FINAL

THERMAL TREATMENT TECHNOLOGY CONCEPTUAL DESIGN

McCormick and Baxter Superfund Site
Stockton, California

November 12, 2001

Prepared for

EPA REGION 9

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ABBREVIATIONS AND ACRONYMS

ARAR	applicable or relevant and appropriate requirement
BTU	British thermal unit
°C	degree Celsius
Cal EPA/DTSC	California Environmental Protection Agency/Department of Toxic Substances Control
CAA	Clean Air Act
CDMG	California Division of Mines and Geology
CEMS	continuous emission monitoring system
CFR	Code of Federal Regulations
Cl_2	chlorine gas
CO	carbon monoxide
CO_2	carbon dioxide
COC	chemical of concern
CPA	Cellon Process Area
DAF	dissolved air flotation
dBA	decibel A-weighted
DNAPL	dense nonaqueous-phase liquid
DO	dissolved oxygen
DTS	distributed temperature sensing
DWR	Department of Water Resources (state of California)
E-MPA	area east of Main Processing Area
EPA	U.S. Environmental Protection Agency
ERH	electrical resistance heating
ERT	electrical resistivity tomography
°F	degree Fahrenheit
FID	flame ionization detector
FS	feasibility study
ft^2	square foot
ft/day	feet per day
GAC	granular activated carbon
gpm	gallon per minute
HCl	hydrogen chloride or hydrochloric acid
HEPA	high-efficiency particulate air
HF	hydrogen fluoride
HHGIT	hybrid hydrologica-geophysical inverse technique
hp	horsepower
IAG	interagency agreement
J/kg/K	joule per kilogram per Kelvin

ABBREVIATIONS AND ACRONYMS (Continued)

kJ	kilojoule
km	kilometer
kPa	kilopascal
kW	kilowatt
lb	pound
lb/hr	pound per hour
LIF	laser-induced fluorescence
LNAPL	light nonaqueous-phase liquid
m	meter
MB	McCormick and Baxter
MCL	maximum contaminant level
$\mu g/m^3$	microgram per cubic meter
MG	million gallons
mg/kg	milligram per kilogram
mg/L	milligram per liter
mm	millimeter
MM	million
MPA	Main Processing Area
mph	miles per hour
msl	mean sea level
MW	megawatt
N-MPA	area under slough north of Main Processing Area
NAPL	nonaqueous-phase liquid
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
NPDES	National Pollutant Discharge Elimination System
NVD88	North American Vertical Datum of 1988
O&M	operation and maintenance
OD	outside diameter
OSHA	Occupation Safety and Health Act
OWPA	Oily Waste Pond Area
PAH	polycyclic aromatic hydrocarbon
PCDD/F	polychlorinated dioxins and furans
PCP	pentachlorophenol
PCS	power control system
PEL	permissible exposure limit
PM	particulate matter
POTW	publicly owned treatment work

ABBREVIATIONS AND ACRONYMS (Continued)

ppb	parts per billion
PPE	personal protective equipment
ppmv	parts per million vapor
psi	pound per square inch
psig	pound per square inch gauge
RAM	realtime aerosol monitor
RAO	remedial action objectives
RCRA	Resource Conservation and Recovery Act
RWQCB	Regional Water Quality Board (state of California)
S-CPA	area south of Cellon Process Area
S-MPA	area south of Main Processing Area
SAC	spent activated carbon
SCAPS	site characterization and analysis penetrometer system
scfm	standard cubic feet per minute
SO_2	sulfur dioxide
SO_x	sulfur oxides
STVZ	Socorro-Tech Vadose Zone
SVOC	semivolatile organic compound
TAP	toxic air pollutant
TCE	trichloroethene
TCLP	toxicity characteristics leaching procedure
TDR	time-domain reflectometer
TDS	total dissolved solids
THC	total hydrocarbon
TOC	total organic carbon
TPH	total petroleum hydrocarbon
TRS	Thermal Remediation Services, Inc.
UPRR	Union Pacific Railroad
USACE	U.S. Army Corps of Engineers
VEA	vertical electrode array
VOST	Volatile Organic Sampling Train
yd^3	cubic yard

1.0 INTRODUCTION

1.1 PURPOSE OF DOCUMENT

The purpose of this document is to provide a 10 percent conceptual design for in situ thermal remediation of the McCormick and Baxter Superfund site, a former wood treating facility in Stockton, California. This document addresses fundamental engineering design and cost issues related to the installation, operation, and post-operational stages of a combined steam and electrical heating remediation strategy.

This document will be used by the U.S. Environmental Protection Agency (EPA) and the U.S. Army Corps of Engineers (USACE) to prepare a feasibility study (FS) report that evaluates alternatives for a final groundwater remedy at the site. EPA is the lead agency for remediation of the McCormick and Baxter site, with the California EPA/Department of Toxic Substances Control (Cal EPA/DTSC) acting as the support agency.

1.2 PROJECT DESCRIPTION

The USACE has been tasked by EPA through an interagency agreement (IAG) to provide assistance with evaluation of dense nonaqueous-phase liquid (DNAPL) remediation technologies, including technical implementability and cost effectiveness as part of the FS. The USACE obtained services from URS Corporation through an indefinite delivery order contract to assist with this task. URS Corporation has contracted with SteamTech Environmental Services for expert engineering assistance on development of an in situ thermal treatment system conceptual design for the McCormick and Baxter site.

The engineering design aspects of the thermal remediation approach were produced by SteamTech Environmental Services, Inc., working in collaboration with Thermal Remediation Services, Inc. (TRS). Many design details were compared to the design for the Wyckoff-Eagle Harbor pilot test (USACE 2001b). Integration of a long-term pump-and-treat strategy with the thermal remediation was developed by the USACE. Additional technical advice was provided by URS Corporation. All cost estimates were prepared by URS Corporation, based on the engineering design and operational parameters supplied by SteamTech Environmental Services and TRS.

All site characterization data, including hydrogeology and contaminant distribution, were provided to SteamTech and TRS by the USACE.

Development of the conceptual design was further refined through the use of internal review meetings where expert consultants from research institutes provided advice regarding engineering, geophysical monitoring, and contaminant hydrology. In addition, representatives from state and federal regulatory agencies participated in these meetings to provide input on technical and regulatory compliance issues.

Production of the final conceptual design document was the responsibility of URS Corporation.

1.3 OVERALL PROJECT ASSUMPTIONS

Fundamental assumptions regarding operations and post-operational use of the McCormick and Baxter site are as follows:

- The ultimate land use at the site is expected to remain industrial.
- The selected remedy for arsenic and dioxin in surface soil after thermal remediation (a sitewide cap) will remain unchanged.
- Subsurface structures at the site, including concrete basements, pipe galleys, concrete and metal debris, and a rail car, will not be excavated during the remediation.
- Wells or other boreholes employed during thermal remediation operations at the site cannot be placed on adjacent private property. They may be placed in Old Mormon Slough, provided appropriate monitoring and emissions controls are in place.
- Old Mormon Slough cannot be permanently filled.
- Treated groundwater cannot be disposed of, at the anticipated full-scale operation volumes, to the Stockton Regional Wastewater Control Facility.

1.4 TECHNOLOGY CHOICE

The technologies chosen for this source removal are relatively innovative, but robust, thermal technologies that were shown to be successful in the 1990s. They include the following:

- Steam injection to heat the subsurface and drive contaminants toward extraction wells

- Electrical resistance heating to heat low-permeability zones internally by application of electric power to an array of electrodes

- Liquid and vapor extraction for removing contaminants and maintaining hydraulic and pneumatic control

- In situ destruction of chemicals of concern (COCs) by chemical and biological processes that are accelerated by the presence of dissolved oxygen at elevated temperatures and pressures (such as hydrous pyrolysis oxidation)

- In situ monitoring of the heating and steam flow using temperature measurements and electrical resistance tomography

- On-site cooling, separation, and treatment of effluent streams containing nonaqueous-phase liquid (NAPL), water, steam, and air

This combination of technologies can reduce NAPL source zones in a matter of years.

2.0 BACKGROUND AND OBJECTIVES

2.1 PERTINENT HISTORY AND SITE CHARACTERISTICS

The McCormick and Baxter Superfund site occupies approximately 32 acres in a predominantly industrial area near the Port of Stockton and the junction of Interstate 5 and State Highway 4 (Figure 2-1). Old Mormon Slough forms the boundary to the north and connects to the Stockton Deepwater Channel on the San Joaquin River. Site boundaries include Washington Street to the south, the Interstate 5 freeway to the east, and an industrial facility, which is located at the Port of Stockton Turning Basin, to the west. An 8-acre parcel in the southeastern portion of the site is owned by the Union Pacific Railroad (UPRR). The UPRR property boundaries shown in Figure 2-1 have been approximated from parcel maps.

The former processing areas and tank farm at the site are paved. The rest of the site surface is unpaved, with limited vegetative cover. A layer of gravel between 1 and 3 feet thick is found across most of the site. Railroad tracks are located on many areas of the site. Most of the former structures have been removed. The only remaining aboveground structures are the office building, two storage sheds, a stormwater collection system lift station, remnants of an old gas station (i.e., foundation and building, not a tank), a wooden tower, and a building near the tower. Underground sump-like basement foundations and associated piping for the former pressure treatment units remain in the central portion of the site. Entry to the site is controlled by a perimeter fence and 24-hour security service.

The site is located on the margin of the Sacramento River–San Joaquin River Delta in the Great Valley geomorphic province of California. The site terrain is relatively flat and near sea level, ranging from 8 to 15 feet above mean sea level (msl). Surface water bodies in the vicinity of the site include Old Mormon Slough, New Mormon Slough, the Stockton Deepwater Channel, and the San Joaquin River. Old Mormon Slough is approximately 2,500 feet long and 180 feet wide. Most of the slough is approximately 10 feet deep, although the western portion near its mouth has historically been dredged for barge access. Old and New Mormon Sloughs are tidally influenced, with a maximum tidal range of approximately 3 feet. Stockton Channel, the Port of Stockton Turning Basin, and Old Mormon Slough are areas of net sediment deposition, and all but the inner portion of Old Mormon Slough are periodically dredged to maintain depths appropriate for ship traffic.

The McCormick and Baxter Creosoting Company operated at 1214 West Washington Street in Stockton, California, from 1942 until 1991. Various wood preservation processes were used at the site during its operational history. The treated wood products were used primarily by power utilities, railroads, and in construction. The preservatives included creosote, pentachlorophenol (PCP), arsenic, copper, chromium, and zinc. Solvents or carriers for these preservatives included petroleum-based fuels (such as kerosene and diesel), butane, and ether. A list of wood-preserving chemicals used at the site is shown in Table 2-1.

Most treatment processes consisted of pressure impregnation of the preservative solutions in retorts. Pressure-treated wood was removed from the retorts and allowed to dry in various wood storage areas throughout the site. The primary facility areas identified as the probable sources of contamination at the site include the Main Processing Area, Oily Waste Ponds Area, and Cellon Process Area. Figure 2-2 shows the potential source areas defined at the site.

The surface geology of the McCormick and Baxter site has been mapped as undifferentiated recent alluvium and Victor Formation (DWR 1967). These deposits are underlain by the Plio-Pleistocene Laguna Formation, which is underlain by the Mehrten Formation of Miocene to Pliocene age. The flood basin deposits contain delta equivalents of the Victor and Laguna Formations (i.e., the Victor and Laguna Formations interfinger with flood basin deposits).

More recently, surface deposits have been mapped as Modesto Formation (CDMG 1990) and as fan deposits of the Calaveras River (Atwater 1982). The Modesto Formation represents Pleistocene glacial outwash fans that are approximately 10 to 15 feet thick. For the purposes of this design, the Modesto Formation and the Calaveras Fan deposits are considered to be equivalent to the Victor Formation.

Subsurface materials at the McCormick and Baxter site at elevations higher than approximately −230 feet North American Vertical Datum of 1988 (NVD88) consist primarily of two types. The most abundant volumetrically, forming about 60 percent of the subsurface, is a uniform stiff to very stiff gray-green micaceous clayey silt with common calcite nodules and/or veins. The remainder consists of a gray to gray-green fine- to medium-grained sand and silty sand. Sedimentary structures such as laminations and cross-bedding are not observed in the soil samples of site sands and silts. Contacts between the two materials are typically abrupt but may be gradational.

Sand zones exist both as laterally continuous horizontal layers and as discontinuous layers and pods within and between the clayey silt material. These sand zones range in thickness from a few feet up to 30 feet thick. Most laterally continuous sand units are approximately 10 feet thick.

Some general trends in the occurrence of silts and sands in the deeper subsurface are apparent. The sand units are vertically well connected to –100 feet elevation beneath the former Cellon Process Area. Thus, many laterally extensive sand units at various depths are vertically connected beneath the Cellon Process Area. The proportion of silt to sand appears to be greater below an elevation of approximately –200 feet and above the gravelly sand/sandy gravel unit at a −240-foot elevation.

The observed vertical and lateral relations of the sand and silt materials at the site are consistent with features attributed to bedload channel (sand) deposits and flood basin overbank (silt and clay) deposits of a fluvial system, suggesting that the subsurface materials are flood basin deposits as described by Atwater (1982) and in various USACE reports (USACE 1999, 2000a). Since sand channel deposits represent a large percentage of the subsurface materials (approximately 40 percent), channels tend to overlap each other, allowing a locally high degree of horizontal and vertical connectivity of the sand deposits.

A sandy gravel/gravelly sand unit is encountered at an elevation of approximately –240 feet. This unit is laterally continuous and varies in thickness from 5 to more than 20 feet thick. The gravel and sand consists primarily of quartz/quartzite, volcanic, and metamorphic lithic fragments.

The bottom of the sandy gravel/gravelly sand unit has been penetrated at two locations. Sand and silts encountered below the gravelly unit are similar in grain size, color, and consistency to those encountered at higher elevations.

Old Mormon Slough sediments in the slough adjacent to the McCormick and Baxter site contain stratified clay, silt, and sand. The uppermost sediments consist of up to 6 feet of soft, dark-colored clay and silty clay. These have been interpreted as being deposited in a quiescent, stagnant water environment (comparable to the current conditions) after the channel was cut off from its upstream source in 1970 during the construction of Interstate 5. The uppermost sediments are underlain by a thin, soft, very dark or dark olive-gray silt with plant remains and occasional discontinuous, thin sand layers. The contact between the recent unconsolidated slough deposits and the older pre-Old Mormon Slough recent flood basin deposits occurs between 3 and 5 feet below the mudline (–11 to –13 feet NVD88). Silt identical in color and consistency to that observed at adjacent locations was present at 5 feet below the mudline. The change in consistency from soft to firm within the silts noted in the previous sediment core descriptions has been interpreted to be the contact between the older pre-Old Mormon Slough recent flood basin deposits and the recent Old Mormon slough unconsolidated deposits (USACE 2000a).

The upper 200 feet of sediments are collectively referred to as the shallow aquifer. Groundwater in this zone occurs primarily in laterally continuous sand layers and lenses of fine- to coarse-grained greenish-gray sand. The sediments from approximately −190 feet NVD88 downward have been termed the deep aquifer.

The horizontal and vertically overlapping distribution of relatively permeable versus impermeable materials in the subsurface throughout most of the depth range examined prohibits the presence of well-defined aquifers and aquitards. Previous site investigations have divided the subsurface into five distinct sand zones designated A, B, C, D, and E (Figures 2-3 and 2-4).

Sand units at a given elevation may have some lateral continuity across the site, but silt deposits can separate sands at equal elevation (e.g., the A1-zone aquifer is discontinuous between the UPRR property and the western portion of the site.) The sandy zones beneath the former Cellon Process Area (SE-08) are well connected vertically, effectively connecting the A- and B-zones in this area. Therefore, the aquifer zone designation applies only locally to areas of the site where the silts are laterally continuous and not vertically bisected by sand channels.

Hydraulic conductivity measurements have been derived from laboratory tests of recovered samples (vertical conductivity) and from pumping tests (horizontal conductivity). Horizontal values are summarized in Table 3-2. Vertical conductivity for geologic materials is often one or more orders of magnitude lower than horizontal conductivity. Thus, the laboratory permeability data are likely to be biased in favor of low values. Detailed information on test methodology and results is contained in USACE reports and references therein (USACE 1999, 2000a).

The horizontal component of groundwater flow at the site is toward the southeast in the A-zone, turning gradually towards the east-northeast in successively deeper aquifer zones. A flow in the E-zone toward the east-southeast is consistent with historical regional groundwater flow data (DWR 1967; USEPA 1998) that show a large groundwater cone of depression in response to groundwater pumping centered over the central portion of the city of Stockton. The calculated average horizontal velocities of groundwater in the A-, B-, C-, D-, and E-zone sand units are 0.3, 0.1, 0.1, 0.05, and 0.5 foot/day respectively. The observed vertical gradient of flow has been downward between all aquifer zones. The calculated vertical groundwater flow velocities between aquifer zones A and B, B and C, C and D, and D and E are 0.0008, 0.0012, 0.0014, and 0.0011 foot/day respectively. Calculated vertical groundwater flow velocities are two to three orders of magnitude less than horizontal groundwater velocities. Therefore, the predominant direction of groundwater flow and dissolved-phase contaminant transport is horizontal within sand zones. Vertical velocities are likely to be higher in areas where sand units have a strong vertical connection.

The southeasterly flow of groundwater within the A- through D-zones suggests that groundwater recharge of the upper aquifer is from the northwest and/or local pumping of the upper aquifer is to the southeast. The Stockton Deepwater Channel is north of the site, and the main channel of the San Joaquin River is west of the site. These are likely groundwater recharge sources for the upper aquifer. Old Mormon Slough is considered to have only a poor hydraulic connection to the upper aquifer (USACE 2000a).

2.2 REMEDIAL ACTION OBJECTIVES

EPA will set separate remedial action objectives (RAOs) for the remediation of NAPL and the remediation of dissolved-phase groundwater contamination at the McCormick and Baxter site.

The RAOs for remediating NAPL will address mass removal of NAPL source areas that represent principal threat wastes; the RAOs for dissolved-phase contaminants in groundwater will address the subsequent remediation of remaining dissolved-phase contamination to achieve groundwater cleanup standards that will be established by EPA and the state.

The relevant RAOs for this conceptual design document are the NAPL RAOs, which are to (1) remove NAPL to the maximum extent technically feasible to protect the E-zone drinking water aquifer, and (2) to reduce the need for long-term pump-and-treat.

Due to the complexity of the site and the extent of NAPL contamination, thermal treatment is not being considered as a stand-alone remedy. Thermal treatment is being evaluated for source removal and may be used in conjunction with dissolved-phase pump-and-treat and/or monitored natural attenuation as part of the final groundwater remedy.

RAOs and the overall groundwater cleanup approach will be discussed in detail in the FS report to be prepared separately by EPA and the USACE.

2.3 CRITERIA FOR SELECTION OF THERMAL TREATMENT AREAS

The following criteria were provided by EPA and the USACE, with input from Cal EPA/DTSC, the California Regional Water Quality Control Board (RWQCB), and the technical advisors, as the basis for prioritizing areas of the site for thermal treatment:

- Relative amount of NAPL present
- Proximity of NAPL to drinking water risk receptors (i.e., the E-zone aquifer)
- Certainty of the data indicating the presence of mobile NAPL
- Potential for future changes in land use and/or subsurface conditions that might facilitate mobilization of currently immobile NAPL (e.g., increased pumping from E-zone downgradient of the site)
- Ease of access for followup remediation activities

2.4 DEFINITION OF TREATMENT VOLUMES AND SCENARIOS

This section provides a detailed description of the thermal treatment scenarios and the associated volumes of NAPL-impacted soil. The site was split in the areas shown in Table 2-2.

2.4.1 Treatment Scenarios

Scenario 1—Main Process Area (MPA), Cellon Process Area (CPA), and North-MPA

The MPA and CPA are the major historical sources of the NAPL that have contaminated soil and groundwater within the boundaries of the McCormick and Baxter site. Subsurface migration from the MPA and CPA has also impacted the deep subsurface zones under the slough (North-MPA). SteamTech has estimated that up to 1.54 million yd^3 of NAPL-impacted soil is present in the area delineated for this scenario, representing 52 percent of the total volume of NAPL-impacted soil believed to be present at the McCormick and Baxter site.

Scenario 2—MPA, CPA, North-MPA, South-MPA, and South-CPA

This scenario includes the areas designated for Scenario 1 (MPA, CPA, North-MPA) and extends to the south (South-MPA and South-CPA). SteamTech has estimated that up to 2.10 million yd^3 of NAPL-impacted soil is present in the area delineated for this scenario, representing 71 percent of the total volume of NAPL-impacted soil believed to be present at the McCormick and Baxter site. Scenario 2 consists of the same treatment processes as those indicated for Scenario 1. However, Scenario 2 would require increased steam injection, NAPL/groundwater extraction and treatment, power demand for electrical resistance (ERH), and larger-size equipment due to the larger volume of soil and groundwater to be treated.

Scenario 3 — MPA, CPA, North-MPA, South-MPA, South-CPA, East–MPA, and Oily Waste Pond Area (OWPA)

This scenario includes the areas designated for Scenario 2 and extends east to the East-MPA and west to the OWPA. The scenario includes known and suspected areas of NAPL-impact documented for the McCormick and Baxter site. SteamTech has estimated that up to 2.95 million yd^3 of NAPL-impacted soil is present in the area delineated for this scenario, representing 100 percent of the total volume of NAPL-impacted soil believed to be present at the McCormick and Baxter site. Scenario 3 consists of the same treatment processes as those indicated for Scenarios 1 and 2. However, Scenario 3 would require increased steam injection, NAPL/groundwater extraction and treatment, power demand for ERH, and larger-size equipment due to the larger volume of soil and groundwater to be treated.

2.4.2 Treatment Volumes

The main treatment areas are shown in Figure 2-5. Details of the volume calculations are provided in Table 2-3, which also shows how the Main Processing Area (MPA), the area south of the MPA (S-MPA), the area under the slough north of the MPA (N-MPA), and the area south of the Cellon Process Area (S-CPA) were divided into smaller areas with different vertical treatment intervals (this is due to the complex three-dimensional distribution of the NAPL in the subsurface and an effort to minimize the overall treatment volume). These subdivisions are shown in Figure 2-5, and their priorities for treatment are shown in Figure 2-6.

The approximate depths of NAPL-impacted material are indicated in Figure 2-7.

Volume estimates were made using simple three-dimensional geometric shapes based on a manual interpretation of all available data.

For the area east of the MPA (E-MPA), our volume calculation assumed that treatment will be from an elevation of 120 feet and down, since NAPL has not been confirmed during the site characterization and analysis penetrometer system (SCAPS) investigation to a total depth of approximately 100 to 130 feet. We have assumed treatment from 120 to 260 feet, since we understand that the lack of NAPL detection in this deeper zone may be partly due to lack of data, especially for the deeper D- and E-zones.

The N-MPA zone, which is under the slough north of the MPA, was extended to the east after we reviewed the NAPL data. The NAPL present at depth could influence the treatment efficiency in the MPA. This zone has a volume of 266,000 yd^3.

The total sand volume estimated within the total NAPL-impacted areas listed above is about 720,000 yd^3, with about 39 percent of this (253,000 yd^3) located in the MPA. This affects the estimated cost to treat each cubic yard of NAPL-impacted soil, since only between one-fifth and one-third of the sediment volume is sand, which will be readily flushed by steam.

The three scenario areas are indicated in Figure 2-8. Areal extent of the thermal treatment volume is shown for each scenario in Figures 2-9, 2-10, and 2-11. Table 2-3 indicates the associated total volumes and sand fractions for all scenarios.

Partial thermal treatment under Old Mormon Slough is included in each of the three scenarios. One treatment design for each of Scenarios 1, 2 and 3 is provided. Scenario 1 involves treatment of the C-, D-, and E-zones under the slough using angled wells, and electrical heating of the D-E aquitard. This treatment is restricted to the two easternmost subareas of the N-MPA (2 and 3). Scenarios 2 and 3 involve treatment of the N-MPA from the B-zone down. This involves wells or electrodes installed through the slough (shallowest boreholes) and by angled drilling as described for Scenario 1.

At this point there are no plans of designing thermal remediation for the shallow sediments under the slough other than those in the N-MPA deeper than –30 feet elevation. However, extraction and operation close to the slough is part of the design because adverse effects on the slough will be minimized (see Section 3.7).

All scenarios involve treatment of the A-zone aquifer in MPA. Since NAPL-containing sediments from the OWPA have been placed under the current asphalt cap, it is desirable to attempt remediation beneath the cap (see Section 3.11).

The ultimate operational goal of the thermal treatment system will be to operate until such time as free product is no longer being recovered from extraction wells within the treatment area. In parallel with this goal, the intent is to operate the system until the whole target volume has been raised to a specific target temperature for a defined period of time.

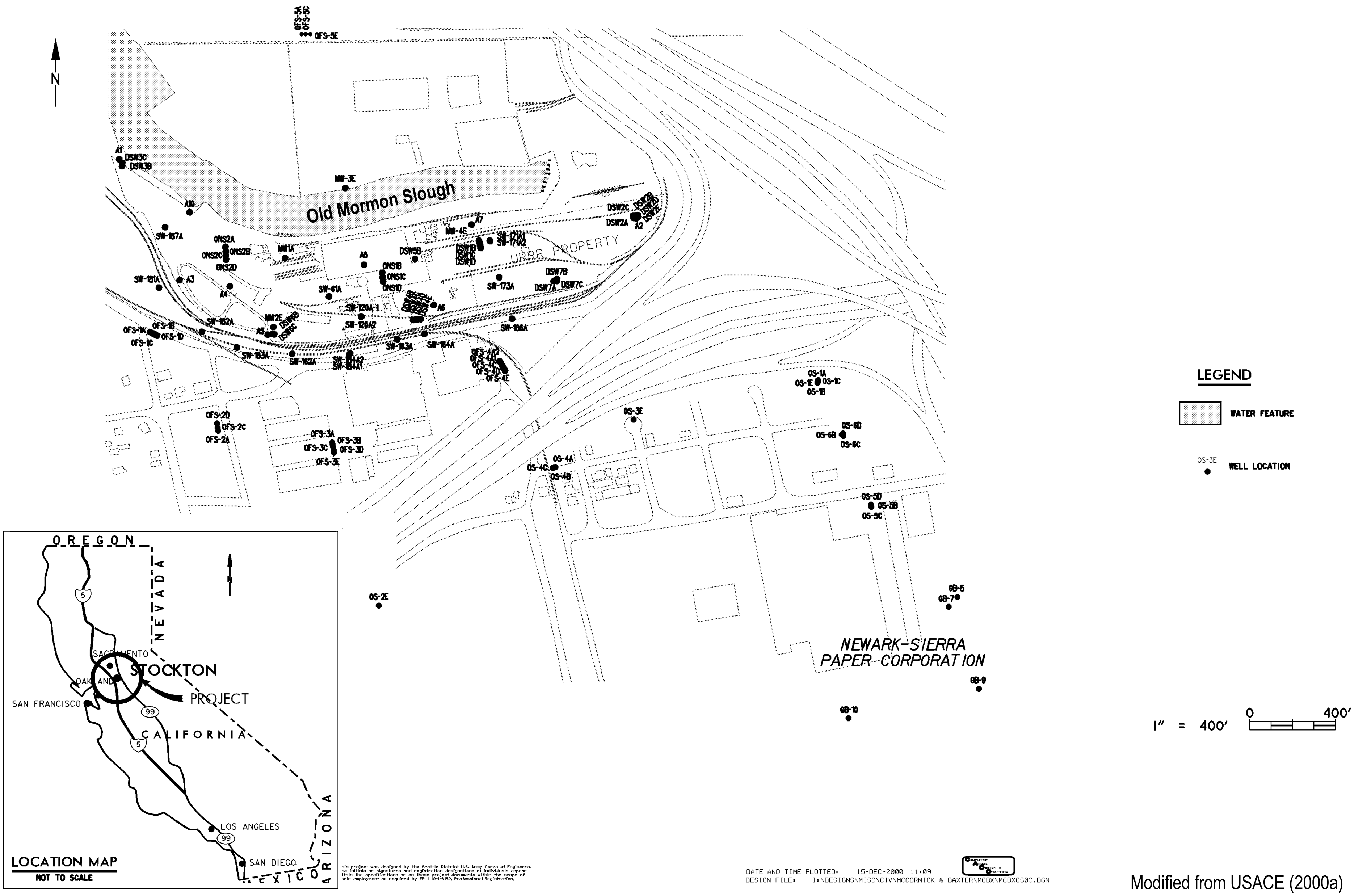
2.5 COMBINED THERMAL TREATMENT AND PUMP-AND-TREAT

A pump-and-treat system will be an integral part of the full design for all three scenarios discussed in this document. The pump-and-treat system will be operated during thermal treatment and during cool-down.

The main focus of the pump-and-treat is to extract mobile NAPL from contaminated areas and zones that are not being treated by thermal remediation and to incidentally remove dissolved-phase contaminated groundwater. The proposed extraction wells will be located outside the steam wells and electrical heating electrodes at several depth zones. The wells will be located preferentially in areas where mobile NAPL has been observed or is suspected to be present. It is anticipated that both NAPL and dissolved-phase contaminants may be recovered by the pump-and-treat system. Limited spreading of steam and heat away from the target thermal treatment zones will allow for some thermal enhancement in the pump-and-treat wells. This is a desirable effect leading to increased removal of NAPL from the volumes not directly heated; it also serves the purpose of containing small amounts of contaminants that may migrate outward from the thermal remediation target zones.

After thermal treatment, continued pumping will be used to control the flow of water during the cool-down period. A subset of the full well-field will be used for the pump-and-treat system, determined during operation as the wells that contain most contaminants, are located in optimal positions for hydraulic control, and function appropriately as extraction wells.

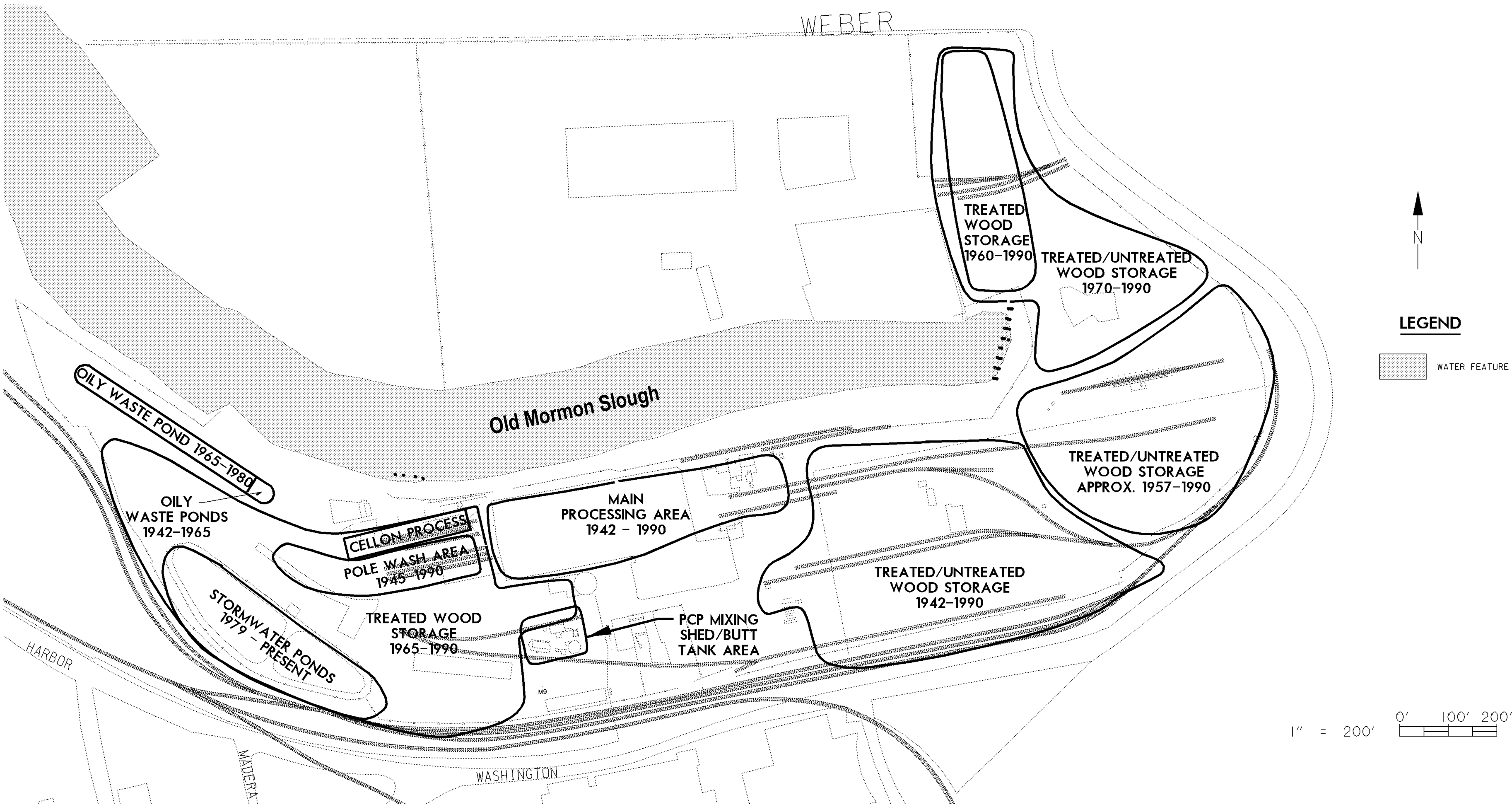
Well locations for both thermal treatment and pump-and-treat are indicated in Section 3.1. Hydraulic control and removal of mobile NAPL is discussed in more detail in Section 3.9.3. The full treatment period for each scenario is defined in Section 5.7.



Modified from USACE (2000a)

Figure 2-1
General Location Map

THERMAL TREATMENT TECHNOLOGY
CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California



This project was designed by the Seattle District U.S. Army Corps of Engineers. The initials or signatures and registration designations of individuals appear within the specifications or on these project documents within the scope of their employment as required by ER 1110-1-8152, Professional Registration.

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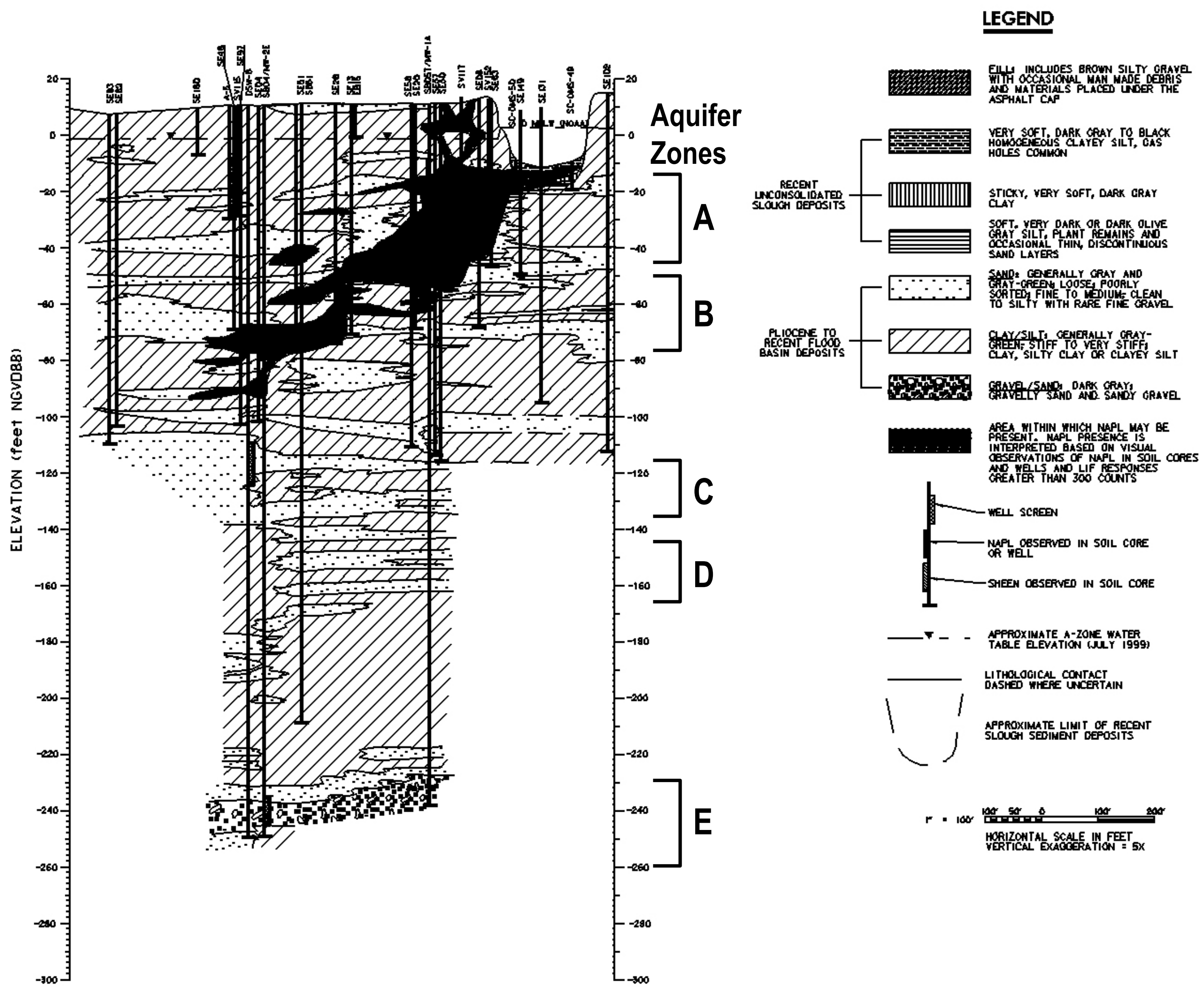
Computer Aided Design & Drafting

Modified from USACE (2000a)

Figure 2-2
Detail of Site, Showing Historical Usage

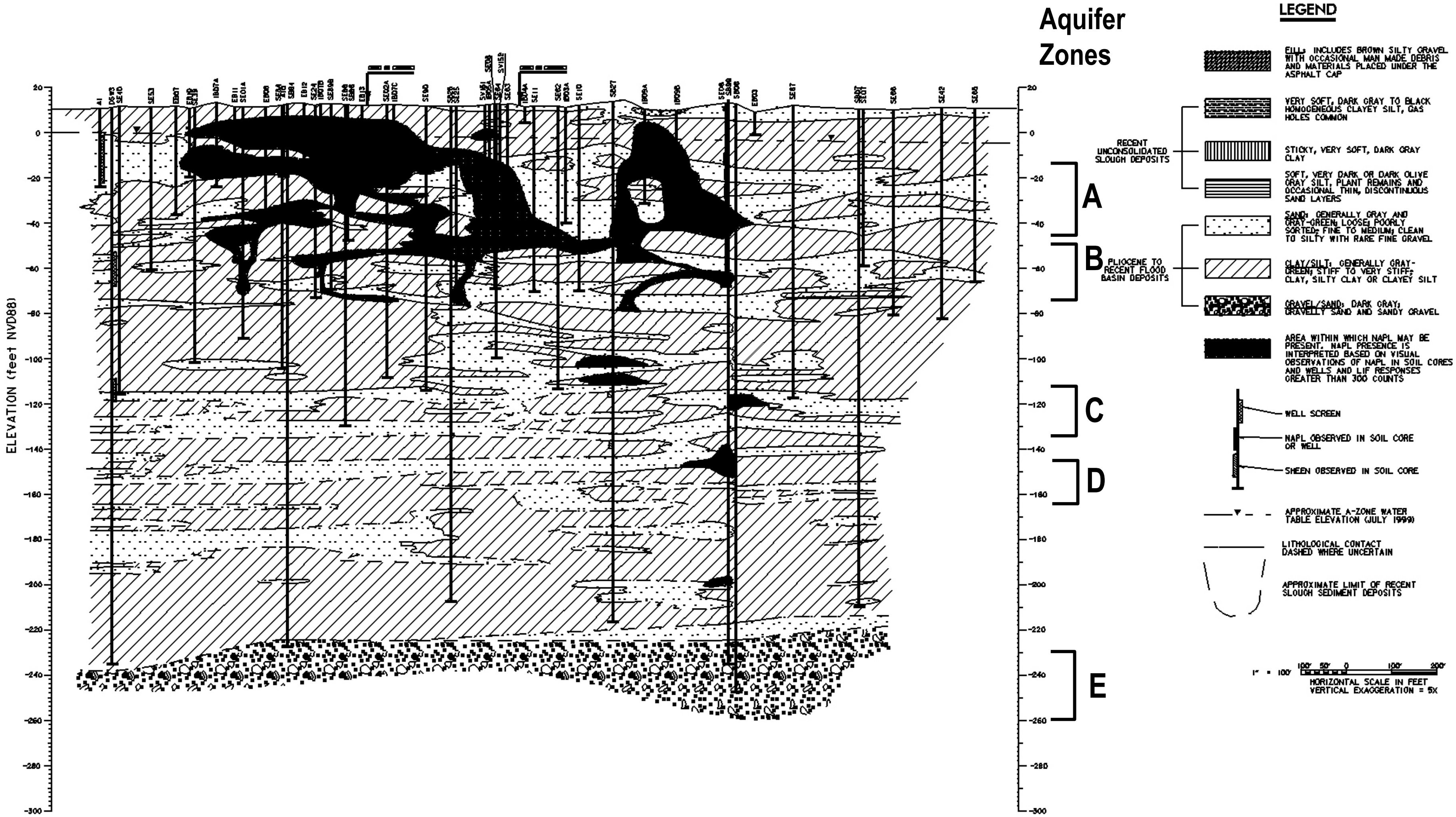
THERMAL TREATMENT TECHNOLOGY CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California



