distributes $8.

Discusses groundwater availability. Includes maps of well and spring locations for which water-quality data are available, and identifies location of aquifers.

Hampton, O.W., 1957, Structural Geology of the Foothills Region from Plainview to Golden, Univ. of CO Thesis T-1957. Source: Univ. of CO H189 s C.1.

Discusses the area in the foothills zone between Golden and the Boulder County-Jefferson County line, T. 2 S. to T. 3 S., R. 70 W. to R. 71 W. Provides an areal geologic map, delineation of geologic structures, and an outline of the tectonic history of the eastern flank of the Front Range. Describes the relationship of local structural features to the regional features of the Front Range. Includes stratigraphy and lithology of the Arapahoe-Denver Formation, the Green Mountain conglomerate, and Tertiary igneous rocks, and the structural geology and genesis of the regional setting, sedimentary rocks, and faults.

Harms, J.C., 1961, Laramide Faults and Stress Distribution in Front Range, Colorado [abs.], In abstracts of the 46th Annual Meeting in Denver, April 24-27, 1961, American Association of Petroleum Geologists Bulletin, vol. 45, no. 3, p. 413-414. Source: USGS Library G(200) Am3.

Analysis of the Front Range faults with discussion of fault origins.

Hillier, D.E., Schneider, P.A., Jr., and Hutchinson, E.C., 1979, Hydrologic Data for Water-Table Aquifers in the Greater Denver Area, Front Range Urban Corridor, USGS Open-File Rpt. 79-214, 83 p. Source: USGS Library (200) R290, USGS distributes $14.25.

Provides hydrologic data for water-table aquifers in the greater Denver area collected and compiled during 1976-1977. Consists of records for 325 wells and 11 springs and chemical analyses of the water for 272 of the wells and all of the springs.

Hoffman, N.D., 1984, Nonradioactive Groundwater Data Summary, 1975-1983, Rockwell International. Source: RFP Library.

Report summarizes selective nonradiological data and trend evaluation on the monitoring wells from 1975 through 1983. States approximately 50 non-radiological parameters are analyzed on groundwater samples each quarter. Included in report are drinking water parameters, nitrate and selenium, groundwater quality parameters, groundwater contamination parameters, conclusions and recommendations. Appendices include graphs on nitrate concentration in monitoring wells, TDS (total dissolved solids) concentrations in monitoring wells, and conductivity in monitoring wells. Figures in report include locations of groundwater monitoring wells at Rocky Flats; ranges of nitrate, TDS and conductivity concentrations in monitoring wells; nitrate, selenium, manganese and iron concentrations above drinking water standard; high TDS and conductivity wells. Tables include drinking water parameters data for monitoring well, nitrate, TDS, and conductivity data summary.

Hofstra, W.E., and Hall, D.C., 1975, Basic Data 36, Hydrogeologic and Water-Quality Data in Western Jefferson County, Colorado, CO Geol. Survey MI 11, 51 p., 2 figs., 12 tables (accom. CGS Bull 36). Source: USGS Library, not avail. for purchase.

Discusses an area of 300 square miles in the mountainous parts of Jefferson County cornered by Clear Creek, Pike National Forest, the Front Range, and the western boundary of Jefferson County. Studies water availability and water-

quality problems associated with sewage disposal.

Hofstra, W.E., and Hall, D.C., 1975, Geologic Control of Supply and Quality of Water in the Mountainous Part of Jefferson County, Colorado [with abs.], CO Geol. Survey Bulletin 36, 51 p., 42 figs., 8 tables. Source: USGS Library, CO Geol. Survey distributes $4.

Study indicates that water-quality problems are related to geology and hydrology of the mountain environment. Contains geologic and hydrologic descriptions for Jefferson County.

Horner, W.P., 1954, The Fox Hills-Laramie Contact in the Denver Basin, Univ. of CO Thesis, 62 p. Source: Univ. of CO Library.

Study of the Fox Hills and Laramie Formations in six major outcrops between Golden and Milliken, Colorado. The Formations are described by textures, structures, and compositions, and further defined and separated by deposition, provenance of material, agents of transportation, and other forces acting on the sediments. In the southern part of the area, the Laramie differs from the Fox Hills by having more detrital quartz, chert, and clay, and less feldspar. The bedding of the Laramie is thinner and more variable, the grains have a slightly closer correlation between size and roundness. Two of the outcrops studied occur near Boulder--the Denver and Rio Grande West Railroad cut (S.E. 1/4 sec. 21, T. 2 S., R. 70 W.) and the Marshall, Belmont Bluff (S.E. 1/4 N.E. 1/4 sec. 21, T. 1 S., R. 70 W.).

Hunter, M., 1949, Geologic Patterns in the Foothills of the Front Range, Boulder-Lyons Area, Colorado, Univ. of CO Thesis. Source: Univ. of CO Earth Science Library 3.

Study of an area adjacent to Boulder and Lyons at 105*10′ west longitude and 105*20′ west latitude. Covers the stratigraphy of the Idaho Springs Formation, Coal Creek series, Boulder Creek quartz monzonite, and Silver Plume granite, the sediments of the Fountain, Ingleside, Lykins, Jelm, Dr. Bond, Morrison, Dakota, Colorado group, Frontier, Montana group, and Laramie Formation. Discusses geologic chronology and regional structure.

Hurr, R.T., 1976, Hydrology of a Nuclear-Processing Plant Site, Rocky Flats, Jefferson County, Colorado, USGS Open-File Report 76-268, 68 p.. Source: USGS, RFP, CSM, and USGS (200) R290 Libraries, USGS distributes $21.75.

Reports on the potential impact of plant operations on the surface-water and ground-water hydrology of the plant and vicinity. Assesses the distribution of contaminants as they move spatially and temporally through the hydrologic system. Data complements earlier reports with geologic mapping, test drilling, surface and borehole geophysical measurements, collection of additional well data and water-level measurements, and installation of three stream-gaging stations (two equipped with recording rain gages) and a stream-sediment sampler. Includes diagram of surface water hydrology and ground water hydrographs of selected wells.

Hydro-Search, Inc., 1985, Draft Report, Hydrogeologic Characterization of the Rocky Flats Plant, Golden, Colorado, prepared for Rockwell Int'l. Corp. under Project No. 1520, 163 p., 5 tables, 11 figs., 2 plates, appendices A-F. Source: RFP Library.

Report describes the ground-water hydrology and chemical conditions at Rocky Flats with recommendations for improvement. Provides data for 56 on-site wells, completion information for geologic logs and wells, and geochemical data for 1983 and 1984. Discusses two field programs-a geophysical logging of 9 existing wells to define sub-surface stratigraphy, and single hole draw-down-recovery tests in ten wells for developing on-site hydraulic conductivity

values for the Rocky Flats alluvium, the Arapahoe Formation, and the valley fill materials. Appendices include geophysical logs, geochemical data, volatile organic data, and procedures for ground-water sampling, field water quality testing, and water sample preservation.

Hydro-Search, Inc., 1986, Electromagnetic Survey, Rocky Flats Plant, Golden, Colorado (Project No. 106G05502). Source: RFP Library.

Report discusses the electromagnetic survey that was conducted along the periphery of the security area and the downgradient drainages in the buffer zone. It was performed along relatively constant geologic materials so that the only variable would be the conductivity of the groundwater. The survey found several areas of relatively high ground conductance which appear to correlate with the areas of saturated surficial material based on the 1986 drilling program.

Hydro-Search, Inc., 1986, Geological and Hydrogeological Data Summary, USDOE Rocky Flats Plant, Golden, Colorado. Source: RFP Library.

The existing geologic, hydrologic, and water quality data for the Rocky Flats Plant are summarized in this report. Included is a description of the geology, both regional and local geologic setting, groundwater hydrology, groundwater chemistry and surface-water hydrology. This information is based on previously collected data and reports. Includes a complete reference of all known hydrologic and soils reports. Figures, tables and plates, cover cross-sections, water table conditions, possible contaminant source areas, surface water monitoring locations, details of existing monitoring wells at the Rocky Flats Plant, details of drawdown-recovery tests at the plant, groundwater sampling program, and monitor well location at the plant.

Hydro-Search, Inc., 1988, Front Range Lightweight Aggregate Project, Official Development Plan, Written Restrictions, Supporting Documentation, Prepared for L.C. Holdings, Inc., Project No. 241P08252, 38 p., 3 tables, 10 maps. Source: RFP Library.

Zoning plan prepared in response to a proposal by L.C. Holdings, Inc. in which an open pit mine containing shale, sand, and gravel (located west of CO Hwy. 93) and a processing plant (located east of CO Hwy. 93 in the vicinity of Rocky Flats) would be reactivated and operated. Discusses the surface and ground-water hydrology of two channels--Coal Creek and the South Boulder Diversion Canal, the impact of precipitation on the surficial materials, and the hydrology of the Fox Hills sandstone, the Hygiene Sandstone Member, and the sandstones of the Dakota group. Describes the water infiltration from the Rocky Flats gravels into the Coal Creek drainage basins and sub basins (p. 19-23), and provides drainage design criteria and hydrologic data. [NOTE: Information on drainage, geology, and soils, etc., is contained in the Official Development Plan supporting documentation].

Lackey, J.G., Jones, E.B., and Wollenberg, H.A., E.G. and G., Inc., 1976, Summary of Non-Nuclear Remote Sensing at the Rocky Flats Site and Status of Analysis of Geological and Hydrological Indicators--July 1975 Through December 1975, EGG-1183-1679, In U.S. Department of Energy, Final Environmental Impact Statement, 1980, vol. 2, appendix C-1, p. C-1-1 to C-1-19. Source: RFP Library.

Project to acquire a catalog of remotely sensed data in the form of photographic and thermal infrared imagery to supplement available data about and help in the interpretation of geological, hydrological, and ecological environment at Rocky Flats.

Lackey, J.G., Jones, E. B., and Wollenberg, H. A., 1976, Summary of EG&G Non-nuclear Remote Sensing at Rocky Flats Site and Status of Analysis of Geological and Hydrological Indicators- July 1975 through December 1975, 20 p. Source: RFP

Library.

Report includes a description of the data acquisition and activities that produced all available imagery and data, the findings of the program to date relative to hydrological and geological indications, the field investigation performed to verify the interpretations and results of the investigation, and interim recommendations for additional investigations necessary to resolve uncertainties identified to date.

Lavington, C.S., and Thompson, W.O., 1948, Structural Geology, In Field Trip 1: Geology of the Eastern Flank of the Front Range of Colorado, CSM Quarterly, vol. 43, no. 2, p. 28 and 31. Source: USGS Library S(271) C78.

Briefly describes the structural geology of the Front Range and the faults that run parallel to the mountains near Boulder. Explains that the faults were the result of forces that originated south of Boulder which caused en echelon folds to develop in the north and a series of faults, mostly of the thrust type such as the Golden Fault, to develop west of Boulder.

Lavington, C.S., and Thompson, W.O., 1948, Post-Mississippian Stratigraphy, In Field Trip 1: Geology of the Eastern Flank of the Front Range of Colorado, CSM Quarterly, vol. 43, no. 2, p. 36-52. Source: USGS Library S(271) C78.

Attributes folding along the east margin of the Front Range to the Laramide revolution. Discusses stratigraphic units in rising order of deposition from the Pre-Fountain surface to the Laramie and younger Formations mentioning the Dawson, Arapahoe, and Denver Formations.

Lindstrom, L.J., 1978, Stratigraphy of the South Platte Formation (Lower Cretaceous), Eldorado Springs to Golden, Colorado, and channel Sandstone Distribution of the J Member, CSM Thesis T-2053, 305 p., 6 pl. Source: CSM Library Front Desk.

Study describes and correlates the members of the South Platte Formation (T. 1 N. to T. 3 S., R. 71 W. to R. 65 W.) exposed in outcrop along the Dakota Hogback to establish environments of deposition of the individual process-controlled genetic units, as well as the units comprising the J Sandstone Member. Describes measured sections in T. 2 S. to T. 3 S., R. 70 W. to R. 71 W.

Machette, M.N., 1975b, The Quaternary Geology of the Lafayette Quadrangle, Colorado, Univ. of CO, M.S. thesis T-1974, 106 p. Source: Univ. of CO Library M123 C.1.

Thesis on an area 8 miles east of the mountain front in the central Colorado Piedmont to report on pre-Quaternary and Quaternary deposits, soils, correlation and age of Quaternary deposits, and Quaternary geologic history.

Machette, M.N., Birkeland, P.W., Markos, G., and Guccione, M.Q., 1976, Soil Development in Quaternary Deposits in Golden-Boulder Portion of CO Piedmont, In Studies in Colorado Field Geology, CSM Prof. Contrib. no. 8, p. 339-357. Source: USGS Library S(271) C78pc.

Result of a field trip between Golden and Boulder to examine the changes in several key properties of soils, primarily as a function of time. Stopped at terraces made up of gravely alluvium derived from the mountains to the west, identified buried soils, and compared these to mountain soil. Observed the bedrock geology, the core of the Front Range composed of Precambrian granite, gneiss, and schist, and the outcrop west of the mountain front near Clear Creek formed by quartzite, the steeply dipped beds of Paleozoic and Mesozoic sandstone, shale, and limestone located near the east flank of the range, and the more resistant sandstone units which form the hogbacks and flatirons. The

bedrock in the plains is formed by Cretaceous shale and sandstone and some Tertiary sandstone and basalts. Quaternary alluvial gravel overlie the surfaces cut on the resistent and nonresistant rock types. See USGS Open-File Report 76-804 below.

Machette, M.N., Birkeland, P.W., etal., 1976, Field Descriptions and Laboratory Data for a Quaternary Soil Sequence in the Golden-Boulder Portion of the Colorado Piedmont, USGS Open-File Report 76-804. Source: USGS Library (200) R290.

Provides field descriptions of soil and laboratory data for seven gravel pits, roadcuts, and arroyos measured at ground level to 10 to 15 feet below the surface.

Major, T.J., Robson, S.G., Romero, J.C., and Zawistowski, S., 1983, Hydrologic Data from Parts of the Denver Basin, Colorado, USGS Open-File Report 83-274, 425 p. Source: USGS Library (200) R290, not avail. for purchase.

Presents hydrologic data collected and compiled during 1956-1981 for all major aquifer systems above the Pierre shale-including the Alluvium, Castle Rock Conglomerate, Dawson, Arapahoe, and Laramie-Fox Hills. Consists of records for 870 wells, including water-level data for 158 wells, and water-quality analysis for 561 wells.

Malde, H.E., 1955, Surficial Geology of the Louisville Quadrangle, Colorado, USGS Bulletin 996-E, p. 217-259. Source: USGS Library (200)M, USGS distributes $2.25.

Study of three main divisible groups of surficial deposits--pre-Wisconsin, Wisconsin, and Recent--including extensive descriptions of gravel deposits from each group. The dissected erosion surface known as, Rocky Flats, fans out from Coal Creek Canyon and ends near the south border of the quadrangle. It transects the Pierre shale, Fox Hills sandstone, and Laramie Formation, and cuts across the steeply dipping older sediments including the Dakota and Fountain Formations. Rocky Flats is capped by a strongly weathered gravel composed of about 60% quartzite, 20% schist and gneiss, 12% granite and pegmatite, and 8% sandstone and siltstone.

Malde, H.E., and Van Horn, R., 1965, Stratigraphy, Soil, and Geomorphology of the Nonglacial Quaternary Deposits Between Boulder and Golden, Colorado, Trip 8: In Guidebook for 1-Day Field Conf., Boulder Area, Colorado, Int'l. Assoc. of Quaternary Research, 7th Congress, USA, 1965, Lincoln, NE, Acad. of Sci., p. 40-47. Source:

Field trip describing a sequence of alluvial deposits between Boulder and Golden.

Mann, D.M., 1960, The Geology of an Area Near Eldorado Springs (Boulder County), Colorado, Univ. of CO Thesis T-1960. Source: Univ. of CO Library M315 g C.1.

Discusses post Cambrian sedimentary rocks, Precambrian rocks, faults, folds, lineation, and foliation in Precambrian rocks and joints for an area 18 miles northwest of Denver in the foothills of the Colorado Front Range.

Murray, D.F., 1967, Gravel Mounds at Rocky Flats, Colorado, Mtn. Geol., vol. 4. Source: USGS Library G(200)M 864.

Study of mounds of sorted gravel upon a pavement of cobbles and small boulders on the coarse alluvium of the Rocky Flats pediment. Pocket gophers are the source of the mounds.

Oliveria, R.B.B. de, 1975, Exploration for Buried Channels by Shallow Seismic Refraction and Resistivity and Determination of Elastic Properties at Rocky

Flats, Jefferson County, Colorado, CSM Thesis T-1718 (unpub.), 131 p. Source: CSM Library Front Desk.

Seismic investigation undertaken at Rocky Flats, a gravel-capped pediment, to reveal an irregular bedrock surface with several ancient channels. Explains that the channels (unnamed) were probably eroded by streams flowing from Coal Creek Canyon and over time Rocky Flats alluvium was deposited on a pediment surface that had replaced earlier sedimentary deposits. The broader channels at the bedrock surface were filled with gravel. Successive erosional cycles cut lower pediments creating nine alluvial formations in the Colorado Piedmont. Numerous intermittent streams dissect the surface of Rocky Flats and springs and seeps are common along the contact between the permeable sands and gravels of the Rocky Flats alluvium and underlying impermeable shales. The Arapahoe Formation of the Upper Cretaceous is a conspicuous conglomerate averaging 100 feet in thickness containing fragments derived from local sedimentary rocks of older age and from the crystalline complex farther west.

Pearl, R.H., 1974, Geology of Ground Water Resources in Colorado, CO Geol. Survey SP 4, 47 p., 18 figs., 7 tables. Source: CGS Library, CO Geol. Survey distributes $3.

Report describes the ground-water resources of Colorado in relation to water quantity, quality, and distribution for various geographic regions. Discusses the geological and hydrological conditions of the following geographic regions: South Platte River Basin, Eastern Colorado, Northern High Plains, North Platte River Basin, Arkansas River Basin, Southern High Plains (Cimarron River Basin), Rio Grande River Basin, and Western Colorado.

Quiett, F.T., 1951, The Geology of the Plainview Area, Jefferson County, Colorado, CSM Thesis T-720, 80 p., 2 pl. Source: CSM Library Front Desk.

Study of the physiography, stratigraphy, and structure of a 4.2 square mile area located between Coal Creek Peak on the south and Bull Gulch on the north, including a portion of the Rocky Flats pediment formed from the eroded Dakota Formation. The composition of the quartzite boulders found at the Rocky Flats pediment is the same as the rocks found on Coal Creek Peak. The pediment has its final development on the Dakota and as it spreads out to the east it probably covers most of the Laramie group. The Dakota sandstone, along with the other sediments, is considerably disturbed in the vicinity of Rocky Flats, causing faulting. The surface of the pediment is dissected by eastward flowing streams from the Front Range, most notably the South Boulder Creek and Coal Creek.

Rahmanian, V.D., 1975, Deltaic Sedimentation and Structure of the Fox Hills and Laramie Formations, Upper Cretaceous, Southeast of Boulder, Colorado, CSM Thesis T-1671, 83 p., maps. Source: CSM Library Front Desk.

Investigation of the stratigraphy, sedimentology, and depositional environments of the Fox Hills and its associated formations and a study of the effects, if any, on growth faulting in Late Cretaceous sedimentation in T. 1 S., R. 70 W. and sections 1, 12, 13, and 24 of T. 1 S., R. 71 W.

Riecker, R.E., 1956, Geologic History of the Boulder Region, Earth Science, vol. 9, no. 5, p. 20-26 and vol. 19, no. 6, p. 22-26. Source: USGS Library G(200) Ea6.

Report on the Coal Creek vicinity about 5 miles south of Boulder in the east foothills reveal considerable areas of quartzite, quartz-mica schists, and mica schists which are probably early Proterozoic in age. The Arapahoe Formation of the Eocene age is interpreted as a series of alluvial fanglomerates composed chiefly of fine-to-coarse grained clastics, thinning rapidly to the south and

southeast away from the highland source. The basal conglomerate of the Arapahoe contains pebbles of all the older formations, including the Precambrian, and shows small erosional unconformity with the Laramie. No evidence suggests a greater time interval between the development of the Laramie and Arapahoe than that between the Fox Hills and Laramie Formations. The Precambrian pebbles in the Arapahoe reveal that deposition occurred during the Laramide Revolution.

Robb, G.L., 1948, Quaternary Pediments in the Golden Area, Colorado [Abs.], Colorado Wyoming Academy of Science, vol. 3, no. 5, p. 37. Source: USGS Library, S(271) C88.

Reports that many of the gravel capped mesas along the eastern slope of the Front Range are in reality pediment surfaces. Three major surfaces are represented in the Golden area--the highest surface being the Coal Creek pediment that extends east from the mouth of Coal Creek, the middle or Ralston pediment between Ralston Creek and Leyden Gulch, and on the eastern edge of the Coal Creek pediment the Ralston pediment is present in many places only as a transition zone between the upper and lower surfaces. It is believed that many of the gravel capped surfaces along the Front Range can be correlated with these three pediment surfaces. The upper pediment may be the high plains representation of Orodell Berm.

Robson, S.G., 1984, Bedrock Aquifers in the Denver Basin, Colorado-A Quantitative Water-Resources Appraisal, USGS Open-File Report No. 84-431, 111 p. (superseded by USGS Prof. Paper P 1257, Robson). Source: USGS Library (200) R290, not avail. for purchase.

Contains a hydrologic evaluation of ground-water resources of the Denver Basin. Includes mapping of aquifer extent, thickness, structure, hydraulic characteristics, and water-level and water-quality conditions. Provides a simulation of aquifer response to various pumpage estimates and ground-water development plans. Plates dated 1978 show measured and model-calculated potentiometric surfaces of bedrock aquifers.

Robson, S.G., 1987, Bedrock Aquifers in the Denver Basin, Colorado; A Quantitative Water-Resources Appraisal, USGS Prof. Paper 1257, 73 p., 5 pl. (supersedes O-F Rpt. 84-431). Source: USGS Library, USGS distributes $4.25.

Information on study preformed in order to evaluate the effects of future pumpage on ground-water supplies. The study area is 6,700 square miles and has 4 bedrock aquifers. Study involved mapping of aquifer extent, thickness, structure, hydraulic characteristics, and water-level and water-quality conditions. Report includes: other related studies, the natural hydrologic system, its stratigraphy, aquifer characteristics, water levels, recharge and discharge, and water quality. Simulated hydrologic system, model simulations and groundwater development plans including satellite well field, Metropolitan well field, pumpage for park and golf course irrigation and bedrock storage of municipal water. Supplemental information includes historical pumpage estimates, future pumpage estimates and modeling errors and limitations. An extensive use of maps accompany the report.

Rockwell Int'l., 1986a, Draft Work Plan-Geological and Hydrological Site Characterization, USDOE, RFP, Golden, Colorado. Source: RFP Library.

Work plan that describes the activities and tasks to be preformed at the Rocky Flats Plant in order to characterize site geology, hydrology and water quality. Included is the initial site evaluation, its hydrogeologic setting, waste disposal activities, and prioritization of potential containment, and the nature and extent of contamination. The site characterization, topography, geology, ground water hydrology, surface water hydrology, sediments, and laboratory materials testing are discussed. Work plan includes figures, tables

and plates of Rocky Flats Plant, surficial geology, shallow and bedrock monitor well completion diagrams, graphic schedule, surface-water sampling parameters, monitor well locations, and locations of surface and sediment monitoring stations.

Rockwell Int'l., 1987, Ground-Water Modeling of Impacts of Proposed Spray Irrigation, RFP, Golden, Colorado. Source: RFP Library.

Assesses impacts of proposed spray irrigation on the ground-water flow systems at the facility. Estimation was made of the impact to the water table, as well as the to ground water flow directions, from spray irrigating 80 million gallown per year (220,000 gallons per day) of tertiary treated sewage effluent. The assessment used an analytical ground-water flow model to make quantitative analyses of two locations. The analytical solution was used to calculte the changes in the elevation of the water table (hydraulic head) through time. With this analytical model, which used field data generated by Rockwell contractors, several application scenarios were modeled.

Rockwell Int'l., 1987, Remedial Investigation Report for 903 Pad, Mound, and East Trenches Area, December 31, 1987, 11 vols. Source: RFP Library.

Report illustrates the existence and location of the waste disposal sites, their characterization, evaluates the nature and extent of contamination and develops data needed for feasibility studies of remedial alternatives. The three areas are the 903 Pad, Mound, and East Trenches area at the Rocky Flats Plant. Volume I includes site locations and descriptions, previous investigation, the nature and extent of the problem and remedial investigation summary. The regional setting and site features including the land use, natural resources, climatology, physiography, regional hydrogeologic setting and water resources are described. Volume II is the characterization of the waste sources of the 3 areas. Volume III describes the site hydrogeology including the surficial geology, bedrock geology, ground-water flow, and ground-water chemistry. Volume IV describes the surface water, hydrology, surface water chemistry, sediments and flood potential. Also included are descriptions of the plants ambient air monitoring and sampling for radionuclides and the remedial investigation of the air sampling results. The biota, its flora, wildlife and aquatic life of the area is evaluated. Included are public health and environment concerns, potential receptors, public health impacts and environmental impacts. Volume V reports on Phase 2 of the CEARP- Rocky Flats site specific monitoring plan, report of geophysical investigations of the 3 areas- soil gas survey data and description of drilling activities. Volumes VI, VII, and VII, are the hydrogeologic data. Volume IX is the analytical chemistry and soils data. Volume X describes the ground-water data, surface-water and sediment data and quality assurance. Volume XI details biota data and RAAMP sampler summary data.

Rockwell International, 1987, Remedial Investigation Report for High Priority Sites (881 Hillside Area), Prepared for the U.S. DOE, Rocky Flats Plant, Golden, Colorado, July 1, 1987, Vol. I-text and plates, Vols. II to V-Appendices. Source: RFP Library

Volume I presents results of a remedial investigation undertaken to verify the existence and location of waste disposal sites in the general vicinity of the 881 Hillside area, to characterize the site, to evaluate the nature and extent of contamination, and to develop data needed for feasibility studies of remedial alternatives as appropriate. Discusses the Fountain, Upper Laramie, and Arapahoe Formations and the creeks of North and South Walnut, Woman, Coal, and Rock, and Leyden Gulch. Volume II reports on the geophysical investigation, the soil gas survey, and drilling activities. Volume III provides hydrogeologic data, volume IV presents analytical chemistry results, and volume V discusses quality assurance and biota.