Modified from USACE (2000a)

Figure 2-3
South-to-North Section, Based on USACE Data

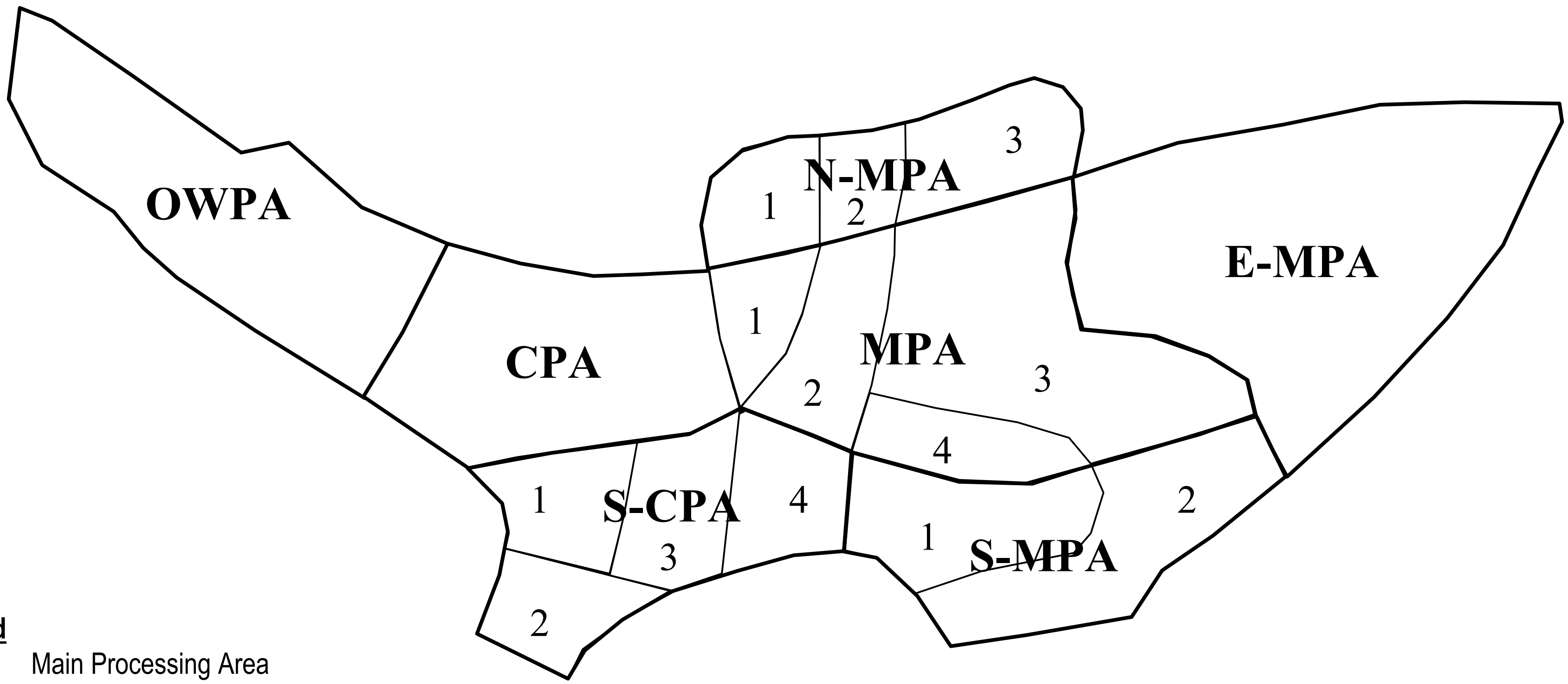
THERMAL TREATMENT TECHNOLOGY CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California



Modified from USACE (2000a)

Figure 2-4
West-to-East Section, Based on USACE Data

THERMAL TREATMENT TECHNOLOGY CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California



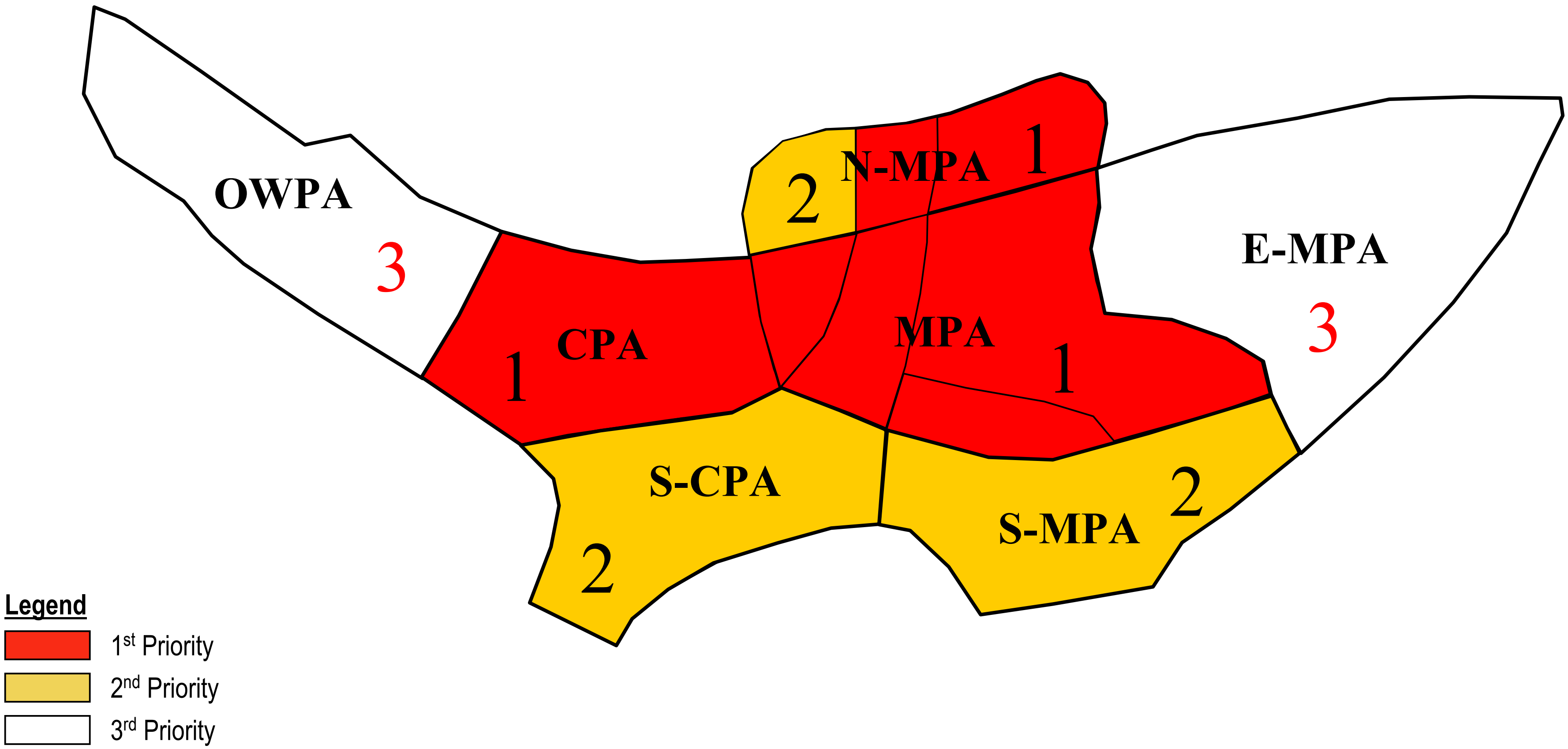
Legend

MPA Main Processing Area
E-MPA East MPA
N-MPA North MPA
S-MPA South MPA
CPA Cellon Process Area
S-CPA South CPA
OWPA Oily Waste Ponds Area

Note: Numbers in each zone indicate the priority for treatment.

Figure 2-5
Map of Main Treatment Zones, Showing Subdivisions and Abbreviations

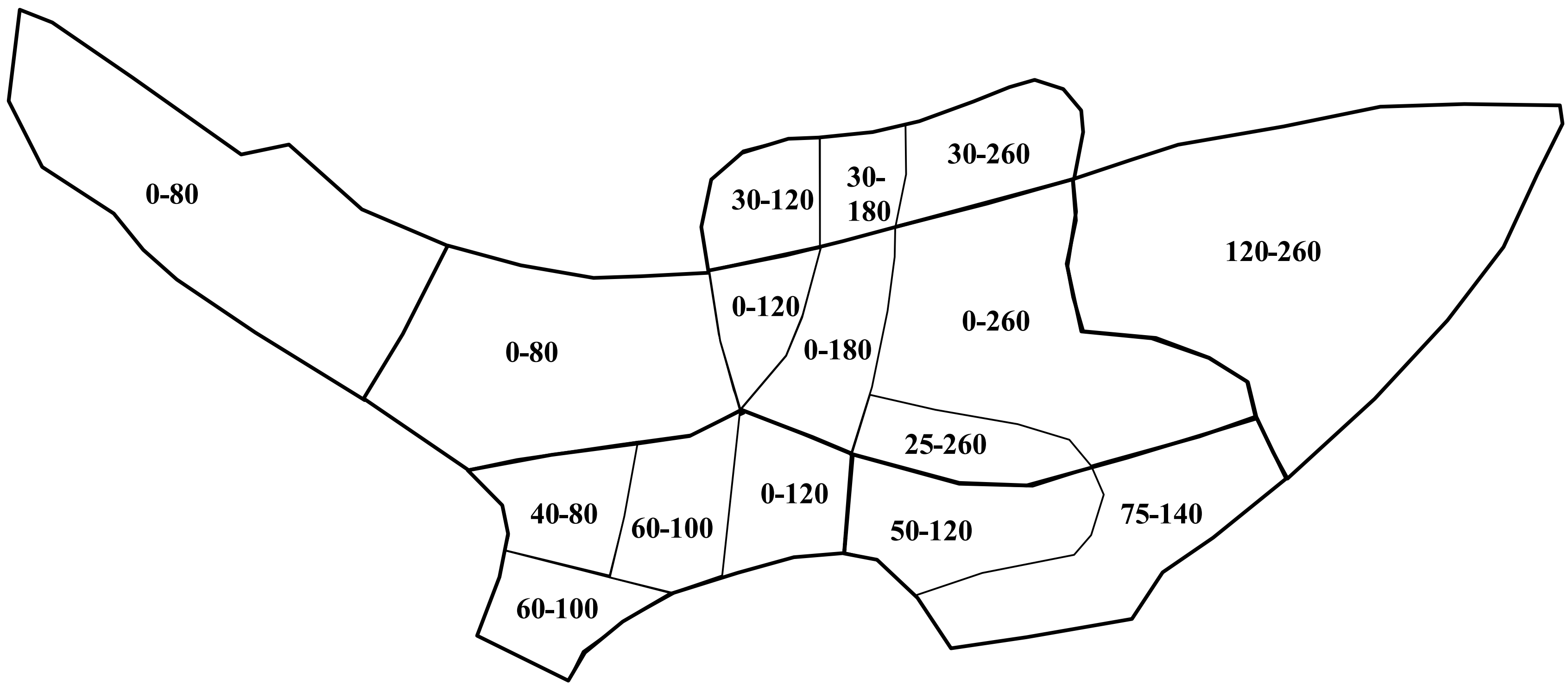
THERMAL TREATMENT TECHNOLOGY
CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California



Note: Numbers in each zone indicate the priority for treatment.

Figure 2-6
Remediation Priorities Assigned to Each Treatment Zone

THERMAL TREATMENT TECHNOLOGY
CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California



Note: Depth zone of impact is in feet below mean sea level.

Figure 2-7
Approximate Depth Intervals of NAPL-Impacted Soil and Groundwater

THERMAL TREATMENT TECHNOLOGY
CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

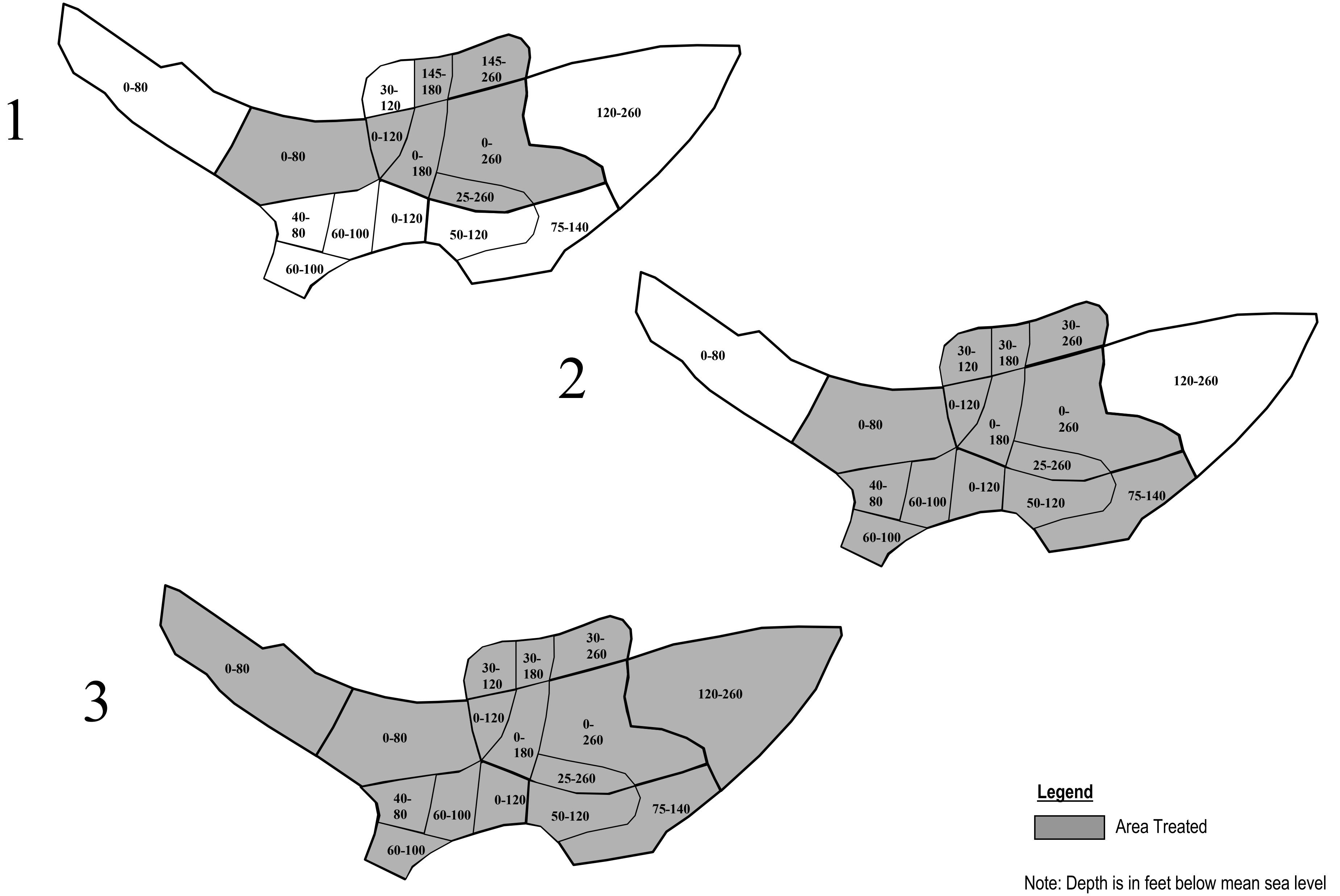
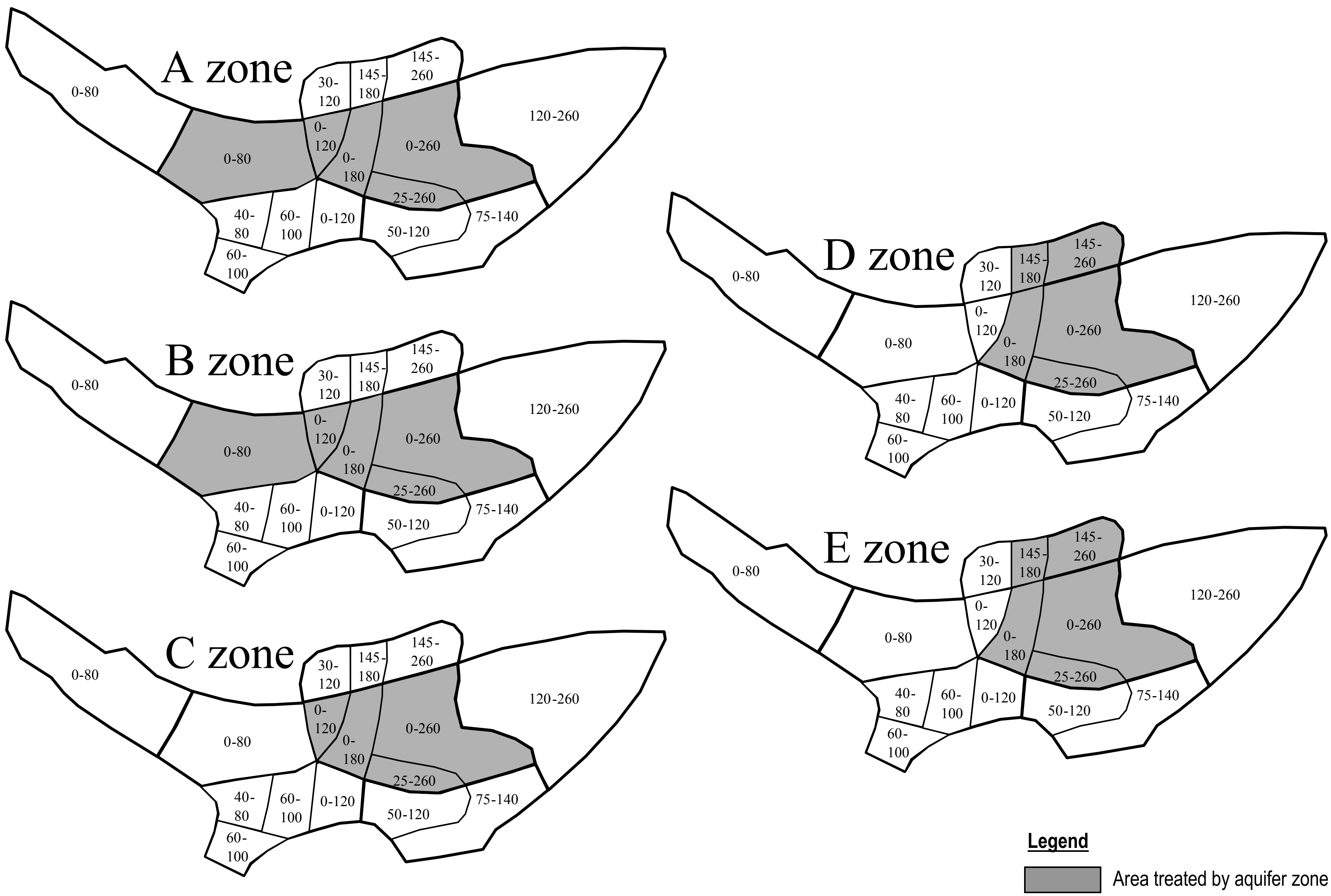


Figure 2-8
Overview of Areas Treated in Each of Three Scenarios

THERMAL TREATMENT TECHNOLOGY
CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California



Note: Depth is in feet below mean sea level

Figure 2-9
Scenario 1: Areas of Thermal Treatment in Each of Five Aquifer Zones

THERMAL TREATMENT TECHNOLOGY
CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

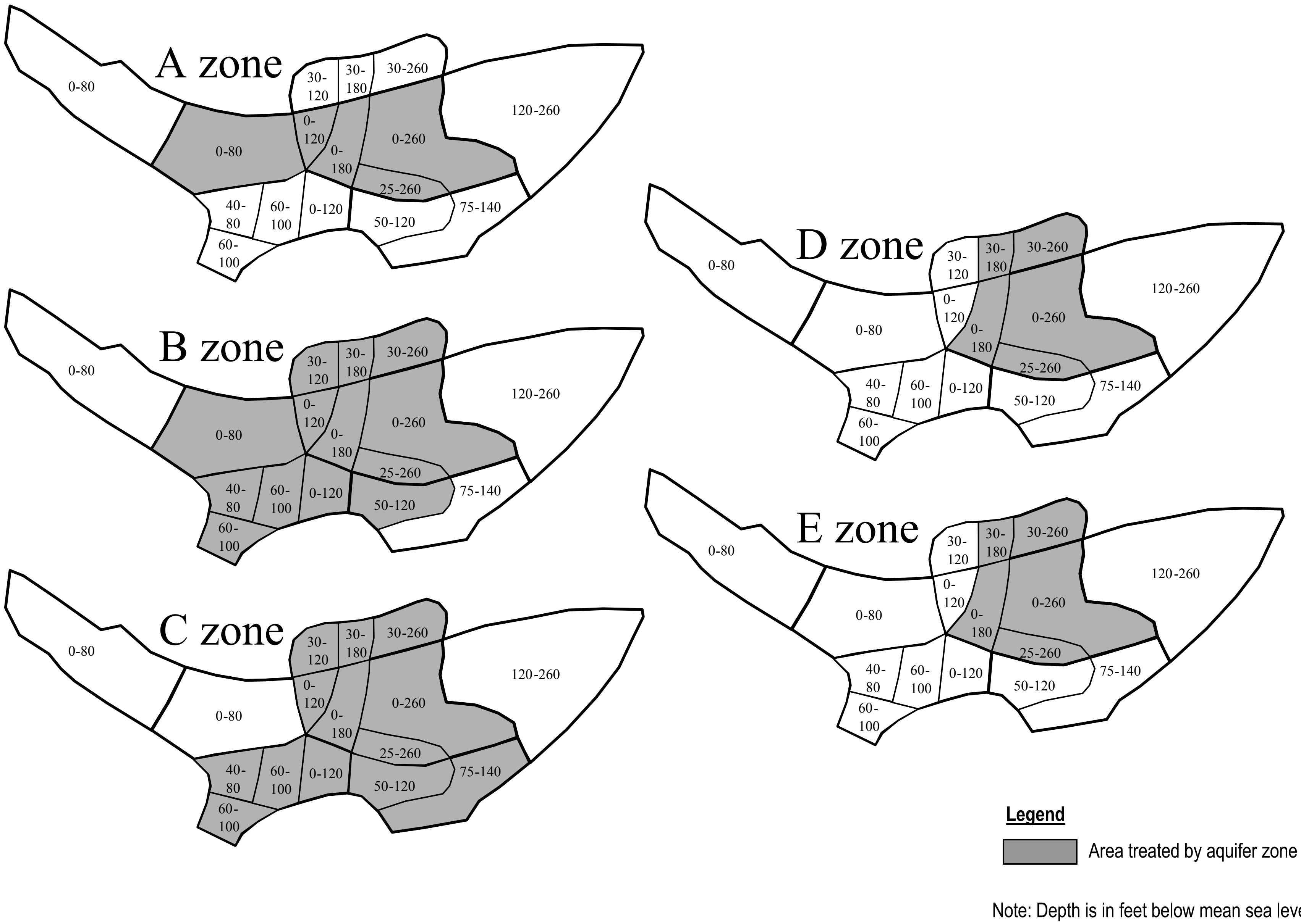


Figure 2-10
Scenario 2: Areas of Thermal Treatment in Each of Five Aquifer Zones

THERMAL TREATMENT TECHNOLOGY
CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

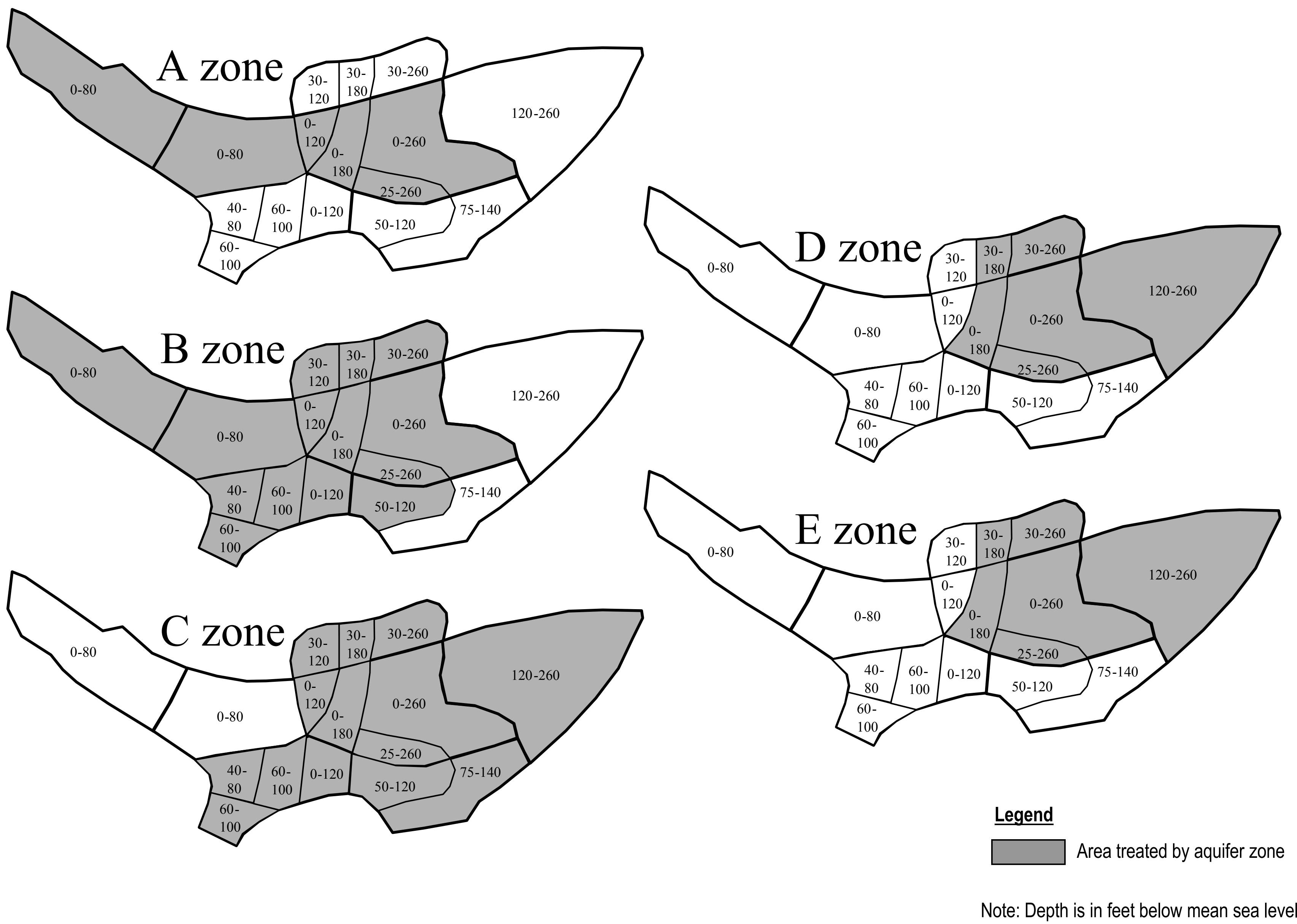


Figure 2-11
Scenario 3: Areas of Thermal Treatment in Each of Five Aquifer Zones

THERMAL TREATMENT TECHNOLOGY
CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

Table 2-1
Wood-Preserving Chemicals Used at McCormick and Baxter Site

Common Name	Chemical Components	Period of Use
Creosote	Creosote and fuel oil	1942-1990
Pentachlorophenol	Pentachlorophenol and oil	1946-1990
Bouliden salts	Chromium, copper and arsenic	1949-1952
CCA	Chromated copper and arsenic	1952-1970
Cellon	Pentachlorophenol, butane, and ether	1965-1988
ACA	Ammoniacal copper arsenate	1970-1986
Flamescape	Diammonium phosphate, ammonium sulfate, and boric acid	1976-1988
ACZA	Ammoniacal copper-zinc arsenate	1986-1990

Table 2-2
Overview of Areas, Priorities, and Volumes of NAPL-Impacted Material

Abbreviation	Explanation	Priority	Volume of NAPL Impact (yd^3)
MPA	Main Processing Area	1	1,152,000
CPA	Cellon Process Area	1	290,000
N-MPA	Area under slough north of MPA	1 and 2[a]	266,000
S-MPA	Area south of MPA	2	200,000
S-CPA	Area south of CPA	2	196,000
E-MPA	Area east of MPA	3	597,000
OWPA	Oily Waste Pond Area	3	252,000
Total			2,952,000

[a] Deepest parts of the N-MPA are priority 1; the western part of N-MPA is priority 2. Details are shown in Figures 2-9 and 2-10.

Table 2-3
Estimation of Bulk Volume and Sand Fractions in Each Priority Treatment Zone

												Zone	Zone	
Zone/area	**Sub**	**Priority**	**Area (ft^2)**	**Top (ft)**	**Btm (ft)**	**Depth (ft)**	**Volume (yd^3)****	**Total (yd^3)**	**% of total**	**Sands***	**Silts**	**Sands**	**Silts**	**% sand**
MPA	1	1	17,695	0	-120	120	78,651			17,303	61,348			
	2	1	28,419	0	-180	180	189,475			41,685	147,791			
	3	1	74,247	0	-260	260	715,028			157,306	557,722			
	4	1	19,398	-25	-260	235	168,848	1,152,002	39.0	37,147	131,701	253,440	898,562	22
CPA		1	97,739	0	-80	80	289,620	289,620	9.8	92,678	196,942	92,678	196,942	32
N-MPA	1	2	11,097	-30	-120	90	36,993			8,138	28,855			
	2	1	9,538	-30	-180	150	52,993			11,658	41,335			
	3	1	20,628	-30	-260	230	175,734	265,720	9.0	36,904	138,830	56,701	209,019	21
S-MPA	1	2	30,977	-50	-120	70	80,317			17,670	62,647			
	2	2	49,504	-75	-140	65	119,186	199,503	6.8	26,221	92,965	43,891	155,612	22
S-CPA	1	2	18,380	-40	-80	40	27,232			5,719	21,513			
	2	2	17,965	-60	-100	40	26,617			2,662	23,955			
	3	2	30,653	-60	-100	40	45,415			4,542	40,874			
	4	2	21,853	0	-120	120	97,132	196,396	6.7	21,369	75,763	34,291	162,105	17
E-MPA		3	115,068	-120	-260	140	596,697	596,697	20.2	161,108	435,589	161,108	435,589	27
OWPA		3	85,187	0	-80	80	252,426	252,426	8.5	80,776	171,650	80,776	171,650	32
Sums								2,952,365	100	722,886	2,229,479	722,886	2,229,479	24
Scenario		**Zones included**						**Total (yd^3)**	**% of total**	**Sand (yd^3)**	**Silts (yd^3)**	**% sand**		
1		MPA, CPA, N-MPA DE zones only***						1,541,854	52.2	370,400	1,185,586	24.0		
2	all	MPA, CPA, N-MPA, S-CPA, S-MPA (all depths)						2,103,242	71.2	481,002	1,622,240	22.9		
3	all	All areas and depths						2,952,365	100.0	722,886	2,229,479	24.5		
*used minimum sand fraction of 0.10 for any zone that needs steam treatment														
**volume estimates are rough based on simple geometric shapes and assuming each subarea/volume simplified as a box														
***note that scenario 1 involves 50% of the soil column from 30 to 260 ft only, due to D and E zone treatment														

3.0 SUBSURFACE REMEDIAL DESIGN

3.1 WELL-FIELD AND VOLUMES

The boundary of the area impacted by NAPL migration has been defined on the basis of direct and indirect soil sampling. NAPL was visually observed in a number of soil borings as a brown to black liquid with a strong odor of naphthalene. Qualitative NAPL saturations observed in soil cores ranged from oozing and/or dripping product to brown stains and/or sheen. The highest saturation was most commonly observed in sandy lithology but was also observed in silt in a limited number of cases. The presence of polycyclic aromatic hydrocarbon (PAH) NAPL was also interpreted on the basis of SCAPS laser-induced fluorescence (LIF) data, indicated by a LIF count of greater than 300 (USACE 2000b). SCAPS data also indicate the presence of NAPL in both sand and silt, being found more commonly in sandy lithology. Sandy layers contaminated by NAPL tend to be effectively uniformly saturated in cores, whereas contaminated clayey silt layers more typically contain discontinuous blobs or thin, vertically oriented stringers of NAPL.

The shaded areas in Figures 2-3 and 2-4 represent subsurface volumes interpreted as containing NAPL. NAPL within these regions may occur as mobile and/or residual NAPL; as pools of DNAPL, ponded on low-permeability layers; or as thin, vertically discontinuous fingers or stringers. DNAPL may not be present everywhere within such regions. The labeled treatment zones and subzones (MPA, OWPA etc.) define the lateral extent of subsurface areas of interpreted NAPL presence based on direct soil sampling and SCAPS LIF pushes. These generally lie within the "maximum extent of interpreted NAPL" line on earlier field investigation reports (e.g., Figures 5-5 to 5-8 in USACE 2000). In certain areas, notably at the east end of the site, the defined zones extend beyond the known or interpreted NAPL presence. These boundaries represent convenient demarcation lines for well installation in areas where high dissolved-phase concentrations of COCs suggest that presently unsampled NAPL may be present nearby.

The overall thermal remediation strategy proposed for this site entails heating the volumes of soil known or suspected to contain NAPL, as defined in Section 2.4. These soil volumes will be heated by steam injection in aquifer zones A, B, C, D, and E, where permeability is sufficient for effective steam migration. In those "aquitards" where NAPL is known or suspected to be present and permeability is too low for effective steam injection, ERH will be used to heat the soil to the target temperature (this applies to zones below the C-zone aquifer). Steam injection will be focused on individual aquifer zones by screening injection wells at appropriate depths.

Extraction wells will be screened so as to straddle both the aquifer zones and parts of the adjacent aquitards. Liquid and vapor extraction will thus be achieved throughout the entire

NAPL-impacted interval in any given treatment area. The vertical distribution of injection and extraction intervals is summarized in Figures 3-1 and 3-2.

A seven-spot configuration has been used for the basic well-field cell, in which a central extraction well is surrounded by six injection wells. The interwell separation varies between aquifer zones and is dependent on the assumed bulk permeability of that zone (USEPA 1998; USACE 2000a). In the A-, B-, and D-zones, a well separation of 60 feet has been used. The higher permeability of the C- and E-zones has permitted 120- and 180-foot well separations, respectively. Multiples of 60 feet have been used as well separations for convenience of design (Section 3.3 and Appendix B). It is assumed that wells would not be collocated in reality (although they are presented as such in the accompanying plans), but clustered in groups within 10 to 20 feet of each other. Because of the large size and complex stratigraphy and range of permeability at this site, relatively conservative permeability values have been used in calculating the radius of influence of each injection well. Consequently, the well spacing presented here should be regarded as a minimum. The relatively high-density well-fields generated using these spacings are, however, the most robust configurations for the prevailing conditions at the site.

For the E-zone wells, the contaminated area was surrounded by injection wells, eliminating the need for outside extraction. However, if contaminants are detected during installation of the injection wells, the well-field will have to be adapted according to the principles outlined in Section 7.4.

3.1.1 Scenario 1

The well-field layout for Scenario 1 is presented, by aquifer zone, in Figures 3-3 to 3-7. In the A-zone, the basic 60-foot separation cell is repeated to cover the MPA and the CPA. A series of A-B-zone extraction wells forms a perimeter on the north, south and west sides where NAPL is known or suspected to be present close to the margins of the treatment area. An additional two extraction wells, screened only in the A-zone and extended to a shallower elevation of –5 feet are present in the area of the repository, at locations coincident with B-zone injection wells. This approach is intended to address contamination of imported soil in the repository, which must be surrounded by injection wells to ensure an effective steam drive toward the central extraction wells. The immediate concern of NAPL in the A- and B-zones beneath Old Mormon Slough is addressed by the presence of two rows of extraction wells, screened across the A- and B-zones in the N-MPA.

In the C- and D-zones (Figures 3-5 and 3-6), the relevant unit cell has been repeated to provide coverage across the MPA and the CPA. As in the overlying aquifer zones, a perimeter of extraction wells is proposed where potential for lateral mobilization of NAPL exists. Angled injection and extraction wells extending beneath Old Mormon Slough in these zones are shown in plan view.

In the E-zone (Figure 3-7), a variant of the basic unit cell has been adopted. An outer ring of injection wells surrounds an inner ring of extraction wells, which in turn, surrounds a central dual-purpose well. The central dual-purpose well is intended to be used initially as an injection well and will be completed as such. However, should circumstances warrant, it may be readily converted for use as an extraction well. The outermost ring of injection wells can be justified on the basis of the absence of confirmed NAPL in the E-zone. The well-field for this zone may require modification if NAPL were to be identified during installation (as discussed in Section 7.4).

3.1.2 Scenario 2

The well-field layout for Scenario 2 is presented, by aquifer zone, in Figures 3-8 to 3-12. The well-field for the A-zone is as for Scenario 1; however that for the B-zone extends coverage into the S-MPA and the S-CPA. A perimeter of extraction wells extends along the southern boundary of the treatment area in recognition of the potential for off-site mobilization of NAPL in these areas. B-zone injection wells extend through the central part of the repository immediately adjacent to the additional A-zone extractors. In contrast to Scenario 1, EHR electrodes are collocated with A-B-zone extraction wells in the N-MPA beneath Old Mormon Slough (Figure 3-9).

Coverage of the C-zone well-field is extended further into the S-MPA and the S-CPA than that of Scenario 1 (Figure 3-10). The eastern boundary of the C-zone is marked by a line of extraction wells in order to address the risk of lateral mobilization of known or suspected NAPL into the E-MPA. A line of extraction wells forms the eastern boundary of the D-zone in response to the same risk in that aquifer zone (Figure 3-11).

The E-zone well-field for Scenario 2 is no different from that of Scenario 1 (Figure 3-12).

3.1.3 Scenario 3

The well-field layout for Scenario 3 is presented, by aquifer zone, in Figures 3-13 to 3-17. The A- and B-zone well-fields in Scenario 3 differ from that of Scenario 2 only in that coverage has been extended into the OWPA (Figure 3-13 and 3-14). The northern, southern, and western boundaries of the OWPA well-field are formed by A-B-zone extraction wells in view of the potential for off-site mobilization of NAPL in this area.

The C-zone well-field in Scenario 3 is extended into the E-MPA (Figure 3-15). The presence of NAPL has not been confirmed in the C-zone of the E-MPA; however, high dissolved-phase naphthalene concentrations have been recorded in well DSW-1C (5,400 ppb). Consequently, it is proposed that a C-zone extraction well be located close to DSW-1C, surrounded by injection wells. The fence of C-zone extraction wells along the southern shore of Old Mormon Slough has been extended eastward to address the possibility of northward mobilization of NAPL in the C-zone by those injection wells around DSW-1C.

NAPL is not known or suspected to be present in the D-zone in the E-MPA; however, historically high dissolved-phase naphthalene concentrations in well MW-4D in the central E-MPA, coupled with recently high concentrations in the C- and E-zones at that location, suggest that NAPL may be present in the D-zone in this area. The D-zone well-field has been extended to cover this area to address this risk (Figure 3-16).

The E-zone well-field of Scenarios 1 and 2 has been extended into the E-MPA for Scenario 3, in order to address the potential presence of NAPL in this area, as suggested by the presence of high dissolved-phase naphthalene concentrations in well MW-4E (Figure 3-17).

The number of wells is indicated in Table 3-1.

3.2 COMBINED STEAM AND ELECTRICAL RESISTANCE HEATING BOREHOLES

3.2.1 Materials

The ERH electrodes consist of three elements: a down-hole electrical supply cable, a metal electrode, and a conductive backfill.

The down-hole electrode cables consist of highly flexible copper stranding that is insulated with a Teflon™ outer covering. This cable type is similar to type K and is selected based on the high temperature (165°C) and chemical aggressiveness of the subsurface. The cables will be 2-O gauge, doubled-up to provide the required amperage.