Rockwell Int'l., 1986, Resource Conservation and Recovery Act Part, B-Operating Permit Application, Prepared for the U.S. DOE-Rocky Flats Plant, Section E, November 1986

Section E describes ground water monitoring and protection. Provides a description of the hydrogeologic setting and the identification of the uppermost aquifer at Rocky Flats based on existing hydrogeologic data.

Rockwell International, 1988, Resource Conservation and Recovery Act, Part B-Operating Permit Application, Transuranic Mixed Wastes, July 1, 1988, Prepared for the U.S. DOE-Rocky Flats Plant, Project No. C07890010526, vol. 1 which contains Section B. Source: RFP Library.

Applicable sections discuss site environment and climate (p. B-2, B-6 to B-7), surface waters, drainage patterns, and controls (p. B-28 to B-29), and seismic considerations and historic seismicity (p. B-41 to B-54). Describes the geologic bench known as Rocky Flats as covered with a thin layer of gravely topsoil underlain by a 20 to 50 foot thick layer of coarser, clayey gravel with poor water holding capacity. The western soils are very cobbly, stony sandy loams and clay loams in Hydrologic Group C, while the eastern soils are clayey with some cobbly clays in Hydrologic Group D. Five creeks flowing on or near the Plant are--North and South Walnut, Woman, Coal, and Rock.

Rockwell International, 1988, Resource Conservation and Recovery Act Post-Closure Care Permit, vol. 1, section E, October 5, 1988. Source: RFP Library.

Features regional and plant hydrology information--methods of ground water recharge for the Laramie-Fox Hills Aquifer and the Arapahoe Aquifer, and ground water directions and flow rates. Covers plant site geology and stratigraphy, including discussion of the Laramie and Arapahoe Formations, and the lower sandstone unit and upper claystone unit. Includes graphics and plant area cross section.

Rockwell International, 1988, Resource Conservation and Recovery Act Post-Closure Care Permit, vol. VI, appendix 6, section 5 (general geology), Oct. 5, 1988; and section 3 (site hydrology, solar ponds), 30 p. Source: RFP Library.

Section five describes regional surface picture and plant surficial geology specifying six Quaternary unconsolidated units (alluvium) and provides cross sections of formations and listing of GSA classifications for formations. Discusses regional ground water hydrology--recharge/discharge conditions, ground water flow DxNs, bedrock flow systems, the Laramie-Fox Hills and Arapahoe Aquifers, and surface water hydrology--natural drainages and ditches. Section three discusses site hydrogeology and solar ponds, including the surficial geology, bedrock geology, and ground water geology of solar ponds.

Rockwell International, 1988, Resource Conservation and Recovery Act Post-Closure Care Permit, vol. VII, appendix 6, section 3, appendix B, October 5, 1988. Source: RFP Library.

Provides hydrogeologic data, boring logs, and aquifer test data.

Rockwell International, 1989, Seismic Reflection Profiling of the Arapahoe Formation at the Rocky Flats Plant, Draft Report, U.S. Department of Energy, August 1989. Source: RFP Library.

Report on the shallow, high-resolution seismic reflection technique using seismic modeling. Work to determine the feasibility of using this technique to answer detailed geologic question, optimize groundwater monitoring well placement, and verify results. Field testing was done within the parameters set and the results are presented in this report. Includes seismic data acquisition, data processing, interpretation of information, and

recommendations.

Rojas, I. de, 1980, Stratigraphy of the Mowry Shale (Cretaceous), Western Denver Basin, Colorado, CSM Thesis T-2343, 148 p., 6 pl. Source: CSM Library Front Desk.

Study to interpret the characteristics of how the Mowry Shale, overlying the J Sandstone, was deposited and the depositional processes that controlled the sediment distribution in T. 6 N. to T. 7 S., R. 60 W. to R. 70 W. Discusses geology, marine sedimentation, and ash fall clay minerals. Appendices include measured surface sections, subsurface core data, and X-ray diffraction patterns of ash falls and shales.

Rutt, K.L., 1966, Report of Sampling Wells North of North Patrol Road (North of 90, 95) and East of Parking Lot (East of 25), 2 p.

Report subpoenaed by FBI.

Schneider, P.A., Jr., 1980, Water Supply Assessment of the Laramie-Fox Hills Aquifer in Parts of Adams, Boulder, Jefferson, and Weld Counties, Colorado, USGS Open-File Report 80-327, 21 p., 81-002. Source: USGS Library (200) R290, USGS distributes $13.50.

Reports on sources of recharge and discharge, aggregate sand and aquifer thickness, well yields, and water quality. Covers the Erie, Lafayette, Louisville, Niwot, and Superior Quadrangles of the Front Range.

Scott, G.R., 1960, Quaternary Sequence East of the Front Range Near Denver, Colorado, In Guide to the Geology of Colorado, Geologic Society of America, Rocky Mountain Association of Geologists, and Colorado Scientific Society, Weimer, R.J., and Haun, J.D., (eds)., p. 206-211. Source: USGS Library G(200) G29gf.

Discusses the soils, geomorphology, and stratigraphy (including Rocky Flats alluvium) of the Kassler and Littleton Quadrangles. Correlates the Quaternary deposits to geomorphic development.

Scott, G.R., 1960, Subdivision of the Quaternary Alluvium East of the Front Range Near Denver, Colorado, Geol. Soc. America Bull., vol. 71, no. 10, p. 1541-1543. Source: USGS Library G(200) G29.

Discusses the recognition and differentiation of alluvial formations near Denver including the Rocky Flats, Verdos, Slocum, Louviers, Broadway, and Recent.

Shuck, E.L., 1976, A Seismic Survey of the Ralston Area, Jefferson County, Colorado, CSM Thesis T-1835, 45 p. Source: CSM Library Front Desk.

Report on a multifold seismic reflection survey to identify subsurface information about the Ralston area (T. 3 S., R. 70 W., sections 4, 5, and 9) that is largely covered with Quaternary colluvium and Rocky Flats alluvium. Discusses geology, survey procedures and results, drape-folding of the Fox Hills and Laramie Formations, and features of the Golden Fault and area surrounding Ralston dike.

Soister P.E., 1978, Stratigraphy of Uppermost Cretaceous and Lower Tertiary Rocks of the Denver Basin, Rocky Mountain Association of Geologists - Symposium, p. 223-230. Source: CSM Library.

Discusses the stratigraphy, thickness, and the relative locations of the Laramie, Arapahoe, Denver, and Dawson Formations.

Thompson, W.O., 1949, Lyons Sandstone of Colorado Front Range, American

Association of Petroleum Geologists Bulletin., vol. 33, no. 1, p. 52-72. Source: USGS Library G(200) Am3.

Describes in detail the original structures of the Permian Lyons sandstone of the Front Range. Includes sedimentation study and cross sections.

Tieje, A.J., 1923, The Red Beds of the Front Range in Colorado; A Study in Sedimentation, Jour. Geol., vol. 31, p. 192-207. Source: USGS Library G(200) J83.

Report on the "Red Beds" of the Fountain, Lyons, and Lykins Formations and their time-equivalents east of the Continental Divide. Describes the conditions under which the sediments were laid down.

Van Horn, R., 1976, Geology of the Golden quadrangle, Colorado: With Emphasis on Deposits of Pliestocene Age and Their Economic Potential, Engineering Characteristics, and Environmental Implications, USGS Prof. Paper 872, 116 p. Source: USGS Library, USGS distributes $3.65.

Comprehensive geologic study of physiography, stratigraphy, structural features, history, economics, and engineering (see accompanying USGS map I-761-A). Provides an in-depth description of the Arapahoe and Denver Formations present in the southern part of the quadrangle (p. 35-47). Discusses Quaternary deposits of alluvium (including Rocky Flats), colluvium, loess, transported mantle, artificial fill, and landslides (p. 53-79). Includes chart showing pebble count, size, and longitudinal stream and terrace profiles of alluvial deposits for Clear, Van Bibber, Ralston, and Leyden Creeks, and Tucker Gulch.

VanSlyke, G., Romero, J., and Wacinski, A., 1986, Aquifer Data from Geophysical Logs, Denver Basin, Colorado, Basic Data Report 1, Office of the State Engineer, Colorado Division of Water Resources, text p. 1-12, data p. 13-67. Source: CO Div. of Water Resources $8.

Briefly describes the Denver Basin (approximately 6,700 square miles) and the Dawson, Denver, Arapahoe, and Laramie-Fox Hills aquifers, and lists interpretative data for over 2,400 geophysical logs of oil, gas, and water wells in the Denver Basin. Includes geophysical log files for sections in T. 1 S. to T. 3 S., R. 69 W. to R. 70 W. The data was compiled to assist in the formulation of rules and regulations on the withdrawal of ground water. Data covers well location, surface elevation, elevation of tops and bases of aquifers identified on each well log and total thicknesses of sandstones and siltstones.

Van Tuyl, F.M., and Lovering, T.S., 1935, Physiographic Development of the Front Range, Geol. Soc. America Bull., vol. 46, no. 9, p. 1291-1350. Source: USGS Library G(200) G29.

Discusses the physiographic development of the Front Range, describes and correlates the Tertiary erosion surfaces of the peneplains of Flattop, Green Ridge, Cheyenne Mountain, Overland Mountain, and Bergen Park, and the berms of Flagstaff Hill, Mount Morrison, and Orodell, and explains the modifying effects of alpine glaciation, Quaternary terraces, deformation of erosion surfaces, and age relations.

Visher, Glenn, S., 1972, Physical Characteristics of Fluvial Deposits, Recognition of Ancient Sedimentary Environments SEPM Special Publication, no. 16, February, p.84-97. Source: CSM.

Relates the characteristics of fluvial deposits to the geomorphic and hydraulic processes that are responsible for their formation. Discussion includes

description of a series of fluvial models, physical aspects of fluvial deposits, and genetic implications of fluvial processes.

Weimer, R.J., 1973, A Guide to Uppermost Cretaceous Stratigraphy, Central Front Range, Colorado: Deltaic Sedimentation, Growth Faulting, and Early Laramie Crustal Movement, Mountain Geologist, vol. 10, no. 3, p. 53-97. Source: USGS Library G(200)M 864, not avail. for purchase.

Study of late Cretaceous stratigraphic and structural history based on four outcrop sections along a north-south distance of 25 miles from highway I-70 to Golden, Leyden, and White Rocks (7 miles northeast of Boulder). Contains generalized bedrock map for the area west of Denver, Cretaceous stratigraphy map of the central Front Range, and sedimentation and tectonics discussions.

Weimer, R.J., 1976, Cretaceous Stratigraphy, Tectonics, and Energy Resources, Western Denver Basin, In Studies of Colorado Field Geology, CSM Prof. Contributions no. 8, p. 180-227. Source: USGS Library S(271) C78pc.

Examines the Cretaceous outcrops along the west margin of the Denver Basin and discusses the stratigraphic models and associated energy resources--coal, petroleum, and uranium. Summarizes the diagnostic characteristics of the upper Pierre shale and Fox Hills sandstone, looks at the Arapahoe and Denver Formations, and fault patterns. Includes general bedrock geology map, general stratigraphic section for the Golden-Morrison area, structure cross section along Leyden Gulch, and lithologic descriptions.

Weimer, R.J., and Tillman, R.W., C 1980, Tectonic Influence on Deltaic Shoreline Facies, Fox Hills Sandstone, West-Central Denver Basin, CSM Prof. Contributions, vol. 1, no. 10, 131 p. Source: USGS Library S(271) C78pc.

Describes sedimentation, paleogeography, structures, petrology, and stratigraphy for parts of Jefferson, Boulder, Weld, and Adams Counties. Discusses the Fox Hills sandstone in the west-central flank of the Denver basin where listric-normal growth faults caused an abnormal thickness of shoreline deposits to accumulate during the Cretaceous Maestrichtian stage. Reports on the Laramie Formation, Front Range Uplift, regression, growth faults, cyclic processes, Laramide orogeny, and well logs. Includes stratigraphic model, paleogeographic maps, tables, geologic cross sections, and geologic sketch map.

Weimer, R.J., and Davis, T.J., 1979, Stratigraphic and Seismic Evidence for Late Cretaceous Growth Faulting, Denver Basin, Colorado, CSM 930385 79-14122, p. 277-299. Source:

Interpretation of 250 miles of reflection seismic data in conjunction with surface maps and well data along the east flank of the Denver Basin (T. 3 N. to T. 2 S., R. 71 W. to R. 67 W.) that reveals two distinct types of Late Cretaceous faulting--an early Laramide and a new Rocky Mountain tectonic style. Discusses geologic structure and stratigraphy, seismic investigation data, the new tectonic style, and applications to petroleum exploration.

Wells, J.D., 1967, Geology of the Eldorado Springs Quadrangle, Boulder and Jefferson Counties, Colorado, USGS Bulletin 1221-D, 85 p. Source: USGS Library (200)M, not avail. for purchase.

Reviews the petrography, stratigraphy, and structural geology of the Precambrian metamorphic and igneous rocks, Paleozoic and Mesozoic sedimentary rocks, ad the cenozoic surficial deposits.

Wheeler, W.W., and Associates, Inc., 1972, Report on Hydrologic Investigations-Rocky Flats, Job no. 4410-210-980-106, prepared for C.F. Braun and Company, Contract no. AT (29-2)-2996. Source: W.W. Wheeler and Associates, Inc.

Results of a hydrologic study to determine the magnitudes of floods to be expected under extreme conditions at various points near the proposed construction of a Plutonium Recovery Facility at the Rocky Flats Plant. Areas studied were the drainage basin of Walnut Creek above the northwest Perimeter Road; the drainage basin above the proposed flood runoff diversion canal between coordinates N 36,500 to N 37,500+, E 17,500; the drainage basin below the diversion canal to the plant area; and the drainage along the plant access road. Includes analyses of water supply for cooling and dispersion and dilution characteristics of the system, appendix by Dr. Robert A. Clark on the storm potential up to and including the probable maximum.

Wilson, W.W., 1965, Pumping Tests in Colorado, Colorado Water Conservation Board, Colorado Ground Water Circ. 11 (prepared by USGS), 361 p. Source: USGS Library 490(271) qC71c.

Examines and analyzes ground water data and presents results in graphical form to show pumping rates, drawdown, and recovery measurements, depths of wells, pretest water levels, thickness of saturated materials, specific capacities, and aquifer designations. Shows data for sections of basins containing the Arkansas River, Colorado River, Kansas River, Platte River, and the Rio Grande River.

Woodward-Clyde Consultants, 1987, Spray Irrigation Facility, Rocky Flats Plant, Jefferson County, Colorado, Prepared for Merrick and Company, Job no. 22050-350. Source: Woodward-Clyde Consultants.

Results of geotechnical studies for developing geotechnical and geohydrological design criteria for proposed spray irrigation facility. Includes summary of laboratory test results, hydraulic loading rates, test hole and field permeability test locations, summary logs of test holes, gradation analysis, swell-consolidation test results, gradation and compaction test results.

Woodward-Clyde Consultants, 1985, Phase I Engineering Services, Consolidated Environmental Projects, Rocky Flats Plant, Golden, Colorado, Prepared for Merrick and Company, Job no. 21616-350. Source: Woodward-Clyde Consultants.

Reports on the bedrock geology in the Rocky Flats area including discussion of the Arapahoe, Laramie, Fox Hills, and Pierre Formations, Rocky Flats Alluvium, the Eggleston Fault, and site hydrogeology including the Arapahoe Aquifer, Great Western Reservoir, South Platte River, and domestic irrigation wells. Includes graphics on site and regional hydrogeology.

Woodward-Clyde Consultants, 1980, Geotechnical Services, Buildings 444, 447, 865, 881, 883, and Three Stacks, Rocky Flats Plant, Golden, Colorado, Prepared for Bernard Johnson, Inc., Job no. 19732-350. Source: Woodward-Clyde Consultants.

Results of geotechnical studies to determine specific engineering characteristics of foundation materials, foundation alternatives, and criteria for foundation design for proposed additions. Discusses subsoils and ground water. Includes locations and summary logs of test holes, gradation analysis, swell-consolidation test results, and summary of laboratory test results.

Woodward-Thorfinnson and Associates, Inc., 1974, Investigation of Ground Water Possible Contamination, Atomic Energy Commission, Rocky Flats Plant, Rocky Flats, Colorado, Prepared for Swinerton and Walberg Company, Job No. 17893-350. Source: Woodward-Clyde Consultants.

Investigation of five evaporation ponds on the northeast corner of the main plant site where water moves to the north toward Walnut Creek. Includes vicinity map and location of ground water study area, bedrock contour map, and summary logs of test holes.

Woodward-Clevenger and Associate, Inc., 1973, Water Level Measurements at

Plutonium Recovery Facility, Atomic Energy Commission, Rocky Flats Plant, Denver, Colorado, Prepared for C.F. Braun and Company, Job No. 16450-350. Source: Woodward-Clyde Consultants.

Includes location of test holes and test pits.

Zeff, Cogorno, and Searly, Inc., 1974, Report of Subsurface Studies for U.S. Atomic Energy Commission Sanitary Landfill Renovations, Rocky Flats Plant, Golden, Colorado, Contract No. AT(29-2)-3422, Project No. 13759, 19 p. Source: Rocky Flats Soil Investigation Files.

Results of subsurface studies made for the proposed site of the Sanitary Landfill Renovations at the Rocky Flats Plant. Field and laboratory investigations of subsoil conditions were made with the use of borings and test pits. Samples were inspected both visually and in a laboratory to evaluate the physical and mechanical properties. Includes description of the setting, seismicity, which was noted as a zone 1 seismic risk area, the natural slope stability, and subsurface conditions. The sampling structure and borrow areas with their findings are described. Groundwater studies indicate that the dominant flow is through the alluvium above the bedrock surface. A second type is within the fracture zones of the claystone bedrock. Complete design considerations are given in conjunction with the results. Included is site location plan, slope map, typical cross-section of sampling structure, gradation analysis and graphs of soils. Appendices explain field investigations and laboratory testing.

MAPS, CHARTS, AND GRAPHICS

Blair, R.W., 1951, Subsurface Geologic Cross Sections of Mesozoic Rocks in Northeastern Colorado, USGS Oil and Gas Investigation Chart OC-42 (2 sheets). Source: USGS Library M(200)OC, not avail. for purchase.

Chart shows stratigraphy of subsurface and exposed mesozoic rocks in northern Colorado in parts of Larimer, Clear Creek, Jefferson, Yuma, and Sedgwick Counties.

Chase, G.H., and McConaghy, J.A., 1972 (R 1973), Generalized Surficial Geologic Map of the Denver Area, Colorado, USGS Misc. Geol. Inv. Map I-731, Lat 39*22'30" to 40*, long 104*37'30" to 105*20', scale 1:62,500, sheet 41.5x51 inches. Source: USGS Library M(200)I, USGS distributes $3.10.

Portrays areal distribution of 12 map units and briefly describes lithologic character and water-yielding characteristics of included formations. Geology was mapped and compiled between 1956 and 1963.

Hampton, E.R., 1975, Map Showing Availability of Hydrologic Data Published by the U.S. Environmental Data Svc., the U.S. Geol. Survey, and Cooperating Agencies, Greater Denver Area, Front Range Urban Corridor, Colorado, USGS Misc. Geol. Inv. Map I-856-C ($1.25), Lat 39*22'30" to 40*, long 104*37'30" to 105*22'30", scale 1:100,000, sheet 33.5x36.5 inches. Source: USGS Library M(200)I, USGS distributes $2.40.

Map of the Greater Denver area between Boulder and Golden shows hydrologic data by symbols and color. Presents climatological data including precipitation, temperature, and evaporation; surface water data of stage and discharge of streams, chemical quality of streams, lakes, and reservoirs, and sediment load of streams; and ground water data showing water levels and chemical quality.

Hillier, D.E., Schneider, P.A., Jr., and Hutchinson, E.C., 1983, Well Yields and Chemical Quality of Water from Water-Table Aquifers in the Greater Denver Area, Front Range Urban Corridor, Colorado, USGS Misc. Geol. Inv. Map I-856-J, 2 sheets, Lat 39*22'30" to 40*, long 104*37'30" to 105*22'30", scale 1:100,000, sheet 1-33x36 inches, sheet 2-33x38 inches. Source: USGS Library M(200)I, USGS distributes $6.70.

Shows yields ranging from less than 100 to 3,500 g/min which have been measured and reported from industrial, irrigation, and public-supply wells completed in unconsolidated alluvial deposits and in the Dawson, Denver, and Arapahoe aquifers. Most of the unconsolidated alluvial deposits in the northern two-thirds of the area yield water containing dissolved-solids concentrations of more than 500 mg/L. Water quality constituents include iron, manganese, magnesium, nitrogen, selenium, and sulfate.

Hillier, D.E., Schneider, P.A., Jr., and Hutchinson, E.C., 1983, Depth to the Water Table (1976-1977) in the Greater Denver Area, Front Range Urban Corridor, Colorado, USGS Misc. Geol. Inv. Map I-856-K, Lat 39*22'30" to 40*, long 104*37'30" to 105*22'30", scale 1:100,000. Source: USGS Library M(200)I, USGS distributes $3.10.

Shows that depths to the water table in unconsolidated alluvial aquifers ranged from 1.1 to 55.5 feet during 1976-1977. Depths to the water table in the consolidated rock of the Dawson, Denver, and Arapahoe aquifers generally ranged from 20 feet to 100 feet.

Hunter, M., 1955, Geology of the Foothills of the Front Range in Northern Colorado, Rocky Mountain Association of Geologists Map, scale 1:48,000. Source: CSM MPRM.

Map shows the outcrop sedimentary rocks on the east flank of the Front Range north of Golden, Colorado to the Wyoming-Colorado boundary. Includes the sedimentary rocks from the contact of the fountain formation on Pre-Cambrian rocks to the Hygiene member of the Pierre Formation. When possible map is extended on the eastern margin to the Laramie Formation. Information concerning the geologic formations of the area are described in detail on the map along wiht visual images.

Kiteley, L.W., 1978, Stratigraphic Sections of Cretaceous Rocks of the Northern Denver Basin, Northeastern Colorado, and Southeastern Wyoming, USGS Oil and Gas Investigation Chart OC-78. Source: USGS Library M(200)OC, USGS distributes $7.30.

Chart shows selected well locations, lines of cross sections, and formations for an area cornered by Laramie and Cheyenne in Wyoming and Jefferson County and Adams County in Colorado.

Lindvall, R.M., 1972, Geologic Map of the Arvada Quadrangle, Adams, Denver, and Jefferson Counties, Colorado, USGS Misc. Geol. Field Studies Map MF-348, 2 sheets: sheet 1, Lat 39*45' to 39*52'30", long 105* to 105*07'30", scale 1:24,000, each sheet 20x31 inches. Source: USGS Library M(200)MF, not avail. for purchase.

The Arvada Quadrangle, bounded by Standley Lake in the northwest, Thornton in the northeast, Speer Boulevard and I-25 in the southeast, and Lakewood in the southwest, shows the distribution and physical description of unconsolidated surficial deposits. Rocky Flats is not shown.

Machette, M.N., 1975, Geologic Map of the Lafayette Quadrangle, Adams, Boulder, and Jefferson Counties, Colorado, USGS Misc. Field Studis Map MF-656, Lat 39*52'30" to 40*, long 105* to 105*07'30", scale 1:24,000, sheet 29x40 inches. Source: USGS Library M(200)MF, not avail. for purchase.

The Lafayette Quadrangle, bounded on the northwest by Lafayette, on the southwest by Ketner Reservoir, on the southeast by Thornton, and on the northeast by 160th Avenue and I-25, shows faults, railroads, artificial fill, mines, and altitude. Depicts soil horizon and stratigraphic relationships between alluvial, colluvial, and eolian deposits.

Norris, J.M., Robson, S.G., and Parker, R.S., 1985, Summary of Hydrologic Information for the Denver Coal Region, Colorado, USGS Water Resources Investigation 84-4337, 68 p. Source: USGS Library (200)WRI, availability unknown.

Figure 29, page 48, depicts the approximate location and extent of bedrock aquifers; Figure 30, page 49, provides generalized geologic sections (one from west to east, another from north to south), Plate 1 shows the approximate extent and water-table altitudes of major Alluvial Aquifers; Plate 2 shows the altitude of the potentiometric surface in the Denver Aquifer; and Plate 3 shows dissolved-solids concentrations of the water in the Denver Aquifer.

Office of the State Engineer, 1985, Location Map for Hydrogeological Cross-Sections, Colorado Division of Water Resources, scale 1:250,000. Source: CO Div. of Water Resources and distributes $3.

Map shows the location of the 15 Denver Basin cross-sections (see Office of the State Engineer, Denver Basin Cross-Sections). Sites geophysical log C-C1 that extends from the vicinity of the Rocky Flats Plant to Broomfield.

Office of the State Engineer, 1985, Denver Basin Cross-Sections, Colorado Division of Water Resources, 15 sections. Source: CO Div. of Water Resources and distributes $35/set; $3 each.

Contains 11 east-west and four north-south sections based on geophysical logs and shows hydrogeological correlation of aquifers throughout the Denver Basin. Sheet 3 of 15, cross-section C-C1, sections C1, C2, and C3 are applicable to the study area. C1 is the Remington Deep Well #1 in section 25, T. 2 S., R. 70 W.; C2 is the N.W. Water Development Well #7 in section 19, T. 2 S., R. 68 W.; and C3(L-14 intersecting log) is the LFH 1 P#26944-F in section 3, T. 2 S., R. 68 W. The logs reflect data for the Arapahoe Aquifer, Laramie Formation (upper shale portion), Laramie-Fox Hills Aquifer, and Pierre Shale.

Office of the State Engineer, 1987, Aquifer Map of the Denver Basin, Colorado Division of Water Resources, scale 1:250,000. Source: CO Div. of Water Resources and distributes $3.

Map shows the location of the outcrop/subcrop of the various aquifers in the Denver Basin. Identifies the approximate hydrogeologic contact and fault lines.

Office of the State Engineer, 1987, Designated Ground Water Basins and Management District Boundaries, Colorado Division of Water Resources, scale 1:1,000,000. Source: CO Div. of Water Resources and distributes $6.