The initial current of the D-E-zone electrodes will be about 305 amperes. The N-MPA electrodes (beneath the slough) will have two discrete elements to independently control the power to each depth. Each of these electrode elements will draw about 395 amperes.

The electrode cables will be bolted to a metal plate that provides a larger surface area for electrical conduction to the electrode backfill. A number of metal types could serve the purpose in this application. Due to the great depth and resulting cost of the borehole installation, two electrode cables and metal electrodes will be installed in each borehole to provide redundancy against failure during the remediation period.

The electrode backfill is the most important part of the electrode because it is the contact with the native soil that has the highest potential resistance of the electrode. As an analogy, the sand pack is the critical element of a water well. The electrode backfill consists of a granular steel shot with a mixture of particle sizes ranging from 0.5 to 2 mm in diameter. The steel shot is remarkably dense at 270 pounds per cubic foot; this density provides high contact pressures against the borehole sides, and its particle nature provides a conformable contact to match the native soil contours.

3.2.2 Electrical Isolation

The potential for electrical shock is a concern whenever ERH is used for site remediation. In many cases, extensive voltage damping measures must be used to prevent high induced voltages at the surface, where personnel may be exposed. However, the McCormick and Baxter site does not require any special voltage damping measures due to the depth of application for ERH. This depth provides the physical separation required to reduce surface voltages to far below OSHA safe limits as described in the following paragraphs.

The D-E aquitard electrodes require no special electrical isolation measures due to their great depth. They will be separated from the D-zone injectors and extraction wells by a 10-foot interval of tremmied grout; however, the main purpose of this grout is to prevent injected steam intrusion into the electrode. Steam intrusion is not desired because the steam can push the native water away and lead to a dry out condition, where the native soils lose their electrical conductivity.

Up to 300 volts of electricity will be applied to the D-E aquitard at a 175- to 210-foot elevation. The bottom of the D-zone injection wells at a 170-foot elevation will be subjected to a voltage of about 70 volts, albeit within a sand backfill that has very high native electrical resistance. The high electrical resistance of the sand backfill will prevent it from transmitting a large electrical current to the metal well casing.

The voltage of a good conductor (such as a metal steam injection or extraction well casing) is equal to the average contact voltage over its entire length, with some corrections for the electrical resistance of the backfill materials. The average induced electrical field over the entire length of an isolated D-zone injection well will be about 12 volts. Due to the fact that the high-voltage bottom of the well will be located within a nonconductive sand pack, the actual induced voltage of an isolated well will be somewhat less, probably about 8 volts.

The above voltages refer to an electrically isolated well. In practice, the wells will be connected via conductive steel piping. The interconnection of all of the wells causes their induced voltage to regress toward the mean voltage of the entire site, which is neutral (0 volts). In practice, inhomogeneities of the site prevent piping networks from stabilizing at exactly 0 volts; an induced voltage of 1 to 2 volts is most common.

Without special measures, the voltage of the injection wells and extraction wells will stabilize at some very low and safe value, well below the Occupational Safety and Health Act (OSHA) limit of 30 volts. However, some additional “belt and suspenders” measures are appropriate:

- The bottom of the D-zone injectors and extractors will rest on the grout interval that separates them from the electrodes. In order to increase the electrical resistance at this contact point, a second oversized Teflon™-lined end cap will be epoxied over the bottom cap of the wells. This over-cap will increase the electrical resistance of the wells in this important region.

- Although the wells will be interconnected by piping, this piping might fail or be disconnected for maintenance. To maintain continuous electrical contact between the wells, a 1-O bare copper wire will be interconnected to each well at ground level as a redundant grounding connection. This grounding network will also incorporate any monitoring wells that are located in the heated zone.

Of note, any components that are inside the wells, such as pumps, will be at the same low voltage as the well network. No special measures will be required to protect pumps or other internal well components.

The electrical resistivity tomography (ERT) electrodes will pick up any induced AC voltage in their vicinity during ERH operation. Grounding of the ERT electrodes is NOT a preferred option because we do not want to encourage any non-uniform current flow (and resulting electrical heating) in their vicinity. The ERT electrodes require electrical insulation at the surface for proper operation. This electrical isolation can be easily accomplished by configuring the surface connections of the electrodes with the female end toward the subsurface to provide protection against the ERH voltages that are induced in them. The ERT-induced voltages will probably be in the range of 3 to 100 volts, depending on the individual ERT electrode location. For the purpose of accurate monitoring, it is not good practice to place an ERT string near an electrode or well. Locating the ERT strings at a distance from the ERH electrodes also lowers their induced voltage.

3.3 STEAM INJECTION AND MIGRATION

3.3.1 Steam Injection Intervals

The locations and layouts of the steam injection well screens are presented in Section 3.1 for the three scenarios. The intervals were chosen based on the following criteria:

- For thermal treatment of the chosen areas, steam will be injected in all of the depth intervals representing the treatment depths, except the upper A-zone in some locations where the A and B sands are sufficiently connected to allow for steam migration upward from the B-zone into the A-zone.

- Where a zone has a good definition of the outer bounds of the NAPL area, steam injection wells were placed outside the target zones, allowing for an outside-in steam migration.

- For zones where NAPL is confirmed or suspected to be present outside the thermal treatment zone, the steam injection intervals are typically surrounded with extraction wells equipped with both liquid and vapor extraction capability.

- For thick sand zones that need steam flow in the bottom section, the injection screens are designed so they preferentially inject steam in the lower half of the aquifer interval. This is done by using short injection screens, typically screened from the middle of the aquifer to several feet into the underlying silt layer/aquitard.

- Where a sand zone is overlain by a thick silt/aquitard (such as the D-E aquitard in large areas of the site), it is desirable to allow steam injection in the bottom half of the aquitard into sand lenses that may be present. Often, it is not known where such lenses are, but the likelihood of sand sections is recognized. In such cases, the deeper zone steam injection wells are completed with the top of the screened interval located in the overlying aquitard. As an example, E-zone steam wells may be screened from about –200 feet of elevation (the middle of the D-E aquitard) to the bottom of the E aquifer. This will allow steam heat-up of any sand lenses that allow steam penetration in the lower D-E aquitard, without preventing sufficient heating in the E-zone, since the permeability in the E-zone aquifer is orders of magnitude higher than that of the D-E aquitard.

- For thinner aquifers where the achievable steam injection rate may be limiting heat-up and performance, the injectors are screened across the entire aquifer, but not in the overlying aquitard, allowing a higher injection pressure (due to a greater depth to the top of the screen), and the maximum achievable transmissivity of the aquifer interval.

3.3.2 Steam Injection Rates

The steam injection rates are critical for estimating the size of the steam generation equipment, for setting the well spacing, and for predicting the duration of thermal treatment. The estimation of achievable steam injection rates for the wells at different depths is provided in Appendix B. The procedure used to estimate the rates is as follows:

- The A through E zonation for the dominating aquifers was adapted, with an assumption of average depth for each zone as provided by Mike Bailey, USACE, in a summary table (Bailey 2001).

- The sand fraction in each zone was estimated based on Bailey (2001) and used to make a rough assumption of the steam zone thickness during the initial steam migration and heat-up. Typically, it was assumed that the steam zone filled 50 percent of the average aquifer thickness, with a condensate zone surrounding the steam zone.

- Four-inch injection well screens in 10-inch boreholes were assumed, and the maximum injection pressures were defined as 0.5 psi per foot measured from surface to the top of the injection screen.

- Permeability averages from Bailey (2000) were used for each aquifer zone. Three calculations were made for each depth interval, one where the average conductivity was used, one where one-third of the average was used, and one where three times the average was used. This allows for a simple evaluation of how local heterogeneity may affect the steam injection rates across the site, assuming that the same injection pressure will be applied.

- The simulations are simple radial, cylindrical calculations based on a numerical solution for one steam injection well, as described in Heron, Heron, and Udell (2000) and USACE (2001b).

Table 3-2 indicates the achievable steam injection rates at the maximum allowable injection pressures for the scenarios described above.

Average steam injection rates per well in each of the zones after about 180 days of injection were estimated as follows:

Zone A: 900 lb/hr
Zone B: 2,400 lb/hr
Zone C: 4,800 lb/hr
Zone D: 2,000 lb/hr
Zone E: 12,800 lb/hr

For the E- and C-zone wells, a reduced injection pressure was used, since the maximum allowable pressure would lead to excessive injection rates (more than 25,000 lb/hr per well).

For design purposes, the wells will allow for at least 150 percent of the average injection rate listed above, leading to design injection ranges as follows:

Zone A: 300 to 1,500 lb/hr
Zone B: 800 to 4,000 lb/hr
Zone C: 1,600 to 6,000 lb/hr
Zone D: 600 to 3,000 lb/hr
Zone E: 4,000 to 16,000 lb/hr

For the E-zone injection wells, the need to exceed the estimated injection rate is less important than it is for the upper zones, since the permeability is sufficiently high that all injection wells are expected to allow for injection at the design rate.

3.3.3 Radius of Influence and Choice of Well Spacing

The radii of the steam zones were calculated simultaneously with the injection rates described in Section 3.3.2. For design purposes, the most important parameter is the optimal distance between injection and extraction wells for each depth zone. For this purpose, the time needed for steam breakthrough to the nearest extraction well was estimated by making the steam zone radius equal to the well spacing.

The criteria used to choose the well spacing were the following:

- The well spacing cannot significantly exceed the predicted radius of influence after 90 days of steam injection for the simulation using the average hydraulic conductivity values for that particular depth interval.
- The well spacing will allow for steam breakthrough within 360 days in the scenario using one-third of the average hydraulic conductivity.

Based on the results provided in Table 3-2 and Appendix B, the following maximum well spacings were achieved for each zone:

Zone A: 52 feet
Zone B: 83 feet
Zone C: 112 feet
Zone D: 69 feet
Zone E: >300 feet

For practical purposes, it is desirable to group the depth zones so only two or three different well spacings are used. This allows for a logical well-field layout and minimizes the area occupied by wells and the piping from the wells to the steam and treatment systems, and it allows for access to the individual wells during operation. In addition, the E-zone injectors were predicted to allow for almost unlimited steam injection rates. For that purpose, a set of simulations was run with a lower injection pressure (840 kPa compared to the maximum allowable 928 kPa). This simulation showed that at injection rates of about 12,500 lb/hr per well, steam will break through to a well 180 feet away within 100 days of injection. Thus, the following well separations were chosen:

Zone A: 60 feet
Zone B: 60 feet
Zone C: 120 feet
Zone D: 60 feet
Zone E: 180 feet

For zone A, the well spacing is slightly higher than the 52 feet calculated above, but in this case we expect a positive effect by upward steam migration from the underlying zones. In conclusion, the 60-foot separation seems to be a good compromise.

3.3.4 Predicted Steam Breakthrough for Each Depth Interval

Based on the simulations included in Appendix B and the chosen well spacings and injection pressures, the breakthrough times were estimated for each zone as follows, using the average hydraulic conductivity values:

Zone A: 116 days (60-foot separation)
Zone B: 30 days (60-foot separation)
Zone C: 88 days (120-foot separation)
Zone D: 44 days (60-foot separation)
Zone E: 105 days (180-foot separation)

These times are for constant injection at the design pressures and may, therefore, be considered reasonable predictions of the earliest steam breakthrough in areas where the hydraulic conductivity value is similar to the average value given by Bailey (2000). Due to less than 100 percent operation for the steam injection system, temporary pressure reductions, less than average hydraulic conductivity values in many areas, and the intended reduction of steam injection rates in some wells to allow for a more uniform steam distribution, more realistic steam breakthrough times are listed below:

Zone A: 100 to 180 days
Zone B: 30 to 60 days
Zone C: 90 to 180 days
Zone D: 40 to 80 days
Zone E: 100 to 180 days

During operation, the steam migration in certain zones may be reduced in order to control the direction of vertical pressure gradients, to minimize the risk of downward NAPL migration, and to achieve uniform heating with a minimal fuel demand during the heat-up phase. For design purposes and for sizing the steam supply and effluent treatment systems, the overall steam injection rate and pumping rates were fitted for a heat-up time of 180 days as an average across the site. This is a reasonable compromise among the following factors:

- The desire to heat and remediate the site rapidly (to shorten the overall operation time)
- The need to minimize the number of wells (to reduce drilling and hardware/instrumentation cost)
- The desire to have steam and treatment system sizes in practical and economic ranges (to minimize the capital cost of equipment)
- An allowance for contingencies in the actual field performance of each depth interval and the performance of each of the wells

In conclusion, the chosen well separation will allow controlled heating of the five dominant aquifer zones, with steam breakthrough to extraction wells within 180 days after initiating steam injection. Contingencies were built in for poorer performance in some areas of the site.

3.4 ELECTRICAL RESISTANCE HEATING FOCUS

The purpose of ERH in Scenario 1 is to heat and remediate critical regions of the site that have permeabilities that are too low to ensure an effective steam sweep. In scenarios 2 and 3, ERH is extended to the region under Old Mormon Slough, at an elevation of −40 to −120 feet. Angled steam wells from the slough sides would be impractical for targeting these zones.

3.4.1 Electrical Heating Intervals and Areas

Scenario 1

ERH will be used to remediate the D-E aquitard in Scenario 1 because of the low permeability of the aquitard. The D-E aquitard is adjacent to the E-zone aquifer, which is presently used as a drinking water source; this makes immediate remediation of the D-E aquitard more critical than that of the other aquitards at the site. The D-E aquitard is impacted in areas 2, 3, and 4 of the MPA and in areas 2 and 3 of the N-MPA under Old Mormon Slough. The total area of the D-E aquitard impact is 124,000 ft^2 or just under 3 acres.

The D-E aquitard ERH electrodes will be located at the bottom of the boreholes that are used to install the steam injection wells and extraction wells in the D-zone aquifer. The electrodes will be electrically conductive from an elevation of −175 to −210 feet. The electrical current fans out slightly as it flows between the electrodes; this fanning results in strong electrical heating over the interval from about –163 to –222 feet of elevation. Electrical heating extends a few feet up into the D-zone aquifer to improve the steam sweep of its bottom surface. The total volume of D-E aquitard heating will be 271,000 yd^3.

Scenarios 2 and 3

In Scenarios 2 and 3, ERH will be extended into the region below Old Mormon Slough from -40 to −120 feet elevation. In Scenarios 2 and 3, steam will be injected in the C-zone, D-zone, and E-zone aquifers below the slough. However, steam injection shallower than the C-zone aquifer is not practical for several reasons, as detailed in Appendix C:

- Under the slough, the soil level is obviously lower than it is in the uplands. The lower soil level provides less overburden pressure at any given depth. At low levels of overburden pressure, it is possible to liquefy the soil through steam agitation. The risk of soil liquification or steam breakthrough to the surface limits the use of steam injection under the slough to the C-zone aquifer and deeper.

- Angled wells from the shore will be used to inject steam under the slough. At depths shallower than the C-zone aquifer, the drilling angle would become excessive for conventional drilling methods.

- Although vertical steam wells could be installed in the slough, such wells would require thermal insulation to prevent boiling the slough water and mud, with resulting creosote releases. Although thermal insulation could be applied, its use would complicate the installation of the steam injection wells.

Steam injection requires a certain overpressure to force the steam to leave the casing and flow away from the well. ERH generates steam everywhere and there is no significant overpressure at the electrode. However, ERH is also capable of soil liquefaction if it is applied at very shallow depths under the slough. The risk of liquefaction limits the use of ERH to depths greater than a –40 foot elevation, or about 30 feet below the slough mud line.

Electrodes under the slough will be completed with vertical boreholes and will have two separate depth elements to allow independent control of the heating of (1) the B-C aquitard, and (2) the B-zone aquifer and thin A-B aquitard. The electrodes under the slough will also incorporate collocated extraction wells that will target the B-zone aquifer. These extraction wells will have nonconductive fiberglass casings above an elevation of −52 feet to prevent any electrical current flow and resultant heating. Pumps in the electrode extraction wells will have nonconductive hoses.

The total area of ERH treatment under the slough in Scenarios 2 and 3 will be 41,000 ft^2, or just under 1 acre. The total volume of ERH treatment under the slough will be about 122,000 yd^3.

3.4.2 Power Injection Rates

The ERH system is designed to produce a heat-up rate similar to that of the steam injection system. Coordinating the heat-up rates by steam and ERH will heat the site more uniformly and reduce condensation zones that might cause migration of NAPL into cooler regions. The ERH power control system will have sufficient capacity to heat the ERH regions to the boiling temperature of water in 180 days, if operated continuously at full power. In practice, about 365 days are scheduled for heat-up in order to account for ERH downtime for ERT shots and maintenance and to allow a margin of safety in the schedule.

ERH is commonly applied using either three or six phases of electricity. Six-phase heating is wonderfully optimized for the remediation of a small circular area. For other geometric shapes or for large regions, a disadvantage of the six-phase heating method is an inherent non-uniform heating pattern.

Three-phase heating is preferred for the remediation of large and irregularly shaped regions and has been used for all successful ERH remediations beyond the pilot scale.

In Scenario 1, the D-E aquitard ERH power control system will have a capacity of 5,100 kW (17.4 MM BTU/hr). There will be very low heat losses during the heating of the D-E aquitard because the top and bottom of the aquitard will be heated by steam. Only 6 percent of the input energy will be lost via thermal conduction through the sides of the treatment volume. In Scenarios 2 and 3, this D-E aquitard ERH system will be supplemented by a 2,300-kW (7.9 MM BTU/hr) ERH power control system. The heat losses during the treatment of the area under Old Mormon Slough will be about 29 percent of the input energy. Since the slough region is at the remediation boundary, it will be subject to greater thermal conduction losses than a more central region would be. However, it is the aggressive groundwater extraction from under the slough that accounts for the majority of the heat losses; hot water that is pumped from under the slough will be replaced by cool water from the slough itself.

3.4.3 In Situ Steam Generation and NAPL Displacement

The ERH system is very similar to the steam injection system in operation. The in situ steam production rates are equal to the steam injection rates on a per unit volume basis. In a steam injection system, all of the steam is introduced at the injection wells and it sweeps toward the extraction wells. In a classic ERH system, the steam is produced uniformly throughout the target area and then it sweeps toward the extraction wells. In the interest of overall cost savings, the spacing between the ERH electrodes has been increased by a factor of about 2.7 in this remediation (60-foot spacing versus typical 22-foot spacing). As a result, the steam production is no longer completely uniform. About 55 percent of the ERH steam will be produced within 10 feet of the electrodes. Because most of the steam will be produced near the electrodes, the ERH steam flow pattern at the McCormick and Baxter site will resemble that of a steam injection system—from the electrodes to the extraction wells.

Although much of the ERH energy will be deposited near the electrodes, almost half of the energy will be deposited in soils that are farther away. This energy will raise the subsurface temperatures to boiling and drive steam generation in the target soils, regardless of their permeability. In fact, low-permeability sediments tend to be more electrically conductive than sands and thus attract greater current for faster heat-up and stronger boiling.

Steam that is produced in low-permeability sediments will force its way out into the sandier deposits. In doing so, the steam will purge the NAPL out of fractures and thin channels that are typically the most difficult to remediate.

In each case, the power input rates are well within the practical limits of ERH, and no particular difficulty is expected in maintaining the desired heat-up and steam generation rates.

3.5 EXTRACTION APPROACH

3.5.1 Liquid Extraction

Liquid extraction during thermal remediation is crucial, for the following reasons:

- It is mandatory to maintain hydraulic control in order to minimize losses of contaminated fluids to surrounding areas.
- Steam condensate will contain high concentrations of COCs and needs to be recovered.
- NAPL may be extracted directly due to the increased mobility at the elevated temperatures and in the pressure fields induced by pumping. NAPL recovery as a liquid is desirable since the NAPL will contain nonvolatile components as well as the more volatile COCs that may be removed by steam distillation/stripping. As such, liquid NAPL recovery enhances the removal of the heavy PAHs substantially.

During the cool-down phase following thermal remediation, liquid pumping is also desirable for preventing the spread of leftover COCs, and since active cooling of the site is desired, liquid extraction provides the heat-transfer medium (cool water entering, hot water being extracted) needed to accomplish cooling in a timeframe of a few years.

Liquid extraction will be conducted for all depth intervals spanning from the vadose zone to the E-zone (an approximate elevation of 0- to –260 feet). Since the exact location of NAPL and high-concentration COC zones will never be known in sufficient detail to surgically install short extraction wells, it is important to install extraction screen intervals throughout the depth intervals, including the aquitard zones believed to have very low hydraulic conductivity (e.g., the D-E aquitard).

Each extraction well will be equipped with a minimum of one down-hole pump. The needed maximum design extraction rates for these pumps by depth zone are as follows (ranges represent all three treatment scenarios with varying numbers of injection and extraction wells):

Zone A: 2.4 to 3.4 gpm (average 0.6 to 0.8 gpm)
Zone B: 6.4 to 7.2 gpm (average 1.6 to 1.7 gpm)
Zone C: 6.0 to 7.7 gpm (average 1.3 to 2.0 gpm)
Zone D: 8.1 to 10 gpm (average 1.9 to 2.5 gpm)
Zone E: 55 to 72 gpm (average 14 to 18 gpm)

For this calculation, it was assumed that all the extraction wells in a depth zone will extract 150 percent of the total liquid steam injection rate for the injection wells in that zone. For instance, if the total steam injection rate in zone A is 10,000 lbs/hr, equivalent to 20 gpm, the total extraction rate will be at least 1.5 times 20 gpm, or 30 gpm for this zone. If the well-field has a total of 40 extraction wells in the thermal remediation area, the average extraction rate will be 30 divided by 40, or 0.75 gpm.

For zones A, B, C, and D, pneumatic positive displacement pumps rated for 10 to 12 gpm will be acceptable. For the deepest E-zone, much higher pumping rates will be needed. A turbine pump (or equivalent) rated at between 50 and 70 gpm is expected. The design criteria for selecting the pumps are as follows:

- The pumps will allow pumping at the design rates listed above.
- Pumps will minimize emulsification during liquid extraction.
- All materials will be compatible with the elevated temperatures and chemicals. Temperatures in each zone will be as high as:
  - Zone A: 115°C
  - Zone B: 134°C
  - Zone C: 154°C
  - Zone D: 160°C
  - Zone E: 171°C
- The pump dimensions will allow placement in 6-inch-outside-diameter (OD) stainless steel wells.
- NAPL recovery will be optimized by design of the pump intake location. The pump intake will be adjustable depending on whether LNAPL or DNAPL is present in the extraction wells. At present, two extraction pumps per well are included in the design (this is to be tested during the pilot study at Wyckoff-Eagle Harbor Superfund site (USACE 2001b).
- Pumping rates will be adjustable in increments no larger than 10 percent of the maximum pumping rate either by direct setting of the pump speed/frequency or by automated adjustment based on the pressure in the fluid column.

The strategy for liquid extraction and the design around sensitive surface water bodies are discussed in Sections 3.7 (Old Mormon Slough Protection and Remediation), 3.9 (Hydraulic and Pneumatic Control), and 5.4 (Contaminant Extraction).

3.5.2 Vapor Extraction

Vapors will be extracted from all extraction wells located in the thermal treatment zones and in adjacent extraction wells where thermal effects are expected due to outward migration of steam and condensate. The vapor extraction will be facilitated by the connection of a vacuum extraction port on the wellheads. Extracted vapors will include atmospheric air entering the extraction wells from the vadose zone, steam that breaks through to the extraction wells, vaporized contaminants, and inorganic gases (such as nitrogen, carbon dioxide), and the organic gas methane exsolved from the groundwater during thermal treatment and vacuum extraction.

Besides controlling contaminant-laden vapor migration at the site (Section 3.9), the vapor extraction will assist in liquid recovery from wells screened in low-permeability zones by vacuum-enhanced recovery.

Vapor flow rates are difficult to predict in thermal remediation projects due to several factors:

- In the vadose zone, infiltration rates are affected by surface construction and by the design of gravel or vapor caps.
- In deeper zones, the time and magnitude of steam breakthrough are difficult to estimate accurately.
- The flow of injected air is somewhat unpredictable.
- Degradation reactions producing carbon dioxide and methane are difficult to estimate.

In conclusion, the sizing of the vapor extraction system and associated hardware is based on several rough assumptions, which are provided in Section 3.10.

As later shown in Section 5.4, the applied vacuum at each well will be used to control contaminant migration and adverse thermal effects across the site.

3.6 SUBSURFACE MONITORING

The steam front progression and the zones that become heated will be monitored by ERT and by distributed temperature sensing (DTS). ERT generates two-dimensional and three-dimensional images of the subsurface, whereas DTS generates data that can be viewed numerically, with the ERT images, or graphed on temperature distribution maps. Detailed descriptions of these two methods are provided in Appendix D.

Subsurface monitoring has four goals:

- Observing heat-up of the entire site on a large scale, with general site coverage from the surface to the bottom of the treatment zone.
- Monitoring property boundaries to prevent off-site migration of steam and hot water, using a vertical "fence" of monitoring surrounding the thermal treatment zones.
- Monitoring the subsurface beneath the south bank of Old Mormon Slough, thereby ensuring that potential lateral migration of steam is prevented, using a vertical electrode array (VEA) "fence" along the southern side of the slough for detailed monitoring of the A-, A-B-, and B-zones.
- Detecting any initial heat-up of upward steam migration from depth to the slough sediments, with a horizontal ERT plane under the slough.
- Providing data for operational decisionmaking.

Overall, the subsurface ERT and temperature monitoring are intended to prevent adverse impacts on surrounding receptors due to thermal treatment and to optimize remediation by providing guidance for operations.

3.6.1 ERT Monitoring

The VEAs needed for collecting ERT data should be placed in a configuration that maximizes the distance between any two boreholes without losing image resolution. The number of electrodes in the VEAs for each zone, A through E, is also driven by the resolution desired.

Table 3-3 indicates the desired resolution for each of the four goal areas and other suggested design parameters. This table was designed with the idea that the closer the spacing of electrodes, the greater the resolution, but also the greater the sensitivity to changes in resistivity, as affected by temperature. The total number of VEAs is indicated for each of the three scenarios. The VEA layouts proposed for each of the three scenarios are summarized in Figures 3-18 to 3-20. Those VEAs used for monitoring the Site Perimeter are part of the entire site network.

Using these configurations, VEAs would be placed around the perimeter of the steam injectors and extractors. Inside this perimeter, VEAs would be arranged in a network spaced at a set distance from each other to ensure spatial coverage of the entire site. The spaces would be smaller for the shallower boreholes, and larger for the deeper boreholes. The spaces between electrodes would vary for the four different goal areas, smaller where resolution needs to be finer and larger where resolution can be coarser.

Shallower VEAs, especially for zones A and B, would have the benefit of providing better resolution in these shallower areas and would not require drilling deeper than the areas of interest. However, shallower VEAs would require tighter spacing, which would require the emplacement of more boreholes on the site with a consequent increase in the total amount of drilling. In scenario 3 for example, using a 75-foot VEA separation in the CPA, S-CPA and OWPA, where contamination does not extend below −120 feet, would require 54 more VEAs and 3,600 more feet of drilling than the number required for the 180-foot separation layout proposed. With fewer, deeper VEAs, the whole site can be monitored with acceptable resolution and less total drilling than if the holes were shallower, closer together, and more numerous.

The slough ERT resolution is a separate issue, since we are dealing with horizontal ERT planes. The resolution is a compromise between high resolution (by having close electrode separation and many strings of ERT electrodes) and not plowing the entire slough for ERT electrode installation.

The ERT electrodes are typically constructed of 1-foot lengths of stainless steel tubing affixed with a holding screw to a fiberglass rod that provides a rigid structure from the top of the borehole to the bottom depth. The electrodes, spaced at regular intervals along the fiberglass rod, are each electrically connected to the surface with individual Teflon-coated wires that are soldered on and protected with high-temperature silicon and heat shrink tubing. The spaces between electrodes are further protected with heat shrink tubing. Each VEA is lowered into a borehole and grouted into place. From the wellhead, the wires are extended to an on-site measurement trailer for data collection.

ERT data would be collected using an automated system that is housed in the data collection trailer. This system, consisting of a transmitter, receiver, multiplexer, and power supply, would be fully computer controlled. Data collection would be automated for each data plane between two boreholes, or set of data planes. Once data are collected, the data would be transferred to the inversion code for reduction. Finally, the results would be imaged into tomographic cross sections, or three-dimensional images, for interpretation.

3.6.2 Thermal Monitoring

Thermal monitoring would be focused in the following areas:

- Temperature measured in all VEAs and ERT locations
- Temperature in injection and extraction wells

- Temperature in new pump-and-treat extraction wells placed in the A-, B-, and C-zones

- Temperature in new monitoring wells installed to verify hydraulic control and dissolved COC concentrations

- Temperature measured in dedicated boreholes placed in ERT data planes for calibration/verification of actual temperatures

It is suggested that temperature data be collected using DTS instead of arrays of individual thermocouples. DTS is a proven technology in oil field applications, where it has been used in enhanced recovery, in conditions very similar to those encountered in steam remediation (Normann, Weiss, and Krumhansl 2001). It requires less labor to collect data and generates more reliable data quality than is possible using thermocouples alone.

To outfit the site with DTS, a high-temperature plastic-coated fiber optic cable would be attached to the side of a VEA. The fiber would run from the top of the borehole to the bottom, and then it would loop back up to the top. The loop would have a minimum 2.5-inch-diameter turn to enable the optically scattered data to be collected properly. At the surface, the fibers from several wells could be spliced together to form a chain of wells, with the cumulative fiber lengths totaling 5 km, each extending to the measurement trailer. The more boreholes that can be "daisy-chained" together, the better for optimizing channel usage on the DTS data collection system, as one length of 5-km fiber occupies only one channel.

It is important to collect temperature data particularly in any injection or extraction well that lies within ERT planes. These data can be used as independent confirmation of the temperatures inferred by interpretation of the ERT data.

3.6.3 Groundwater COC Monitoring

Groundwater quality is evaluated through analysis of extracted water from hundreds of wells during operation. Therefore, the only dedicated monitoring wells are the once located outside the thermal treatment area, as described in Section 6.8.

3.7 OLD MORMON SLOUGH PROTECTION AND REMEDIATION

Since NAPL is located under Old Mormon Slough and in the adjacent sediments, thermal treatment involves facing the risk of pushing NAPL into the slough with adverse ecological effects. This section describes the options for minimizing the risk of adverse impacts, and the chosen solution.

3.7.1 Dewatering Option

The option of dewatering the slough to prevent adverse effects on the surface water during thermal treatment was rejected due to the excessive cost and difficulty involved. Appendix E provides more details of this evaluation.

3.7.2 Thermal Treatment Under Slough

All three treatment scenarios include treatment of the N-MPA area under Old Mormon Slough (Section 3.1). However, Scenario 1 includes thermal treatment for the two easternmost subareas only (N-MPA 2 and 3) and only the deeper zones below –120 feet of elevation (the C-, D-, and E-zone aquifers and the D-E aquitard). Scenarios 2 and 3 involve treatment below –30 feet of elevation, with extraction above this depth for NAPL recovery. The scenarios are summarized in Table 3-4.

The C-D aquitard is considered too thin to justify electrical heating in any of the scenarios.

The selection of angled drilling for steam injection wells and ERH electrodes for the zones below the B-C aquitard is based on limitations of the angle during drilling. Details and justification are provided in Appendix F.

All scenarios involve thermal treatment along the southern boundary of the slough. The treatment depth intervals along the west-east running boundary vary from −10 to −80 feet in the OWPA and CPA to −260 feet of elevation in the MPA. The three main tasks for protecting the slough are the following:

- Prevent northern migration of steam and NAPL from the thermal treatment zones into the slough sediments and water.
- Prevent upward migration of steam, condensate, and NAPL from the thermal treatment zones located below the slough.
- Minimize or prevent potential mobilization of NAPL resulting from the boiling of water around wells installed directly in the slough.

The design accounts for these potential adverse effects by the following:

- Thermal treatment will not occur in the A-zone aquifer under the slough. Only extraction will be performed in the A-zone aquifer, and a constant downward gradient will be maintained by ensuring that the A-zone wells are pumping during the thermal remediation.

- Steam injection will not be performed immediately south of the slough. Extraction wells will be installed as a row of guard wells as close to the slough as practical after installation of the sediment cap and the associated soil grading and placement of rip-rap, etc.

- For treatment of the shallower zones under the slough (Scenarios 2 and 3), where angled drilling is impractical due to the slope of the boreholes, only electrical heating will be used for heating. This was chosen because electrical heating can be completed through vertical boreholes installed in the slough without substantial heating of the shallow portion of the boreholes. Steam injection wells would potentially lead to heating of the sediments surrounding the wells, and boiling of the sediment pore water could lead to upward spreading of NAPL from the shallow sediments into the surface water.

- Any potential upward migration of NAPL and condensate around the ERH electrodes will be mitigated by designing the ERH boreholes as both extraction wells and electrodes. Therefore, by extracting liquids and vapors from shallow depths around the boreholes, the sediment will remain cool, and preferential migration of NAPL upward along the borehole will be eliminated.

In conclusion, it was determined that thermal treatment adjacent to, and under Old Mormon Slough, is practical with the present design.

3.7.3 Merits of Sediment Cap Installation in Slough Before or After Thermal Treatment

A brief description of the sediment cap is found in (USACE 2000c):

> The selected sediment remedy consists of in situ capping of contaminated Old Mormon Slough sediments in order to isolate areas of principal-threat wastes (approximately three-fourths of the slough) by blanketing them with a minimum of 2 feet of clean fine sand. The cap materials would be armored with rip-rap and gravel filter layer where needed to prevent erosion. The portion of the slough to be capped would run from just north of the oily waste pond (OWP) area to the east end of the slough.

COCs for the sediment capping are PAHs, chiefly low-molecular weight PAHs, and polychlorinated dioxins and furans.

For our evaluation of risks associated with thermal treatment under the slough, it is obvious that the Old Mormon Slough water quality could be compromised in the following cases:

- NAPL migrates into the slough and forms either a sheen, a floating LNAPL layer, or a DNAPL cover on top of the sediment cap. This would carry PAHs and potentially dioxins and heavy metals into the surface water above the sediment cap. If the NAPL spread across the entire slough and settled on top of the cap, the entire cap would be compromised.

- Steam channeling to the slough occurs, and a substantial amount of sediment is released upward to the slough by hydrodynamic forces. This would potentially involve upward migration of sediment-associated COCs such as dioxins, PAHs, and heavy metals. If the sediment settled across the entire slough on top of the cap, the entire cap would be compromised. If the escape and settlement was localized, only a part of the sediment cap would be compromised.

- A substantial amount of water migrates upward into the surface water through the sediment cap, carrying soluble COCs, such as PCP.

- COC diffusion into the slough is encouraged by the thermal remediation operations.

Consequently, the objectives for protecting the slough during thermal treatment are relatively simple:

- Prevent NAPL migration into the slough.

- Prevent steam escape to the slough.

- Prevent heating the sediment cap to temperatures that would lead to NAPL boiling and upward escape.

- Prevent upward hydraulic gradients across the sediment cap that would lead to advection of COC-laden fluids into the slough.

The main argument for installing the sediment cap prior to thermal treatment is that the installation will prevent potential releases at least 5 years earlier than if the cap is placed after thermal treatment, with the increased benefit to the environment.

3.7.4 Monitoring and Safety Features of Design

Adverse impacts on the Old Mormon Slough will be minimized by the actions described in Section 3.7.2. In addition, the following monitoring and contingencies are included in the design:

- A row of monitoring boreholes will be installed along the slough to document the temperatures along the southern boundary of the slough. This will allow near-realtime monitoring in a vertical transect and an opportunity for advance warning if steam or hot water begins to migrate toward the slough. The monitoring will be used to guide nearby steam injection and extraction rates, so adverse effects can be minimized or eliminated (see Figures 3-18, 3-19, and 3-20 for locations).

- A horizontal ERT monitoring grid will be installed under the slough to provide high areal resolution of the monitoring under the slough.

- Boreholes completed in the slough will incorporate extraction wells in the A-zone. Groundwater extraction from the A-zone will provide three benefits:

  - Groundwater extraction will remove heat directly.

  - Groundwater extraction will exert hydraulic control and drive downward water flow from the slough

  - By monitoring the temperature of the extracted groundwater, operators will gain access to high-quality, hydraulic-conductivity-averaged subsurface temperature data. These data can be used to adjust A-zone pumping rates as needed to maintain the desired temperatures under the slough.

- A detailed mass balance will be maintained for the wells adjacent to the slough, ensuring that net extraction is maintained during thermal treatment. This mass balance is based on pumping rate measurements at each wellhead, steam injection rate monitoring, and simple calculations performed routinely as part of the daily data evaluation.

- Temperatures in the A- and B-zones under the slough will be monitored regularly during thermal treatment. Steam injection and electrical heating will be slowed if the temperature of the extracted water, or the temperature measured in the sediments, exceeds well-defined levels (e.g., 50^{o}C in extracted water or at locations 10 feet or less below the mudline, or 30^{o}C at locations 5 feet or less below the mudline).

- If steam or NAPL escapes to the slough, LNAPL will be contained using booms and skimming, and the spread of contaminant-laden sediments will be minimized by aggressive pumping using adjustable submersible pumps, with pump discharge into the effluent treatment system or temporary storage tanks. Any DNAPL that may settle on top of the surface cap will be sucked off the bottom, and fresh sediment cap material will be installed to replace it.

In conclusion, it is recommended that the sediment cap be placed prior to thermal remediation, and that the detailed subsurface monitoring under the slough and along the southern slough boundary be implemented.

3.8 SURFACE CAP

3.8.1 Cap Options

This section presents three options for the shallow soils at the site during thermal treatment and pump-and-treat:

- Leave the surface as is with minor leveling work (no cap option below).
- Install a low-permeability asphalt cap before treatment.
- Install a permeable gravel cap before treatment.

An evaluation matrix used for choosing the best option is provided in Table 3-5.

3.8.2 Recommendations

A surface cap is desirable due to the potential difficulty of heavy traffic during the rainy season. For this reason, as a minimum requirement, a gravel cap is recommended for most of the site prior to drilling activities. Such a cap is likely to function as a base for the final surface cap after thermal treatment and cool-down.

Due to the thick clay and silt layers under the top soils at the site, it is questionable whether a low-permeability asphalt cap will significantly affect the vertical movement of vapors, steam, and COCs. Therefore, the asphalt cap will be installed only in the portion of the CPA (Figure 3-3) that has very volatile NAPL components such as ethers (USACE 2000a). The main purpose of the cap in this area is to capture volatile contaminants during thermal treatment.

The approximate areas covered by the surface caps will be the following:

- The gravel cap will cover approximately 525,000 ft^2.

- The existing asphalt cap in the MPA covers 85,000 ft^2.
- The new low-permeability asphalt cap installed over a portion of the CPA will cover 38,000 ft^2.

The detailed design of the asphalt cap will be provided at a later stage in the design process. A simple asphalt cap with shallow vapor extraction has been assumed for cost estimating purposes.

3.9 HYDRAULIC AND PNEUMATIC CONTROL

A central aspect of the thermal remediation design is the prevention of escape of NAPL, steam, contaminated vapors, and hot condensate to surrounding areas. This is ensured by maintaining hydraulic control via pumping and by maintaining pneumatic control via vacuum extraction.

3.9.1 Net Liquid Extraction From Treatment Volumes

At all times, the cumulative amount of water extracted from the thermal treatment zones will exceed the cumulative amount of water injected as steam and hot water by at least 25 percent. However, since steam occupies a much larger volume than the associated water does in a liquid form, it is not sufficient to rely only on this net extraction across the site. During peak steam injection rates, more than 50 percent over-extraction will be performed, and the subsurface monitoring will be used to verify that the steam zones do not migrate off site. The treatment system will be designed to treat 50 percent more fluids than injected.

Due to the large depth and the presence of multiple aquifers at the McCormick-Baxter site, hydraulic control will be maintained on a depth-specific level. At least three distinct zones will be included in the mass balance calculations:

- The combined A- and B-zone aquifers and the A-B aquitard, where present
- The combined C- and D-zone aquifers and the C-D aquitard, where present
- The deep D-E aquitard and the underlying E-zone aquifer

Where steam or water migration is observed between the distinct depth zones, for instance by upward steam migration through the D-E aquitard into the D-zone aquifer, the mass balances will be corrected based on assumed flow rates and approximate cross-sectional areas of the vertical migration paths. This will be a highly uncertain calculation, and a substantial contingency factor will be added. For instance, if an estimated 10,000 lb/hr of steam migrates upward through the D-E aquitard, the liquid pumping rate in the D-zone aquifer will be increased by no less than the equivalent 20 gpm multiplied by a contingency factor of 2, in this case 40 gpm. The final choice of guidelines will be settled in a more detailed design.

It was assumed that the total net extraction necessary for each of the five aquifer zones can be reasonably estimated by Alternative 4 in the FS report (USEPA 1998), with an additional amount of pumping in each zone due to the potential outward push from the thermal treatment areas.