Map shows the boundaries of Colorado's seven water divisions and 80 water districts. Includes boundaries of designated basins and management districts. The study area lies in the South Platte Water Division #1 and overlaps Divisions #6 (Boulder), #7 (Golden), and #2 (Broomfield).

Pierce, K.L., and Schmidt, P.W., 1975, Reconnaissance Map Showing Relative Amounts of Soil and Bedrock in the Mountainous Part of the Ralston Buttes Quadrangle and Adjoining Areas to the East and West in Jefferson County, Colorado, USGS Misc. Field Studies Map MF-689, Lat 39*45' to 39*52'30", long 105*14' to 105*24', scale 1:24,000, sheet 27.5x37.5 inches. Source: USGS Library M(200)MF, USGS distributes $1.50.

Map shows relative amounts of soil and hard bedrock within the upper six feet of land surface. Descriptive chart covers landscape characteristics, relative constraints regarding septic systems with leach fields, and relative ease of excavating in the upper six feet for map units ranging from alluvial soil to mostly rock.

Pierce, K.L., and Schmidt, P.W., 1975, Reconnaissance Map Showing Relative Amounts of Soil and Bedrock in the Mountainous Part of the Eldorado Springs Quadrangle, Boulder and Jefferson Counties, Colorado, USGS Misc. Field Studies Map MF-695, Lat 39*52'30" to 40*, long 105*15' to 105*22'30", scale 1:24,000, sheet 28x38 inches. Source: USGS Library M(200)MF, USGS distributes $1.50.

Map shows relative amounts of soil and hard bedrock within the upper six feet of land surface. Descriptive chart covers landscape characteristics, relative constraints regarding septic systems with leach fields, and relative ease of excavating in the upper six feet for map units ranging from alluvial soil to mostly rock.

Robson, S.G., 1983, Hydraulic Characterization of the Principal Bedrock Aquifers in the Denver Basin, Colorado, USGS Hydro. Inv. Atlas HA-659, 3 sheets, Lat 39* to 40*, long 104* to 105*, scale 1:500,000, sheets 34x67 inches. Source: USGS Library, USGS distributes $10.90.

Studies indicate that hydraulic conductivity values for the principal bedrock aquifers of the Denver Basin range from about 0.05 to 7 ft/d, with the highest values occurring in the suburban area south of Denver in the Arapahoe and Laramie-Fox Hills aquifers.

Robson, S.G., and Romero, J.C, 1981, Geologic Structure, Hydrology, and Water

Quality of the Denver Aquifer in the Denver Basin, Colorado, USGS Hydro. Inv. Atlas HA-646, 3 sheets, Lat 39* to 40*, long 104* to 105*, scale 1:500,000, sheet 1-27x37 inches, sheet 2-22x26 inches, sheet 3-27x30 inches. Source: USGS Library, USGS distributes $8.80.

Geologic structure, depth to the base, total sandstone and siltstone thickness, and potentiometric surfaces for 1958 and 1978 were mapped. Ground water generally is a calcium bicarbonate or sodium bicarbonate type with dissolved-solids concentrations commonly ranging from 100 to 500 milligrams per liter and dissolved-iron concentrations as high as 600 micrograms per liter in a few areas.

Robson, S.G., Romero, J.C., and Zawistowski, S., 1981, Geologic Structure, Hydrology, and Water Quality of the Arapaho Aquifer in the Denver Basin, Colorado, USGS Hydro. Inv. Atlas HA-647, 3 sheets, Lat 39* to 40*, long 104* to 105*, scale 1:500,000 & 1:250,000, sheet 1-36x41 inches, sheet 2-27x40 inches, sheet 3-33x40 inches. Source: USGS Library, USGS distributes $9.10.

Geologic structure, depth to the base, and total conglomerate, sandstone, and siltstone thickness, and potentiometric surfaces for 1958 and 1978 were mapped. Ground water generally is of the sodium bicarbonate type with dissolved-solids concentrations commonly ranging from 200 to 1,000 milligrams per liter. Concentrations of dissolved-sulfate in excess of 250 milligrams per liter occur in a 350-square mile area along the N.W. margin of the aquifer.

Robson, S.G., Wacinski, A., Zawistowski, S., and Romero, J.C., 1981, Geologic Structure, Hydrology, and Water Quality of the Laramie-Fox Hills Aquifer in the Denver Basin, Colorado, USGS Hydro. Inv. Atlas HA-650, 3 sheets, Lat 39* to 40*, long 104* to 105*, scale 1:500,000, sheet 1-35x41 inches, sheet 2-26x45 inches, sheet 3-31x42 inches. Source: USGS Library, USGS distributes $9.10.

Geologic structure, depth to the base, total sandstone and siltstone thickness, and potentiometric surfaces for 1958 and 1978 were mapped. Ground water generally is of the sodium bicarbonate type.

Romero, J.C., and Hampton, E.R., 1972, Map Showing the Approximate Configuration and Depth to the Top of the Laramie-Fox Hills Aquifer, Denver Basin, Colorado, USGS Misc. Geol. Inv. Map I-791, Lat 38*45′ to 40*30′, long 104* to 105*, scale 1:500,000, contour intervals-100 and 500 ft., sheet 22x30.5 inches. Source: USGS Library M(200)I, USGS distributes $2.40.

Defines available water resources via configuration, altitude, and depth to the top of the Laramie-Fox Hills aquifer.

Sheridan, D.M., Maxwell, C.H., Albee, A.L., and Van Horn, R., 1958, Preliminary Map of Bedrock Geology of the Ralston Buttes Quadrangle, Jefferson County, Colorado, USGS Misc. Field Studies Map MF-179, Lat 39*45′ to 39*52′30", long 105*15′ to 105*22′30", scale 1:24,000, contour interval 50 ft. Source: USGS Library M(200)MF, not avail. for purchase.

Map shows sedimentary rocks, Precambrian rocks, fault systems, and formations for 58 square miles on the eastern flank of the Front Range within the Ralston Buttes Quadrangle.

Spencer, F.D., 1961, Bedrock Geology of the Louisville Quadrangle, Colorado, USGS Geol. Quad. Map GQ-151, Lat 39*52′30" to 40*, long 105*07′30" to 105*15′. scale 1:24,000, contour interval 10 ft. Source: USGS Library M(200)GQ, USGS distributes $3.60.

Map shows bedrock of the Laramie Formation, Fox Hills sandstone, and Pierre shale, points of contact, fault lines, strike and dip of overturned beds, structure contours, mines, sand, gravel, or clay pits, and drill holes with

show of gas. Includes lithologic cross section and lengthy description of stratigraphy, structure, and economic geology of clay, sand and gravel, ground water, coal, and oil and natural gas resources. Area covers part of Rocky Flats.

Van Horn, R., 1957, Bedrock Geology of the Golden Quadrangle, Colorado, USGS Geol. Quad. Map GQ-103, Lat 39*45' to 39*52'30", long 105*07'30" to 105*15', scale 1:24,000, contour interval 10 ft. Source: USGS Library M(200)GQ, USGS distributes $3.60.

Map shows bedrock of the Laramie Formation, Fox Hills sandstone, and Pierre shale, points of contact, fault lines, strike and dip of overturned beds, structure contours, mines, sand, gravel, or clay pits, and drill holes with show of gas. Includes lithologic cross section and lengthy description of stratigraphy, structure, and economic geology of clay, sand and gravel, ground water, coal, and oil and natural gas resources. Area covers part of Rocky Flats.

Van Horn, R., 1968, Preliminary Surficial Geologic Map and Materials Test Data of the Golden Quadrangle, Jefferson County, Colorado, USGS unn O-F Rpt., 3 sheets, 1:24,000. Source: USGS.

Illustrates 8 of the streams which have truncated tilted bedrock and have formed eastward-sloping alluvial plains in the Golden quadrangle. Describes the plains formed, the alluvium, and deposits. Illustrations included are local alluvium fans, residuum, over 90 landslide areas, colluvium, loess, artificial fill, and bedrock outcrops. Deposits less than 3 feet are not shown. Results of materials test data represent the gross characteristics of the geologic formations involved. Report is noted as being a preliminary report and had not, at the time, been edited for conformity with USGS standard and nomenclature.

Van Horn, R., 1972, Surficial and Bedrock Geologic Map of the Golden Quadrangle, Jefferson County, Colorado, USGS Misc. Geol. Inv. Map I-761-A ($1.50), Lat 39*45' to 39*52'30", long 105*07'30" to 105*15', scale 1:24,000, sheet 29x42 inches. Source: USGS Library M(200)I, USGS distributes $3.60.

Map describes and locates formations for an area bounded by Rocky Flats on the northwest, Standley Lake on the northeast, 20th Avenue and Simms Street on the southeast, and Golden on the southwest.

VanSlyke, G., Romero, J., Morevec, and Wacinski, A., 1988, Geologic Structure, Sandstone/Siltstone Isolith, and Location of Non-Tributary Ground Water for (the Dawson [DBA-1], Denver [DBA-2], Arapahoe [DBA-3], and Laramie-Fox Hills [DBA-4]) Aquifers, Denver Basin, Colorado, 4 Plates. Source: CO Div. of Water Resources and distributes $20 each/$60 set of 4-reduced price.

Atlases expand and refine the previous work of the USGS and the Colorado Division of Water Resources--distributed by the USGS as HA 643, HA 646, HA 647, and HA 650, 1981. The Dawson Aquifer is in T. 4 S. to T. 13 S, R. 68 W. to R. 61 W., Denver is in T. 1 N. to T. 14 S., R. 70 W. to R. 61 W., Arapahoe is in T. 2 N. to T. 15 S., R. 70 W. to R. 59 W., and the Laramie-Fox Hills is in T. 5 N. to T. 15 S., R. 70 W. to R. 58 W. which intersects with the eastern part of the study area.

Wells, J.D., 1963, Preliminary Geologic Map of the Eldorado Springs Quadrangle, Boulder and Jefferson Counties, Colorado, USGS Misc. Geol. Inv. Map I-383, Lat 39*52'30" to 40*, long 105*15' to 105*22'30", scale 1:24,000, contour interval 50 ft., sheet 30x40 inches. Source: USGS Library M(200)I, not avail. for purchase.

Map shows alluvium, formations, faults, and strikes and dips for an area that

extends from Boulder in the northeast to Hurricane Hill Fault in the southwest (Jefferson County) with part of Rocky Flats occupying the southeast corner.

Whitkind, I.J., 1976, Preliminary Map Showing Known and Suspected Active Faults in Colorado, USGS Open-File Report 76-154, 42 p. Source: USGS Library (200) R290, USGS distributes $9.75.

Map of known and suspected active faults in the northern Rocky Mountains. Includes pertinent data about each fault and historic breaks of other faults that have been recurrently active since the middle Miocene.

Wrucke, C.T., and Wilson, R.F., 1967, Geologic Map of the Boulder Quadrangle, Boulder County, Colorado, USGS Open-File Temp. 596, Lat 105*22'30" to 105*15', long 40*07'30" to 40*00', scale 1:24,000, 2 sheets. Source: USGS Library behind Reference Desk, not avail. for purchase.

Polyconic projection shows topography by elevation with the city of Boulder occupying the southeast corner of the quadrangle. The accompanying sheet color codes rock types and lists combinations of rock types (i.e., Alluviums, Boulder Creek Granodionite, various formations, shales, and sandstones) and their ages.

B

APPENDIX B
CASE HISTORIES OF SLURRY WALL CONSTRUCTION

Case History

GKN Hayward Baker
Slurry Wall

Oxnard Slurry Wall
Oxnard, California

Background

The potential migration of methane gas from the reclaimed Santa Clara landfill in Oxnard, CA into adjacent land zoned for residential housing required that an effective gas migration barrier be constructed to protect existing and future developments. Presently, an 18 hole golf course occupies the abandoned landfill site owned by the City of Oxnard. Geotechnical Engineers, Staal, Gardner, and Dunne Inc., of Ventura, CA, specified that a maximum permeability of $1x10^{-6}$ cm/sec should be achieved to a depth of 25 ft below existing grade. GKN Hayward Baker (GKN-HB) was awarded the design/construct contract to provide the required barrier, and selected a soil-bentonite slurry cut-off wall and geomembrane liner (figure 1). This 40 mil geomembrane liner would be incorporated into the wall to further cut off gas migration above the groundwater table (@ 10 ft below ground level) and would also serve to virtually eliminate any detrimental effect due to long-term drying and cracking in the slurry wall above groundwater

Above: After excavation a 40 mil liner is installed and secured to the side of the trench.

Ground Modification Design and Application

The slurry wall was 7000 ft in length along the perimeter of the landfill and was aligned as close to the property boundary as possible. Construction of the gas barrier was

Left: A stainless steel mechanical splice joins the 40 mil thick, high-density polyethylene liner together.

Cover: Slurry trench construction procedes between residential building and an active golf course.

executed in a continuous operation. Excavation of the 2 1/2 ft wide, 25 ft deep trench was carried out under bentonite-slurry, used to stabilize the sides of the trench. As excavation progressed, a 40 mil thick, high density polyethylene liner was installed through the slurry along the outside face of the wall to a depth of 15 ft (see figure 2). Stainless steel mechanical splices with a one piece neoprene gasket provided a continuous length rather than overlapping sheets. Controlled replacement of the excavated backfill, blended with bentonite, displaced the slurry thus forming the soil-bentonite cut-off barrier.