3.9.2 Vapor Extraction and Pneumatic Control

Vapor extraction will be preformed in all thermal treatment extraction wells and in those wells surrounding the thermal treatment zone for the following purposes:

- To capture contaminant-laden air and steam that can migrate to the wells under an applied vacuum
- To prevent escape of contaminant-laden gases to the atmosphere
- To pull atmospheric oxygen-rich air into the shallow soils in order to stimulate oxidation reactions in the vadose zone during remediation

Complete pneumatic control is not practical unless a surface cap is installed across the entire thermal treatment area. Local heterogeneity prevents a reliable prediction of the radius of influence of shallow vapor extraction points. However, as a measure of maintaining control with the injected air at this site, the total vapor extraction rate will exceed the total air injection rate (from co-injection with steam) at all times.

3.9.3 Mobile NAPL Extraction From Outside Treatment Volumes

The pumping from wells located outside the thermal treatment zone serves two purposes:

- To remove as much mobile NAPL as possible.
- To extract enough water to promote hydraulic control in all areas of the site, and in all depth zones where NAPL exists outside the thermal treatment zones. Hydraulic control would address potential increased mobility of NAPL during thermal remediation and cool-down in the event that heating occurs outside the thermal treatment zones.

For preliminary planning purposes, the placement, number, and pumping rates of supplemental NAPL extraction wells are based on a groundwater model developed by ICF Kaiser for a pump-and-treat scenario (USEPA 1998). Actual extraction well-field parameters (placement, number, and pumping rates of wells) will be refined by additional flow modeling to be completed during design to ensure that supplemental extraction wells do not compete with thermal extraction wells, thereby drawing NAPL outside the thermally treated zones. Operational extraction rates will be influenced locally by the location of heating wells and electrodes, and an evaluation of the potential for outward migration of fluids will be included in a later design stage.

Because it is assumed that all mobile NAPL will be removed under all scenarios in the D- and E-zones, supplemental extraction wells are not necessary for those zones. Zones A through C would have the approximate number of wells and pumping rates shown in Table 3-6 for the three scenarios.

3.10 SIZING STEAM, POWER, AND EFFLUENT TREATMENT SYSTEMS

This section describes the principles used to size the process equipment and the assumptions made in areas where predictions are difficult.

3.10.1 Treatment Volumes and Heat Capacity Calculations

A detailed calculation was made for each depth interval in each of the treatment zones, including the following:

- Heat capacity
- Total steam and power needed to heat the volume to steam temperature, with and without assumed heat losses
- Number of pore volumes of steam needed to heat the volume to steam temperature
- Total fuel demand to heat the volume and to flush a certain number of steam pore volumes or a certain amount of electrical energy through the volume
- The steam and electrical heating demand for each volume, assuming necessary heat-up periods of 90 and 180 days, respectively
- Total steam and electrical power rate demands to inject the necessary amount of steam and power, assuming total thermal treatment times of between 3 and 6 years and the amount of flushing defined as follows (details are discussed in Section 7):
  - Zone A: two pore volumes, 50 percent heat loss at fringes and to surface
  - A-B aquitard: twice the electrical energy needed for heat-up

  - Zone B: two pore volumes, 15 percent heat loss at fringes
  - Zone C: two pore volumes, 10 percent heat loss at fringes
  - Zone D: three pore volumes, 15 percent heat loss at fringes
  - D-E aquitard: twice the electrical energy needed for heat-up of the upper 85 percent of the aquitard, 6 percent heat loss
  - Zone E: four pore volumes, 50 percent heat loss at fringes and downward
- Summed energy demands for steam and electrical heating for each of Scenarios 1, 2, and 3
- Minimum number of injection wells needed in each subvolume and area to meet the goal of delivering the energy during heat-up

Assumptions:

- The total sediment volume is heated. However, the aquitards will not be flushed with as many pore volumes of steam as the aquifers.
- Heat-up of one pore volume of groundwater was included in the energy calculation. In reality, some of the groundwater will be pumped out during heat-up, but this is in part compensated for by continued extraction during thermal treatment, allowing outside cool water to enter the treatment zone.
- Temperatures at depth were set equal to the saturated steam temperature (adjusted for the steam injection pressure, the depth below the surface, and the depth below the water table).
- Density, energy content, and pressure were calculated using standard tabulated values for steam.
- An average porosity of 35 percent.
- Rock heat capacity of 1,000 J/kg/K and water heat capacity of 4,186 J/kg/K.
- Heat of vaporization of 2,230 kJ/kg.
- Steam generator energy efficiency of 85 percent and heat loss in pipes of 5 percent.

- ERH power control system efficiency of 97 percent and energy loss in cables of 2 percent.

The results are provided in Table 3-7.

3.10.2 Well and Electrode Spacing

The criteria for setting the spacing of injection wells is described in Section 3.3. In summary, 60-foot spacing was chosen for the A-, B-, and D-zones; 120-foot spacing was chosen for the C-zone; and 180-foot spacing was determined to be appropriate for the E-zone.

For electrical heating electrodes, the spacing was determined in Section 3.4. It was concluded that a 60-foot separation is preferred. This will allow for collocation of wells and electrodes, reducing the drilling cost.

3.10.3 Steam Injection and Electrical Resistance Heating Rates

The final choice of heat-up period and total duration of thermal treatment is a tradeoff among several factors:

- If you want to treat a site rapidly, the size of steam generators and effluent treatment system can be cost prohibitive. For practical purposes, the largest available steam generators allowing for vapor destruction in their oxidation chambers have capacities of 50 MM BTU/hr, or 50,000 lb/hr. Other practical steam generator sizes are 25, 18, and 12 MM BTU/hr.

- The heating rate is limited by the rate at which one can extract the ambient water and steam condensate in order to maintain hydraulic control during expansion of the steam zones. The necessary pumping rate in each depth zone was calculated based on given steam injection rates and the number of extraction wells located in that zone.

- The heating rate of aquitard layers is limited by the power injection rates that may be achieved using the 60-foot electrode spacing. It was assumed that 365 days can be allowed for heating the aquitard layers electrically, and another 365 days is allowed for injecting an equivalent amount of energy into the layers for in situ steam production and flushing. This is a practical rate for ERH at a site of these dimensions.

The detailed calculations are provided in Table 3-7.

In conclusion, the following heating scenario was chosen as a compromise among all the factors:

- Site heat-up will be accomplished in less than 365 days.
- Aquitards will be steam-flushed within 730 days with an energy amount equivalent to the heat-up energy.
- Steam will be flushed through the aquifers for a period of up to 3 years after initial site heating, or as long as it takes to inject the necessary amount of steam pore volumes in each of the depth zones.

The sizing of the steam and power systems is summarized in Table 3-8. Details of the ERH design are summarized in Table 3-9.

3.10.4 Extraction Rates and Control

The minimum extraction rates necessary to maintain hydraulic control within the thermal treatment areas are estimated as 150 percent of the equivalent steam injection rate. However, as discussed in Section 3.9, this extraction rate is not sufficient across the site. For sizing the effluent treatment system, the following were assumed:

- Extract a minimum of 150 percent of the equivalent injection rates.
- Add the pumping rate necessary for maintaining hydraulic control in areas that are not being treated thermally, estimated based on the FS (USEPA 1998).
- Add a contingency pumping rate for wells located near the property boundary where NAPL presence is expected or suspected based on prior investigations (USACE 2001c).
- Assume that the thermal treatment system will handle a maximum total of 40, 55, and 70 gpm of secondary water used in the process (generator blow-down, filter backwash water, excess seal water from liquid ring pumps, etc.) for Scenarios 1, 2, and 3, respectively.

The total effluent treatment system sizes for each scenario are indicated in Table 3-10.

The total rates were calculated as the injected water rate plus 235 gpm plus the miscellaneous process water usage. This over-extraction was chosen as the best compromise in order to provide hydraulic control on a sitewide basis. It means that the effluent treatment systems will be sized to extract more than 150 percent of the equivalent steam injection rate.

3.11 TREATMENT OF SHALLOW SOILS UNDER ASPHALT CAP IN MPA

During past source removal activities at the site, NAPL-impacted soil was placed in the MPA and capped with asphalt. Under the current cap are three areas with different characteristics:

- The track pit (under the western part of the cap). This area is characterized by the presence of only a thin layer of soil that was placed on top of the old grade and is intact with rails and other metal objects.

- The central section containing basements and large amounts of debris and metal objects. The basements were filled with soil, and more soil was placed on top to form a level surface, currently under asphalt.

- The repository, which is a deeper layer of heavily impacted soil placed on top of a thin plastic membrane, which probably has been compromised by the contact with NAPL. The repository is up to 15 feet deep.

The potential for treating these soils as an integral aspect of the thermal treatment is discussed below.

3.11.1 Properties of Shallow Soils

In the track pit area, the deposited materials consist of a compacted layer 1 to 3 feet in thickness containing a mixture of sands, silts, clays, gravel, and debris. It is assumed that permeability and NAPL content are highly variable. This layer is overlain by 0.5 to 0.9 feet of aggregate, which is in turn overlain by about 0.25 foot of asphaltic concrete (USEPA 1998).

The soils placed in the basements are expected to be similar to the shallow soils.

The soils placed in the repository are heavily NAPL-impacted and believed to have a higher sand content than the average soils since they contain sandy soil excavated from the OWPA. Thermal treatment of the soils in the repository is highly desirable.

3.11.2 Underlying Layers and Potential for Steam Penetration From Depth

Examination of available drilling logs (summarized in crosssections in USACE 2001c) that penetrate the area with the asphalt cap indicates that laterally extensive sand bodies are present at shallow depth beneath the northern and southern margins of the cap. These sand bodies range in thickness up to about 10 feet, pinching out to insignificant thickness along a roughly east-west trending line along the center of the asphalt cap. The near-surface sand bodies underlying the cap are separated from the sand bodies of the main A-zone aquifer by 10 to 20 feet of low-permeability clay or silt. Thus, upward steam migration to the shallow soils from the A-zone injection wells is unlikely to be efficient, except in the area of the deeper repository.

Heating the shallow surface soils by thermal conduction from the underlying sand zones is not likely to be an effective way of treating the shallow soils. The thickness of the clay and silt layers may exceed 25 feet under the asphalt cap, which prohibits sufficiently rapid heating by thermal conduction. Also, due to the heat losses to the surface, it is unlikely that the temperature depth profile will be such that the shallow soils will reach steam temperatures.

This suggests that the likelihood of heating and treating below the asphalt cap using steam injection wells in the A- and B-zone interval is very small, except below the repository. Should the shallow soils require thermal treatment, a special design for heating and extraction will need to be designed.

3.11.3 Design Options for Shallow Thermal Treatment

Steam injection is rejected for heating the shallow soils in the track pit area due to the low expected hydraulic conductivity of the underlying silts and clays.

Electrical heating may be used to heat the target layer to steam temperature, but the recovery of the heated NAPL and COCs will be problematic due to the low soil permeability and the need for shallow extraction wells.

It is concluded that designing a focused thermal treatment for the shallow soils under the asphalt cap is a feasible option only for the repository and the areas with buried basements. Should steam find its way to the shallow soils during injection in the A- and B-zone aquifers, the design as it stands will allow for extraction under the cap and, therefore, a beneficial treatment of those areas.

For the areas with basements, five dual-purpose wells will be used to inject steam and extract fluids. The location of these wells will be determined at a later design stage, based on improved data on the depth and shapes of existing buried basement features. Therefore, the five wells have not been included in the figures.

For the repository, steam injection wells are located along the boundary, and extraction wells are located in a row along the central west-east axis. The extraction well spacing in this area was reduced to 30 feet to optimize recovery from the NAPL-rich soils (Figure 3-3). The wells in contact with the repository soils are expected to be operated similarly to the other wells located in the upper zone. More detail will follow at a later stage in the design.

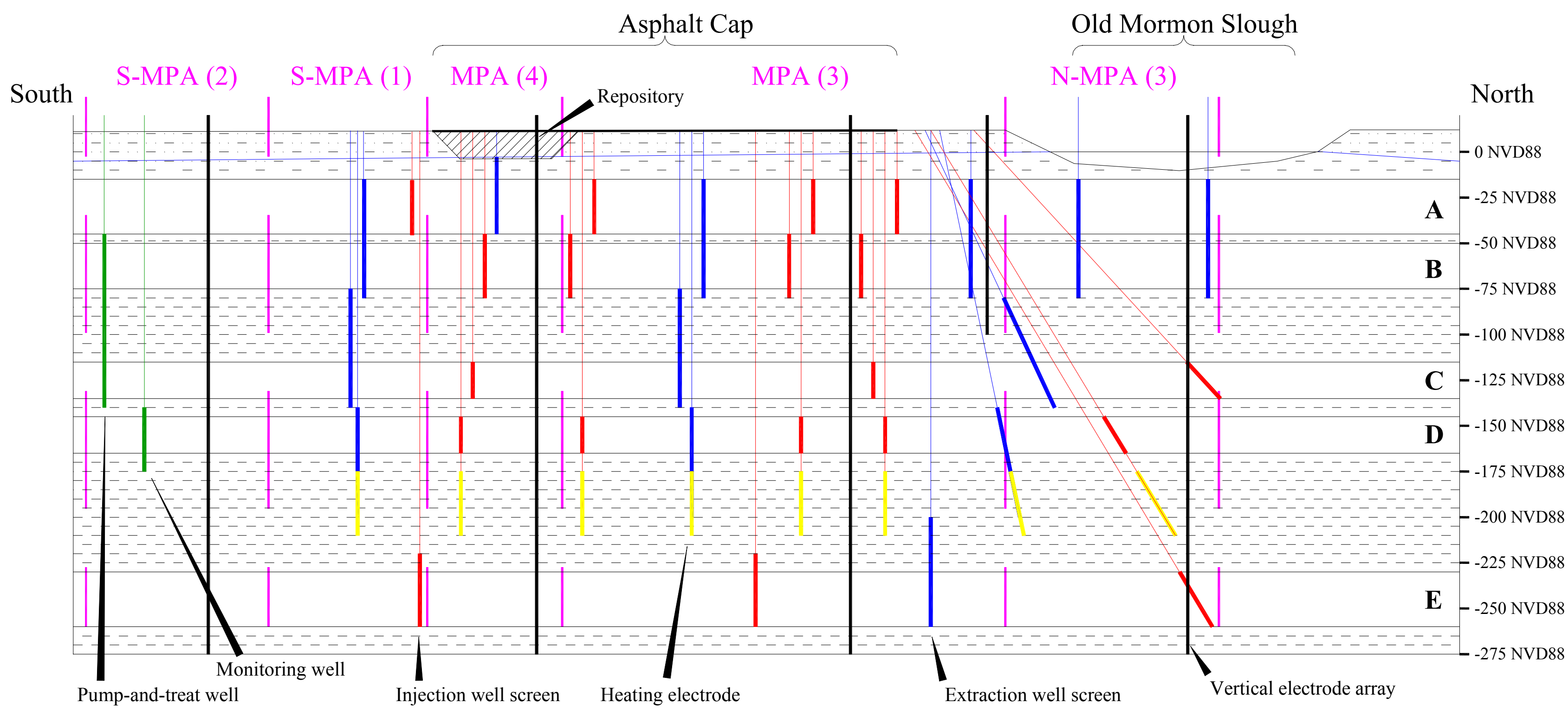


Figure 3-1
Cross Section A-A' Showing Well Layout in Scenario 1

THERMAL TREATMENT TECHNOLOGY CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

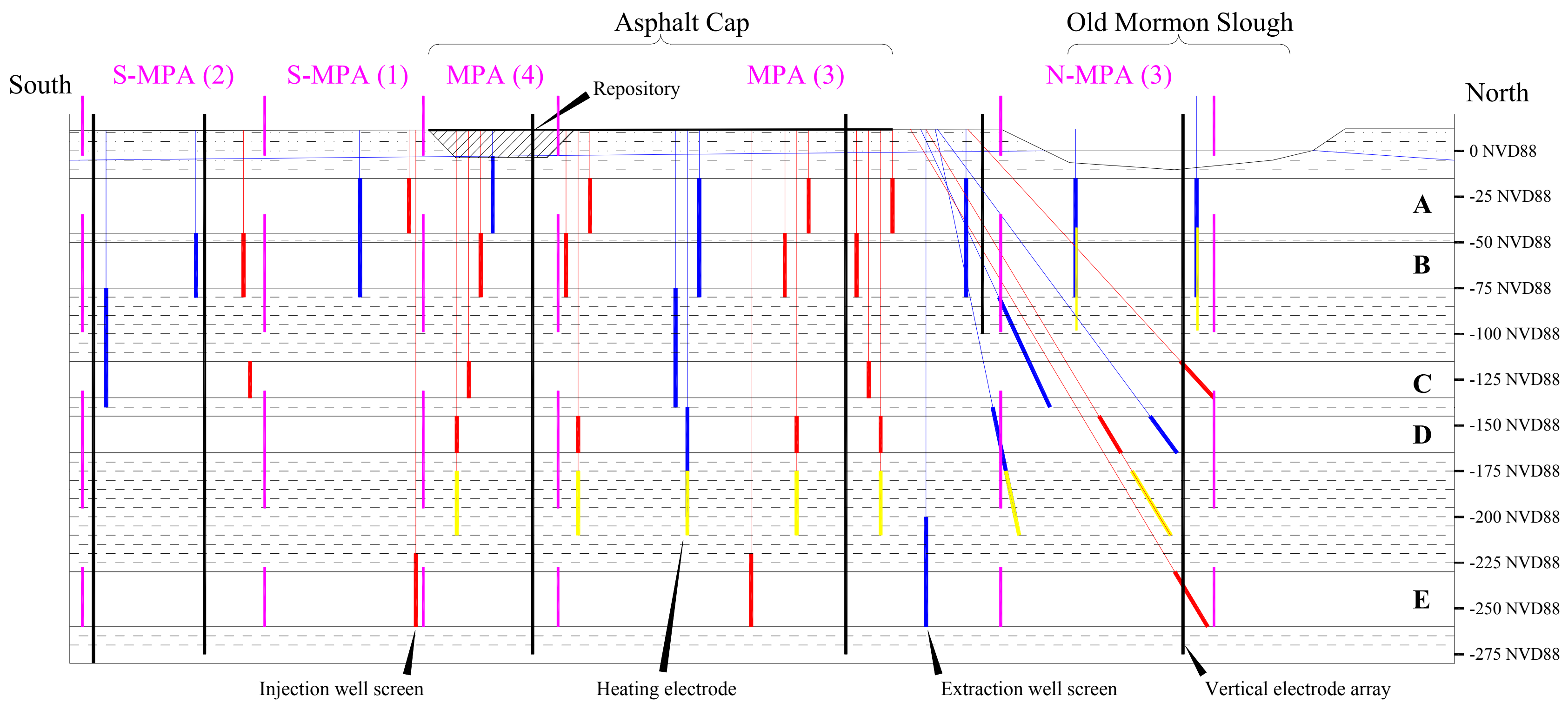


Figure 3-2
Cross Section A-A' Showing Well Layouts in Scenarios 2 and 3

THERMAL TREATMENT TECHNOLOGY
CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

Figure 3-3
Scenario 1: A-Zone Well-Field–53 Injection Wells, 2 Extraction Wells, 55 Total

THERMAL TREATMENT TECHNOLOGY CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

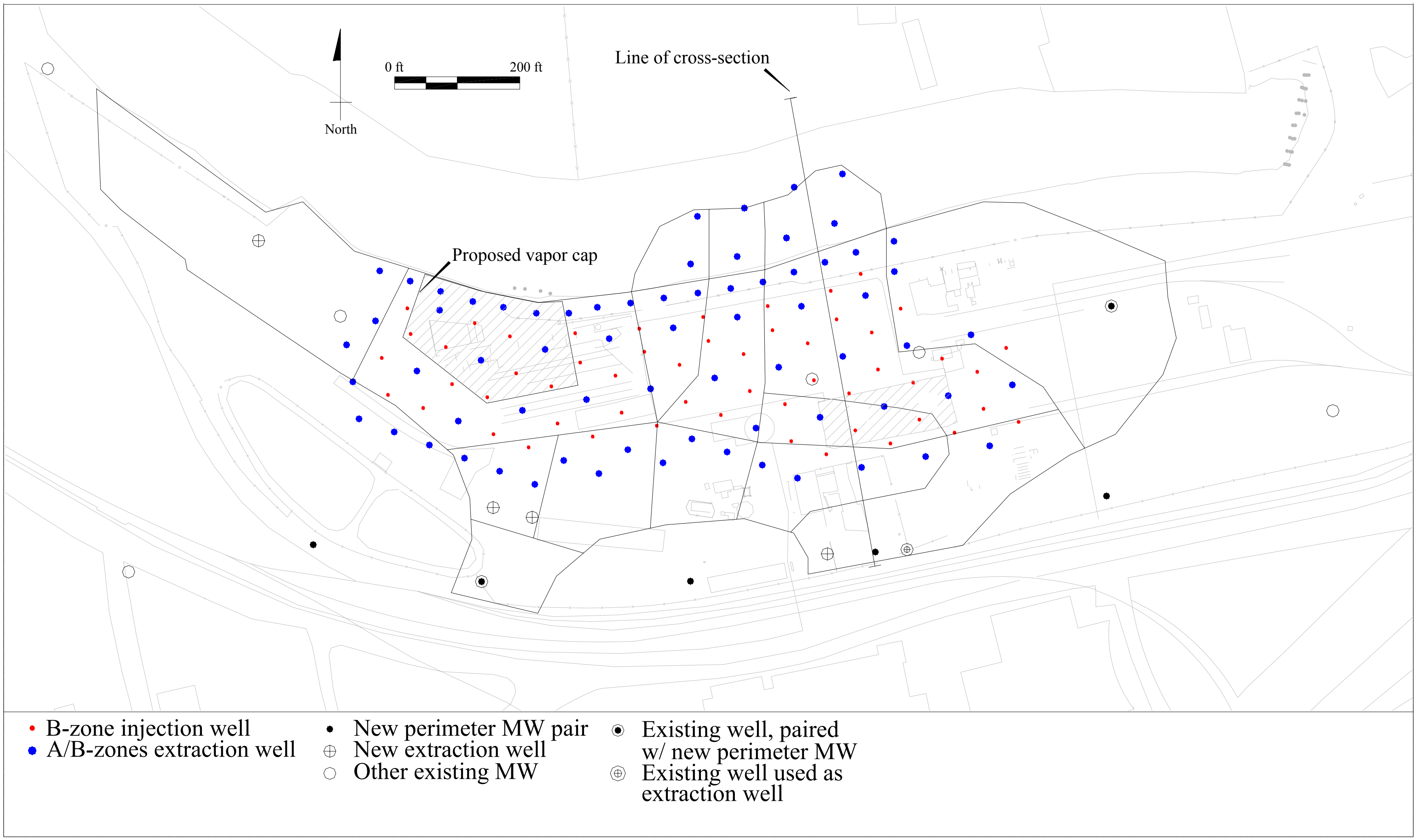


Figure 3-4

Scenario 1: B-Zone Well-Field–54 Injection Wells, 69 A/B Extraction Wells, 123 Total

THERMAL TREATMENT TECHNOLOGY
CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

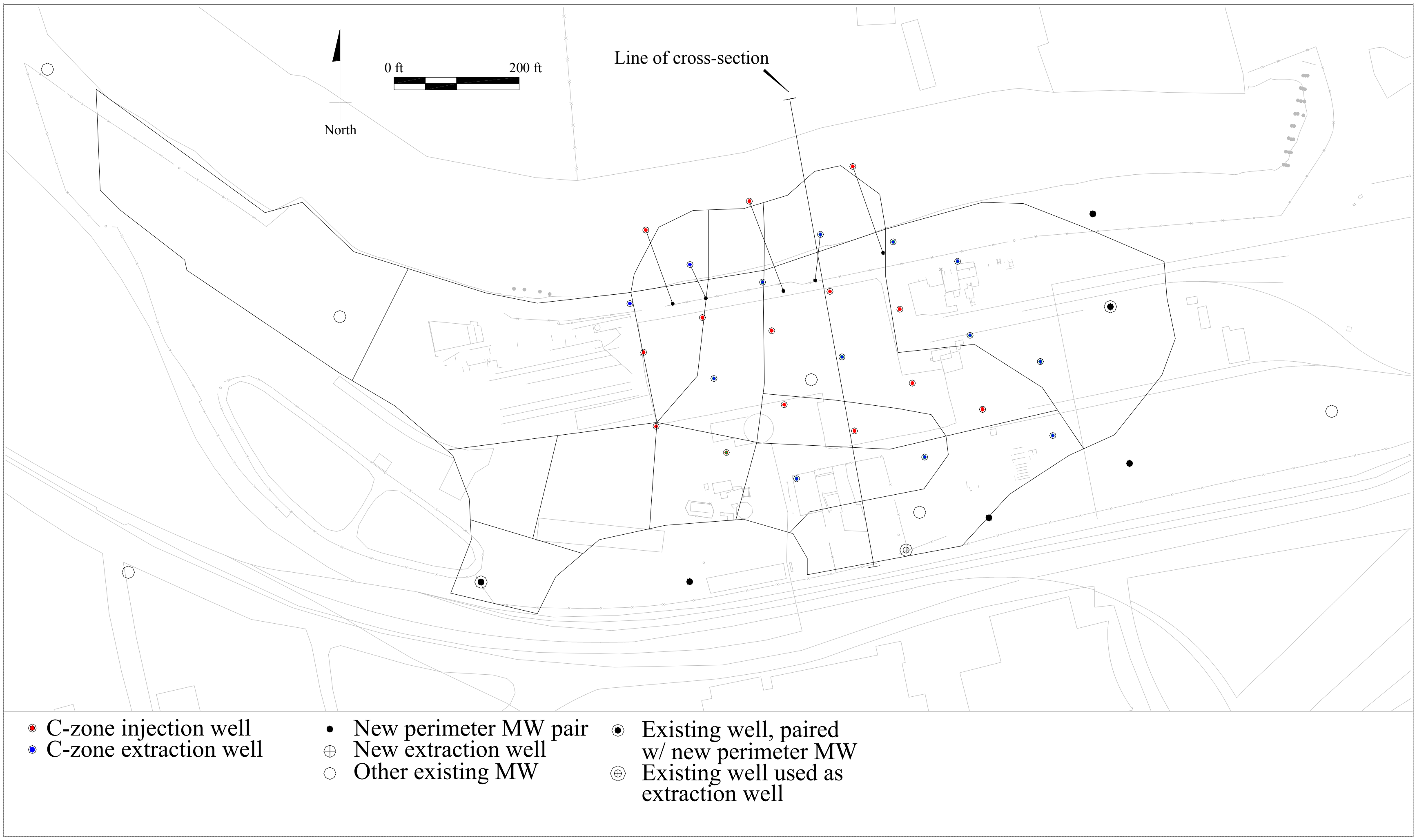


Figure 3-5
Scenario 1: C-Zone Well-Field–13 Injection Wells, 14 Extraction Wells, 27 Total

THERMAL TREATMENT TECHNOLOGY CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

Figure 3-6
Scenario 1: D-Zone Well-Field–35 Injection Wells (32 Collocated With Electrodes), 24 Extraction Wells (13 Collocated With Electrodes, 59 Total

THERMAL TREATMENT TECHNOLOGY CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

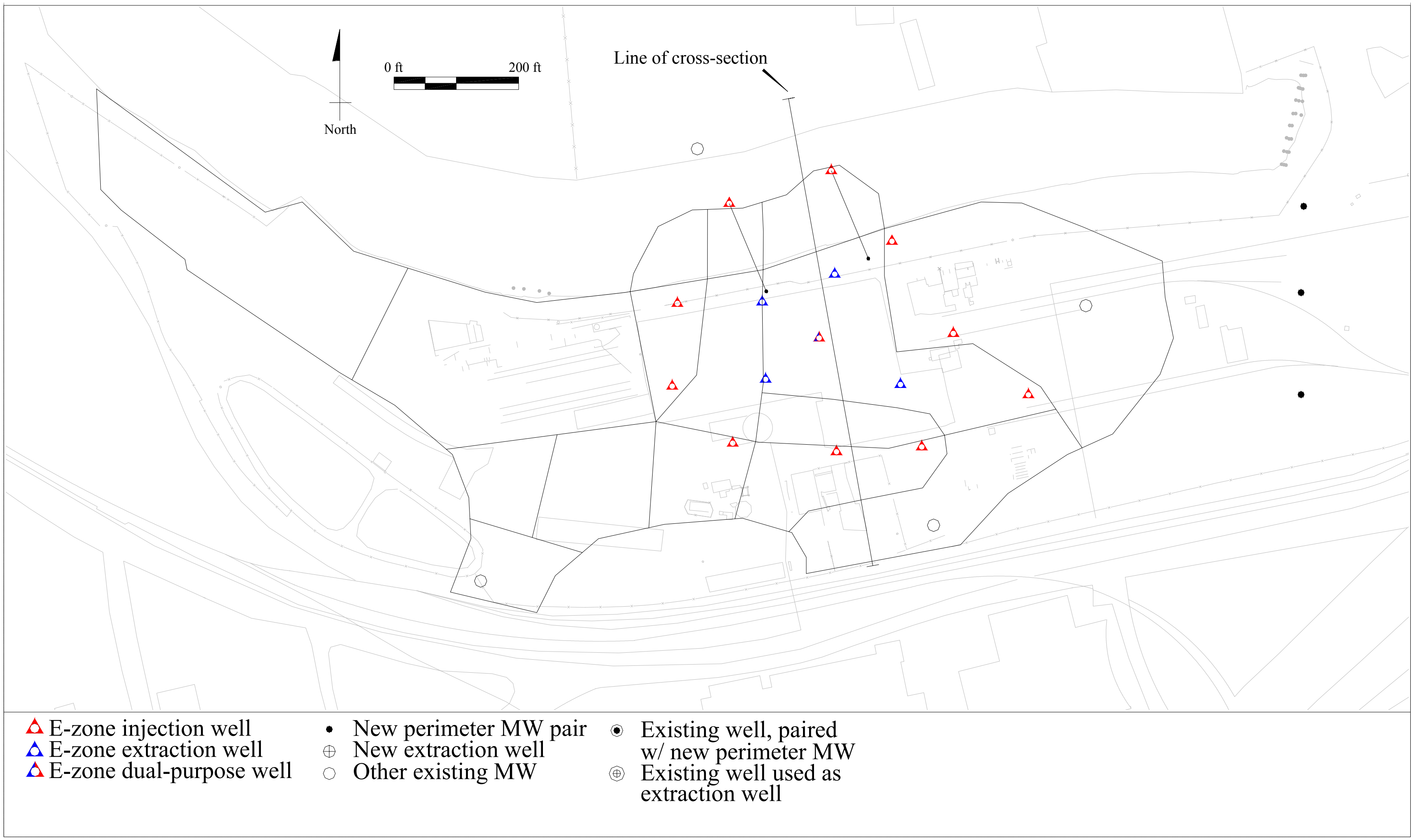


Figure 3-7

Scenario 1: E-Zone Well-Field–10 Injection Wells, 4 Extraction Wells, 1 Dual-Purpose, 15 Total

THERMAL TREATMENT TECHNOLOGY CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

Figure 3-8
Scenario 2: A-Zone Well-Field–57 Injection Wells, 2 Extraction Wells, 59 Total

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McCormick and Baxter Superfund Site
Stockton, California

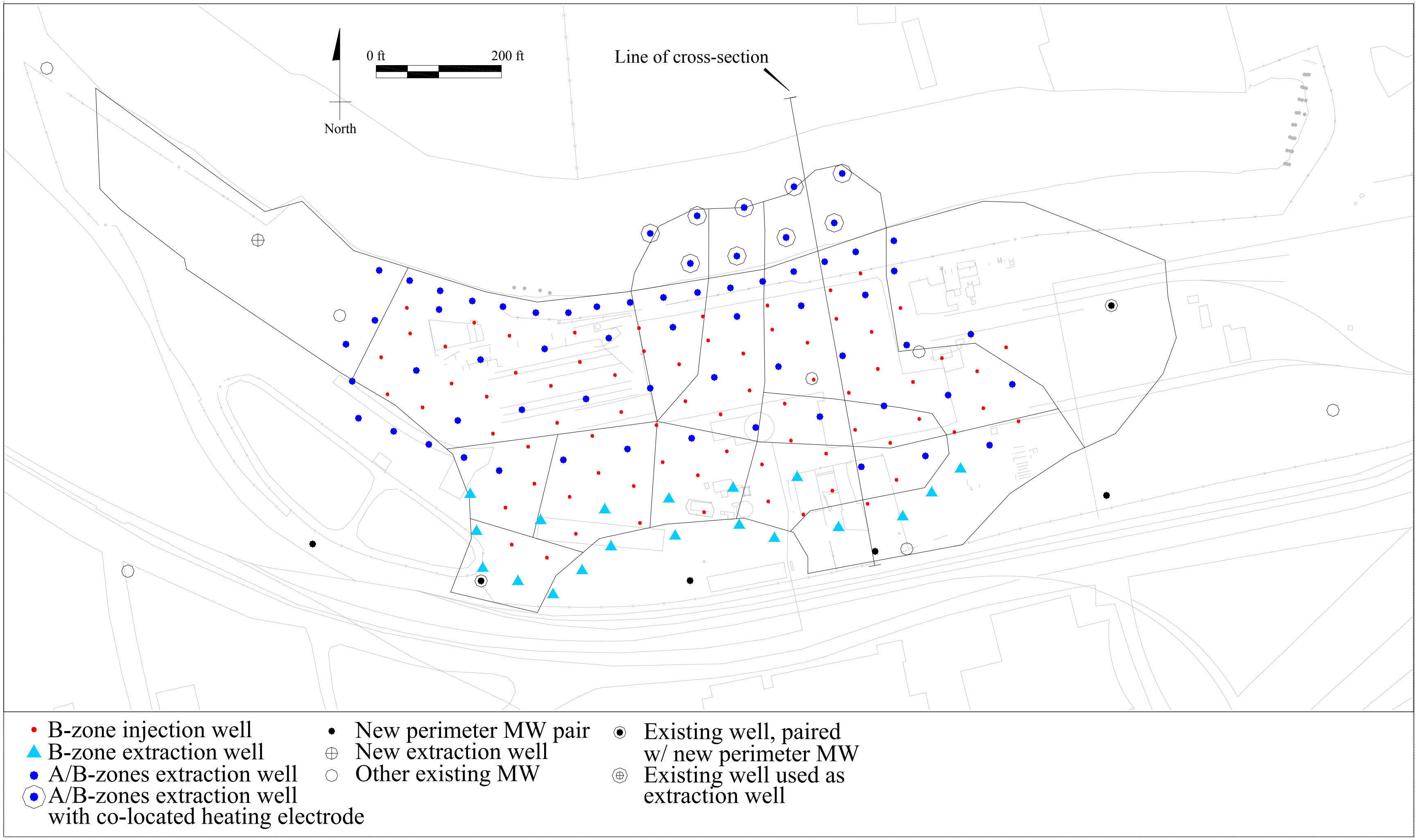

Figure 3-9
Scenario 2: B-Zone Well-Field–73 Injection Wells, 64 A/B Extraction Wells (9 Collocated With Electrodes), 19 B Extraction Wells, 156 Total

THERMAL TREATMENT TECHNOLOGY CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

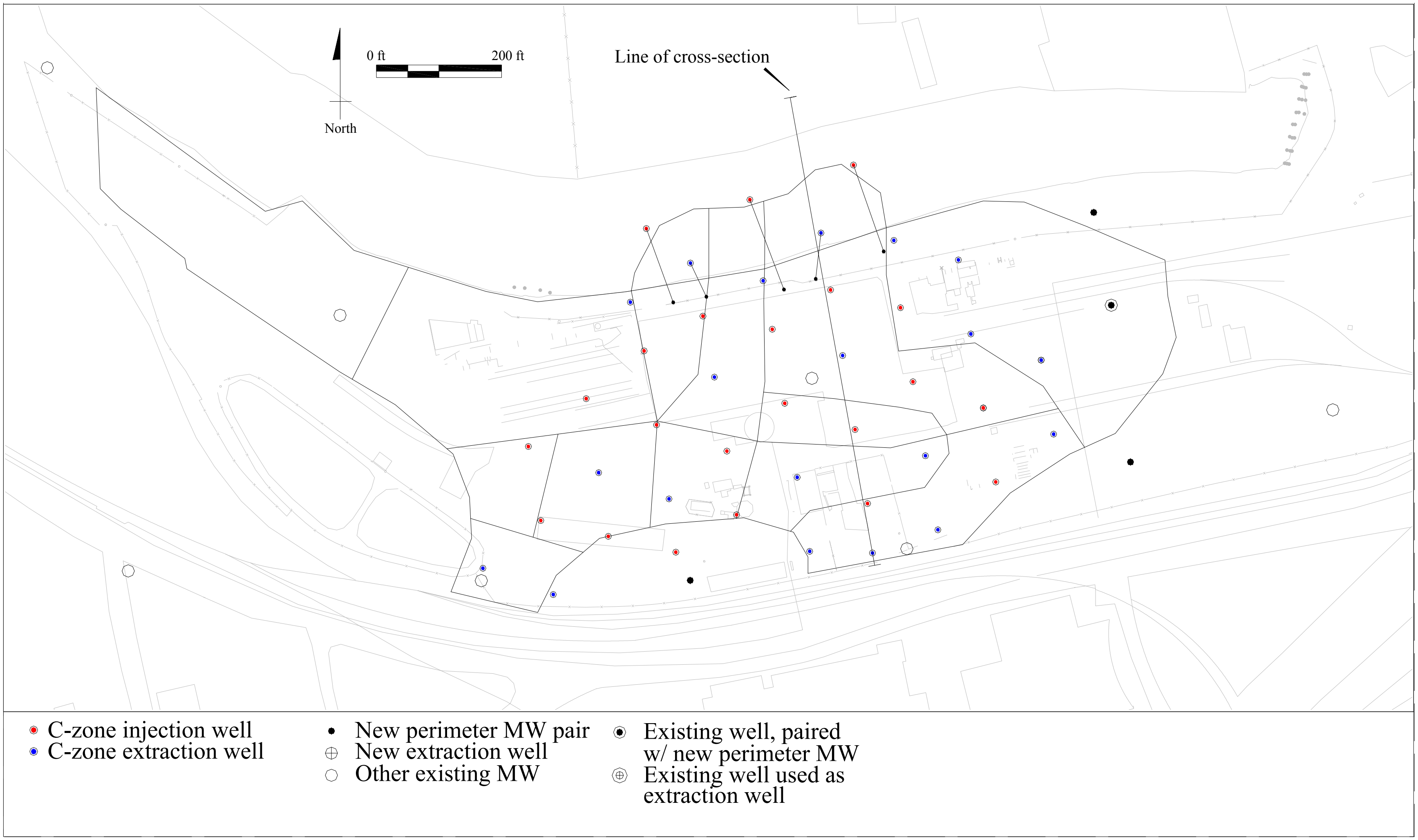

Figure 3-10
Scenario 2: C-Zone Well-Field–22 Injection Wells, 20 Extraction Wells, 42 Total

THERMAL TREATMENT TECHNOLOGY
CONCEPTUAL DESIGN
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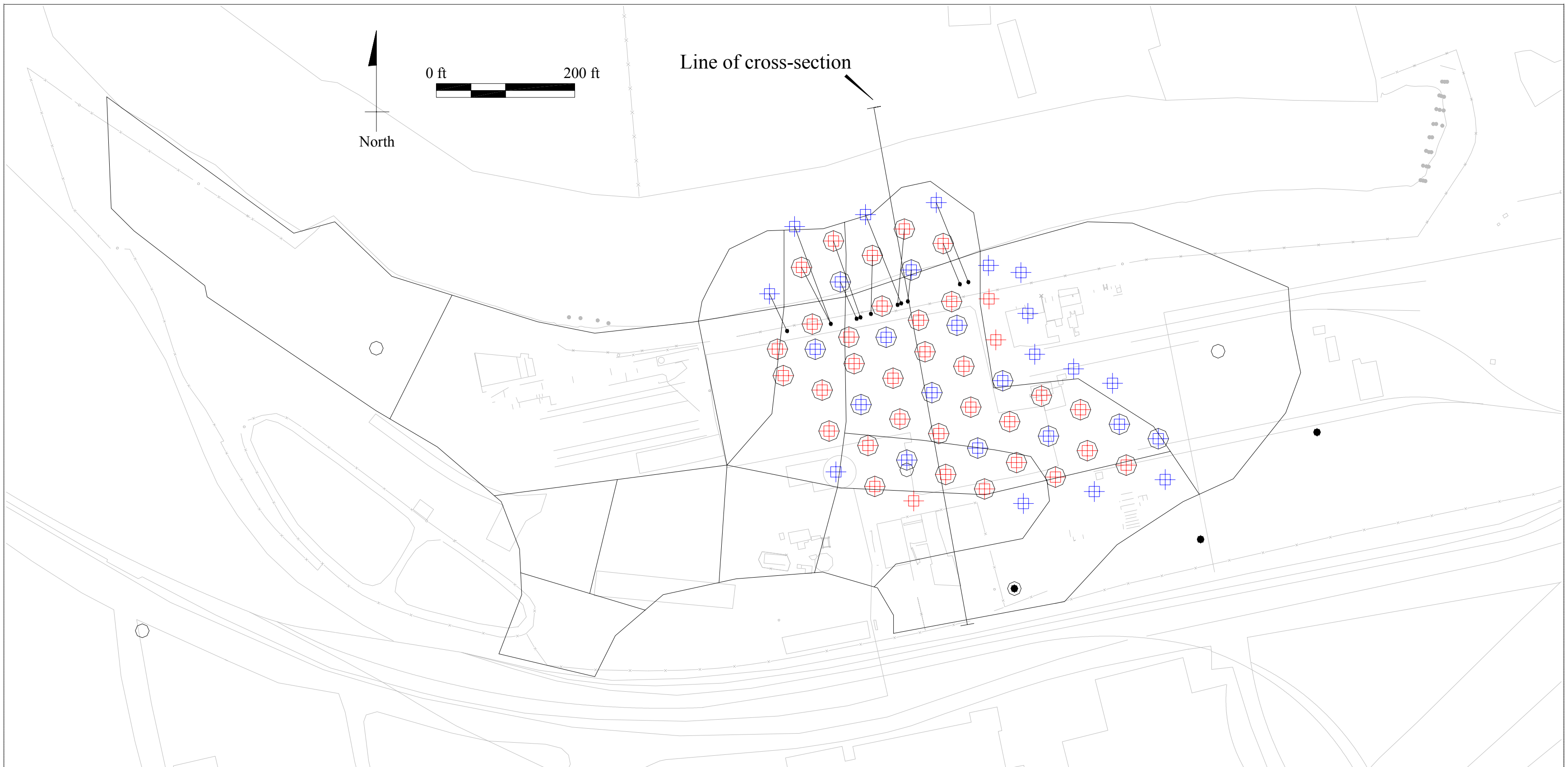

Injection well
Extraction well
Injection well with co-located heating electrode
Extraction well with co-located heating electrode
New perimeter MW pair
New extraction well
Other existing MW
Existing well, paired w/ new perimeter MW
Existing well used as extraction well

Figure 3-11
Scenario 2: D-Zone Well-Field–35 Injection Wells (32 Collocated With Electrodes), 27 Extraction Wells (13 Collocated With Electrodes), 62 Total

THERMAL TREATMENT TECHNOLOGY CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

Figure 3-12
Scenario 2: E-Zone Well-Field–10 Injection Wells, 4 Extraction Wells, 1 Dual-Purpose, 15 Total

THERMAL TREATMENT TECHNOLOGY CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

Figure 3-13
Scenario 3: A-Zone Well-Field–69 Injection Wells, 2 Extraction Wells, 1 Dual-Purpose, 71 Total

THERMAL TREATMENT TECHNOLOGY CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

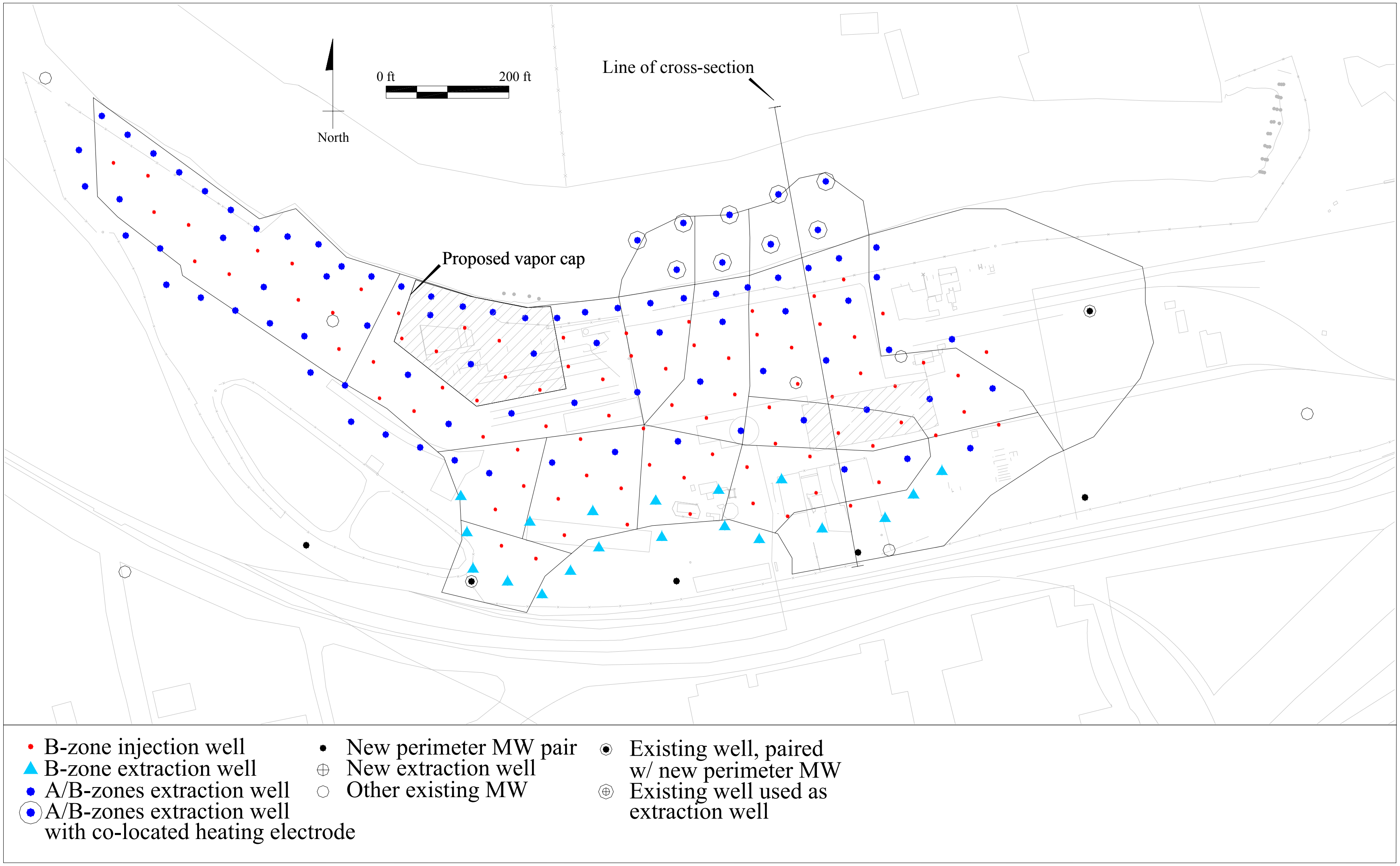

Figure 3-14

Scenario 3: B-Zone Well-Field–85 Injection Wells, 87 A/B Extraction Wells (9 Collocated With Electrodes), 19 B Extraction Wells, 191 Total

THERMAL TREATMENT TECHNOLOGY CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

Figure 3-15
Scenario 3: C-Zone Well-Field–28 Injection Wells, 22 Extraction Wells, 50 Total

THERMAL TREATMENT TECHNOLOGY CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

Figure 3-16
Scenario 3: D-Zone Well-Field–55 Injection Wells (33 Collocated With Electrodes), 29 Extraction Wells (12 Collocated With Electrodes), 84 Total

THERMAL TREATMENT TECHNOLOGY CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

Figure 3-17
Scenario 3: E-Zone Well-Field–12 Injection Wells, 6 Extraction Wells, 2 Dual-Purpose, 20 Total

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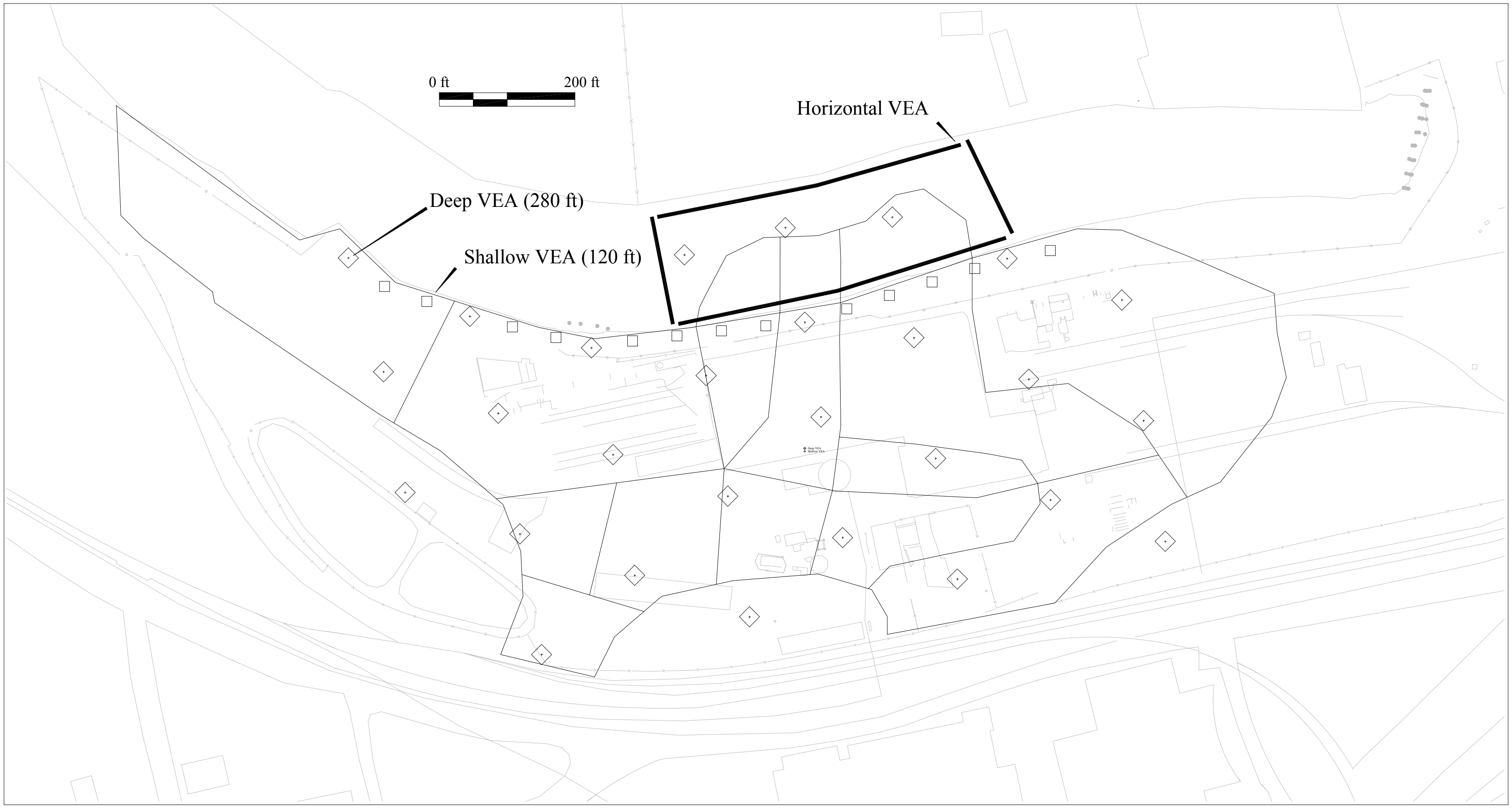

Figure 3-18
Scenario 1: Layout of Vertical Electrode Arrays–28 Deep Holes, 13 Shallow, 4 Horizontal VEAs

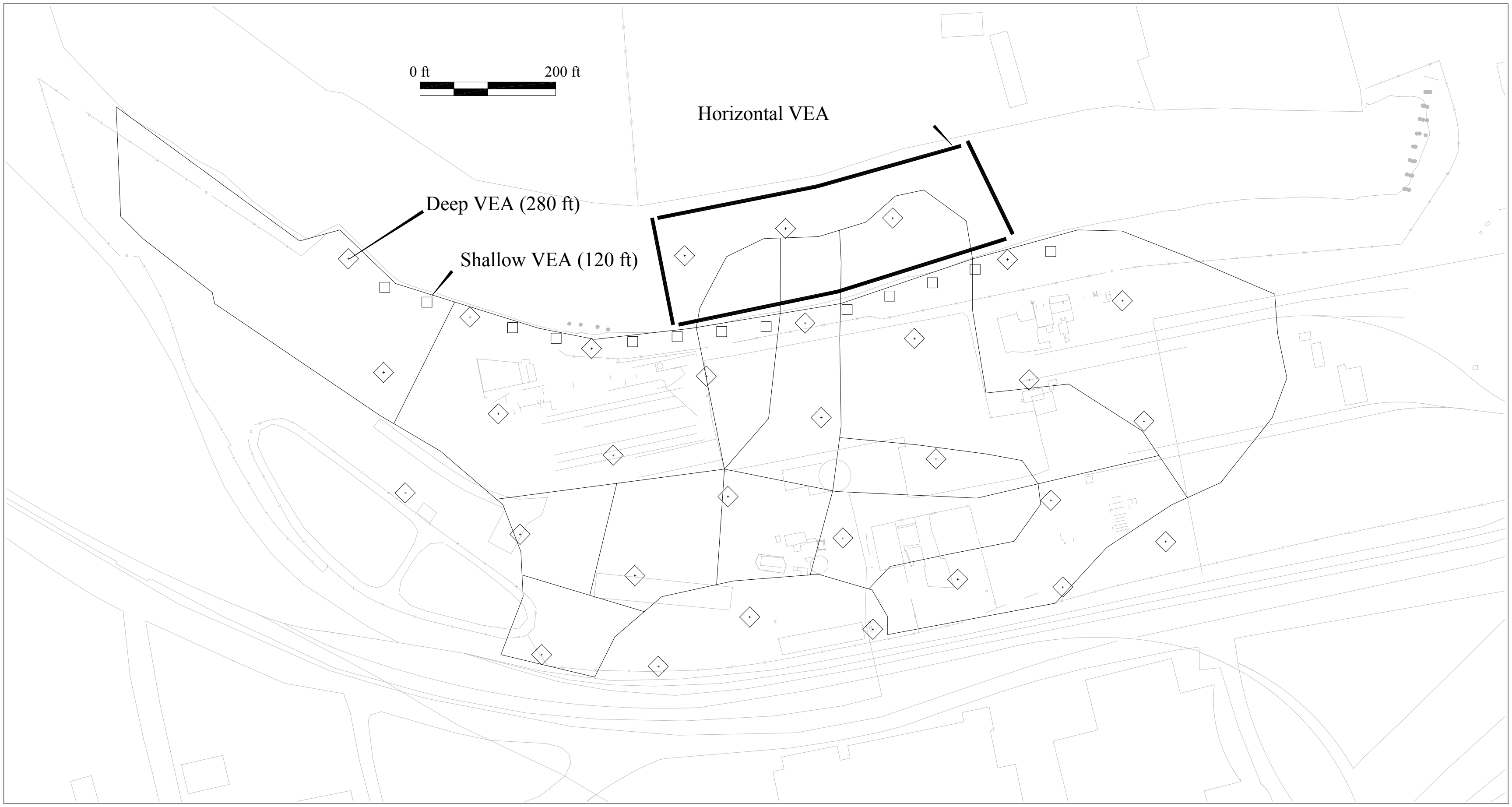

Figure 3-19
Scenario 2: Layout of Vertical Electrode Arrays–31 Deep Holes, 13 Shallow, 4 Horizontal VEAs

THERMAL TREATMENT TECHNOLOGY
CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

Figure 3-20
Scenario 3: Layout of Vertical Electrode Arrays–42 Deep Holes, 21 Shallow Holes, 4 Horizontal VEAs

THERMAL TREATMENT TECHNOLOGY
CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

Table 3-1
Summary of Well Counts by Layer and Scenario

Scenario 1	SES Injection Wells	SES Extraction Wells	SES Dual Purpose Wells	Collocated Injection and Electrical Heating Wells	Collocated Extraction and Electrical Heating Wells	New Perimeter Monitoring Wells	New NAPL Extraction Wells	Deep VEA Hole	Shallow VEA Hole
Completion Zone									
A	53	2	0	0	0	8	5	0	0
B	54	69	0	0	0	10	4	0	13
C	13	14	0	0	0	10	0	0	0
D	3	11	0	32	13	5	0	0	0
E	10	4	1	0	0	6	0	25	0
Scenario 2	**SES Injection Wells**	**SES Extraction Wells**	**SES Dual Purpose Wells**	**Collocated Injection and Electrical Heating Wells**	**Collocated Extraction and Electrical Heating Wells**	**New Perimeter Monitoring Wells**	**New NAPL Extraction Wells**	**Deep VEA Hole**	**Shallow VEA Hole**
Zone of Completion									
A	57	2	0	0	0	8	5	0	0
B	73	74	0	0	9	10	1	0	13
C	22	20	0	0	0	7	0	0	0
D	3	14	0	32	13	5	0	0	0
E	10	4	1	0	0	6	0	27	0
Scenario 3	**SES Injection Wells**	**SES Extraction Wells**	**SES Dual Purpose Wells**	**Collocated Injection and Electrical Heating Wells**	**Collocated Extraction and Electrical Heating Wells**	**New Perimeter Monitoring Wells**	**New NAPL Extraction Wells**	**Deep VEA Hole**	**Shallow VEA Hole**
Zone of Completion									
A	69	2	0	0	0	8	0	0	0
B	85	97	0	0	9	10	0	0	13
C	28	22	0	0	0	8	0	0	0
D	23	16	0	32	13	5	0	0	0
E	12	6	2	0	0	6	0	27	0

Table 3-2
Summary of Steam Injection Rate and Radius of Influence Calculations

				Hydr. Cond.						Steam	K sensitivity range (darcy)		
	Thickness	Top	Bottom	ft/day	darcy	TOS (ft)	Pinj (psig)	Pinj (Pa)	T(K)	zone (ft)*	Min	Avg	Max
A	30	15	45	23	8.1	25	12.5	187,439	388	15	2.7	8.1	24
A-B	5	45	50										
B	25	50	75	40	14.1	60	30	308,035	407	12.5	4.7	14	42
B-C	40	75	115										
C	20	115	135	43	15.2	125	62.5	531,997	427	10	5.1	15	46
C-D	10	135	145										
D	20	145	165	12	4.2	155	77.5	635,365	433	10	1.4	4.2	13
D-E	55	165	220										
E	30	230	260	136	48.0	240	120	928,239	448	15	16	48	144
E	30	230	260	136	48.0	240	107.2	840,000	444	15		48	

Injection rates, 30 days (lbs/hr)			Injection rates, 90 days (lbs/hr)			Injection rates, 180 days (lbs/hr)			Injection rates, 360 days (lbs/hr)		
Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
354	965	2,620	327	898	2,450	313	861	2,357	301	831	2,280
975	2,660	7,346	910	2,490	6,917	873	2,401	6,680	844	2,325	6,486
1,959	5,300	15,004	1,837	4,995	14,200	1,770	4,826	13,750	1,715	4,685	13,373
790	2,162	6,139	737	2,029	5,788	709	1,956	5,592	685	1,895	5,431
20,030	55,800	156,000	18,875	52,800	148,000	18,230	51,100	144,000	17,700	49,700	140,000
	14,160			13,300			12,860			12,480	

RO steam, 30 days (m)			RO steam, 90 days (m)			RO steam, 180 days (m)			RO steam, 360 days (m)		
Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
6.9	11.4	18.7	10.1	16.7	27.5	12.8	21.2	35.0	15.9	26.3	43.5
11.3	18.5	30.7	16.3	27.0	44.8	20.6	34.0	56.6	25.3	41.9	69.8
15.6	25.6	42.9	22.4	36.8	62.0	28.0	46.1	77.6	34.1	56.3	95.0
9.7	16.0	26.9	13.9	23.0	38.7	17.3	28.7	48.7	21.1	35.0	59.2
41.0	68.2	113.9	60.7	101.3	169.5	77.3	129.2	216.0	96.0	160.7	270.0
	34.9			51.7			65.8			81.8	

Well spacing, 90 day breakthru (ft)			Well spacing, 180 day breakthru (ft)			Well spacing, 360 day breakthru (ft)			Max well spacing	Chosen
Min (ft)	Avg (ft)	Max (ft)	Min (ft)	Avg (ft)	Max (ft)	Min (ft)	Avg (ft)	Max (ft)	recommended	spacing
33.1	54.8	90.2	42.0	69.5	114.8	52.1	86.2	142.6	53.4	60
53.4	88.5	146.9	67.5	111.5	185.6	83.0	137.4	228.9	85.7	60
73.4	120.7	203.3	91.8	151.1	254.4	111.8	184.6	311.5	116.2	120
45.6	75.4	126.9	56.7	94.1	159.7	69.2	114.8	194.1	72.3	60
199.0	332.1	555.7	253.4	423.6	708.2	314.8	526.9	885.2	NA	180
	169.5			215.7			268.2		169.5	

Table 3-3
Suggested Design Parameters for Reaching Monitoring Goals

Goal Area	Desired Resolution (ft)	VEA Depth (ft)	Avg. Spacing Between VEAs (ft)	Electrode Spacing (ft)	Number of Electrodes per VEA	Total Number of VEAs
1) Entire Site	5	280	180	20	14	1. 26 2. 31 3. 43
2) Site Perimeter	2.5	280	180	10	28	1. 18 2. 19 3. 26
3) South of Slough	2.5	120	66	5	24	1. 13 2. 13 3. 21
4) Under Slough	10	50 (horizontal plane)	NA	20	66 (total)	NA

Table 3-4
Thermal Treatment Under Old Mormon Slough

	A	AB	B	BC	C	CD	D	DE	E
Scenario 1	Extraction only	Extraction only	Extraction only	Extraction only	Extraction only	Extraction only	Steam, angled	Electrical heating, angled	Steam, angled
Scenario 2	Extraction only	Extraction only	Electrical heating, vertical	Electrical heating, vertical	Steam, angled	Extraction only	Steam, angled	Electrical heating, angled	Steam, angled
Scenario 3	Extraction only	Extraction only	Electrical heating, vertical	Electrical heating, vertical	Steam, angled	Extraction only	Steam, angled	Electrical heating, angled	Steam, angled

Note: All injection and electrical heating zones will have liquid and vapor extraction as well.

Table 3-5
Evaluation Matrix for Considerations Regarding Surface Cap

Option	Advantages	Disadvantages	Evaluation
No cap	Least expensive option. Allows air infiltration which will fuel degradation reactions. Allows for visual inspection of surface and direct temperature measurement by hand-held probes or IR camera.	Air infiltration will be heterogeneous and not controllable. Heavy vehicle traffic may be difficult after precipitation. No surface fugitive emissions control. No control of surface steam escape.	Acceptable with detailed near-surface monitoring of temperatures and some contingency for steam and vapor escape control, and establishment of heavy vehicle traffic routes.
Low permeability asphalt cap	Controlled air infiltration to fuel degradation reactions. Allows higher vacuum applied in vadose zone and improves shallow soil remediation. Allows heavy vehicle traffic. Can be sloped for drainage. Controls surface fugitive emissions. Some control of surface steam escape. Public perception: Safer.	High capital cost. Need air infiltration ports with controls. Need draining and vapor collection system. Design may not be identical to the final remedy cap. Importance is questionable in areas with a competent clay/silt layer already blocking horizontal vapor flow.	Desirable in areas with shallow volatile NAPL, such as a section of the CPA. Already in place in large parts of MPA, including the locations where shallow NAPL-impacted soil is present.
Gravel cap	Allows air infiltration which will fuel degradation reactions. Provides better surface for heavy vehicle traffic. A gravel cap is likely to be suited as the base for a permanent, final cap which will be the remedy for shallow soils.	Air infiltration will be heterogeneous and not controllable. No surface fugitive emissions control. No control of surface steam escape.	Desirable for ease of heavy traffic.

Table 3-6
Supplemental Mobile NAPL Extraction Wells

	A-Zone		B-Zone		C-Zone	
	No. Wells	Avg Q	No. Wells	Avg Q	No. Wells	Avg Q
Scenario 1	6	4	5	4	1	1
Scenario 2	6	4	1	10	0	—
Scenario 3	0	—	0	—	0	—

Note: Q is extraction rate in gallons per minute, derived from results of Scenario 4 of USEPA (1998) groundwater model.

Table 3-7
Steam Injection and Electrical Heating Rate Calculations

	A	B	C	D	E	F	G	H	I	J	K
2			**MPA**								
3	**Calculation of steam density**		A	AB	B	BC	C	CD	D	DE	E
4	Thickness of aquifer	ft	30	5	25	40	20	10	20	65	30
5	Inj P	Pa	187439	187440	308035	308035	531997	531997	635365	635365	840000
6	Inj T	K	391	391	407	407	427	427	433	433	444
7		C	118.2	118.2	134.2	134.2	153.4	153.4	160.0	160.0	170.8
8		F	244.7	244.7	273.5	273.5	308.0	308.0	320.0	320.0	339.5
9	Steam density	kg/m^3	1.062	1.062	1.677	1.677	2.766	2.766	3.253	3.253	4.196
10	Steam energy content	kJ/m^3	2369	2369	3740	3740	6169	6169	7254	7254	9356
11	Area	ft^2	120,361	139,759	139,759	139,759	139,759	120,361	120,361	93,645	93,645
12	Volume	ft^3	3,610,830	698,795	3,493,975	5,590,360	2,795,180	1,203,610	2,407,220	6,086,925	2,809,350
13	Cleanup volume	yd^3	133,734	25,881	129,406	207,050	103,525	44,578	89,156	225,442	104,050
15	T ambient	°C	22	22	22	22	22	22	22	22	22
16	T final	°C	118	118	134	134	153	153	160	160	171
17	Rock heat capacity	J/(kg K)	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
18	Water heat capacity	J/(kg K)	4,186	4,186	4,186	4,186	4,186	4,186	4,186	4,186	4,186
19	Porosity	(-)	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
20	Mineral density	kg/L	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65
31											
32	**Calculation of steam need for heatup**										
33	per m3	kg/m^3	137	137	160	160	188	188	197	197	213
34	pv water	pv water	0.39	0.39	0.46	0.46	0.54	0.54	0.56	0.56	0.61
35	pv steam	pv as steam	370	370	273	273	194	194	173	173	145
36	Whole site	kg steam	1.4E+07	2.8E+06	1.6E+07	2.6E+07	1.5E+07	6.5E+06	1.3E+07	3.4E+07	1.7E+07
37	Whole site	kJ	3.1E+10	6.1E+09	3.5E+10	5.7E+10	3.3E+10	1.4E+10	3.0E+10	7.7E+10	3.8E+10
38	Whole site	BTU	2.98E+10	5.82E+09	3.36E+10	5.43E+10	3.15E+10	1.37E+10	2.85E+10	7.27E+10	3.58E+10
39											
40	**Site size and heatup rates / steam demand**										
45	Energy demand, no loss	kJ	3.14E+10	6.08E+09	3.54E+10	5.67E+10	3.32E+10	1.43E+10	3.00E+10	7.60E+10	3.78E+10
46	Energy demand, no loss	BTU	2.98E+10	5.76E+09	3.36E+10	5.37E+10	3.15E+10	1.36E+10	2.85E+10	7.20E+10	3.58E+10
47	Estimated heat loss %	%	50	0	15	0	10	0	15	0	50
48	Heatup pv needed	pv as water	0.39	0.39	0.46	0.46	0.54	0.54	0.56	0.56	0.61
49	Total pv designed	pv as water	2.00	0.79	2.00	0.92	2.00	1.07	3.00	0.56	4.00
50	Boiler efficiency		0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
51	Delivery efficiency		0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
52	Total BTU need w/losses	BTU	3.75E+11	1.43E+10	2.14E+11	1.33E+11	1.61E+11	3.36E+10	2.21E+11	8.92E+10	5.84E+11
53	Total BTU need, flushing, no loss	BTU	1.52E+11	1.15E+10	1.47E+11	1.07E+11	1.17E+11	2.71E+10	1.52E+11	7.20E+10	2.36E+11
54	Total BTU need no losses	BTU	2.98E+10	5.76E+09	3.36E+10	5.37E+10	3.15E+10	1.36E+10	2.85E+10	7.20E+10	3.58E+10
55											
70	Steam demand, 180 d heatup	MM BTU/hr	7	1	8	12	7	3	7	17	8
71	Steam demand, 4 yrs operation	MM BTU/hr	11	0	6	4	5	1	6	3	17

Table 3-7 (Continued)
Steam Injection and Electrical Heating Rate Calculation

	L	M	N	O	P	Q	R	S	T	U	V	W
2	CPA			N-MPA								
3	A	AB	B	A	AB	B	BC	C	CD	D	DE	E
4	35	5	35	30	5	25	40	20	10	20	65	30
5	187439	187440	308035	187439	187440	308035	308035	531997	531997	635365	635365	840000
6	391	391	407	391	391	407	407	427	427	433	433	444
7	118.2	118.2	134.2	118.2	118.2	134.2	134.2	153.4	153.4	160.0	160.0	170.8
8	244.7	244.7	273.5	244.7	244.7	273.5	273.5	308.0	308.0	320.0	320.0	339.5
9	1.062	1.062	1.677	1.062	1.062	1.677	1.677	2.766	2.766	3.253	3.253	4.196
10	2369	2369	3740	2369	2369	3740	3740	6169	6169	7254	7254	9356
11	97,739	97,739	97,739	41,263	41,263	41,263	41,263	41,263	30,166	30,166	20,628	20,628
12	3,420,865	488,695	3,420,865	1,237,890	206,315	1,031,575	1,650,520	825,260	301,660	603,320	1,340,820	618,840
13	126,699	18,100	126,699	45,848	7,641	38,206	61,130	30,565	11,173	22,345	49,660	22,920
15	22	22	22	22	22	22	22	22	22	22	22	22
16	118	118	134	118	118	134	134	153	153	160	160	171
17	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
18	4,186	4,186	4,186	4,186	4,186	4,186	4,186	4,186	4,186	4,186	4,186	4,186
19	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
20	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65
31												
32												
33	137	137	160	137	137	160	160	188	188	197	197	213
34	0.39	0.39	0.46	0.39	0.39	0.46	0.46	0.54	0.54	0.56	0.56	0.61
35	370	370	273	370	370	273	273	194	194	173	173	145
36	1.3E+07	1.9E+06	1.6E+07	4.8E+06	8.1E+05	4.7E+06	7.6E+06	4.4E+06	1.6E+06	3.4E+06	7.6E+06	3.7E+06
37	3.0E+10	4.3E+09	3.5E+10	1.1E+10	1.8E+09	1.0E+10	1.7E+10	9.8E+09	3.6E+09	7.5E+09	1.7E+10	8.3E+09
38	2.82E+10	4.07E+09	3.29E+10	1.02E+10	1.72E+09	9.92E+09	1.60E+10	9.29E+09	3.43E+09	7.14E+09	1.60E+10	7.90E+09
39												
40												
45	2.97E+10	4.25E+09	3.47E+10	1.08E+10	1.79E+09	1.05E+10	1.67E+10	9.80E+09	3.58E+09	7.53E+09	1.67E+10	8.33E+09
46	2.82E+10	4.03E+09	3.29E+10	1.02E+10	1.70E+09	9.92E+09	1.59E+10	9.29E+09	3.40E+09	7.14E+09	1.59E+10	7.90E+09
47	50	0	15	50	0	15	0	10	0	15	0	50
48	0.39	0.39	0.46	0.39	0.39	0.46	0.46	0.54	0.54	0.56	0.56	0.61
49	2.00	0.79	2.00	2.00	0.79	2.00	0.92	2.00	1.07	3.00	0.56	4.00
50	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
51	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
52	3.56E+11	9.98E+09	2.09E+11	1.29E+11	4.21E+09	6.31E+10	3.93E+10	4.77E+10	8.41E+09	5.53E+10	1.96E+10	1.29E+11
53	1.44E+11	8.06E+09	1.44E+11	5.20E+10	3.40E+09	4.33E+10	3.17E+10	3.46E+10	6.79E+09	3.80E+10	1.59E+10	5.20E+10
54	2.82E+10	4.03E+09	3.29E+10	1.02E+10	1.70E+09	9.92E+09	1.59E+10	9.29E+09	3.40E+09	7.14E+09	1.59E+10	7.90E+09
55												
70	7	1	8	2	0	2	4	2	1	2	4	2
71	10	0	6	4	0	2	1	1	0	2	1	4

Table 3-7 (Continued)
Steam Injection and Electrical Heating Rate Calculations

	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ
2	**S-MPA**			**S-CPA**					**E-MPA**				
3	B	BC	C	A	AB	B	BC	C	C	CD	D	DE	E
4	25	40	20	30	5	25	40	20	20	10	20	65	30
5	308035	308035	531997	187439	187440	308035	308035	531997	531997	531997	635365	635365	840000
6	407	407	427	391	391	407	407	427	427	427	433	433	444
7	134.2	134.2	153.4	118.2	118.2	134.2	134.2	153.4	153.4	153.4	160.0	160.0	170.8
8	273.5	273.5	308.0	244.7	244.7	273.5	273.5	308.0	308.0	308.0	320.0	320.0	339.5
9	1.677	1.677	2.766	1.062	1.062	1.677	1.677	2.766	2.766	2.766	3.253	3.253	4.196
10	3740	3740	6169	2369	2369	3740	3740	6169	6169	6169	7254	7254	9356
11	80,481	80,481	80,481	21,853	40,233	88,851	70,471	70,471	115,068	115,068	115,068	115,068	115,068
12	2,012,025	3,219,240	1,609,620	655,590	201,165	2,221,275	2,818,840	1,409,420	2,301,360	1,150,680	2,301,360	7,479,420	3,452,040
13	74,519	119,231	59,616	24,281	7,451	82,269	104,401	52,201	85,236	42,618	85,236	277,016	127,853
15	22	22	22	22	22	22	22	22	22	22	22	22	22
16	134	134	153	118	118	134	134	153	153	153	160	160	171
17	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
18	4,186	4,186	4,186	4,186	4,186	4,186	4,186	4,186	4,186	4,186	4,186	4,186	4,186
19	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
20	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65
31													
32													
33	160	160	188	137	137	160	160	188	188	188	197	197	213
34	0.46	0.46	0.54	0.39	0.39	0.46	0.46	0.54	0.54	0.54	0.56	0.56	0.61
35	273	273	194	370	370	273	273	194	194	194	173	173	145
36	9.2E+06	1.5E+07	8.6E+06	2.6E+06	7.9E+05	1.0E+07	1.3E+07	7.5E+06	1.2E+07	6.2E+06	1.3E+07	4.2E+07	2.1E+07
37	2.0E+10	3.3E+10	1.9E+10	5.7E+09	1.8E+09	2.3E+10	2.9E+10	1.7E+10	2.7E+10	1.4E+10	2.9E+10	9.4E+10	4.6E+10
38	1.93E+10	3.13E+10	1.81E+10	5.40E+09	1.67E+09	2.14E+10	2.74E+10	1.59E+10	2.59E+10	1.31E+10	2.72E+10	8.94E+10	4.40E+10
39													
40													
45	2.04E+10	3.27E+10	1.91E+10	5.70E+09	1.75E+09	2.25E+10	2.86E+10	1.67E+10	2.73E+10	1.37E+10	2.87E+10	9.33E+10	4.65E+10
46	1.93E+10	3.10E+10	1.81E+10	5.40E+09	1.66E+09	2.14E+10	2.71E+10	1.59E+10	2.59E+10	1.30E+10	2.72E+10	8.85E+10	4.40E+10
47	15	0	10	50	0	15	0	10	10	0	15	0	50
48	0.46	0.46	0.54	0.39	0.39	0.46	0.46	0.54	0.54	0.54	0.56	0.56	0.61
49	2.00	0.92	2.00	2.00	0.79	2.00	0.92	2.00	2.00	1.07	3.00	0.56	4.00
50	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
51	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
52	1.23E+11	7.67E+10	9.30E+10	6.82E+10	4.11E+09	1.36E+11	6.71E+10	8.14E+10	1.33E+11	3.21E+10	2.11E+11	1.10E+11	7.18E+11
53	8.45E+10	6.19E+10	6.76E+10	2.75E+10	3.32E+09	9.32E+10	5.42E+10	5.92E+10	9.66E+10	2.59E+10	1.45E+11	8.85E+10	2.90E+11
54	1.93E+10	3.10E+10	1.81E+10	5.40E+09	1.66E+09	2.14E+10	2.71E+10	1.59E+10	2.59E+10	1.30E+10	2.72E+10	8.85E+10	4.40E+10
55													
70	4	7	4	1	0	5	6	4	6	3	6	20	10
71	4	2	3	2	0	4	2	2	4	1	6	3	20

Table 3-7 (Continued)
Steam Injection and Electrical Heating Rate Calculations

	AK	AL	AM	AN	AO	AP	AQ
2	**OWPA**			**Totals**			
3	A	AB	B	Scenario 1	Scenario 2	Scenario 3	
4	30	5	25				
5	187439	187440	308035				
6	391	391	407				
7	118.2	118.2	134.2				
8	244.7	244.7	273.5				
9	1.062	1.062	1.677				
10	2369	2369	3740				
11	85,187	85,187	85,187				
12	2,555,610	425,935	2,129,675	38,891,310	57,990,045	79,786,125	ft^3
13	94,652	15,775	78,877	1,440,419	2,147,779	2,955,042	yd^3
15	22	22	22				
16	118	118	134				
17	1,000	1,000	1,000				
18	4,186	4,186	4,186				
19	0.35	0.35	0.35				
20	2.65	2.65	2.65				
31							
32							
33	137	137	160				
34	0.39	0.39	0.46				
35	370	370	273				
36	1.0E+07	1.7E+06	9.7E+06	1.9E+08	2.8E+08	4.0E+08	kg steam
37	2.2E+10	3.7E+09	2.2E+10	4.3E+11	6.3E+11	8.8E+11	kJ
38	2.11E+10	3.55E+09	2.05E+10	4.05E+11	5.93E+11	8.38E+11	BTU
39							
40							
45	2.22E+10	3.70E+09	2.16E+10	4.26E+11	6.23E+11	8.80E+11	kJ
46	2.11E+10	3.51E+09	2.05E+10	4.04E+11	5.90E+11	8.34E+11	BTU
47	50	0	15				
48	0.39	0.39	0.46	pv heatup			
49	2.00	0.39	2.00	pv design			
50	0.85	0.85	0.85				
51	0.95	0.95	0.95				
52	2.66E+11	4.35E+09	1.30E+11	2.61E+12	3.55E+12	5.15E+12	BTU
53	1.07E+11	3.51E+09	8.94E+10	1.43E+12	2.05E+12	2.89E+12	BTU
54	2.11E+10	3.51E+09	2.05E+10	4.04E+11	5.90E+11	8.34E+11	BTU
55							
70	5	1	5	93	137	193	MM BTU/hr
71	8	0	4	75	101	147	MM BTU/hr 4 yrs

Table 3-8
Summary of Steam, Power, and Water Demand

	Scenario 1	Scenario 2	Scenario 3
Steam demand during 360 day heat-up	93,000 lbs/hr (100 MM BTU/hr gas)	137,000 lbs/hr (150 MM BTU/hr gas)	193,000 lbs/hr (200 MM BTU/hr gas)
Steam demand during years 2-4	75,000 lbs/hr	101,000 lbs/hr	147,000 lbs/hr
Power demand for electrical heating during year 1 and 2	5,100 kW max 2,550 kW avg	7,400 kW max 3,680 kW avg	7,400 kW max 3,680 kW avg
Maximum water supply for steam generation	205 gpm	310 gpm	440 gpm

Table 3-9
Electrical Heating Design Parameters and Power Demand

	MPA & N-MPA DE	N-MPA B/BC
Electrical Resistance Heating (ERH) Area:	123,811 sq. ft.	41,263 sq. ft.
Shallow Extent of ERH:	173 ft bgs	40 ft MLLW
Deep Extent of ERH:	232 ft bgs	120 ft MLLW
Typical Depth to Groundwater:	10 ft bgs	0 ft MLLW
Treatment Volume:	270,500 cu yds	122,300 cu yds
Estimated Number of Electrodes:	46	13
Electrode Boring Size:	10-inch o.d.	10-inch o.d.
Electrode Depth Interval Drill Cuttings:	50 tons	35 tons
Estimated Distance Between Electrodes:	60 ft	60 ft
Total Depth of Electrodes:	220 ft bgs	108 ft MLLW
Depth to Top of Electrodes:	185 ft bgs	52 ft MLLW
Electrode Steel Shot Required:	119 tons	54 tons
Liquid Groundwater Pumping Rate:	0 gpm	12.5 gpm
Controlling Contaminant:	NAPL	NAPL
Maximum Expected Temperature:	177°C	150°C
Rating of Power Control Units:	5,100 kW	2,300 kW
Average Electrical Heating Power Input:	2,550 kW	1,130 kW
Electrical Heating Steam Production Rate:	2,900 scfm	830 scfm
Time to Heat-up Treatment Volume:	365 days	365 days
Time to Boil Treatment Volume:	365 days	365 days
Total Heating Treatment Time:	730 days	730 days
Design Remediation Energy:	44,718,000 kW-hr	19,765,000 kW-hr

Table 3-10
Total Liquid Extraction Rates and Design Capacity of Effluent Treatment System

	Scenario 1	Scenario 2	Scenario 3
Equivalent steam injection rate	186 gpm	274 gpm	386 gpm
Design extraction rate	280 gpm	410 gpm	580 gpm
Miscellaneous process water	40 gpm	55 gpm	70 gpm
Over-extraction need from pump & treat estimate	235 gpm	235 gpm	235 gpm
Total effluent treatment system capacity	475 gpm	575 gpm	700 gpm

4.0 SURFACE PROCESS DESIGN

The design criteria for the surface treatment process are based on proven technology and many years of practical experience leading to a simple robust design. The design has been developed with consideration of daily operation and maintenance factors. The design has built-in flexibility for addressing the wide range of anticipated process conditions and unforeseen difficulties, and it consists of a modular approach, which provides the ability to scale changes in actual process conditions.