Normally, gases from a landfill are collected in a piping system and vented or burned off periodically. Unlike this system, which required continuous operation and maintenance, the slurry wall is a passive construction, both invisible and maintenance-free.

Quality Control

Throughout the project, GKN-HB conducted frequent testing of the slurry properties (ph, unit weight, filtrate loss, and viscosity). Testing of the backfill consisted of unit weight, permeability, and gradation tests at specified intervals. As an additional safety precaution in areas where landfill materials were encountered, periodic air measurements were taken for detectable levels of combustible gas. Outside the landfill, long-term monitoring wells have been installed along the wall to monitor methane levels.The innovative addition of a geomembrane liner to the already proven in-ground barrier technique of slurry-wall construction has provided an economical and successful solution to the problem.

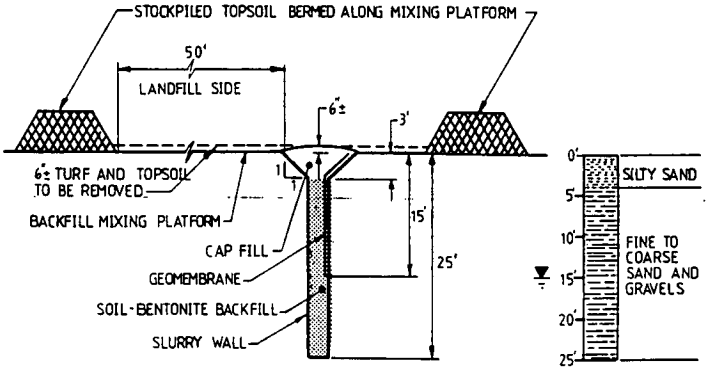
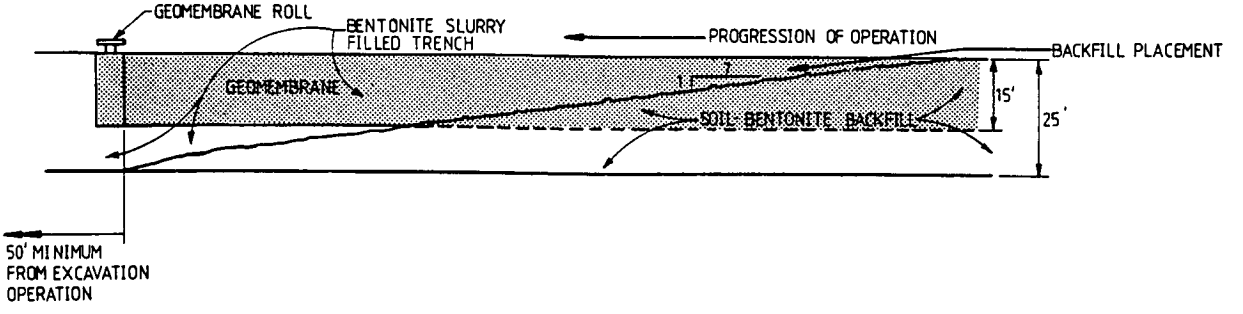


Figure 1: Typical Work Area Cross Section.

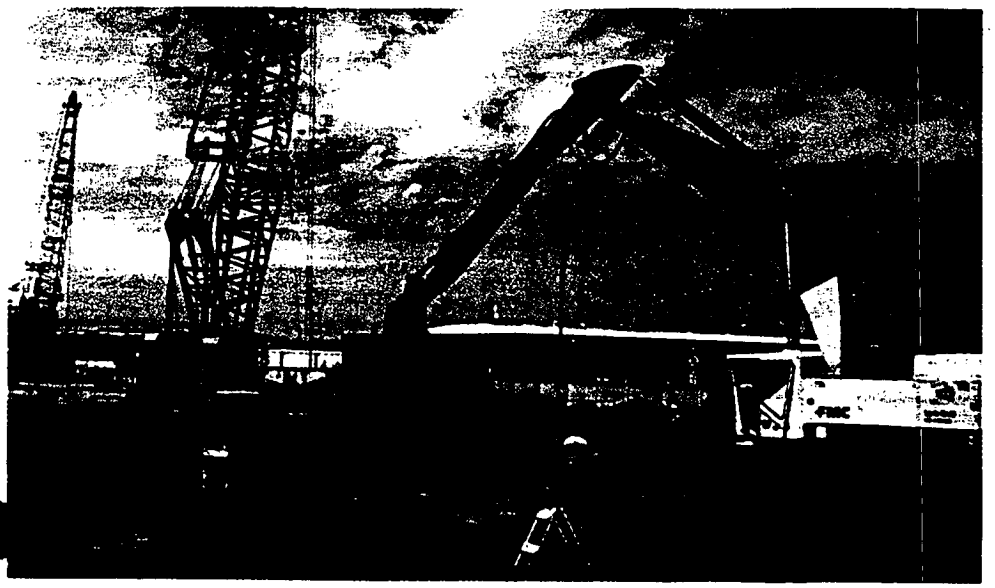
Figure 2: Typical Excavation and Backfill Procedure.

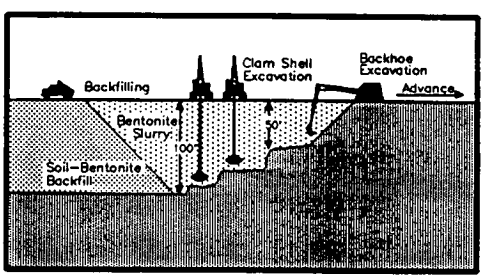


Slurry Trench Cut-off Wall
Raytheon Company
Mountain View, California

Case History

GKN Hayward Baker





Above: Excavation operation

Top: Deep excavation in very restrictive space limitations.

Top Left: Extended boom backhoe excavation preceding deep excavation with clamshell-equipped cranes.

Background

Since 1982, Raytheon Company of Mountain View, California, has mounted an exhaustive program to determine the lateral and vertical distribution of chemicals in soils and groundwater about its Ellis Street semiconductor facility. The principal pathway of concern for release of chemicals is by transport in the groundwater. To eliminate the release of chemicals from on-site sources and also to prevent the migration of chemicals on to the site from off-site sources, geotechnical engineers Golder Associates of Redmond, Washington, designed a 3400 ft long, 100 ft deep slurry trench cut-off wall to encircle the project site and complement an existing water extraction and cleaning system. Of all available alternatives, the slurry trench cut-off technique, using a soil-bentonite backfill, was considered to best satisfy all objectives and provide the greatest environmental and public health protection. GKN Hayward Baker (GKN-HB) was awarded the contract for the project.

Ground Modification Design And Application

The difficult construction problems associated with working with hazardous materials in very close proximity to a continuously operational manufacturing facility, within tight schedule restrictions, and performing excavation to a depth of 100 ft, made this a challenging Ground Modification[sm] project.

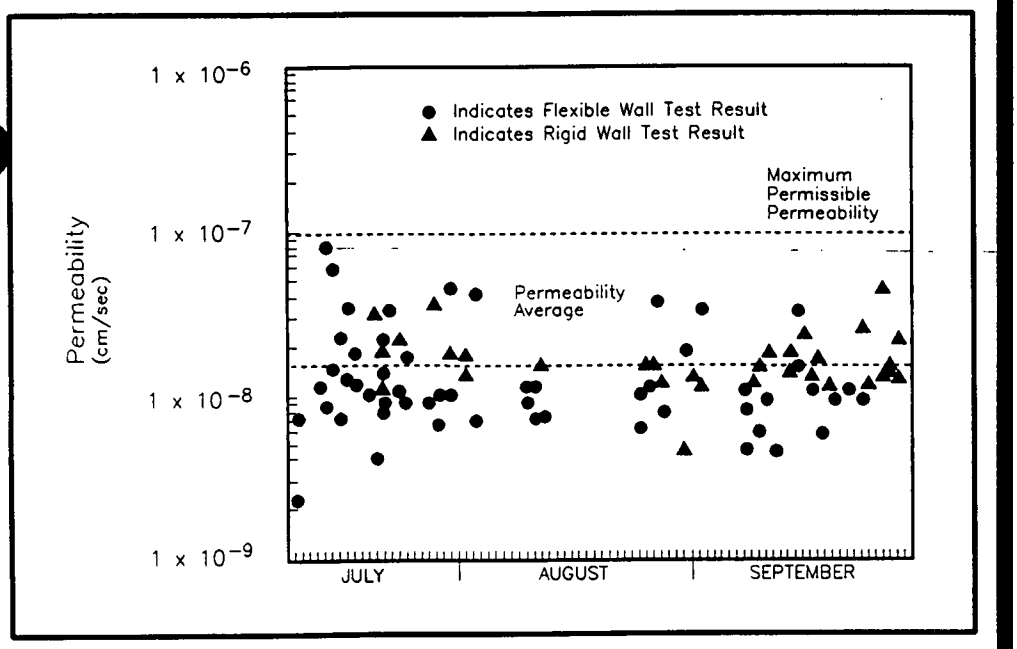
Slurry trench excavation and construction was carried out in a continuous, synchronized operation. The unusually deep excavation required specially extended backhoe equipment for the upper 50 ft of the trench, followed by clamshell-equipped cranes to excavate to the full depth. As excavation progressed (penetrating three separate aquifers), the trench was stabilized with

a hydrated bentonite slurry. Excavated material was transported to an on-site stockpile location and classified as to concentration levels of hazardous chemicals to ensure that only non-detectable materials were blended with bentonite for trench backfill. Materials categorized as contaminated were stockpiled within a containment berm. Controlled replacement of the blended soil-bentonite displaced the stabilizing slurry, thus forming the impermeable barrier.

Operations Control

Prior to commencement of construction, GKN-HB was required to prepare control documents to ensure the health and safety of site personnel and quality assurance of the construction activity. As part of the quality assurance program, GKN-HB established and operated a complete on-site laboratory. Here, frequent testing was performed for bentonite quality, new slurry density, viscocity and filtration, trench slurry density and viscocity, excavated soil properties and backfill properties. Innovations developed on site included extensive comparative testing of the standard flexible wall permeameter with the rigid wall consolidometer/permeameter which served to justify the rigid wall device for soil-bentonite materials and greatly reduced testing time.

Altogether, GKN-HB completed approximately 100 laboratory permeability tests during the project. Results were excellent, providing an average wall permeability five times lower than specifications which confirms that the slurry trench cut-off wall is preventing hazardous waste migration as designed. This project was completed two weeks ahead of a very restrictive construction schedule.



Above: Laboratory Permeability Test Results for Slurry Wall Backfill.

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GROUND MODIFICATION

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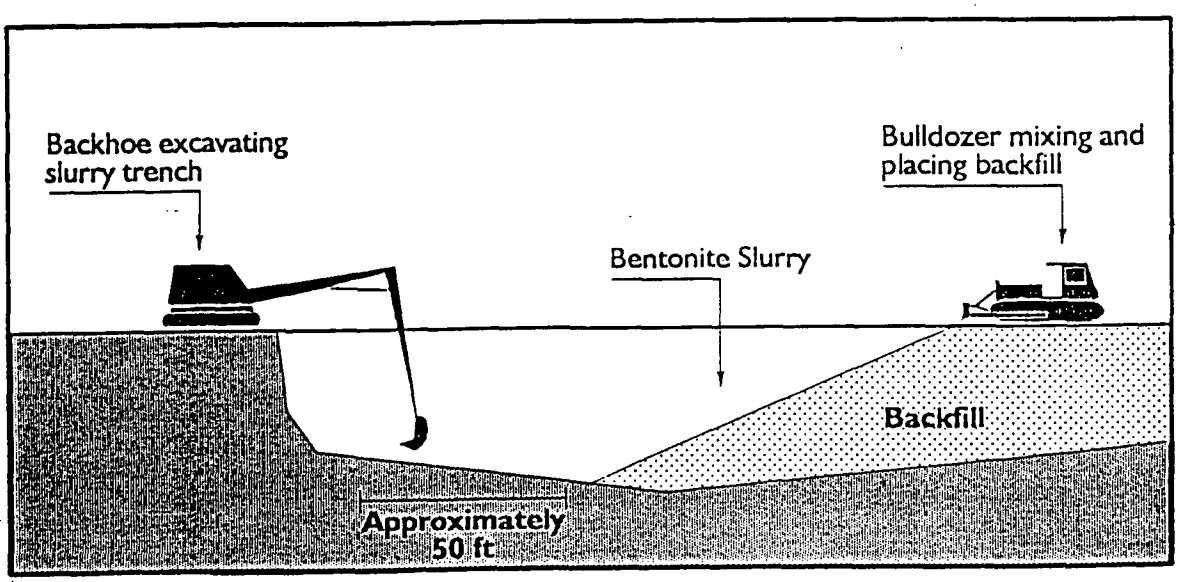
Guide Specifications for Soil-Bentonite Slurry Trench Cut-Off Wall Construction

Slurry trench cut-off walls have a U.S. history spanning over 30 years for groundwater control and pollution abatement. It is considered by regulatory agencies to be the containment technique of choice for many hazardous substances carried by groundwater.

A slurry trench wall is constructed by excavating a narrow vertical trench, typically 24 to 36 inches wide, through pervious materials to a relatively impervious underlying strata. The trench is kept full during the excavation with a suspension of hydrated bentonite in water. The slurry acts to stabilize the walls of the trench by exerting a slurry head pressure on the trench walls after formation of a filter cake of bentonite, thus preventing collapse during excavation. The filter cake also contributes to the low permeability of the completed cut-off wall.