4.1 STEAM GENERATION

Steam will be needed for the thermal remediation process. Subsurface heating by the application of steam enhances the recovery of site contaminants via several thermodynamic mechanisms. Steam generation will be a constant operation, although the steam generation rate may vary depending on operational needs during the 4 years of steam injection.

4.1.1 Steam Purchased From Outside Source or Service Provider

A quote for purchasing steam was obtained from a boiler vendor close to the site. The vendor indicated that the charge for providing steam as a commodity to McCormick and Baxter at the design requirements would be $7.00/1,000 lb of steam produced. The cost includes everything necessary to make 100,000 lb/hr of steam including the fuel (Scenario 1). Even though the quote for off-site steam generation compares favorably with the cost of on-site generation (see Section 4.1.2), the on-site steam generation option was chosen for inclusion in the scenarios because of the need for vapor destruction and the beneficial cogeneration option. A more detailed analysis and comparison will be made at a later design stage.

Currently, a steam line runs south of the McCormick and Baxter property line. The capacity and pressure of this line was investigated, with the following conclusions:

- The maximum amount of steam that could be delivered to the thermal remediation system is 20,000 lb/hr.
- The steam pressure would be in the range of 100 to 150 psig.
- The service is expected to be interrupted.

In conclusion, the off-site steam supply was not included in the design for any of the three scenarios.

However, the off-site supplier expressed interest and offered to increase the supply to accommodate the expected demand and should not be completely ruled out in the final design phase.

4.1.2 Steam Generation Using Purchased or Rented Boiler

Renting a boiler for up to 1.5 years would cost the same as purchasing the same boiler. This does not include the salvage value of the purchased boiler, which may decrease the rental time necessary for the rental cost to be equivalent to the purchase cost. For a project with 4 years of steam generation and the need for using the steam generator combustion chamber for destruction of COC-laden vapors, the optimal solution is to purchase the steam generators.

The cost estimate for purchasing steam production equipment and operating the steam plant (e.g., not purchasing steam as a commodity) indicated that the unit cost for steam would be $8.31/1,000 lb of steam produced, excluding the cost for pretreating the feed water. However, it is assumed that the pretreatment would cost no more than $1.00/1,000 lb of steam produced, based on 1999 fuel oil costs.

4.1.3 Boiler Type Selection

With a total anticipated maximum steam injection rate of 100,000 lbs/hr (Scenario 1), 150,000 lb/hr (Scenario 2), and 200,000 lb/hr (Scenario 3), it is recommended that the boiler plant consist of packaged 1,500-horsepower (hp) water tube boilers (each rated at about 50 million BTU/hr). Water tube boilers are, in general, less efficient and require more maintenance than fire tube boilers. Water tube boilers are traditionally used in high-pressure operations, such as deep oil exploration (thousands of psig steam pressure). The steam generation for the remediation will be a low-pressure process (maximum of 150 psig steam pressure). However, a water tube design is best suited for vapor recycling, as described in Section 4.5, and the high-pressure steam that is produced can be used to generate electricity, as described in Section 4.1.7.

Vapor recycling requires a 1 second or better residence time in the combustion chamber to fully reduce latent hydrocarbons in the vapor stream to nonharmful components before release to the atmosphere along with the boiler flue gas stream. This is best done in oil-field-style water tube boilers due to their large combustion chambers. Overall, oil-field-style water tube steam generators offer the best value for a 4-year thermal remediation project with the need to destroy vapors, and the benefit of using the power produced during the pressure reduction step.

4.1.4 Fuel Source

Boilers require a hydrocarbon fuel source to generate the high temperatures necessary to convert water to steam. The fuel source would most likely be natural gas. While propane has been employed as a backup fuel source for natural-gas-fired boilers in this size range, propane as the primary fuel source is not planned. It is anticipated that the local utility company will provide the fuel. Bulk storage of propane would be more costly because the vessels must be pressure rated, and the cost of propane necessary for any given thermal capacity would exceed the cost of natural gas.

Should fuel prices change such that diesel would be a cheaper overall fuel source, this is a viable option as well. The final decision will be made based on current fuel prices at the time of the final design.

4.1.5 Fresh Water Source

Water is necessary for steam generation at the site. A sustained rate of between 200 and 400 gpm will be needed to make steam for up to 1 year, after which the requirement will decrease to between 60 and 75 percent of these amounts (see Section 4.6). The actual steam generation rate will vary depending on operational needs. It will also be necessary to have additional water available for boiler blow-down, wash down, and water softener regeneration. This water will be introduced into heat exchange equipment; therefore it must be as free of minerals and other chemicals as possible, to reduce the level of pretreatment required for the feed water. Pretreatment would be needed to limit the fouling of boiler heat exchange surfaces. Fouling makes heat exchange less efficient and thus increases the cost of making steam. More importantly, scaling may cause overheating of the boiler tube metal and subsequent tube failures resulting in boiler downtime and costly repairs. Since it is assumed that steam generation will be a nonstop operation during the heating phase of the remediation, the water supply must be uninterrupted during that entire time.

The fresh water supply will be city water. Other options were ruled out:

- Surface water from Old Mormon Slough was rejected because pumping of water would increase the need for boiler water pretreatment compared to using fresh water.
- Water from a deep well was rejected because it would not offer any advantage over treated effluent water.

The total water need for the different phases of operation is discussed in Section 4.6. The principles used to generate the numbers are as follows:

- Water will be recirculated to the extent practical, thereby minimizing both the water supply and the treated water disposal rate.

- The fresh water supply will be regulated so the potential scaling problems discussed above may be kept tolerable, while the disposal of treated water will be minimized.

4.1.6 Feed Water Treatment Systems

Feed water for the boiler will require pretreatment due to natural occurring minerals. A sample of the untreated feed water should be analyzed during the treatment design to provide data that will allow proper design of a pretreatment system. Depending upon the analysis, various pretreatment methods may be used to prepare make-up water for the boiler feed water system. The objectives of boiler water treatment are as follows:

- Prevent hard scale deposits or soft sludge-type deposits that would impair the rate of heat transfer and possibly result in overheating and damage to the pressure vessel.

- Prevent general corrosion or pitting to ensure maximum life of the boiler at the lowest maintenance cost.

- Prevent intercrystalline cracking or caustic embrittlement of boiler metal.

- Prevent carryover to ensure high-quality steam at an economical rate of continuous and intermittent blow-down.

The accomplishment of these objectives will involve several forms of treatment including the following:

- Pretreatment of the make-up water before it enters the boiler feed water system (filtering and softening using an ion-exchange resin).

- Chemical treatment of the boiler water internally in the boiler (addition of oxygen scavenger and scale inhibitor chemicals).

- Preheating of the water prior to steam generation.

It is probable that recirculating a portion of the treated water will gradually increase the total dissolved solids, if in situ degradation reactions produce substantial amounts of inorganic carbon. The extra solids will reduce the life of the water softening resin, which in turn will increase the amount of salt needed to regenerate the units.

4.1.7 Electrical Cogeneration Option

The use of off-the-shelf, low-technology steam turbines deserves attention. Since the steam directly leaving the steam generation chamber will be at a high pressure and a pressure reduction step is needed, using a turbine for this purpose can save fuel overall and reduce the power cost for electrical heating.

- The steam turbine to be used for this application is a basic single-wheel impulse-type turbine. These machines are rugged in design and will operate with little or no attendance. They are available as new machines with 6 to 8-month lead time on order; there is also an abundance of used equipment.
- Steam requirements for the turbine are flexible: inlet pressure ranging from 150 to 1,000 psig, with no super heat component required. Outlet pressure can range from 15 to 200 psig.
- Typically the available generators will be in a size range of 100 to 500 kW. A larger generator would be more complicated to install and operate. The generators can be connected together and will operate as a small "grid" with frequency control.
- The power produced is approximately 1,100 kW for a 50 MM BTU/hr steam generator, leading to the following maximum power generation rates for the three scenarios:
  - Scenario 1: 2,200 kW
  - Scenario 2: 3,300 kW
  - Scenario 3: 4,400 kW
- The cost to generate the power is typically assumed to be 4 percent of the energy that is passed through the turbine. However if there is currently pressure reduction required, this number could be improved to as little as 1.5 percent.

The cost estimate for the turbine generator sets based on a reconditioned turbine with a new generator and voltage control is $200/kW.

We suggest that the power generated from the turbines be directed to the electrical heating arrays. It turns out that the potential power generated by the turbines closely matches the average power proposed for the ERH in each case (see Section 4.6.1).

4.2 ABOVEGROUND STEAM AND AIR CONVEYANCE

4.2.1 Steam Injection Pressures

The estimated injection pressures for the five main injection intervals are summarized in Table 4-1. More detail regarding the assumptions and calculations is provided in Section 3.10.

4.2.2 Steam Quality

Steam will be injected below the surface as approximately 75 percent saturated steam vapor and 25 percent condensed liquid. The water-tube-style steam generator is preferred for this application due to the larger combustion chamber. An oil-field-style steam generator with a water tube design is even better due to the extra large combustion chamber required to properly combust crude oil for the primary fuel. The steam quality of an oil-field-style steam generator is 80 percent or less. If a steam turbine is used, the steam quality ratio will remain unaffected. The use of a steam separator may be helpful for better turbine performance for the proposed cogeneration unit. If used the steam and condensate will be rejoined with the dry steam used for electrical power generation before final injection into the wells. Condensate traps will be installed in the steam lines in order to remove water and prevent water hammer during startup and system shutdown.

If the concentration of total dissolved solids (TDS) in the condensate is higher than that of the native groundwater, it can be injected at the electrodes, increasing the electrical conductivity in the vicinity of the electrode.

4.2.3 Air Injection

Steam and compressed air will be piped across the site from the treatment plants' air compressors in pipe mains, with several branches off to sections of the well-field. The main lines will be maintained at relatively high pressures, due to the need for no less than 107 psig for injection in the E-zone aquifer. It is anticipated that the header pressure will be between 125 and 200 psig.

The air injection rates are expected to be in the range of 1 percent by mass of the steam injection range, which equals a total of 240, 360, and 480 standard cubic feet per minute (scfm) for Scenarios 1, 2 and 3, respectively. This estimate is based on experience at the Visalia Pole Yard during full-scale remediation (Southern California Edison 2000). Each injection well will have a pressure reducer and a simple flow meter.

4.2.4 Piping Systems and Control

Steam and air will be distributed to injection wells using Grade A 53 black steel piping. In addition, valves in the pipe system will be manually controlled. Details of the design, including pressure regulators near the injection wells and control for valves, will be developed after the 10 percent conceptual design is completed.

The design of the piping layout should take into consideration ease of access to all wells for operation and maintenance. The piping layout will include a steam “main” from the boiler routed around to the remediation area. Steam supply to each injection well will be branched off from the steam main. This type of layout would not only minimize piping, it would also allow light transport access to all injection and extraction wells by placing ramps at specific locations to avoid aboveground pipes. Carbon steel pipe should be used for steam conveyance during the remediation. The carbon steel pipes will be wrapped with insulation to prevent unnecessary heat loss and provide protection for personnel.

ERH cables will be laid on the ground underneath the piping racks to keep as much of the site as possible open to routine vehicle traffic.

4.3 ELECTRICAL HEATING POWER SUPPLY AND DELIVERY TO ELECTRODES

The ERH system consists of the following components: a power control system, electrical distribution cables, and the electrodes. The electrodes were described previously in Section 3.2.

The ERH power control system (PCS) consists of the various components that reduce the supplied voltage to a level that is appropriate for passage through the subsurface. The PCS also includes all of the automatic safety shutdowns and monitoring equipment for the various electrical parameters. Due to the configuration of the heating zone at the McCormick and Baxter site, the use of three-phase electrical current is most appropriate.

ERH remediation of the D-E aquitard requires greater voltage and less amperage than that required for remediation under the slough. For this reason, one PCS would be required for Scenario 1 and an additional PCS would be required for Scenarios 2 or 3. The D-E aquitard PCS will have a capacity of 5,100 kW and be designed for an output voltage range from about 180 to 320 volts. The slough PCS will have a capacity of 2,300 kW and be designed for an output voltage range from about 120 to 220 volts.

It is premature to provide extensive details about the PCS in the 10 percent design. However, the major components of the PCS will include the following:

- An input power disconnect switch
- Input electrical usage metering
- A contractor to allow local, remote, and automatic shutdown of ERH power
- A step-down transformer to reduce the utility supply voltage (typically 13,800 volts) to an appropriate range for ERH use
- A motorized tap switch to allow local, remote, and automatic adjustment of ERH voltage in response to soil resistance changes
- Output instrumentation for voltage and current flow to the electrode field

For the McCormick and Baxter site, autotransformers would likely be used to provide alternate electrode voltages that are 20 percent above and below the standard voltage. The ERH operator would have the choice of connecting any particular electrode to the standard voltage, to a higher voltage if greater electrode power and current was desired, or to a lower voltage if lesser electrode power and current was desired.

The PCS will be centrally located in a simple pad-mounted building, about 600 to 900 ft^2.

Power to the individual electrodes will be distributed using type W (extra-hard usage) cable. These cables are suitable for routine foot traffic, periodic vehicle traffic, and wet locations.

Electrodes in the slough will be installed inside a pile-driven casing. A barge will carry the drill rig. The electrode cables and flexible extraction hoses from the electrode casing will be supported by a slack-removing pulley and borne to the shore on floats.

4.4 CONTAMINATED LIQUIDS AND VAPOR EXTRACTION AND CONVEYANCE

4.4.1 Wellhead Design and Down-Hole Pumps

Wellheads will be configured from standard 6-inch 150-pound raised-face flanged tees. Each of the injection wellheads will have the following:

- A steam injection port equipped with an on/off valve and a flow meter

- An air injection port with on/off valve and flow meter
- A pressure gauge and/or transducer
- A temperature gauge and/or transmitter
- A cooling port for cooling the well prior to opening it for service
- A pressure relief port

Each extraction well will have the following:

- A vacuum extraction port connected to the main vacuum line
- Connections and piping/tubing for down-hole pumps
- A pressure gauge and/or transducer
- A temperature gauge and/or transmitter
- A cooling port for cooling the well prior to opening it for service
- A pressure relief port
- Appropriate flow meters

Design drawings and more detail will be provided at a later design stage.

4.4.2 Liquid Conveyance

With the higher concentrations of contaminants and higher temperatures of extracted materials during the remediation, pipe material will be selected on the basis of temperature and chemical compatibility, as well as its resistance to corrosion due to the extracted groundwater and the environment. Steel pipe is recommended for use as the primary pipe material due to its cost as well as its ability to be used at the expected temperatures. The rate of corrosion of steel pipe will be evaluated during the remediation. Other piping material such as stainless steel and fiberglass can handle the higher temperatures and contaminants expected during the remediation. Results from related pilot tests such at the one performed at Wyckoff-Eagle Harbor (USACE 2000b) should be used to determine the appropriate lifetime of the selected material. Stainless steel and fiberglass are on the order of two to three times more expensive than comparably sized steel pipe. At this time, steel pipe has been chosen as the most appropriate pipe material for liquid conveyance.

4.4.3 Vapor Conveyance

Vapor extracted from the extraction wells and the vapor collection system under the vapor cap will be conveyed from field locations to the treatment plant. Construction materials for this conveyance system should be similar to those used for the liquid contaminant conveyance system, since the temperatures and constituents will be similar.

A final piping layout will be provided at a later design stage.

4.5 EFFLUENT TREATMENT SYSTEM

An on-site treatment plant is needed to process the contaminant-laden liquid and vapor extracted from the ground. For the conceptual design, it was assumed that effluent water would have to be treated to meet the compliance criteria discussed in Section 6.6, or the background levels, as appropriate, and that treated air would have to meet applicable air quality standards.

4.5.1 Effluent Streams and Composition

Estimates of contaminant concentrations in groundwater cover a large range due to temperature variations during thermal treatment. Although PAH solubilities can be expected to increase as much as three orders of magnitude during heating from ambient to steam temperatures, dissolved concentrations in the field will be limited by mixing with steam condensate and groundwater recharge.

Actual COC concentrations in the extracted water were not calculated because of the degree of associated uncertainty. Therefore, the treatment system was based on previous work (i.e., Visalia Pole Yard full-scale operation data [Southern California Edison 2000] and the Wyckoff-Eagle Harbor pilot test [USACE 2001b]). The Visalia COC concentrations are valuable especially because that site used a similar effluent treatment system; therefore, the waste streams are believed to have a similar composition. One example is the use of other sites to estimate the liquid-phase granular activated carbon (GAC) consumption (see Section 7.1).

4.5.2 Treatment System Components

The treatment system is designed to accommodate all phases of liquids and vapors extracted from the site. Robust proven technology with strong vendor support should be utilized. The primary components of the system are shown in Figure 4-1. Table 4-2 indicates the individual units and their sizes and capacity for each of the three scenarios.

4.5.3 Cooling and Condensation

Cooling Fluids

A shell and tube heat exchanger will be included in the treatment train to recover energy (heat) from the liquid and cool the effluent prior to discharge. If further cooling is needed, cool water from the cooling tower will be circulated on the outside jacket of the exchanger.

Condensing Vapors

The primary condenser for extracted vapors will be an air-to-air fin-fan-style heat exchanger sized to anticipate potential hot condensate loading due to steam breakthrough from multiple extractors at once. A separator vessel equipped with a demister screen and evacuation pump will follow the condenser. Condensed fluids will be directed to the liquid treatment system.

The estimated cooling needs during cool-down are indicated in Table 4-3.

4.5.4 Liquid-Vapor Separation

There will be a small amount of condensate collected in the vapor conveyance that will be captured before the fin fan. A liquid-vapor separator after the air exchanger will separate the bulk of the condensate. The liquid-vapor separators are vertical vessels with multilevel trays and demisting screens that will contact the gas to promote condensation within the vessel. Discrete level controllers will initiate and control the transfer of condensate to the liquid treatment system.

4.5.5 NAPL Removal From Water

Selection of the appropriate treatment processes for treatment of an oily waste is dependent on the oil classification. Under proper quiescent conditions, free oil can be removed by gravity separation. Emulsified oil cannot be removed by gravity separation unless it can first be converted to free oil by breaking the emulsion. Emulsified oil may be removed by air flotation, although the emulsion may first have to be broken for this process to be effective.

Destabilization

Treatment of oil emulsions is usually directed toward destabilizing the dispersed oil droplets, causing them to coalesce and form free oil. The process typically consists of rapidly mixing coagulant chemicals with the wastewater, followed by gentle mixing (flocculation). The agglomerated oil droplets may then be removed by gravity or flotation.

Chemical Processes

Alternative processes for breaking chemical emulsions include either the addition of acid (acid cracking), iron, or aluminum salts (coagulation), or the use of chemical emulsion breakers. In acid cracking, the pH is reduced to approximately 3 to 4, so the wastewater must be neutralized after oil-water separation. The use of iron or aluminum salts with or without polyelectrolytes may be less costly, but it produces additional solids from the chemical precipitates. Proprietary chemical emulsion breakers are very effective, but they are more costly than iron or aluminum salts.

Air Flotation

In the air flotation process, separation of both oil and solid particles is brought about by introducing fine air bubbles into the liquid waste stream. The bubbles attach to the particulate matter and oil droplets, and the buoyant force of the air bubbles causes both particles and small oil droplets to rise to the surface. The oil/solids/air bubble mixture forms a froth layer at the surface, which is skimmed away. The removal efficiency of air flotation separators for free oil is similar to that of gravity separators. However, air flotation units can also remove dispersed oil droplets and more readily accommodate heavier oil loading.

The recommended NAPL-water separation approach is the following:

- Allow long retention time in incoming water surge tanks to allow for phase separation where the NAPL is not present as an emulsion.
- Equip the large holding tanks with oil skimmer pumps so they function as oil-water separators.
- Run the water through induced air flotation units to remove NAPL and particles.
- Encourage emulsion breaking by chemical addition only if deemed necessary, with the necessary pH neutralization after the induced air flotation unit.

At this point, it is anticipated that emulsion breaking will not be necessary.

4.5.6 Dissolved-Phase Treatment Alternatives

The only alternative considered for removal of the organic COCs from the water is adsorption.

Adsorption is a natural process in which molecules of a liquid or gas are physically attracted to and held at the surface of a solid. Treating waste streams by adsorption involves transferring and concentrating contaminants (the adsorbate) from one medium (liquid) to another (the adsorbent). The most commonly used adsorbent is GAC. In liquid-phase carbon adsorption, the contaminated liquid comes in contact with the carbon by flowing through one or more packed-bed units. The activated carbon selectively adsorbs organic hazardous constituents that are attracted to and held in the internal micropores of the carbon granules.

Limitations:

- Cost is high if used as primary treatment of fluids with high contaminant concentrations.

- Spent GAC may require hazardous waste handling and transport before being disposed of.
- Influent streams with high concentrations of suspended solids (>50 mg/L) or oil and grease may cause GAC fouling.
- Metals can foul GAC systems.
- Carbon may require backwashing if suspended solids are present.

It is desirable to regenerate the GAC on site using steam. Details are provided in Section 7.1.

Biological treatment was not included for dissolved COC polishing. If the pilot test at Wyckoff-Eagle Harbor proves successful, biological treatment may be added to the treatment system at a later design stage.

4.5.7 Vapor Treatment Alternatives

Contaminated vapors that are collected from the extraction wells, the vapor cap, and the treatment plant unit operations as off-gas will require treatment prior to discharge to the atmosphere. The alternative treatment options are discussed below.

Oxidation

Vapor emission oxidation is a process in which oxygen and organics react under high temperatures to produce carbon dioxide, water vapor, and in some cases acidic gases (such as hydrochloric acid). Oxidation systems are relatively simple devices capable of achieving destruction efficiencies of 98 percent or greater.

Oxidation by Flares. Flares are typically used for waste streams that have large volumes and high organic concentrations. Basically, a large flame burns the contaminated vapors as they leave a stack or chimney. Since organic concentrations in remediation applications are relatively dilute, flaring is not an applicable technology.

Thermal Oxidation. In thermal oxidation, gas is heated to a sufficient temperature to oxidize organic compounds to carbon dioxide and water. This technology does not offer any advantages over vapor recycling and, therefore, will not be considered further.

Catalytic Oxidation. In catalytic oxidation, a catalyst is used to alter the oxidation/reduction rate causing it to occur faster and/or at a lower temperature. This technology does not offer any advantages over vapor recycling and, therefore, will not be considered further.

Gas-Phase Adsorption

Gas-phase adsorption is a natural process in which molecules of a gas are physically attracted to and held at the surface of a solid. Treating waste streams by adsorption involves transferring and concentrating contaminants (the adsorbate) from one medium (gas) to another (the adsorbent). The most commonly used adsorbent is GAC. In gas-phase carbon adsorption, the contaminated gas comes in contact with the carbon by passing through one or more GAC units, which are usually the fixed-bed type. The activated carbon selectively adsorbs organic molecules, which are held in the internal micropores of the carbon granules.

GAC units may be single- or multistage. Multistage systems make optimal use of carbon stock but increase operation and maintenance (O&M) costs. On-site regeneration using steam is recommended for the primary vapor-phase GAC vessels. A polishing vessel will consist of sacrificial GAC.

Vapor Recycling

Recycling the contaminated vapors in the boiler is a treatment alternative. In this common industrial practice, the vapor stream is blended with excess air and fed to the combustion chamber of the boiler, where it combines with heat and the boiler's fuel (natural gas) to generate more heat, which boils the feed water and makes steam. Proper recycling of the contaminated vapors would require a suitable combustion chamber temperature and retention time in the combustion chamber. It has been reported that the boilers at the Visalia site recycled the contaminated vapors with a retention time of 4.6 seconds. Further evaluation of the proper temperature and retention time requirements will be necessary to complete the design of this system.

Recommended Alternative

Vapor recycling is recommended as the primary vapor treatment alternative. Use of the steam generator for the destruction of vapors collected from the field would significantly decrease the cost and overall operational complexity of the project. The burden on the steam generator and its operator would be minimal. Once the treatment area has been heated, it would be necessary to extract and treat contaminated vapors most of the time to control potential fugitive emissions, regardless of whether the rest of the thermal remediation system is being operated. Thus, a backup treatment system would be necessary for times when the boiler is not operating (e.g., during maintenance and unexpected shutdowns) or not recycling vapors effectively. This backup system could become the primary vapor treatment system once steam generation is no longer needed. For these reasons, it is recommended that a gas-phase adsorption system be used as a secondary vapor treatment system for the remediation. On-site regeneration of the primary vessels using steam is recommended.

The capacities of the chosen units are provided in Table 4-2.

4.6 UTILITY REQUIREMENTS

The processes requiring power, water, and fuel include the following:

- Steam generators and water pretreatment units
- ERH power control units
- Powered valves and down-hole pumps
- Effluent treatment system

The utility requirements will vary considerably over the duration of field operations, depending on the phases. For instance, steam generation and power demand will be at their maximum during the first and second years, when the main focus will be on heating the major sand layers and the D-E aquitard. During subsequent years of thermal treatment, ERH will be discontinued, and the steam injection will be performed in a cyclic manner, where parts of the site will be receiving steam while other parts will be in a depressurization mode. Thus, the average fuel and water demand will be less than the maximum during the last half of thermal treatment.

The cooling capacity will vary considerably over time as well. Since the cooling will be accomplished using water circulated through large cooling towers, the associated utilities will be water (make-up for the water that is evaporated in the towers) and power (for the motors turning the fans that blow atmospheric air across the towers). During the first year of operation, it is expected that the cooling demand will be relatively low, since the site will be heating up during this period. At a later stage, when most of the site has been heated, steam will be extracted by allowing steam to flush through to the extraction wells, and the cooling need will increase as vapors are being condensed for treatment. However, even under the most demanding cooling requirements, the electricity required for cooling will be a small fraction of the total electricity used.

The predicted utility requirements are indicated in Table 4-4. These values were calculated from an overall mass and energy balance for the site and include several assumptions and estimates.

The following subsections describe the individual utilities.

4.6.1 Power

The total power demands are indicated in Table 4-4. The total service need ranges from 6.6 to 9.9 MW for the three scenarios.

On-site electrical cogeneration using steam turbines was discussed in Section 4.1.7. Since the steam directly leaving the steam generation chamber will be at a high pressure, and a pressure reduction step is needed, using a turbine for this purpose can reduce the power cost for electrical heating.

We suggest that the power generated from the turbines be directed to the ERH during the first 2 years of operation. It turns out that the potential power generated by the turbines fairly closely matches the average power proposed for ERH in each case (Table 4-4). During the third and fourth year, the cogeneration power will reduce the need for grid power.

Grid power will be used to ensure that power is available at all times and when the steam generators are inactive. Table 4-5 indicates the estimated grid power that will be needed and the anticipated cogeneration power that will be used during the first 4 years of operation.

4.6.2 Fuel

Boilers require a hydrocarbon fuel source to generate the high temperatures necessary to convert water to steam. The fuel source will most likely be natural gas. It is anticipated that the local utility company will provide the fuel. Natural gas will be delivered to the site using dedicated pressurized pipe. The actual source of the gas and the cost of installing the line will be defined at a later design stage.

Should fuel prices change such that diesel would be a cheaper overall fuel source, that would be a viable option as well. The final decision will be made based on current fuel prices at the time of the final design.

The potential use of recovered NAPL as a supplemental fuel source is discussed in Section 7.3. This option has not been included in the design at this stage, but should be considered carefully later.

4.6.3 Water

Water will be necessary for steam generation at the site. A sustained rate of between 160 and 320 gpm will be needed to make steam for up to 1 year, after which the need will decline as the steam injection rates are reduced (Table 4-4). The actual steam generation rate will vary depending on the remediation operational needs. It will also be necessary to have additional water available for boiler blow-down, wash-down, and water softener regeneration.

The fresh water supply will be city water. The total water needed for different phases of operation is indicated in Table 4-4. The principles used to generate the numbers are as follows:

- Water will be recirculated to the extent practical, thereby minimizing both the water supply and the treated water disposal rate.
- The fresh water supply will be regulated so the potential scaling problems discussed above may be kept tolerable, while the disposal of treated water will be minimized.

Other utilities such as telephone lines will be detailed at a later design stage.

4.7 WASTE GENERATION AND DISPOSAL

4.7.1 Solids From Subsurface

Spent filter cartridges and sludge from the separating tanks will be collected in roll-off bins. The contents will be characterized and sent to appropriate waste disposal facilities. For planning purposes, it was assumed these wastes will not be considered a listed waste.

4.7.2 Nonaqueous-Phase Liquids

The NAPL recovered by the vapor condensation and oil-water separator will be collected in a holding tank on site. As necessary, the wastes will be loaded onto a 5,000-gallon tanker truck and transported to an incinerator for destruction. For planning purposes, SteamTech has assumed that the Clean Harbors facility in Kimball, Nebraska, will be used. The possibility of recycling the NAPL product should be explored further. Also, the possibility of using the NAPL as fuel in the steam generators should be investigated.

4.7.3 Spent Activated Charcoal

Carbon (GAC) will be utilized (see Section 7.1). Liquid-phase carbon that has become fouled with heavier compounds and can no longer be steam regenerated will be slurried from the vessels and loaded onto lined shipping containers. The frequency of replacement was based on scaling from Visalia Pole Yard's full-scale thermal remediation project (Southern California Edison 2000). SteamTech has assumed that this carbon will be incinerated at the Clean Harbors facility in Kimball, Nebraska.

4.7.4 Personal Protective Equipment

Personal protective equipment (PPE) will be stored in drums and periodically disposed of at an appropriate facility, as required.

4.7.5 Other Solid Waste

SteamTech has assumed that any other miscellaneous hazardous solid waste would be disposed of at the Clean Harbors facility in Kimball, Nebraska. Miscellaneous nonhazardous waste will be disposed of at a local Resource Conservation and Recovery Act (RCRA) landfill.

4.8 SITE INFRASTRUCTURE AND LAYOUT

The entire site is currently surrounded with adequate fencing and secured with a 24-hour guard, which will remain throughout the scheduled 7-year remediation and beyond. Close to the site entrance, there is an existing office structure, which could be refurbished for administrative functions and conference space. A small vapor cap is proposed for the CPA area, and there is an existing cap over excavated soils in the center of the site (MPA). A likely location for the installation of the steam generation and treatment system is just west of the existing soil cap in the MPA. The portion of the system that handles contaminated liquids will be placed on a 1-foot-thick 100- by 200-foot concrete containment/decontamination pad and covered with a temporary structure. Holding tanks will remain outside the structure but on the containment pad. Steam generators, the cooling tower, the air-to-air heat exchangers, and the operations office trailers will be positioned close by but off the pad. Footings and other details concerning the containment/decontamination pad will be saved for a later design. Piping for conveyance of steam, liquids, and vapors will dominate the site and pose access problems if not carefully designed. The surface should be covered with gravel or decomposed granite to facilitate vehicle access.

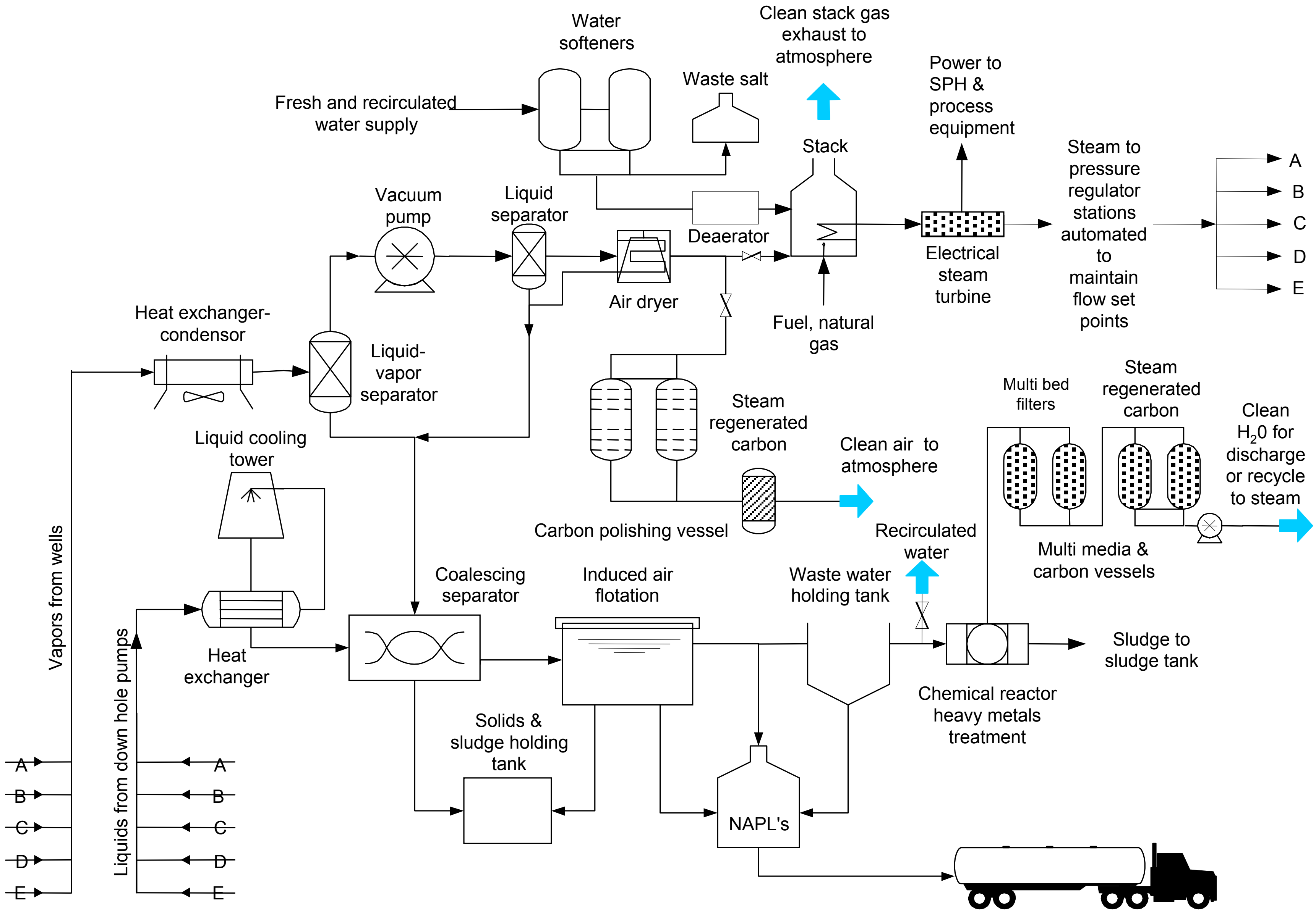

Figure 4-1
Surface Process Diagram

THERMAL TREATMENT TECHNOLOGY
CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

Table 4-1
Maximum Injection Pressures for Different Depth Zones

	A	B	C	D	E
Depth to top of injection screen (ft)	25	60	125	155	240
Injection pressure (psig)	12.5	30	63	78	107

Table 4-2
Effluent Treatment System—Components and Sizes

Component	Parameter	Unit	Scenario 1	Scenario 2	Scenario 3	Comment/assumption
Vapor phase liquid separator 1	Air flow rate	scfm air	4,733	7,100	9,467	Non-condensable gas plus 10% of injected steam as condensable vapor
	Liquid flow rate	gpm condensate	22	27	32	Assuming max 5% of liquid extracted with vapor stream
Liquid phase heat exchanger	Liquid flow rate	gpm water	435	535	635	Injected plus 235 gpm
	Cooling capacity	MM BTU/hr	22	27	32	Assumed 100 F cooling
Vapor phase heat exchanger/condensor	Cooling capacity	MM BTU/hr	12	17	22	Assumed 10% of injected energy as steam and energy in 200F condensate
Vapor phase liquid separator 2	Air flow rate	scfm air	1,000	1,500	2,000	
	Liquid flow rate	gpm condensate	23	34	45	Based on maximum vapor phase cooling capacity
Vacuum pumps	Air flow rate	scfm	1,000	1,500	2,000	
	Vacuum	psig	-10	-10	-10	Need to apply vacuum
Vapor treatment units	Air flow rate	scfm	1,000	1,500	2,000	
Water surge tank	Retention time	hours	1	1	1	Need settling and separation time for solids and NAPL
	Minimum capacity	gallons	26,100	32,100	38,100	
Dissolved Air Floatation	Water flow rate	gpm	435	535	635	Recovered fluid and condensate not to exceed maximum pumping rate
	NAPL flow rate	gpm	11	13	16	Assumed max NAPL ratio of 2.5% of total water flow
Multimedia filters	Water flow rate	gpm	475	575	700	DAF flow rates plus process water
Water treatment unit (GAC)	Water flow rate	gpm	475	575	700	DAF flow rates plus process water
NAPL holding tanks	Capacity	gallons	21,000	21,000	21,000	Tanks added and emptied for disposal as needed
	Minimum number	#	2	2	2	Empty backup tank on-site

Table 4-3
Average Cooling Needed During Cool-Down Period

Cooling (MM BTU/Hour)			
Year	**Scenario 1**	**Scenario 2**	**Scenario 3**
1	21	32	45
2	14	19	28
3	6	11	16

Note:
MM BTU/hr - million British thermal units per hour

Table 4-4
Utility Estimates for Different Phases of Operation for Each Scenario

Fresh water usage estimates		**Scenario 1**	**Scenario 2**	**Scenario 3**		**Comment**					
Heatup	Year 1	200	300	400	gpm	100% fresh water					
Continued thermal treatment	Year 2	133	200	267	gpm	67% fresh water					
Continued thermal treatment	Year 3	100	150	200	gpm	50% fresh water					
Continued thermal treatment	Year 4	100	150	200	gpm	50% fresh water					
Cool-down	Year 5	10	15	20	gpm	100% fresh water					
Cool-down	Year 6	10	15	20	gpm	100% fresh water					
Cool-down	Year 7	10	15	20	gpm	100% fresh water					
Treatment system pumping capacity	Maximum	475	575	700	gpm						
Steam generation water demand	Maximum	200	300	400	gpm						
						General process power			**Electrical heating demand**		
Power consumption estimates		**Scenario 1**	**Scenario 2**	**Scenario 3**		**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Heatup	Year 1	3,550	5,080	5,480	kW	1,000	1,400	1,800	2,550	3,680	3,680
Continued thermal treatment	Year 2	3,551	5,080	5,480	kW	1,000	1,400	1,800	2,551	3,680	3,680
Continued thermal treatment	Year 3	800	1,000	1,200	kW	800	1,000	1,200	0	0	0
Continued thermal treatment	Year 4	800	1,000	1,200	kW	800	1,000	1,200	0	0	0
Cool-down	Year 5	500	650	800	kW	500	650	800	0	0	0
Cool-down	Year 6	500	650	800	kW	500	650	800	0	0	0
Cool-down	Year 7	500	650	800	kW	500	650	800	0	0	0
Max power usage for equipment sizing	Maximum	6,600	9,400	9,900	kW	1,500	2,000	2,500	5,100	7,400	7,400
Natural gas consumption estimates		**Scenario 1**	**Scenario 2**	**Scenario 3**		**Comment**					
Heatup	Year 1	152,381	228,571	304,762	scfh	80% firing rate in average					
Continued thermal treatment	Year 2	133,333	200,000	266,667	scfh	70% firing rate					
Continued thermal treatment	Year 3	114,286	171,429	228,571	scfh	60% firing rate					
Continued thermal treatment	Year 4	95,238	142,857	190,476	scfh	50% firing rate					
Cool-down	Year 5	0	0	0	scfh	No steam generation					
Cool-down	Year 6	0	0	0	scfh	No steam generation					
Cool-down	Year 7	0	0	0	scfh	No steam generation					

Table 4-5
Estimation of Consumption of Grid Power During Operation

Total power consumption		Scenario 1	Scenario 2	Scenario 3	
Heatup	Year 1	3550	5080	5480	kW
Continued thermal treatment	Year 2	3551	5080	5480	kW
Continued thermal treatment	Year 3	800	1000	1200	kW
Continued thermal treatment	Year 4	800	1000	1200	kW
Cool-down	Year 5	500	650	800	kW
Cool-down	Year 6	500	650	800	kW
Cool-down	Year 7	500	650	800	kW
Co-generation power available[1]		Scenario 1	Scenario 2	Scenario 3	
Heatup	Year 1	2200	3300	4400	kW
Continued thermal treatment	Year 2	1760	2640	3520	kW
Continued thermal treatment	Year 3	1540	2310	3080	kW
Continued thermal treatment	Year 4	1320	1980	2640	kW
Cool-down	Year 5	0	0	0	kW
Cool-down	Year 6	0	0	0	kW
Cool-down	Year 7	0	0	0	kW
Grid power comsumption[2]		Scenario 1	Scenario 2	Scenario 3	
Heatup	Year 1	1350	1780	1080	kW
Continued thermal treatment	Year 2	1791	2440	1960	kW
Continued thermal treatment	Year 3	250	350	500	kW
Continued thermal treatment	Year 4	250	350	500	kW
Cool-down	Year 5	500	650	800	kW
Cool-down	Year 6	500	650	800	kW
Cool-down	Year 7	500	650	800	kW
Recommended minimum service	project	2000	2500	2500	kW
1) Co-generation power rates reduced with scaled down steam injection rates					
2) A minimum of 50% of the general process power is assumed to be provided by grid power					

5.0 PROCESS CONTROL, OPERATIONS, AND MAINTENANCE

5.1 OPERATIONAL STRATEGY

5.1.1 Overall Operational Goals

The goals for operating the thermal treatment system include the following:

- Heat target volume to steam temperature within the first 365 days of operation using steam injection and ERH in a manner that optimizes steam sweep from the outside in where possible. Sweep and apply the heat aiming at target pore volume sweeps with steam or as directed by the observed NAPL and dissolved-phase COC recoveries.