On shallow walls a backhoe excavates the trench and casts the excavated material to the side. This excavated material, if suitable, is mixed with bentonite slurry to form the soil-bentonite (SB) backfill. The SB backfill material is usually mixed on the ground surface adjacent to the trench using a bulldozer or other suitable earthmoving equipment. The backfill material is prepared by sluicing the soil with slurry and then tracking and blading until the backfill material is homogeneous and the proper consistency is reached. Trench slurry is typically used to prepare the backfill. The prepared backfill is then pushed or dumped into the trench at the point where backfill rises to the surface. This avoids segregation that might be caused by free-dropping through the slurry.



Backfilling should follow the excavation closely. Enough space should be provided behind the excavation face for cleaning the trench bottom. Usually a distance of approximately 50 ft should be maintained between the excavation and backfill operations, if ground conditions permit.

The SB slurry trench cut-off wall provides an in-place permeability not exceeding 1×10^{-7} cm/sec. The work is performed as a continuous activity so to produce a windowless continuous wall. The Quality Control/Quality Assurance Program will assure that the desired engineering characteristics will be achieved.

December 1990

KELLER

Work Procedures

The work is performed according to the following general task guidelines:

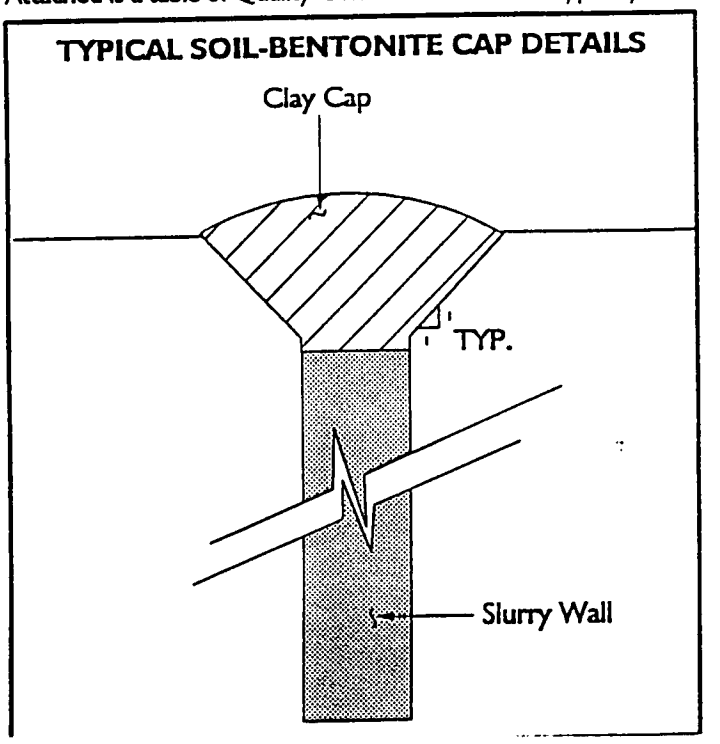
- Bentonite slurry is prepared in a conveniently located storage tank(s) or pond constructed for this purpose. Premium grade sodium bentonite is shear mixed directly with water and placed in the storage unit for final hydration.
- A stable level working platform is prepared along the wall alignment to support excavation equipment and provide a contained mixing and blending area for backfill materials.
- Excavation will progress using a backhoe capable of digging to the specified key depth. If the excavation depth extends beyond the reach of the backhoe, a crane equipped with a special clamshell will complete the excavation. Excavation is performed while maintaining the trench full of bentonite slurry (within 2 ft of working grade) at all times.
- Most excavated soils are suitable for mixing to produce backfill (gradation such that 85 percent is finer than a No. 4 sieve and 20 percent is finer than a No. 200 sieve)
- When excavation progresses sufficiently, backfilling will follow. The lead-in trench technique is typically utilized for the start of backfilling. This technique is usually performed at a corner of the wall so that the plan corner coincides with the toe of the excavated lead-in trench to provide for continuous displacement of slurry and uniformity of in-place backfill.
- A compacted clay cap (see sketch) completes the construction of the trench.
- Road crossings, require temporary relocation and/or a structural slab crossing to accommodate heavy traffic.
- Utility crossings, above and below ground, must be located and either relocated or protected to prevent damage during construction.

Quality Control/Quality Assurance

Quality Control testing is an important part of any quality geotechnical construction and is particularly important for slurry wall construction. Quality will be assured by proper and accurate documentation of the required testing and will always be accessible to inspection by the owner and engineer.

On large projects Hayward Baker can provide a fully equipped laboratory facility capable of performing all tests on-site, if desired. All testing will be under the direction of Hayward Baker's sit representative to best utilize our experience and equipment for testing soil-bentonite samples.

Attached is a table of Quality Control tests that are typically followed.



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Soil Bentonite QA/QC Testing Specifications

Subject	Standard	Test Type	Frequency	Requirements
Water		pH Hardness Total disolved solids	Per source	As required to properly hydrate bentonite
Bentonite	API 13A	Tests to show compliance with standard	Per truckload	Certificate of compliance from the supplier
Pond Slurry	API 13B API 13B API 13B	Viscosity Unit weight Filtrate loss	1 per shift 1 per shift 1 every 3rd shift	Minimum 40 sec. Marsh Funnel Minimum 64 pcf Less than 25 cc in 30 min. @ 100 psi
Trench Slurry	API 13B API 13B	Viscosity Unit weight	2 per shift 2 per shift	Minimum 40 sec. marsh 64-85 pcf
Backfill	USACE guidelines Rigid wall Preferred	Permeability	1 per 1000 cy	1×10^{-7} cm/sec. maximum
	ASTM D-1140 (mod)	Fines content	As required	20% Minimum, Passing No 200
		Unit weight	1 per shift	15 pcf greater than trench slurry unit weight
	ASTM C-143	Slump	1 per 500 cy	3-7 inches
Trench		Slope Profile	1 per shift	No irregularities
		Depth measurement	1 per 10 lf of excavation	Minimum penetration into key
		Key	Continuous	Acceptable key materials

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Proprietary Information. Not to be released without consent.

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Guide Specifications for Cement-Bentonite Slurry Trench Cut-Off Construction

Slurry trench cut-off walls have a U.S. history spanning over 30 years for groundwater control and pollution abatement. It is considered by regulatory agencies to be the containment technique of choice for many hazardous substances carried by groundwater.

A Cement-Bentonite (CB) slurry trench cut-off wall is constructed by excavating a narrow vertical trench, typically 18 to 30 inches wide, through pervious materials to a relatively impervious underlying strata. The trench is kept full during the excavation with a slurry mixture of hydrated bentonite and Portland Cement. The slurry acts to stabilize the walls of the trench by exerting a slurry head pressure on the trench walls after formation of a filter cake, thus preventing collapse during excavation. The filter cake also contributes to the low permeability of the completed cut-off wall.

Excavated materials are removed and the CB material strengthens and "sets" in place to form the cut-off wall. The set of the CB is closely akin to a stiff gel which typically achieves a shear strength of approximately 15 psi in 28 days, yet tolerates strains up to 15 percent without cracking. The mix can generally be designed to duplicate the existing soil strength.

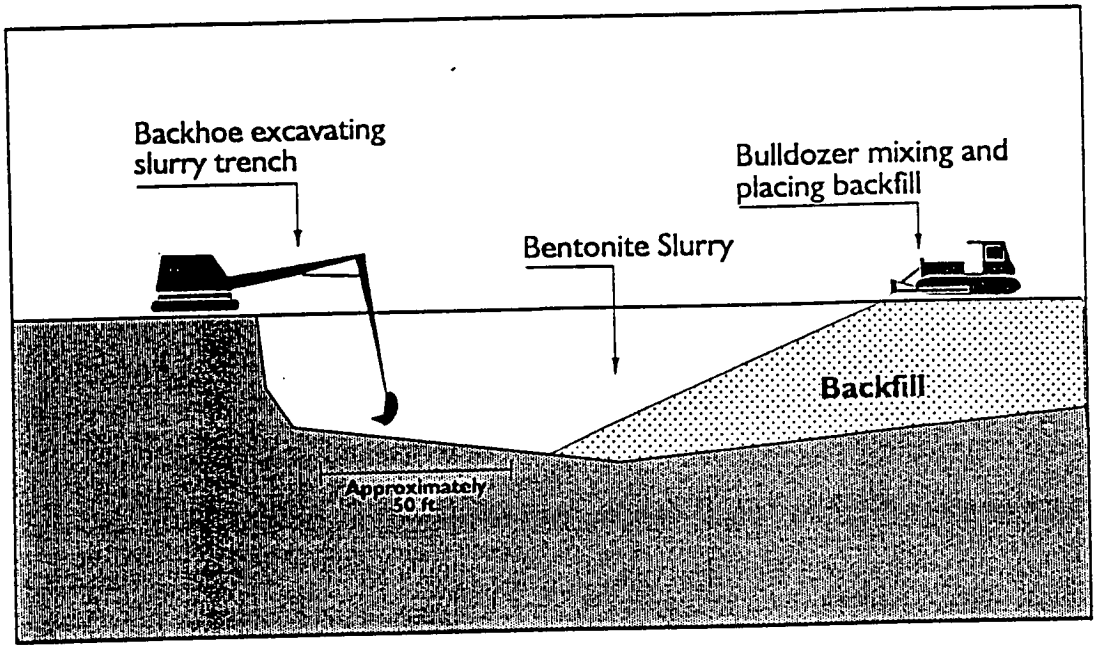
The permeability of a completed CB slurry trench cut-off wall is a function of both the filter cake that forms on the trench walls and the specific mixture of the slurry components.

The CB slurry trench cut-off wall provides an in-place permeability not exceeding 1×10^{-6} cm/sec. The work is performed as a continuous activity so to produce a windowless continuous wall. The Quality Control/Quality Assurance Program will assure that the engineering characteristics desired will be achieved.

Work Procedures

The work is performed according to the following general task guidelines:

- Bentonite slurry is prepared and placed into a conveniently located storage tank or pond constructed for this purpose. Premium grade sodium bentonite is high shear mixed directly with water and placed in the storage unit for final hydration.
- Utilities, above and below ground, must be located and either relocated or protected to prevent damage during construction.
- A stable level working platform is prepared along the wall alignment to support the excavation equipment.
- Hydrated slurry is pumped from the storage unit to a mixer where cement and additives (if required) are added. The mixed CB slurry is then pumped to the trench as the excavation proceeds.
- Excavation will progress through the slurry filled trench using an excavator capable of digging to the specified key depth. If the excavation depth extends beyond the reach of the backhoe, a crane suspended clamshell will complete the excavation. Excavation is performed while maintaining the trench full of CB slurry (within 2 ft of working grade) at all times.
- Excavated materials are removed from the work area to be used as fill or disposed of at a designated location. No backfilling is required for the CB slurry cut-off wall; the CB slurry supporting the trench during excavation sets and becomes the barrier.
- A compacted clay cap (see sketch) generally completes the construction of the trench.

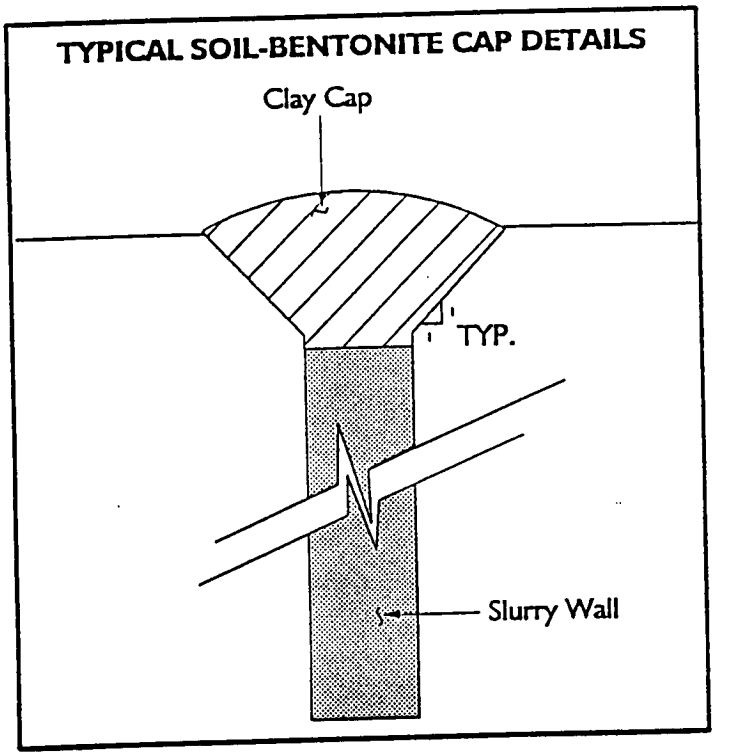


Quality Control/Quality Assurance

Quality Control testing is an important part of any quality geotechnical construction and is particularly important for slurry wall construction. Quality will be assured by proper and accurate documentation of the required testing and will always be accessible to inspection by the owner and engineer.