- At locations where NAPL has been found outside the target volume (or is suspected to be present), operate extraction wells screened over the intervals where NAPL is expected and where steam flow is predicted (both).

- Oxygenate the treated extracted water and re-inject it in locations where there is a benefit of increased biological activity.

- Maximize liquid-phase NAPL recovery by minimizing vaporization and alteration during the first phase of operation. This will optimize recovery of high-boiling-point components of the NAPL, including dioxins/furans and metals dissolved in the NAPL.

- Where liquid NAPL recovery rates diminish in a zone or area, encourage vaporization and degradation by allowing steam breakthrough to wells, induce pressure cycling, and inject oxygen to fuel degradation reactions.

- Operate the thermal treatment system for a period of up to 4 years with stimulation of in situ degradation reactions such as hydrous pyrolysis/oxidation and biodegradation, by injecting of air containing oxygen and by inducing pressure cycles that help mix the injected air with the heated water.

- After active heating has been discontinued, continue with a pump-and-treat system that re-injects treated water to encourage aerobic natural attenuation reactions. Consider modest injection of air into previous steam wells to supply oxygen (biosparging) during cool-down.

5.1.2 Phases of Operation

The operational phases consist of the following:

- Thermal treatment (total duration estimated at 4 years)
  - Heat-up (180 days to 1 year)
  - Continued heating and NAPL recovery with ERH of the aquitards (for as long as 1 year after heat-up)
  - Flushing and pressure cycling (up to 2 years after cessation of ERH)
- Cool-down with continued extraction (3 years)

The phases will overlap both in time and space, as one area heats up more rapidly than others, and one phase may be completed in a depth interval, but not in another.

5.1.3 Prevention of NAPL Spread

The main issues and challenges in preventing the spread of NAPL include the following:

- Prevent NAPL spread to greater depth by a general downward-up steam and power injection strategy, leading to steam rise and formation of hot floors under the mobile NAPL areas before they are heated to steam temperature.
- Prevent NAPL migration northward under Old Mormon Slough by:
  - Aggressive extraction along the boundary between the slough and the main site to its south, or
  - Heating from north of the NAPL (steam or ERH), combined with extraction from wells installed under the slough.
- Prevent NAPL migration southward off the property boundary in S-CPA and S-MPA by aggressive extraction from wells screened in the relevant zones.
- Prevent NAPL migration eastward from MPA into E-MPA in the D- and E-zones.
- Prevent NAPL migration through the mudline into the slough water. Such migration can be caused by diagonal upward migration of steam and condensate from treatment of the A- and B-zones close to the slough, or by the heating of

soils adjacent to well bores if wells or electrodes are installed in the slough without dewatering. Methods for preventing the NAPL migration are discussed in Section 3.7.

5.1.4 Injection of Air and Oxygenated Water

Considerations regarding air and water injection are as follows:

- Air injection will not be initiated during the initial heat-up phase because of the following factors:
  - Potential blocking of sand layers by air, leading to reduced steam injection rates.
  - Risk of COC-laden air escaping to surrounding zones.
  - Potential for the air injection to reduce the stability of the steam front, with the risk of reducing the efficacy of NAPL displacement.
  - Air injection encourages NAPL alteration by vaporization of most volatile COCs and degradation reactions, which could hurt the recovery of the less volatile COCs.
- Air injection will be initiated after peak NAPL recovery in each zone or area to minimize alteration of NAPL and optimize recovery of nonvolatile COCs. Low air-steam ratios will be used, so the air flow does not lead to increased pipe or pump sizes in the vapor recovery system.
- Co-injection with steam is favorable since it encourages mixing.
- Air injection during pressure cycling is favorable since it optimizes mixing.
- Measurement of the dissolved oxygen (DO) content of the extracted water may be used to adjust the rate of air injection. Water in wells where the dissolved oxygen level is less than 1 mg/L is considered anaerobic, and the injection rate of air in neighboring wells can be increased.

Continued aeration after termination of steam and power injection is favorable. During cool-off, when the extraction system is still being operated, the treated oxygenated water will be flushed through the zones where natural attenuation will be supported. Air injection should be evaluated and may be used to supply oxygen to the degradation reactions.

More detail will be provided at a later design stage.

5.2 STEAM AND AIR DELIVERY

Steam and compressed air will be distributed across the site from the steam generators and air compressors (via high-pressure pipelines). Branch lines will extent to different sections of the well-field. The main pipelines will be maintained at relatively high pressures because of the need for no less than 810 kPa (107 psig) for injection in the E-zone aquifer. It is anticipated that the header pressure will be between 125 and 175 psig.

Condensate traps will be installed in the steam lines to remove water and prevent water hammer during system start-up and shut-down.

5.2.1 Temperature and Pressure Regulation

The maximum injection pressure will be applied to the steam header line across the site. Each injection well will be equipped with a secondary pressure regulating valve and temperature and pressure gauges. The steam injection pressure will be controlled to an accuracy of 1 psi using air-powered pressure regulators. The secondary steam pressure (which is the pressure of the steam going down-hole) will be monitored continuously using pressure transducers with data output to a central location. Black iron pipe rated at least for 150 psig steam will be used to deliver the steam to the wellheads.

5.2.2 Injection Rate Control and Measurement

The total steam injection rate for the site will be monitored continuously at the steam generation plant, as the total water consumption minus blow-down. Steam injection rates will be monitored at several locations across the site using orifice plates and differential pressure measuring equipment.

The steam injection rate for each well will be measured using standard steam flow meters such as orifice plates or the equivalent, with automatic data collection and integration.

The injection rates will be scaled by the operators based on observed heating rates and the overall strategy for heating the site. Injection rates will be changed by changing the injection pressure at the steam pressure regulator at each wellhead.

5.2.3 Safety Measures

Each injection well will be equipped with a pressure relief valve set at a predetermined pressure, which will prevent the steam injection pressure from exceeding the maximum allowable pressure at any given location (see Section 3.3).

5.3 ERH PROCESS CONTROL, OPERATIONS, AND MAINTENANCE

5.3.1 ERH Process Control

The ERH system will consist of two independent sections:

- The D-E aquitard heating system used in all scenarios
- The B- and B-C zones heating system under Old Mormon Slough in Scenarios 2 and 3

Ohm's law governs the flow of electrical current through the subsurface in that the current flow is proportional to the applied electrode voltage and the power applied to the heated zone is proportional to the square of the applied electrode voltage. Thus, the voltage applied to the electrodes is varied by the power control system (PCS) in order to control electrical heating and the subsurface steam generation rate. In general, the most cost-effective remediation results from maintaining the highest sustainable ERH power within the capacity constraints of the PCS.

The electrical resistance of the subsurface varies considerably during ERH operation. It decreases as it is heated. A decrease to 30 to 50 percent of initial cold resistance is expected as the ERH zone is heated to boiling. When in situ steam generation begins, steam bubbles displace a portion of the groundwater, and the subsurface electrical resistance increases again, typically to within 70 to 90 percent of the initial cold resistance. The most rapid change in resistance occurs whenever the site is under boiling conditions and then the electrical power is shut down for a few hours. Almost all the steam bubbles rise out of the ERH zone due to buoyancy during the brief shutdown. Upon restart, the electrical resistance is at a minimum due to warm conditions with no steam bubbles; the resistance rises rapidly over the next hour or two as in situ steam bubbles are formed and reach equilibrium steaming conditions.

These changes in resistance require the ability to vary the sitewide electrode voltage with relative ease. The PCS can independently and rapidly vary the voltage of the three electrical phases through local operator action, through remote operator action, or automatically in order to maintain a desired voltage, a desired current, or any ERH desired power. The ERH system can be started and adjusted to any desired power in less than 1 minute. The ERH system can be shut down as simply as flipping a light switch; the subsurface voltage is instantly removed. Upon shutdown, in situ steam generation stops instantly; however, the existing steam bubbles remain in the subsurface and continue to move upward due to buoyancy until they condense or reach an impermeable layer or until they are removed via an extraction well.

In addition to the automatic sitewide PCS control, local operators are able to adjust the operation of individual electrodes relative to the rest of the site. As presently envisioned, each electrical phase will be distributed at three levels: standard voltage, 20 percent high voltage, and 20 percent low voltage. If the operator wants to boost the relative voltage, current, and power of an individual electrode, it is simply disconnected from the standard voltage cable and connected to the 20 percent high voltage cable, an operation that requires about 10 minutes of labor. Similarly, connecting an electrode to the 20 percent low voltage cable will reduce its relative voltage, current, and power. The concentration of conductive ions varies across the McCormick and Baxter site, requiring the operator to determine the appropriate relative voltage for each electrode upon start-up. However, although sitewide resistance varies considerably during operation, the resistance of individual electrodes relative to each other is quite constant. Thus, the selection of the appropriate relative voltage for each electrode is pretty much a “set and forget” operation and we anticipate changing the relative voltage of only two or three electrodes per week following start-up. The preceding discussion has been simplified by treating each electrode as completely independent. In practice, each electrode interacts with all of those in its vicinity, and the relative adjustment of one affects all of its neighbors slightly.

The PCS computer continuously monitors the output voltage and current to the electrodes, sitewide ERH power, and utility demand. In addition to this sitewide monitoring, the ERH operator will verify the current draw of each electrode twice each week during routine operation. The data will be used to determine the need for changes in electrode voltages. The ERH power distribution over the site can be reported at any desired time interval.

5.3.2 ERH Operations

The ERH system is likely to be operated at close to its full capacity by adjusting the voltage as described in Section 5.3.1. However, the ERH system will be shut down under certain conditions:

- The ERH system will be shut down in the event of a significant failure of the vapor extraction, condensing, or vapor treatment systems. Although a short duration upset (less than 1 hour) does not pose any particular problems, an automatic timer will shut down the ERH system in the event of extended vapor extraction shutdowns to prevent ERH generated steam from moving off site.

- The ERH system will be shut down by a sitewide power failure.

- The ERH system will be shut down for several hours in order to complete each ERT shot. The frequency of ERT monitoring varies with the phase of operation (Section 6.1).

- The ERH system will be shut down briefly to allow changing the relative voltage of individual electrodes, as described in Section 5.3.1.

- The ERH system will be shut down for any subsurface maintenance (e.g., extraction pump change-out) to ensure that workers are not exposed to any hazardous voltages.

- The ERH system will be shut down for any major maintenance in the well field (e.g., piping manifold replacement) to reduce the risk to workers if heavy equipment damages an ERH cable. Hard usage cable will be installed to minimize the possibility of damage caused by these events.

In addition to these required shutdowns, the ERH system may also be shut down during periods of high electrical demand, such as hot summer afternoons. Such voluntary shutdowns are a mark of good citizenship; however, self interest also motivates these voluntary shutdowns because the local utility will provide electrical service at far lower rates to customers who modulate usage in this manner. Operating at higher power overnight can easily make up any loss of heating during voluntary and required shutdowns.

5.3.3 ERH Maintenance

Like all electrical components, the ERH system will require relatively little maintenance. The principle maintenance activities and approximate maintenance intervals will be as follows:

- Adjustment of the individual electrode relative voltages as described in Section 5.3.1 (weekly)

- Calibration of the PCS voltmeters and ammeters (monthly)

- Greasing of cooling fan motors (monthly)

- PCS cleaning and infrared inspection (at start-up and semiannually)

- Replacement of ERH distribution cables that become damaged during well-field maintenance (rarely or never)

- Replacement of failed PCS components (rarely or never).

The ERH system should readily last for the planned treatment period. Therefore no major component replacement is foreseen.

5.4 CONTAMINANT EXTRACTION

This section describes how the extraction of water, NAPL and vapors, will be controlled and monitored.

5.4.1 Controlling Liquid Levels in Wells

The levels in the pumping wells will be controlled directly by the placement of the extraction pump intakes and by the applied extraction rate. For pumps designed to optimize LNAPL recovery, the intake will be set at the desired level for water draw-down during extraction, which will optimize the NAPL-water ratio. For pumps designed to optimize DNAPL recovery, the intake will be placed at the well sump and the pumping rate will be adjusted to maintain the desired liquid level in the well.

Water levels will be measured in the wells using standard techniques (details will be provided at a later design stage).

5.4.2 Metering Extraction Rates and Fluid Properties

Liquid discharge rates from the down-hole extraction pumps will be measured using in-line flow meters of a type selected to work optimally with the chosen pump type.

Vapor extraction rates will not be measured for every wellhead due to the difficulty of measuring flow in a stream of air, contaminants, steam, and liquid droplets. Total flow rate per zone will be measured in several locations in order to ensure that vapor extraction rates in each depth zone are sufficient.

5.4.3 Hydraulic Control

The goals of hydraulic control are outlined in Section 3.9. The performance will be measured based on the following:

- Depth-specific water balances, from recorded steam injection rates (from steam flow meters) and liquid extraction rates (from flow meters)

- Overall site water balance based on the volume of water treated and re-injected

- Measurement of water levels and hydraulic gradients at multiple locations close to the property boundary

5.4.4 Pneumatic Control

Pneumatic control is described in Section 3.9.2. The goal of pneumatic control is the extraction of vapors in the form of noncondensable gas (air, not steam). Verification of pressure gradients in the vadose zone is not practical, since this would require burial of thousands of pressure transducers and near-realtime monitoring during thermal treatment. Therefore, pneumatic control strategies are intended not to document that no vapors escape at the site, but to ensure that the selected approach allows for a degree of certainty regarding vapor capture. The monitoring principles are follow:

- Measure the applied vacuum at each extraction well and verify that the desired vacuum is achieved at the well. At a minimum, this should be confirmed by daily reading of vacuum gauges attached to the wellheads.

- Calculate total air injection rates (sum of individual well air injection rates) and total extraction rate for noncondensable gas (measured downstream of the vacuum pump). By ensuring that more vapor is extracted than injected, the net loss of vapor is prevented.

A feature that is likely to assist in maintaining pneumatic control is the presence of a laterally extensive silt and clay layer in the upper 20 feet of the site, minimizing the vertical vapor permeability. Since a vacuum will be applied in the sandy zones below this clay/silt layer, it is anticipated that the radius of vacuum influence will be reasonably large and that contaminant-laden vapors migrating upward into the A-zone aquifer will be captured.

5.5 TREATMENT PLANT OPERATIONS

The effluent treatment plant will be operated continuously after the onset of initial cold water extraction until the end of the cool-down period, with only minor shutdowns for routine maintenance. All the control functions will be governed by a master programmable logic system monitored and adjusted by the plant operators.

5.5.1 Cooling Efficiency and Control

Cooling will be controlled by temperature regulators at each of the individual heat exchangers. Cooling towers are relatively inexpensive and their efficiency increases when operated at 50 to 75 percent of capacity. The controllers will monitor the process stream temperatures and regulate the flow of cool water to maintain the set point temperature.

5.5.2 Phase Separation Efficiency and Control

Phase separation efficiency will be measured by the purity of the phases extracted from the separator. Most separators are controlled by level or interface probes. Separated components are pumped to holding areas for disposal or reuse, as appropriate. The control functions, levels, and flow rates for this system will be governed by a master programmable logic system monitored and adjusted by the plant operators.

5.5.3 Water Treatment Efficiency and Control

The process water will pass through two separation phases. Contaminants and dissolved solids will be separated along the way. Efficiency will be determined through analytical checks. Sampling and analysis of total petroleum hydrocarbons (TPH) and COCs will be used to determine the efficiency of the components.

5.5.4 Vapor Treatment Efficiency and Control

Vapors will be separated from moisture before being combusted in the steam generators or bypassing through GAC units. An on-line flame ionization detector (FID) sensor will track hydrocarbons at the inlet to either unit and at the outlet of the vapor-phase carbon to determine the efficiency and monitor the clean air released to the atmosphere. When vapors are combusted in the steam generator, the efficiency will be determined by stack testing for COCs. Liquids desorbed from the carbon system will be metered as they are transferred to the NAPL holding tank. The control functions for this system will be governed by a master programmable logic system monitored and adjusted by the plant operators.

5.5.5 Adding or Removing Treatment Units During Operation

A modular design of the treatment system will include multiplexed systems in most cases. For example two 1,000-scfm vacuum pumps may be used to pull a 2,000-scfm load (Scenario 3). All piping and utilities will be designed to accommodate an addition or subtraction of components and systems during the remedial effort. This methodology also provides backup during routine maintenance without full interruption of the process. Off-line systems could be demobilized or salvaged as the remediation nears completion. In the same manner, additional systems could be added if the remediation requires more.

The need for heavy metals treatment could potentially arise during operation, if the concentrations of heavy metals in the effluent substantially exceed the E-zone levels (see Appendix A). The treatment system should be designed in a way that allows ready addition of such a unit, should it become necessary.

5.6 BASIC MAINTENANCE REQUIREMENTS

Since the duration of the remediation is planned for a total of 7 years, there could be major maintenance issues for most equipment. It is good practice that a record-keeping system be developed to help manage information and activities related to the following:

- Prevent maintenance schedule and completion
- Repair and maintenance performed
- Master equipment list
- Repair parts list
- Equipment vendor data index
- Operation records

The following equipment will likely require maintenance and repair:

- Boilers
- Pumps (potentially require significant maintenance)
- Compressors
- Piping
- Valves and meters
- Injection and extraction wells (potentially require significant maintenance)

Routine maintenance for pumps consists of lubrication and cleaning every 6 months and checking the oil level every month. Pump seals should be periodically checked, and pumps should be inspected for leaks, cracks, wear, or damage in the piping, especially from the extraction well to the treatment plant. Additionally, valves and flow meters may need to be repaired or replaced.

5.7 DURATION OF THERMAL TREATMENT

This section presents the assumptions made for setting the duration of the thermal treatment and briefly discusses the operational adjustments made in order to optimize the COC removal rates and minimize the use of time and resources.

5.7.1 Criteria for Discontinuing Steam and Power Injection in Areas/Zones

All three scenarios assume a total duration of 4 years for thermal treatment, as defined in Section 5.1.2. However, thermal treatment may be discontinued in certain depth zones or sections of the site if the operational monitoring shows that continued operation will lead to diminishing returns for the invested time and effort.

Guidelines for discontinued steam injection and ERH in areas include the following:

- When the water extracted from the E-zone wells has no more NAPL or sheen.
- No more NAPL is recovered during aggressive extraction in the D-zone and the interval between D and E.
- Practical constraints indicate that recovery of more NAPL from the A-, B-, and C-zones and the silt layers between them is no longer worth the time and resources (diminishing returns).
- The cumulative data indicate that mobile NAPL will not be able to migrate downward after heating is discontinued. (Specific criteria will be established to determine NAPL mobility).
- The whole target volume has been raised to a specific target temperature for a defined period of time.

5.7.2 NAPL Removal Rates

The total NAPL removal rate will be determined on the basis of daily measurements of the NAPL levels in the holding tanks used for on-site storage of recovered product. If the total NAPL removal rate diminishes for the site, the focus will be on the distribution of dissolved COCs across the extraction well-field.

In addition to monitoring the total NAPL recovery rate, the NAPL recovery from individual well clusters and separate wells will be monitored manually by visual observation of the NAPL fraction in the discharge lines from dedicated pumps. This will be performed either by installation of fraction collectors at the desired locations (for an accurate NAPL fraction estimate), or alternatively by visual observation through transparent Teflon™ tubing (for absence or presence of NAPL).

If the NAPL recovery rates from wells in the A-, B-, or C-zones diminish, the thermal treatment may be scaled back in order to save resources. However, several pressure cycles will be conducted in those zones before the decision is made to scale back.

If NAPL recovery rates diminish in the D- and E-zone extraction wells, operations will be continued with the main focus of removing leftover dissolved and adsorbed COCs by in situ destruction and vaporization during pressure cycling. The monitoring then will focus more on the dissolved COC levels in the extracted water

5.7.3 Dissolved Total Organic Carbon and COC Removal Rates

Diminishing NAPL recovery is expected for the D- and E-zones during thermal treatment, since these zones have much less mass of contamination, and will be flushed with more steam pore volumes than the upper zones. When small amounts of NAPL are recovered from certain wells, the dissolved concentration of total organic carbon (TOC) becomes the next relevant parameter. TOC can be measured inexpensively on site. Periodic screening of the well-field for TOC contents can provide a detailed picture of where the remaining extracted mass is coming from, and it will allow the operators to focus thermal treatment in those areas and depth intervals.

The concentrations of individual COCs indicate how far the steam distillation and destruction reactions have proceeded near the well being sampled. For discontinuing thermal treatment in the E-zone, where the targets for groundwater are MCLs (for organic COCs) or background (for inorganic COCs), dissolved COC concentrations will be monitored in point of compliance wells.

5.7.4 In Situ Destruction Rate Evaluation

After most of the NAPL has been removed from the site and the COC concentrations are approaching the cleanup levels, an evaluation of the in situ destruction rates may provide a basis for discontinuing operation prior to the achievement of all the groundwater goals. Such an evaluation will be based on the following:

- Measurement of recovered carbon dioxide in the extracted vapors and comparison to atmospheric levels as well as levels obtained during the proceeding operational phases.

- If practical, measurement of the isotopic composition of the extracted inorganic carbon, allowing for an estimate of the fraction of carbon derived from the oxidation of creosote-related organic carbon, which has a different isotopic signature than naturally occurring organics such as humic and fulvic acids.

If it can be established that the in situ destruction rates are sufficient to degrade the leftover COCs within the cool-down period, active thermal treatment can be discontinued.

5.7.5 Redox Level Measurements and Air Injection Strategy

An important prerequisite for relying on aerobic in situ destruction reactions is that sufficient oxygen is present in the groundwater at the appropriate locations. Oxygen will be injected along with the steam into an initially anaerobic aquifer. Anaerobic conditions were observed as low redox levels, absence of oxygen and nitrate, and the presence of reduced species such as ferrous iron, ammonia, and methane in groundwater (USACE 2001a).

The maximum solubility of oxygen in water at different depths below the water table and at different temperatures is shown in Figure 5-1. At depth, dissolved oxygen concentrations of 10 mg/L or higher can be accomplished, which will encourage hydrous pyrolysis oxidation reactions at depth.

Measurement of dissolved oxygen in the extracted water will be used to evaluate the optimal air injection rates. If possible, the air injection rate will be adjusted to allow for more than 1 mg/L dissolved oxygen in the extracted water.

5.7.6 General Considerations Regarding Steam Pore Volumes

The selection of the necessary number of pore volumes of steam and the needed amount of electrical energy input were based on several sources of information.

Laboratory treatability studies were inconclusive with respect to the number of pore volumes needed to remove the mobile NAPL and to reduce the water concentrations to MCLs. Two pore volumes were sufficient to remove the mobile NAPL. However, this does not scale up directly in the field due to flow regime issues.

Field experience from Visalia (Southern California Edison 2000) indicates the following:

- Mobile NAPL can be removed with an average injection of less than two pore volumes of steam (the Visalia site was more permeable, so it cannot be directly scaled).
- The MCL for PCP can be approached in the best wells with an average steam injection of less than two pore volumes.

The following assumptions were made:

- Mobile NAPL layers will receive at least two pore volumes of steam or an equivalent amount of energy will be injected using ERH.
- Silt and clay layers will be heated to steam temperature, and an additional 100 percent of the energy needed to heat them will be injected to encourage steam production and flushing of mobile NAPL out of these layers. This affects the upper 85 percent of the D-E aquitard in all scenarios and the B- and B-C-zones under the slough in Scenarios 2 and 3.

- The D-zone aquifer will receive at least three pore volumes of steam to ensure the removal of mobile NAPL and continued steam stripping and degradation reactions.

- The E-zone aquifer will receive at least four pore volumes of steam to ensure the removal of mobile NAPL and continued steam stripping and degradation reactions.

- Steam that sweeps upward through aquitard layers will be encouraged, thereby increasing the efficiency of the steam for NAPL removal.

5.7.7 Cool-Down Options and Stimulation of In Situ Destruction Reactions

After approximately 4 years of thermal treatment, a cool-down period is designed for all three scenarios. This period consists of continued pumping and treatment of water from the site, with the following main purposes:

- Preventing the escape of steam and COC-laden vapors from the site to the atmosphere, surface water, or groundwater

- Preventing the heating of Old Mormon Slough by upward migration of hot water and by thermal conduction from nearby heated soils

- Preventing the migration of hot groundwater off site

The main cooling mechanism will be the extraction of hot water from the aquifer zones and the replacement of the water by cool water from the outside. The extracted water will be cooled, treated, and re-injected to assist in cooling at desired locations.

During cool-down, degradation reactions such as hydrous pyrolysis and biological oxidation can play a major role in reducing the groundwater concentrations at the site. These processes can be encouraged by the following:

- Aeration of all re-injected water during the treatment so that the dissolved oxygen levels are in the 5 to 50 mg/L range (depth and pressure dependent)

- Injection of air into zones where supplemental oxygen is needed for degradation of leftover COCs

Other potential enhancements include ozone injection, addition of nutrients to the re-injection water, and the use of pressure vessels to aerate the water, allowing for a dissolved oxygen level higher than 10 mg/L for re-injection. If thermal treatment is selected for source removal, additional methods of enhancing natural degradation processes would still be required to achieve final groundwater cleanup standards at the site.

The duration of the cool-down period for each scenario was calculated using a simple heat removal simulation. It was assumed that the effluent treatment system size would be kept the same as that for thermal treatment and that the extracted water mass would constantly be replaced by inward flow of cool water (from adjacent aquifers or from re-injection wells). A target extracted water temperature of 40°C was chosen. This means that the temperatures at the site boundaries will be well below this temperature, probably much closer to ambient temperatures. As such, the risk of adverse thermal impacts at the cessation of pumping would be minimal.

In Scenarios 1 and 2, some of the extraction wells will be located in unheated regions outside the target volume for thermal treatment, and their pumping will remove essentially no heat. It was assumed that the portion of the pumping occurring in the heated zone is in proportion to the fraction of the total heated region.

The water from the wells will be slightly cooler than the average temperature of the site because the water pulled from the wells will be influenced by the most permeable pathways from outside the site. These permeable pathways will cool more rapidly and we will have to rely on an element of thermal conduction to move heat into the water from the less permeable zones.

The simulated cool-down is shown in Figure 5-2. Resulting cooling times are shown in Table 5-1.

5.7.8 Estimates of Total Operation Time

Figure 5-2 indicates that the desired cooling can be accomplished in a period of 2.5 to 3 years. The total estimated operation time (thermal treatments and cool-down) is to about 7 years for all three scenarios.

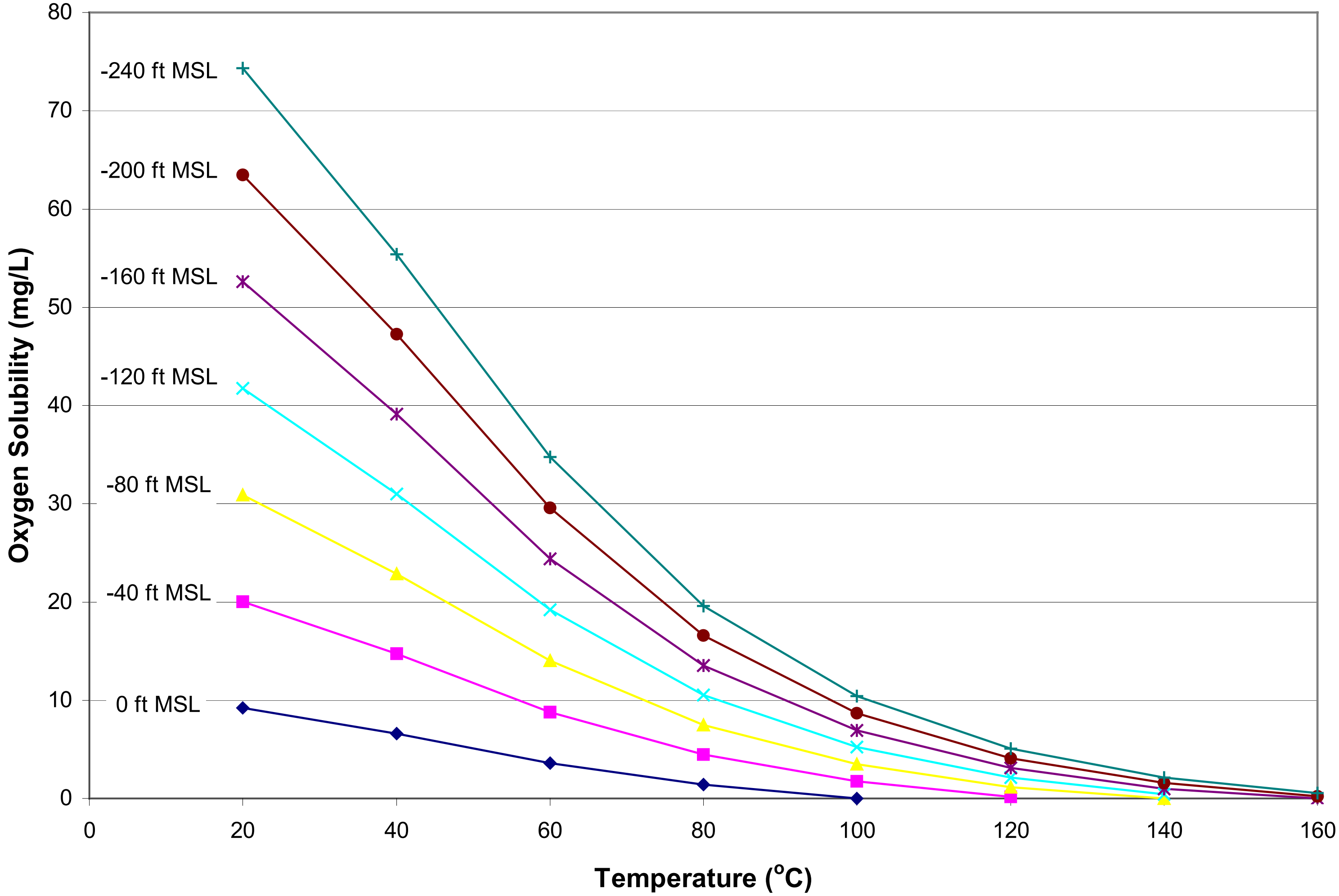

Figure 5-1
Oxygen Solubility in Water as a Function of Depth Below the Water Table and Temperature

THERMAL TREATMENT TECHNOLOGY
CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

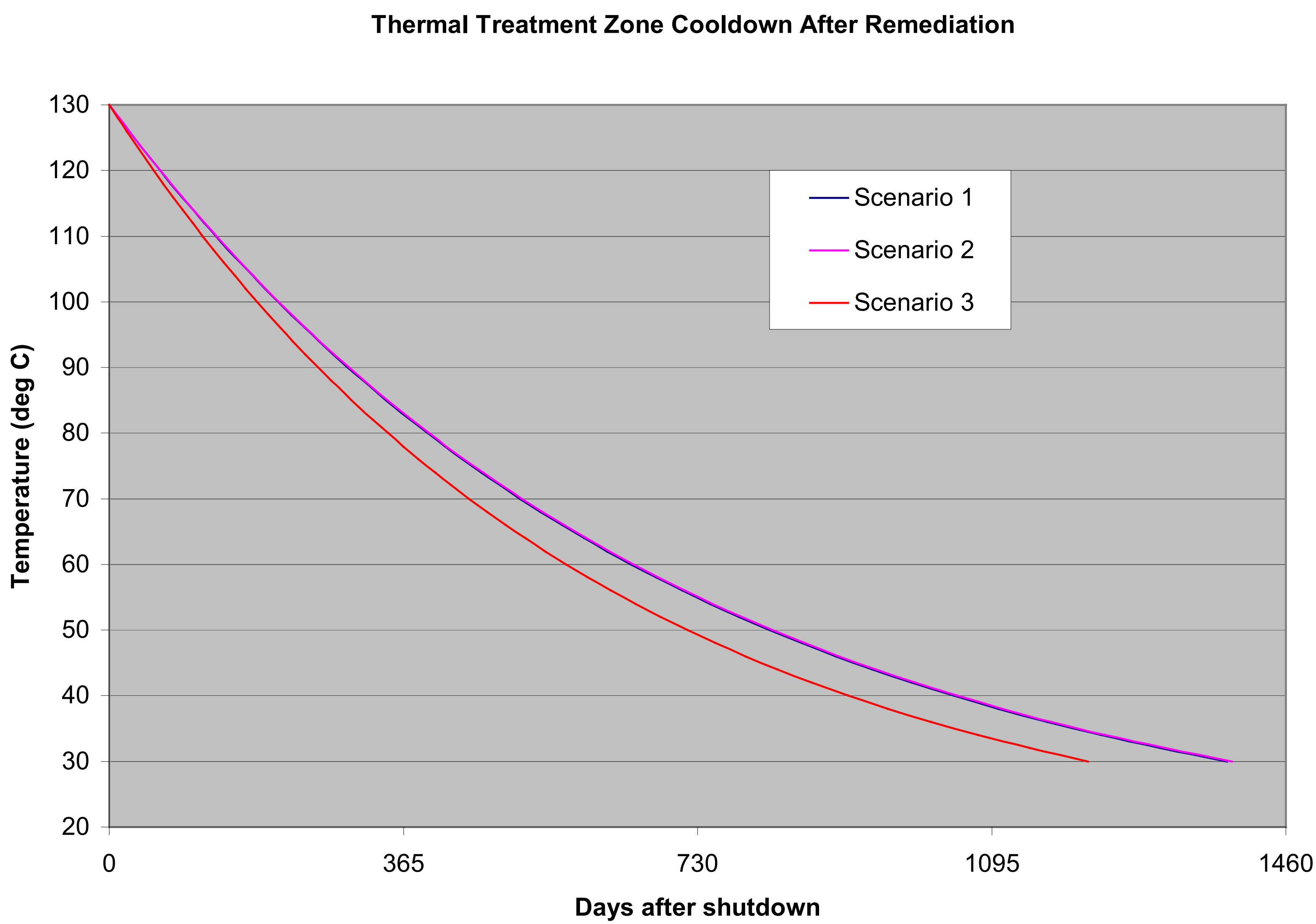

Figure 5-2
Simulated Cool-Down–Average Effluent Water Temperature

THERMAL TREATMENT TECHNOLOGY
CONCEPTUAL DESIGN
McCormick and Baxter Superfund Site
Stockton, California

Table 5-1
Treatment Time Estimates, Including Cool-Down Period

	Pump-and-treat	Scenario 1	Scenario 2	Scenario 3	Unit
Volume in Thermal Treatment (TT) zone	2,952,365	1,541,854	2,103,242	2,952,365	yd^3
% of total treated thermally	0	52	71	100	%
Heated volume[1]	NA	1,927,318	2,418,728	3,247,601	yd^3
Total amount of energy stored	NA	442	674	960	10^9 BTU
Total water extraction rate	NA	475	575	700	gpm
Cooling water extraction rate[2]	NA	282	428	700	gpm
Thermal treatment duration	0	4.0	4.0	4.0	years
Cool-down to 40 °C	0	2.9	2.9	2.5	years
Total duration of activities, 40 °C final	>100	6.9	6.9	6.5	years
1) Heated volume is corrected for steam and heat losses to the surrounding formation					
2) Assuming that not all water can be pumped from the heated areas during cool-down (scaled by volume fraction of full site)					

6.0 PERFORMANCE AND COMPLIANCE MONITORING

6.1 TEMPERATURE AND STEAM DISTRIBUTION MONITORING

This section provides a suggested data collection schedule for acceptable coverage of subsurface monitoring over time.

A complete set of ERT data will be collected, processed, and interpreted, prior to the injection of steam. These data would be collected no sooner than 2 weeks after the last VEA hole has been grouted, to allow time for the grout to dry completely and eliminate any radical resistivity fluctuations that occur during the drying process. This would serve as a background measurement set against which to compare all data collected after thermal treatment begins. A background data set would be collected twice, several days apart. The purpose of the two data sets would be to determine the expected sensitivity of the measurement equipment. In other words, any changes in the resistivity between the two data sets that should otherwise be identical would be indicative of measurement error effects, like noise. Then, when data are collected during a process to observe, it would be understood which resistivity changes are true anomalies and which are just noise effects.

Table 6-1 provides an overview of the estimated data collection schedule during thermal operation, cool-down, and long-term monitoring. This schedule may be refined at a later design stage.

6.2 SUBSURFACE CONTAMINANT REMOVAL RATE MONITORING

It is not absolutely crucial, nor is it possible, to document the mass of contaminants removed or destroyed during full-scale thermal remediation as a means to evaluate remedy effectiveness. The initial NAPL volume at the site was estimated to be in the range of 1 million gallons, but with a high degree of uncertainty. Therefore, it is not possible to determine the amount of NAPL left or the degree of cleanup based on the removed mass. For the contaminant removal rate monitoring design, it has been assumed that the following data objectives apply:

- The cumulative volume of recovered NAPL will be documented for waste disposal and cost tracking.
- The amounts of individual COCs removed in the vapor phase will not be determined accurately, rather they will be estimated based on concentrations detected in grab samples and rough estimates of the amounts of COCs recovered from the GAC during steam regeneration of the vapor-phase GAC vessels.

- The amounts of individual COCs removed in the dissolved phase will not be determined accurately, rather they will be estimated based on concentrations detected in grab samples, and rough estimates of the amounts of COCs recovered from the GAC during steam regeneration of the liquid-phase GAC vessels.

- The amounts of individual COCs in the disposed GAC will not need to be quantified, since the amounts will be small and the data will not be needed.

- The amounts of individual COCs degraded in situ will not be quantified. However, the geochemical and thermodynamic conditions will be optimized to allow for in situ destruction (see Section 5.1), and the water quality monitoring will be used to adjust the operational strategy in order to optimize the in situ destruction.

Since a total COC mass balance is not crucial, the sampling and analysis performed for the effluent treatment system and at the wellhead level will be restricted to the minimum necessary to document the treatment efficiency and to troubleshoot individual system components. The monitoring program will include the following:

- Weekly gauging of the amount of NAPL recovered in the holding tanks (to support the flow rate data, which will be collected automatically).

- Monthly sampling of the major liquid and vapor streams for the major COC levels (semivolatile organic compounds [SVOCs] and metals).

- In-line measurements of bulk parameters in separate waste streams using automated equipment: FID and infrared sensors on dry vapors for estimation of carbon mass and carbon dioxide levels, and TOC analyzer sampling and analysis of key water streams for bulk organic carbon.

- Miscellaneous automated flow rate and cumulative flow measurements on NAPL, water, and vapor streams. The data are collected mainly to ensure that the treatment system is functioning correctly and to optimize individual components. The NAPL flows from holding tanks, dissolved air floatation units, and condensate streams from regenerating carbon will be quantified and used to document the efficiency of each component.

Overall, the flow rate monitoring, grab sampling for COC concentrations, and the measurement of bulk vapor and water parameters will be used to estimate the removed mass and, more importantly, to optimize the treatment system efficiency. Finally, the analysis of the phase distribution of the recovered mass (vapor, dissolved, and NAPL) will be used to optimize the operational strategy.