On large projects Hayward Baker can provide a fully equipped laboratory facility capable of performing all tests on-site, if desired. On smaller projects, properly obtained samples are sent to an independent lab for testing. All testing will be under the direction of Hayward Baker's site representative to best utilize our experience and equipment for testing CB samples.

Attached is a table of Quality Control tests that are typically followed.



HAYWARD BAKER
A Keller Company

Cement Bentonite QA/QC Testing Specifications

12.10.90-1

Subject	Standard	Test Type	Frequency	Requirements
Water		pH Hardness Total disolved solids	Per source	As required to properly hydrate bentonite
Bentonite	API 13A	Tests to show compliance with standard	Per truckload	Certificate of compliance from the supplier
Pond Slurry	API 13B API 13B API 13B	Viscosity Unit weight Filtrate loss	1 per shift 1 per shift 1 every 3rd shift	Minimum 34 sec. Marsh Funnel minimum 63 pcf Less than 30cc in 30 min. @ 100 psi
Trench Slurry	API 13B API 13B	Viscosity Unit weight	2 per shift 2 per shift	Minimum 40 sec. marsh 67-85 pcf
Backfill- Set Slurry	USACE guidelines Rigid wall Preferred	Permeability	1 per 1000 cy	1×10^{-6} cm/sec. maximum
Trench			1 per 10 lf of excavation	Minimum penetration into key
		Key	Continuous	Acceptable key materials

KELLER

Proprietary Information. Not to be released without consent.

C

APPENDIX C
SUMMARY OF COSTS OF REMEDIAL TECHNOLOGIES

PB88-113477

EPA/600/2-87/087
October 1987

COMPENDIUM OF COSTS OF REMEDIAL TECHNOLOGIES AT HAZARDOUS WASTE SITES

by

Edward C. Yang, Dirk Bauma, Linda Schwartz, and James D. Werner
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Washington, DC 20036

EPA Contract 68-03-3113

EPA Project Officer
Douglas Ammon

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16. ABSTRACT

Accurate estimates of hazardous waste site remedial responses are important in order to: (1) budget the Superfund Response Fund, (2) estimate costs at specific sites, (3) cost-effectively select remedial actions, and (4) effectively negotiate with private response parties for private action or cost recovery. Unfortunately, standard engineering costing methodologies have been relatively inaccurate in estimating actual response costs. This is primarily due to the uniqueness of the site problems and the uncertainties in eventual effectiveness of the responses. The purpose of this document is to record and analyze the actual expenses incurred during remedial responses for seven major types of engineering technologies. The costs documented here are the "bottomline" numbers showing the ultimate cost of the responses. The data supporting this compendium is derived from a series of 31 case studies of actual hazardous waste remedial responses. This report also investigates the divergence between actual remedial costs and estimates from existing engineering cost methodologies. In addition, the compendium lists the major factors that cause the costs' movements. Because of the scope of the report coverage and the small sample size the data provided here to be viewed as "bench marks" for the estimation of future response costs. Users are urged to examine the specific site conditions underlying the reported costs by consulting the case studies from which these estimates are derived.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

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SECTION 3

3.0 GROUND-WATER AND LEACHATE CONTROLS

3.1 SLURRY WALL

3.1.1 Definition

A slurry wall is one of several types of subsurface cut-off walls that prevent leachate formation by redirecting upgradient ground-water away from a contaminated area, and/or controlling horizontal leachate movement away from the site. A slurry wall is constructed by filling a trench with a slurry such as bentonite on bentonite-soil-cement during excavation. The backfilled trench has a much lower coefficient of permeability than the surrounding soil and thus creates a barrier to flow of ground-water.

3.1.2 Units of Measurement

Costs are given in dollars per square foot because square feet reflect the functional area of a cut-off wall. In estimating the cost of a cut-off wall, the length and depth (facial area) requirements are usually fixed by the extent of the waste and the depth of the aquiclude. Linear units were not used because they would obscure the effect of depth on slurry wall costs.

3.1.3 Summary Statistics

3.1.3.1 Expenditures

The slurry wall expenditures ranged from:

$0.25/sq.ft.

to

$31.96/sq.ft.

The lowest cost for a slurry wall was for a privately constructed wall using extensive in-house equipment and labor. The next lowest cost wall was relatively shallow (14 feet deep). The highest cost slurry wall was built partly in contaminated soil on a stream bank. Each scoop of soil required analysis with an organic vapor analyzer and was disposed at an engineered landfill. The stream bank restricted and delayed access to the construction area. Operation and maintenance costs involved ground-water monitoring and, possibly, costs of repair. These costs were accounted for separately where information on them exists.

3.1.3.2 Estimates

Slurry wall cost estimates ranged from:

$4.50/sq.ft. soil-bentonite
to
$13.86/sq.ft.

The highest slurry wall cost estimate ($11.56/sq.ft.) was for a Wyoming bentonite slurry wall. The lowest estimate was for a competitively bid soil-bentonite slurry wall, for which another contractor was deemed more reliable. Operation and maintenance costs such as inspection, ground-water monitoring, and repair were not included in the estimates.

3.1.4 Factors Found to Influence Cost

3.1.4.1 Expenditures

The following factors primarily affected slurry wall expenditures:

- Depth
- Thickness
- Wall material
- Inclusion of related costs:
  - Staging area set-up
  - Contaminated trench soil disposal

Perhaps the most salient factor affecting costs (shown in Table 10) was the wall material. Cement-soil-bentonite walls were the most expensive walls; soil-bentonite was in the middle of the cost range, and local clay was the least expensive. Much of the local clay used for the $1.80/sq.ft. California slurry wall was dredged from the adjacent bay. Depth affected costs since a larger excavator (such as a CAT 215 or clamshell instead of a backhoe) was necessary for digging deeper trenches. Once mobilized, however, larger equipment is capable of increasing the trench depth at a reduced marginal cost. Wall thickness was directly proportional to the volume of soil excavated and the volume of slurry mixed into the trench. Since costs are given in terms of dollars per square foot, the cost for this added volume is not precisely reflected in the face-area cost. However, most of the walls had very similar thicknesses, at between 30-36 inches, with two walls varying by two feet. The different thicknesses generally stem from different requirements set forth in a consent decree state or federal agency mandate, and usually account for the variable permeabilities of different slurry wall materials.

Other related costs played a significant role in at least two cut-off walls. At the Pennsylvania site, a large volume of contaminated trench soil required disposal at an engineered landfill. Adding to these disposal costs, was the need to test each excavator scoop with an organic vapor analyzer, which slowed trench construction.

TABLE 10

SLURRY WALL EXPENDITURES

(1982 Dollars)

DATA SOURCE	LENGTH & DEPTH	THICKNESS	MATERIAL	UNIT COST
US EPA ELI/JRB 1981 Pennsylvania	648 feet x 17 feet	1 foot	cement- bentonite	$31.96/sq.ft.
US EPA JRB/ELI 1979 Colorado	1,500 feet x 20 feet	30 inches	85% soil- bentonite; 15% cement	$8.33/sq.ft.
US EPA JRB Florida A (Date unknown)	2,290 feet x 30 feet	30 inches	soil- bentonite	$5.88/sq.ft.
US EPA CH_2 M Hill 1982 New Hampshire	3,500 feet x 60 feet	3 feet	soil- bentonite	$5.64/sq.ft.

TABLE 10

SLURRY WALL EXPENDITURES (continued)

(1982 Dollars)

DATA SOURCE	LENGTH & DEPTH	THICKNESS	MATERIAL	UNIT COST
US EPA JRB (Date unknown) Louisiana	1,500 feet x 20 feet	3 feet	soil- bentonite	$2.78/sq.ft.
US EPA JRB (Date unknown) Florida B	2,900 feet x 20 feet	3 feet	soil- bentonite	$2.60/sq.ft.
US EPA ELI/JRB (1983 Dollars) California	2,765 feet x 14 feet	5 feet	local clay	$1.42/sq.ft.
US EPA ELI/JRB 1980 Arkansas	2,306 feet x 48 feet	3.2 feet	local clay	$0.25/sq.ft.
US EPA ELI/JRB 1983	2360 ft x 30 ft	3 ft	soil - bentonite	$3.80/sq.ft.

The cost given at the Arkansas site may not reflect all slurry wall costs since significant in-house labor and equipment were used but not recorded. Other related costs such as site preparation and geotechnical investigations were inconsistently noted as separate or included. Generally, these costs were excluded from the slurry wall expenditures.

3.1.4.2 Estimates

The following factors affected the estimated costs for slurry walls:

- Depth
- Thickness
- Material
- Inclusion of related costs:
  - Geotechnical investigation
  - Overhead and contingencies

Material costs were again the most clear cost factor in the slurry wall cost estimates (Table 11). The highest cost wall ($10/sq.ft.) was the cement-bentonite wall at the New York site. Slurry wall depth seemed to be, at best, a secondary factor. The deepest (130 foot deep) slurry wall at the New Jersey site was the second to least costly while the shallowest (14 foot) slurry wall was the most costly.

However, the construction of the 130 foot deep slurry wall would be greatly facilitated by the coastal plain sediment of New Jersey for which it was proposed. Complete hydrogeological assumptions were not given for all of the estimation scenarios, but a 1980 paper by Ressi di Cervia (see Table 12) gave the following depth-soil condition cost matrix. The slurry wall thicknesses varied less than did those of the wall studied for the actual expenditures. Only one hypothetical slurry wall was over 3 feet thick.

TABLE 11

SLURRY WALL COST ESTIMATES

(1982 Dollars)

DATA SOURCE	LENGTH & DEPTH	THICKNESS	MATERIAL	UNIT COST
US EPA CH_2 M Hill 1983 New York	7,900 feet x 14 feet	over 2 feet	concrete	$10/sq.ft.
US EPA Weston 1982 New Hampshire	3,733 feet x 70 feet (1)	3 feet	soil- bentonite	$8.05/sq.ft.
US EPA Bids 1982 New Hampshire	3,500 feet x 60 feet	3 feet	soil- bentonite	$7.35/sq.ft.
US EPA JRB-RAM 1980	1,000 feet x 40 feet	3 feet	soil- bentonite	$7.08-13.86/sq.ft.

(1) Dimensions assumed for costing
(3,125 feet x 50 feet expected).

TABLE 11

SLURRY WALL COST ESTIMATES (continued)

(1982 Dollars)

DATA SOURCE	LENGTH & DEPTH	THICKNESS	MATERIAL	UNIT COST
US EPA Radian 1982	100 feet x 40 feet	4 feet	soil- bentonite	$6.94/sq.ft.
US EPA CH_2 M Hill 1983 New Jersey Site A	114,715 sq.ft.	24-30 inches	soil- bentonite (5%)	$6/sq.ft.
US EPA SCS "Impoundment" 1980	911 feet x 49 feet	3.28 feet	Wyoming bentonite- water (1:12)	$6.49-11.56/sq.ft.
US EPA SCS "landfill" 1980	2,362 feet x 49 feet	3.28 feet	bentonite- water (1:12)	$6.02-10.50/sq.ft.

TABLE 11

SLURRY WALL COST ESTIMATES (continued)

(1982 Dollars)

DATA SOURCE	LENGTH & DEPTH	THICKNESS	MATERIAL	UNIT COST
US EPA Bids 1982 New Hampshire	3,500 feet x 60 feet	3 feet	soil- bentonite	$5.44/sq.ft.
US EPA CDM, Inc. 1983 New Jersey Site B	4,257 feet x 130 feet	not given	soil- bentonite	$4.88/sq.ft.
US EPA Bids 1982 New Hampshire	3,500 feet x 60 feet	3 feet	soil- bentonite	$4.50/sq.ft.

TABLE 12

SLURRY WALL COSTS: DEPTH EFFECTS

	Slurry Trench Prices In 1982 Dollars Soil Bentonite Backfill (Dollars/Square Foot)			Unreinforced Slurry Wall Prices in 1982 Dollars Cement Bentonite Backfill (Dollars/Square Foot)		
	Depth 30 Fee	Depth 30-75 Feet	Depth 75-120 Feet	Depth 60 Feet	Depth 60-150 Feet	Depth 150 Feet
Soft to Medium Soil N 40	3-5	5-10	10-13	19-25	25-38	38-95
Hard Soil N 40 -	5-9	6-13	13-25	32-38	38-51	51-121
Occasional Boulders	5-10	6-10	10-32	25-38	38-51	51-108
Soft to Medium Rock, Sandstone, Shale N 200	8-15	13-25	25-64	64-76	76-108	108-222
Hard Rock Granite, Gneiss, Schist*	—	—	—	121-178	178-222	222-298

Notes: N = standard penetration value in number of blows of the hammer per foot of penetration (ASTM D1586-67)

*Normal Penetration Only

For standard reinforcement add $8.00 per sq. ft.
For construction in urban environment add 25% to 50% of price

Reference: Ressi di Cervia 1980.

Additional costs were included in at least two of the estimates. Both geotechnical investigation (impoundment: $11,210-23,010; landfill: $4,543-7,694) costs and overhead (25%) and contingency costs (30%) were included in the SCS estimates. Geotechnical investigation and permeability testing costs were grouped together ($23,600-94,400) in the JRB estimate.

Expenditure Sources

- ELI/JRB Case Studies, 1983
- JRB, 1983
- State and Federal Superfund Work

Estimates Sources

- JRB - RAM, 1980
- Radian, 1983
- SCS, 1981
- US EPA, OERR, Feasibility Studies.

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