6.3 REMEDY EFFECTIVENESS MONITORING

A key component of the thermal treatment is the monitoring conducted to document the remedy effectiveness. For a complex site with multiple injection and extraction zones, the remedy effectiveness can be evaluated by the following data:

- Recovery from the combined well-field (treatment system level)
  - NAPL recovery rate for the combined well-field operated under ideal conditions
  - Bulk TOC recovery rates in the extracted water (most relevant when NAPL removal diminishes)
  - Bulk TOC recovery rates in the vapors extracted
  - COC concentrations in the combined effluent streams of liquids and vapor
- Recovery from individual depth zones and areas
  - NAPL recovery
  - TOC in water and vapor
  - Individual COC levels in water and vapor
- Individual well performance
  - NAPL production
  - TOC in water and vapor
- Individual COC levels in water and vapor
  - Monitoring parameters from surrounding wells
  - Groundwater COC concentrations
- Interim drill-back activities
  - Soil TPH analysis to estimate leaching potential

  - Soil COC concentrations

- Final drill-back and site characterization

  - LIF survey
  - NAPL mobility leach tests
  - Soil COC concentrations
  - Groundwater COC concentrations

Recovery data will be collected during heat-up, continued thermal treatment, and cool-down. The data will be collected as an integral part of the overall sampling and monitoring program.

The interim drill-back activities may be used to determine if individual zones have reached the desired cleanup levels and to identify areas that need additional treatment. One drill-back per year is recommended during thermal treatment (three total). Each activity will involve an estimated 10 boreholes drilled to the target treatment depth at each location, with an estimated average drilling depth of 150 feet per borehole.

The final site characterization will be conducted after cool-down is complete. It will consist of drill-back (approximately 10 boreholes) and groundwater sampling and analysis. The final scope and extent of this effort will be designed at a later stage.

6.4 BOILER AIR EMISSIONS MONITORING

The objective of monitoring boiler emissions is to demonstrate substantive compliance with local, state, and federal regulations and demonstrate that the thermal remediation system would not affect the ambient air quality in the surrounding community.

The Clean Air Act (CAA), which was last amended in 1990, requires the EPA to set National Ambient Air Quality Standards for pollutants considered harmful to public health and the environment. The CAA established primary and secondary air quality standards. Primary standards set limits to protect public health, including the health of "sensitive" populations such as children, the elderly, and individuals with asthma. Secondary standards set limits to protect public welfare, including protection against decreased visibility, and damage to animals, crops, vegetation, and buildings. National Ambient Air Quality Standards for six principal pollutants, which are called "criteria" pollutants, are provided in Table 6-2.

In general, emissions from manufacturing operations are regulated under the CAA. Similarly, emission-control devices or units themselves (e.g., gas-phase activated carbon units) are also subject to CAA control. Therefore, boiler emissions are regulated under the CAA and are subject to compliance with national ambient air quality requirements. It is anticipated that the following criteria pollutants may be analyzed: carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2) or sulfur oxides (SO_x), and particulate mater (PM).

RCRA requirements for boiler emissions are applicable or relevant and appropriate requirements (ARARs). Thermal treatment after a material (solid or liquid) becomes a hazardous waste (i.e., heating it to a gaseous state) is fully regulated under RCRA (54 FR 50973; December 11, 1989). Emissions from boilers and industrial furnaces that burn hazardous waste are regulated under 40 CFR, Part 266, Subpart H. Emission screening limits have been set for various metals (including arsenic and chromium, which are COCs at the site), chlorine gas (Cl_2), hydrogen chloride (HCl), and various volatile organic compounds (VOCs) and SVOCs.

Although it is possible to estimate the composition and volume of noncondensable vapors entering the boiler, it is difficult to estimate the quantity or variability of the constituents over time. Therefore, it is not possible to conclusively predetermine the type or amount of emissions generated by the treatment of the waste stream. Therefore, initial testing of the boiler for toxic air pollutant (TAP) emissions as provided in Table 6-3 would be conducted to determine the type and quantity of emissions produced by the treatment system. EPA guidance allows for sampling to be conducted on one representative unit if the boilers are similar (e.g., same size, operation, influent streams, etc.), and, therefore, emissions would be tested from only one of the four boilers.

Based on the chemicals of potential concern at the site and regulatory requirements, it is anticipated that the boiler exhaust stream would be sampled for dioxins/furans, PAHs, SVOCs, VOCs, HCl, Cl_2, particulate matter (PM), and metals. The boiler would be tested under a single operating condition, and three exhaust gas samples would be collected for each parameter. In addition, a field blank would be collected for each sampling train, and three field blanks would be collected for VOCs (i.e., one pair of resin traps would be collected during each day of sampling). The dioxin/furan, PAH, and SVOC samples would be collected using a Modified Method 5 sampling train. Dioxins/furans would be collected on a separate sampling train according to EPA Method 0023, whereas PAHs and SVOCs would be collected simultaneously on a single sampling train according to EPA Method 0010 procedures. Both sampling trains would be run for approximately 3 hours to collect the appropriate sample volume. The Volatile Organic Sampling Train (VOST) would be used to collect gas samples for VOCs. Six pairs of resin traps would be collected over each sampling run at various sampling volumes; three pairs of traps would be analyzed for each run. One of these three pairs would be analyzed separately to assess potential breakthrough of target analytes. Total hydrocarbon concentrations would be measured using a continuous emission monitor according to EPA Method 25. EPA Method 0050 would be used to collect HCl/Cl_2 and PM samples over an approximate 2-hour period. Metals would be collected over a 1-hour sampling period according to EPA Method 0060 procedures. The boiler exhaust gas would also be sampled for total hydrocarbons (THCs), CO, SO_x, and nitrogen oxides (NO_x) using a continuous emission monitoring system (CEMS).

It has been assumed that at least three sampling ports would be available to conduct the boiler emissions testing. Based on this assumption, it would take approximately 12 hours of steady state operation of the system to collect one run of the required samples. Therefore, boiler exhaust samples would be collected over a 3-day period. One day would be required to set up all equipment and the mobile laboratory and 1 day would be needed for demobilization (i.e., it would take a total of 5 days on site to conduct the boiler testing). It is anticipated that after the initial sampling, the analyte list could be reduced to opacity, CO, SO_x, and NO_x using CEMS.

Emissions testing for the gas-phase activated carbon unit during the steam phase of treatment would likely not be required since it is configured as a bypass (i.e., backup) unit.

Air monitoring of the gas-phase activated carbon is anticipated during the cool down phase. The boilers, which are the system's primary vapor treatment units, are not operating during cool-down.

6.5 SITE FUGITIVE EMISSIONS MONITORING

The objectives of fugitive emission monitoring are (1) to ensure that organic vapors emitted by operations of the thermal remediation system would not affect the surrounding community or on-site personnel, and (2) to demonstrate substantive compliance with local, state, and federal clean air regulations. Conceptually, there are three potential sources of fugitive air emissions: the conveyance system from the wellheads to the treatment plant, the treatment plant, and the soil area surrounding the treatment areas. Since the conveyance system would operate under negative pressure, it is unlikely that the pipe runs from the wellheads to the treatment plant would be a source of organic vapors. COCs include PAHs and PCP.

Potentially the largest source of fugitive emissions during the steam-phase treatment operations is the contaminated soils surrounding the treatment areas. In addition, a substantial volume of NAPL exists in the subsurface (USACE 2000a, 2000b, 2000c). Steam injection in the treatment areas may result in conductive heating of subsurface soils surrounding these areas. Consequently, volatilization of organic vapors may occur outside the perimeter of the planned vapor cap and vapor collection. Fugitive emissions can also occur at wells, pumping systems, and other portions of the treatment plant. Similar to the treatment plant, COCs that may be emitted from heated soils surrounding the treatment areas are PAHs and PCP.

Fugitive emissions would be assessed at two levels. Site worker exposure would be monitored with personal air monitoring. Substantive compliance with local, state, and federal clean air regulations would be assessed with the use of canister air samples collected at the perimeter of the treatment area. The compliance monitoring program for the steam phase (active phase) and cool-down phase of treatment are provided in Table 6-3.

For the steam phase, up to three monitoring stations would be established around the perimeter of the treatment area. The monitoring stations would depend on seasonal changes that may effect the predominant wind direction. At least one station would serve as a background station. Initial sampling frequency would be determined after consultation with the local air quality agency. However it is anticipated that PAHs, PCP, and PM would be analyzed monthly, and CO, SO_x, and NO_x would be analyzed by CEMS. If no regulatory action levels are exceeded, monitoring may be decreased. Monitoring may be re-initiated for each 25°C increase in perimeter soil temperature.

During the cool-down phase, it is anticipated that sampling would be reduced to PAHs, PCP, and PM on a quarterly basis at three monitoring stations.

6.6 TREATMENT PLANT DISCHARGE MONITORING

Effluent from the treatment plant would be re-injected into groundwater at the site. The COCs that would be monitored include TPH, PAHs, PCP, metals (arsenic, chromium, copper, and zinc), and dioxins/furans. Effluent from the treatment system would be sampled and analyzed on a monthly basis, except for dioxins/furans, which would be sampled and analyzed on a quarterly basis. Sampling would likely be required at a higher frequency during the initial treatment phase; however, the frequency may be reduced later in the steam phase and cool-down phase of the treatment program. Cleanup levels (i.e., effluent standards for groundwater re-injection) would likely be set based on background levels in the E-zone aquifer.

A summary of compliance criteria for groundwater re-injection is provided in Table 6-4. The criteria are compared to the quantitation limits and the background contaminant levels. The criteria selected and included in this table are based on the following beneficial uses as presented in the document *The Water Quality Control Plan (Basin Plan) for the California Regional Water Quality Control Board, Central Valley Region, The Sacramento River Basin and the San Joaquin River Basin* (California Regional Water Quality Control Board, Central Valley Region 1998):

- Municipal and domestic water
- Agricultural supply
- Industrial service supply
- Industrial process supply

6.7 WASTE DISPOSAL CHARACTERIZATION

Waste material generated from the thermal treatment at the site would include both liquids and solids. NAPL recovered from the thermal treatment process would require disposal. Additionally, solids collected from the extraction wells during treatment, spent activated carbon (SAC), sludge, and spent filter media would also require disposal. Sampling would be conducted to verify compliance with all applicable state and federal hazardous waste regulations. The reasons for selective sampling are described in the following subsections. The wastes generated from the process would not be handled as RCRA-listed hazardous waste; however, they may be handled as a RCRA-characteristic waste for off-site disposal.

6.7.1 NAPL Disposal Characterization

NAPL requiring disposal would include all recovered product from the treatment plant and extraction at the wells. NAPL would be recovered by the on-site recovery system (i.e., thermal treatment train). The NAPL would likely require off-site disposal at a RCRA-permitted incinerator or permitted boiler. Characterization of the NAPL would include TPH, PAHs, PCP, metals (arsenic, chromium, copper, and zinc), and dioxins/furans. It is anticipated that characterization would be required quarterly during the steam phase of treatment and annually during the cool-down phase.

6.7.2 Solid Waste Characterization

Solid wastes generated during the treatment process would include solids that accumulate in extraction wells during treatment; sludge bottoms from treatment system components (e.g., oil-water separator units); SAC from the GAC unit, which consists of waste material that can no longer be thermally regenerated; and spent filter media from the sand filters. These materials would need to be characterized using the toxicity characteristics leaching procedure (TCLP) to determine disposal requirements. COCs at the site that have established regulatory limits on the TCLP extract for the toxicity characteristics include arsenic, chromium, and SVOCs (e.g., PCP). It is anticipated that solids characterization would be required quarterly during the steam phase of treatment and annually during the cool-down phase.

6.8 SITE PERIMETER ENVIRONMENTAL MONITORING

The objectives of site perimeter monitoring are to evaluate potential impacts of the thermal treatment system operations on the surrounding community and to demonstrate substantive compliance with local, state, and federal environmental regulations. Perimeter monitoring will be focused on measuring and evaluating impacts beyond the perimeter of the site.

6.8.1 Noise Monitoring

The objectives of noise level monitoring are to evaluate the impacts on the surrounding community and to ensure that the exposure of workers to on-site noise complies with the Occupation Safety and Health Act (OSHA) during all operational phases of the thermal treatment system. The federal role in regulating noise is predominately limited to transportation, workplace activities, and certain types of machinery. State and local governments determine the extent to which all other sources of noise are controlled, and regulations for such sources can vary widely among localities. The state of California has not established any standards to restrict noise but does provide model ordinances to assist municipal governments in developing noise-control programs. Sources of noise commonly regulated at the state and local level include commercial, industrial, and residential activities. Regulations for such sources typically control the public's exposure to irritating or potentially harmful noise levels by limiting the activity concerned to specific times of the day.

Prior to actual treatment operations, a background study would be conducted to measure ambient noise conditions at the three or four community monitoring locations. Once ambient noise levels have been established, several monitoring events would be conducted at the site during active construction activities to maintain compliance with worker-related (OSHA) and local ordinances. Background and monitoring events may use Type I or Type II sound level meters with a demonstrated accuracy of ±1 dBA for Type I meters and ± 2 dBA for Type II meters. At the time of testing, wind speed should not exceed 12 mph, and no testing should occur when precipitation is falling at a rate that would affect measurement readings. Typically, a random-incidence microphone is used and oriented vertically to assess ambient noise levels from all potential noise sources. A 25-hour noise-monitoring period is recommended, with hourly noise statistics.

Technically, noise generated by construction activity is exempt from community noise regulations. At the discretion of the EPA, noise monitoring can be instituted during construction to address specific concerns of stakeholders or the surrounding community.

6.8.2 Air Quality

Construction on the site has the potential to create dust that could impact the ambient air quality of the surrounding community. While engineering controls are likely to control the generation of dust during construction, ambient air quality monitoring may be conducted to verify that air quality during construction activities substantively complies with local, state, and federal ambient air standards for airborne particulates. Initial air monitoring is described below.

Air monitoring during construction may include the use of an MIE DataRAM, a realtime aerosol monitor (RAM). The instrument would be placed downwind of construction activities (based on meteorological data). The MIE DataRAM would monitor dust generated on site by construction and operation/maintenance activities, as well as ambient dust levels unrelated to site activities. The monitors can be operated continuously and have the ability to collect and log the data. Analytes for construction monitoring include PM_{10} (particulate matter with a mass median aerodynamic diameter less than 10 micrometers), PCP, and PAHs. Samples would be collected every 8 hours for the first 7 days during construction activities.

During operations, air monitoring instruments would remain at stationary locations (to be determined) surrounding the treatment areas. Analytes for operation monitoring include PM_{10}, CO, SO_x, NO_2, PCP, and PAHs. Particulate matter would be monitored at three stations using a RAM every 8 hours for the 7 days of operation. If any 8-hour measurement exceeds 50 $\mu g/m^3$ in 8 hours, then a RAM would be collocated with a Hi-Vol Sampler or equivalent to determine if the concentration exceeds 150 $\mu g/m^3$ over 24 hours. If this value is exceeded, institutional controls (such as a temporary buffer zone) would be implemented until concentrations decrease below exposure limits. PCP and PAHs would be monitored with a canister sampler, and samples would be sent for laboratory analysis. CO, SO_x, and NO_2 would be monitored with a CEMS. Samples for all of the organics would be taken every 8 hours for the first 7 days of operation. If no permissible exposure limits (PELs) are exceeded, sampling intensity could be decreased.

6.9 GROUNDWATER MONITORING

Compliance monitoring for groundwater would be conducted at the perimeter during treatment (steam phase and cool-down phase) and at the perimeter and within the treatment zone for long-term monitoring (after treatment is complete).

Perimeter monitoring would be conducted to ensure compliance with relevant RAOs. Select perimeter monitoring wells would be analyzed for groundwater contaminant concentrations, and all monitoring wells located outside of the thermal treatment zones would be used to determine hydraulic gradients (horizontal and vertical). Analysis of groundwater samples would be for COCs identified in the Record of Decision (USEPA 1999), including PAHs, PCP, dioxins/furans, and metals (arsenic, chromium, copper, and zinc). Information obtained from the perimeter monitoring well network would be used to evaluate contaminant concentration trends (increasing, decreasing, or stable), horizontal gradients (toward the site, away from the site, or flat), and vertical gradients (downward, upward, or neutral). If that analysis indicates that off-site migration of contaminants is occurring, then remedy modifications would be considered.

To accommodate requirements for determining horizontal hydraulic gradients, new perimeter monitoring wells would be installed as pairs, located less than 100 feet apart and screened across the same stratigraphic interval. Wherever possible, existing monitoring wells would be used, and a new perimeter monitoring well would be installed nearby. For each monitoring well pair, only one would be sampled periodically for contaminant concentrations (Table 6-5).

Monitoring frequency and duration will depend on the amount of NAPL removal achieved under the three remediation scenarios. Additionally, the monitoring frequency for the 7-year period of active remediation (including cool-down period) will be different from that of the post-remediation period. Because mobility of contaminants is enhanced during thermal treatment, monitoring for all scenarios and in all zones would take place semi-annually for the period through cool-down. For all scenarios after cool-down, complete restoration of the D- and E-zones is assumed. For cost estimating purposes, monitoring in the D- and E-zones would occur every 5 years as part of the 5-year review process. More frequent sampling may be required based on remedy effectiveness monitoring and data quality objectives that have yet to be developed by EPA, the state of California, and other stakeholders. Monitoring is assumed to continue for 30 years or until the site is delisted. In zones A through C, a significant amount of NAPL may be left in place, since fewer pore volumes of steam are flushed through the soils. Monitoring would, therefore, take place annually for 30 years and the analyte list would be reduced to PAHs and PCP. The monitoring program is outlined in Tables 6-3, 6-5, and 6-6.

6.10 SOIL CONFIRMATION SAMPLING

Soil borings would be collected at the end of the cool-down phase. An LIF survey would be conducted to select soil samples for analysis. It is anticipated that 10 samples would be collected and tested for TPH, PAHs, and PCP. In addition, an estimated 10 NAPL mobility leach tests would be conducted to evaluate the effectiveness of the thermal treatment at reducing contaminant mobility.

Table 6-1
Overview of Sampling Frequency for Subsurface ERT and Temperature Monitoring

	General Site Coverage		Vertical Plane South of Slough		Horizontal Plane Under Slough	New P&T Extraction Wells	New P&T Monitoring Wells
Phase	**ERT**	**DTS**	**ERT**	**DTS**	**ERT**	**DTS**	**DTS**
Heat-up	Weekly	Daily	Weekly	Daily	Daily	Daily	Daily
Flushing/cycling	Monthly	Weekly	Monthly	Weekly	Daily	Weekly	Weekly
Cool-down	Quarterly	Monthly	Quarterly	Monthly	Weekly	Monthly	Monthly
Long-term monitoring	NA	NA	NA	NA	NA	NA	Quarterly

Table 6-2
National Ambient Air Quality Standards

Constituent	Standard Value ($\mu g/m^3$)	Standard Type
CO		
1- Hour average	40 mg/m^3	Primary
8-Hour average	10 mg/m^3	Primary
NO_2		
Annual arithmetic mean	100	Primary and secondary
O_3		
1-Hour average	235	Primary and secondary
8-Hour average	157	Primary and secondary
Pb		
Quarterly average	1.5	Primary and secondary
PM_{10}		
Annual arithmetic mean	50	Primary and secondary
24-Hour average	150	Primary and secondary
SO_2		
Annual arithmetic mean	80	Primary
24-Hour average	365	Primary and secondary
3-Hour average	1,300	Primary and secondary

Note: Units in microgram per cubic meter of air, unless otherwise noted.

Table 6-3
Performance and Compliance Monitoring and Confirmational Sampling

Characteristic	Media	Analyte	Frequency	No. of Sampling Points	Total No. per Year[a]
Performance Monitoring—Steam Phase					
ERT data	Subsurface	Temperature	Daily/weekly/ monthly (see Table 6-1)	41 to 63 vertical 4 horizontal	NA
Electrical	System	Amps and power	Weekly	59 ERH electrodes	NA
Temperature/DTS distribution	Wellhead	Temperature	Daily/weekly (see Table 6-1)	301 to 416 wells	NA
Steam distribution	Wellhead	Liquid flow	Continuous	169 to 249	NA
	Wellhead, boiler plant, treatment plant	Pressure	Continuous	200 to 300	NA
Contaminant removal rate	NAPL (at wellhead)	Volume	Weekly	132 to 167	NA
	Contaminated water	Flow Volume TOC	Continuous Weekly Weekly	132 to 167 4 to 6 4 to 6	NA NA NA
	Vapor	Flow CO_2 PAHs PCP	Continuous Continuous Continuous Continuous	4 to 6 4 to 6 4 to 6 4 to 6	NA NA NA NA
Well installation soil borings[b]	Soil	Visual TPH PAHs PCP	Initial Confirmation Confirmation Confirmation	20 20 20 20	20 20 20 20
Interim drill-back soil borings	Soil	TPH PAHs PCP	Annual[c] Annual[c] Annual[c]	50[d] 50[d] 50[d]	50[d] 50[d] 50[d]
Groundwater monitoring[b]	Water	TOC PAHs PCP Metals[e] Dioxins/furans	Initial Initial Initial Initial Initial	60 60 60 60 10	60 60 60 60 10
Groundwater treatment plant monitoring	Water	TOC	Weekly	1	52
		PAHs	Monthly	1	12
		PCP	Monthly	1	12
Cool Down Phase					
Temperature/DTS distribution	Subsurface	Temperature	Monthly (see Table 6-1)	301 to 416 wells	NA
Contaminant removal rate	NAPL (at well-head)	Volume	Monthly	132 to 167	NA
	Contaminated water	Flow Volume TOC	Continuous Monthly Monthly	132 to 167 4 to 6 4 to 6	NA NA NA
	Vapor	Flow CO_2 PAHs PCP	Continuous Continuous Continuous Continuous	4 to 6 4 to 6 4 to 6 4 to 6	NA NA NA NA

Table 6-3 (Continued)
Performance and Compliance Monitoring and Confirmational Sampling

Characteristic	Media	Analyte	Frequency	No. of Sampling Points	Total No. per Year[a]
Performance Monitoring—Cool Down Phase (Continued)					
Groundwater treatment plant monitoring	Water	TOC	Weekly	1	52
		PAHs	Monthly	1	12
		PCP	Monthly	1	12
Compliance Monitoring—Steam Phase					
Boiler air emissions/ stack monitoring	Gas	VOCs	Initial	1	4[f]
		SVOCs[g]	Initial	1	4[f]
		Dioxins/furans	Initial	1	4[f]
		Metals[h]	Initial	1	4[f]
		PM	Initial	1	4[f]
		HCl	Initial	1	4[f]
		Cl_2	Initial	1	4[f]
		Total hydrocarbons	CEMS	1	NA
		CO	CEMS	1	NA
		SO_x	CEMS	1	NA
		NO_x	CEMS	1	NA
		Opacity	CEMS	1	NA
		CO	CEMS	1	NA
		SO_x	CEMS	1	NA
		NO_x	CEMS	1	NA
Site fugitive emissions/air quality perimeter monitoring	Air	PAHs	Monthly	3	36
		PCP	Monthly	3	36
		PM_{10}	Monthly	3	36
		Metals	Monthly	3	36
		CO	CEMS	3	NA
		SO_x	CEMS	3	NA
		NO_2	CEMS	3	NA
Treatment plant discharge (groundwater re-injection)	Water	TPH	Monthly	1	12
		PAHs	Monthly	1	12
		PCP	Monthly	1	12
		Metals[e]	Monthly	1	12
		Dioxins/furans	Quarterly	1	4
Waste disposal characterization	NAPL	TPH	Quarterly	1	4
		PAHs	Quarterly	1	4
		PCP	Quarterly	1	4
		Metals[e]	Quarterly	1	4
		Dioxins/furans	Quarterly	1	4
	Solids (well)	TCLP[i]	Quarterly	1	4
	Solids (SAC)	TCLP[i]	Quarterly	1	4
	Solids (sludge)	TCLP[i]	Quarterly	1	4
	Solids (spent filter media)	TCLP[i]	Quarterly	1	4
Perimeter groundwater monitoring	Water	PAHs	Semi-annual	25	50
		PCP	Semi-annual	25	50
		Metals[e]	Semi-annual	25	50
		Dioxins/furans	Semi-annual	25	50

Table 6-3 (Continued)
Performance and Compliance Monitoring and Confirmational Sampling

Characteristic	Media	Analyte	Frequency	No. of Sampling Points	Total No. per Year[a]
Cool-Down Phase					
Site fugitive emissions/air quality perimeter monitoring	Air	PAHs PCP PM	Quarterly Quarterly Quarterly	3 3 3	12 12 12
Treatment plant discharge (groundwater re-injection)	Water	TPH PAHs PCP Metals[e] Dioxins/furans	Monthly Monthly Monthly Monthly Quarterly	1 1 1 1 1	12 12 12 12 4
Waste disposal characterization	NAPL	TPH PAHs PCP Metals[e] Dioxins/furans	Annually Annually Annually Annually Annually	1 1 1 1 1	1 1 1 1 1
	Solids (well)	TCLP[i]	Annually	1	1
	Solids (SAC)	TCLP[i]	Annually	1	1
	Solids (sludge)	TCLP[i]	Annually	1	1
	Solids (spent filter media)	TCLP[i]	Annually	1	1
Perimeter groundwater monitoring	Water	TPH PCP Metals[e] Dioxins/furans	Semi-annual Semi-annual Semi-annual Semi-annual	25 25 25 25	50 50 50 50
Confirmational Sampling					
Soil borings	Soil	LIF survey NAPL mobility leach test[j] TPH PAHs PCP	Final Final Final Final Final	4 weeks 10 10 10 10	4 weeks 10 10 10 10
Long-Term Monitoring (30 years)					
Groundwater monitoring (perimeter and treatment zones)	Water	PAHs PCP	Annually Annually	25 25	25 25

Table 6-3 (Continued)
Performance and Compliance Monitoring and Confirmational Sampling

[a]Total number of samples does not include QA samples. QA samples are 10% per batch.
[b]Includes baseline sampling and analysis during system (e.g., wells) installation.
[c]Will be conducted for years 2, 3, and 4 (i.e., 3 times over the course of the steam treatment period).
[d]Assumes 5 samples from each of 10 borings.
[e]Metals include As, Cr, Cu, and Zn.
[f]Includes 3 samples taken from 1 boiler stack and 1 blank.
[g]SVOCs include PAHs and PCP.
[h]40 CFR 266.106 provides standards to control metals emissions. Subpart I regulated metals include Ag, As, Ba, Be, Cd, Cr, Hg, Pb, Sb, and Th. Of these metals, As and Cr are of concern at the site.
[i]Leachate from TCLP analyzed for As, Cr, and SVOCs
[j]NAPL Mobility Product Leaching Study, methodology leach test to be determined.

Notes:
Performance monitoring: Monitor system performance during remediation. Includes steam phase and cool-down period.
Compliance monitoring: Monitor compliance with disposal/discharge requirements. Includes steam phase and cool down period.
Confirmational sampling: To confirm "long-term effectiveness" of the remediation performed.

Ag: silver
As: arsenic
Ba: barium
Be: beryllium
CEMS: continuous emissions monitoring system
Cd: cadmium
CO: carbon monoxide
CO_2: carbon dioxide
COCs: chemicals of concern (PAHs, PCP, dioxins/furans, As, Cr, Cu, and Zn)
Cl_2: chlorine gas
Cr: chromium
Cu: copper
HCl: hydrogen chloride
Hg: mercury
LIF: laser-induced fluorescence
NO_x: nitrogen oxides
O_3: ozone
PAHs: polynuclear aromatic hydrocarbons
Pb: lead
PCP: pentachlorophenol
PM: particulate matter
SAC: spent activated carbon
Sb: antimony
SO_x: sulfur oxides
SVOCs: semivolatile organic compounds
TAPs: toxic air pollutants
TCLP: toxicity characteristics leaching procedure
Th: thallium
TOC: total organic carbon
TPH: total petroleum hydrocarbons
VOCs: volatile organic compounds
Zn: zinc

Table 6-4
Compliance Criteria for Groundwater Re-injection

Compounds	EPA Primary MCL	EPA Secondary MCLs	EPA IRIS Reference Dose	EPA IRIS 1 x 10^{-6} Cancer Risk Estimates 1 x 10^{-6} Cancer Risk Estimates	EPA Drinking Water Health Advisory (SNARLs) for Toxicity	NAS Drinking Water Health Advisory (SNARLs) for Toxicity	EPA Drinking Water Health Advisory (SNARLs) for Cancer	CA Primary MCLs	CA Secondary MCLs	CA Public Health Goals	CAL/EPA Cancer Potency Factor	CA Proposition 65 Regulatory Level	CA State Action Level - Toxicity	Other Taste and Odor Thresholds	Agricultural Water Quality Goals[4]	Tap Water PRGs	Quantitation Limits or Method 1613B Reporting Limits	Background Levels		
																		Well OFS-5A[11]	Well OFS-5C	Well OFS-5E
PAHs µg/L (Method 8270)																				
Acenaphthene	NA	NA	420	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	370 - nc	0.1 - 10	ND	ND	ND
Anthracene	NA	NA	2100	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1800 - nc	0.1 - 10	ND	ND	ND
Benzo(a)anthracene	0.1[5]	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.029	0.02[1]	NA	NA	NA	0.092 - ca	0.1 - 10	ND	ND	ND
Benzo(a)pyrene	0.2	NA	NA	NA	NA	NA	NA	0.2	NA	0.004	0.029	0.02[1]	NA	NA	NA	0.0092 – ca[9]	0.1 - 10	ND	ND	ND
Benzo(b)fluoranthene	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.029	0.02[1]	NA	NA	NA	0.092 - ca	0.1 - 10	ND	ND	ND
Benzo(g,h,i)perylene[12]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.1 - 10	ND	ND	ND
Benzo(k)fluoranthene	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.029	NA	NA	NA	NA	0.92 - ca	0.1 - 10	ND	ND	ND
Carbazole	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	3.4 - ca	10	ND	ND	ND
Chrysene	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.29	0.1[1]	NA	NA	NA	9.2 - ca	0.1 - 10	ND	ND	ND
Dibenzo(a,h)anthracene	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.085	0.1[1]	NA	NA	NA	0.0092 - ca	0.1 - 10	ND	ND	ND
Dibenzofuran	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	24 - nc	10	ND	ND	ND
Indeno(1,2,3-cd)pyrene	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.029	NA	NA	NA	NA	0.092 - ca	0.1 - 10	ND	ND	ND
Fluorene	NA	NA	280	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	240 - nc	0.1 - 10	ND	ND	ND
Fluoranthene	NA	NA	280	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1500 - nc	0.1 - 10	ND	ND	ND
1-Methylnaphthalene[12]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NS	NS	NS
2-Methylnaphthalene[12]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.1 - 10	ND	ND	ND
Naphthalene	NA	NA	14	NA	100	NA	NA	NA	NA	NA	NA	NA	170	21[7]	NA	6.2 - nc	0.1 - 10	ND	ND	ND
Phenanthrene	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.1 - 10	ND	ND	ND
Pyrene	NA	NA	210	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	180 – nc	0.1 - 10	ND	ND	ND
Pentachlorophenol (PCP)	1	NA	NA	0.3	300 (10-day)	6/21[6]	0.3	1	NA	0.4	0.43	20	NA	30[8]	NA	0.56 - ca	0.0074 - 25	ND	ND	ND
Metals µg/L (Method 6010)																				
Zinc	NA	5000	2100	NA	2000	NA	NA	NA	5000	NA	NA	NA	NA	NA	2000	11000 - nc	20	569.0	24.0	22.8
Arsenic	50[10]	NA	2.1	0.02	NA	NA	0.02[1]	50	NA	NA	0.023	5	NA	NA	100	0.045 - ca	10	18.1	30.0	43.3
Chromium	100	NA	21[3]	NA	1000 (10-day)	NA	NA	50	NA	2.5[2]	0.18[3]	NA	NA	NA	100[3]	110 – nc[3]	10	2.2	1.7	1.5
Copper	1300	1000	NA	NA	NA	NA	NA	1300	1000	170	NA	NA	NA	NA	200	1400 - nc	25	0.8	1.3	1.3
Dioxins pg/L (Method 1613B)																				
2,3,7,8-TCDD TEQ	30	NA	NA	NA	10 (10-day)	700	0.2	30	NA	NA	0.27	2.5	NA	NA	NA	0.45 - ca	10	3.0	10.5	NS

Table 6-4 (Continued)
Compliance Criteria for Groundwater Re-injection

Notes:
NS – Not sampled
ND – Non Detect
NA – Not Applicable
ca – Cancer
nc – Non-Cancer
- In calculation of the mean, values with a U qualifier were divided by 2.
- The mean for well OFS-5A was calculated using data from sampling events taking place on 14 November 1995 and July 1998.
- The mean for well OFS-5C was calculated using data from sampling events taking place on 14 November 1995, 3 August 1997, and July 1998.
- The mean for well OFS-5E was calculated using data from sampling events taking place on 14 November 1995 and 3 August 1997.
- All criteria, except the Tap Water PRGs, were obtained from A Compilation of Water Quality Goals prepared by the California Environmental Protection Agency, Regional Water Quality Control Board Central Valley Region, August 2000.
- The Tap Water PRGs were obtained from the EPA Region 9 website (http://www.epa.gov/region09/waste/sfund/prg/files/PRG2000.pdf).

[1]Draft
[2]Based on the assumption that 7.2% of Cr is Cr(VI)
[3]Value for Chromium(VI)
[4]From Ayers, R.S. and D. W. Westcot, Water Quality for Agriculture, Food and Agriculture Organization of the United Nations-Irrigation and Drainiage Paper No. 29, Rev. 1 , Rome (1985).
[5]Proposed
[6]child/adult
[7]From J.E. Amoore and E. Hautala, Odor as an Aid to Chemical Safety: Odor Thresholds Compared with Threshold Limit Values and Volatilization for 214 Industrial Chemicals in Air and Water Dilution. Journal of Applied Toxicology, Vol. 3, No. 6 (1983).
[8]From U.S. Environmental Protection Agency, Office of Water, Nation Primary Drinking Water Regulations, Contaminant Specific Fact Sheets-Technical Version (October 1995).
[9]CAL-modified PRG is 0.0015.
[10] Potentially lowered to 10 µg/L
[11]The results for Well OFS-5A for the sampling which took place 8/8/96 were not used because the quality of the data was questionable.
[12]No compliance criteria were identified in any of the sources for these chemicals.

Table 6-5
Perimeter Monitoring Wells to Be Sampled

Scenario	Zone				
	A	B	C	D	E
1	7	6	6	3	3
2	7	6	4	3	3
3	7	6	4	3	3

Table 6-6
Perimeter Monitoring Frequency

Years[1]	Scenario	Zone				
		A	B	C	D	E
0-7	1	Semi-annually				
	2					
	3					
7-30	1	Annually	Annually	Annually	5-years	5-years
	2	Annually	Annually	Annually	5-years	5-years
	3	Annually	Annually	Annually	5-years	5-years

[1]Years are from start of thermal remediation.

7.0 DISCUSSION OF DESIGN

7.1 EVALUATION OF LIQUID-PHASE GAC USAGE AND REGENERATION

The estimated load on the liquid-phase GAC system was based on actual GAC consumption from the Visalia Pole Yard remediation (Southern California Edison 2000), assuming the following:

- The dissolved COC levels in the water separated from the NAPL will be approximately the same at McCormick Baxter, since the water treatment systems are similar (dissolved air flotation [DAF] followed by multimedia filtering prior to GAC).

- The COC levels will be similar to those at Visalia; the water is likely to be saturated with the COCs due to close contact with NAPL.

- The load was determined by the total pumping rate, based on an average rate of 400 gpm at Visalia.

- Since more mass is in place at McCormick and Baxter and the remediation will take longer, the monthly carbon usage was stretched out over longer periods than at Visalia. For example, Visalia used the peak 27,000 pounds per month for only 6 months, but we estimate a proportional maximum usage at McCormick Baxter to last 12 months.

- The carbon usage was decreased so that after 3 years of cool-down, it would be at a level that corresponds to the pump-and-treat usage observed at Visalia prior to thermal treatment. This is a conservative, but safe calculation.

The estimated GAC usages range from 1.1 to 1.6 million pounds of GAC for the three scenarios (Table 7-1). Also, the predicted replacement frequency for the primary GAC vessels is high during the thermal treatment, leading to a high labor demand for this service.

The potential for using on-site regeneration of the primary GAC vessels was evaluated. Estimated regeneration frequencies and GAC replacement and total usage are provided in Table 7-1. The total GAC usage is about 10 percent of the usage for the sacrificial GAC option.

Assumption for these estimates include the following:

- The GAC is regenerated on average when the primary vessels are about 50 percent loaded with COCs.

- Each primary vessel can be regenerated 20 times before the GAC is replaced.

Based on capital costs for the GAC units and a potential saving of at least 1,000,000 pounds of GAC for each scenario, which may be regenerated by steam on site, the on-site regeneration option is favorable.

7.2 DISCHARGE OPTIONS FOR EXCESS TREATED WATER

Several options for getting rid of the excess water were considered:

- Injection of the treated water into the E-zone aquifer
- Discharge to surface water (Old Mormon Slough)
- Discharge to the city wastewater treatment facility
- Evaporation in large holding ponds
- Industrial water reuse

This section provides a brief summary of the conclusions.

7.2.1 Injection of Treated Water Into E-Zone

This option is the recommended option. The water quality criteria to be met are summarized in Table 6-4. The general requirements are as follows:

- Organic COCs will be less than background E-zone aquifer levels or MCLs (this is readily met by dual-pass GAC filtration).

- Heavy metal concentrations cannot substantially exceed the existing E-zone levels.

Details of the heavy metals evaluation are provided in Appendix A. It was concluded that heavy metals treatment by a dedicated treatment unit is not needed.

The re-injection design will be finalized at a later design stage. Important considerations will include the following:

- At least three re-injection wells are recommended in order to always have at least one well that can be used for injection, while other wells are being serviced.
- The well locations will be optimized by the use of numerical modeling.
- Both upgradient and downgradient placement of the re-injection wells will be considered. However, downgradient injection is preferred during steam injection to reduce the heat losses that would result from increasing the groundwater flow velocity through the E-zone. Upgradient injection should be considered for oxygen delivery to the target zone.
- Cooling of the water has not been designed, since warmer water will encourage biological degradation.
- Special attention will be paid to the potential for clogging of the re-injection wells due to elevated temperatures and the oxygen content in the water (re-injection of aerobic water into an anaerobic aquifer may lead to precipitation of iron and manganese oxides, as well as biofouling).
- Redevelopment procedures for the wells will be defined (this is routinely done in oil-field applications where process water is injected into disposal wells).

7.2.2 Discharge to Surface Water (Old Mormon Slough)

Surface water discharge was identified as the least desirable option by the State. Treatment for As and Zn may be necessary, and it is likely that Cu and Cr would also require treatment. The capital cost for a dedicated heavy metals treatment system is on the order of $1 million for a 500-gpm unit, with substantial operating costs as well.

7.2.3 Discharge to City Wastewater Facility

The same arguments as those for surface water discharge are valid for discharge to the city wastewater facility. Heavy metals treatment would potentially be needed. In addition, it was established that the City cannot accept the quantities of water to be generated at the McCormick and Baxter site (discharge rates as high as 400 gpm at times).

7.2.4 Evaporation in Large Holding Ponds

This option was ruled out due to practical constraints, including the following:

- The existing holding ponds cannot be used for this purpose during the winter months during which the capacity will be used for stormwater runoff.

- Evaporation ponds for a 400-gpm evaporation rate would be excessively large and cannot be located on site without great difficulty and cost.

In conclusion, the re-injection option is the preferred alternative. However, it is possible that the final solution will also involve some discharge to the city wastewater treatment facility. The decision will be made at a later design stage.

7.3 POTENTIAL FOR RECYCLING RECOVERED NAPL FOR STEAM GENERATION

The disposal cost for several hundred thousand gallons of recovered NAPL will be substantial. The possibility of using the NAPL as a supplemental fuel deserves evaluation. The final decision on whether to recycle the NAPL will be made at a later design stage. At this point, off-site disposal was included in the cost estimates.

7.3.1 Destruction of NAPL as Supplemental Fuel

The NAPL can be vaporized and sprayed into the combustion flame of the oxidation chamber using standard techniques from oil-field firing with crude oil. In the flame section, the organic COCs will be exposed to high temperatures and oxygen and will burn along with the natural gas. Energy will be reclaimed from the NAPL (estimated order of about 100,000 BTU per gallon, depending on the water content). Inorganic COCs, such as heavy metals, are not expected to be destroyed, but will pass through the flame and be collected with the ash. Particulate-borne COCs will be removed by polishing of the off-gases (scrubbing and particle removal); see Section 7.3.3.

7.3.2 Steam Generator Combustion Chamber Conditions

To prevent NO_x formation by oxidation of N_2, the temperature should be limited preferably below 900°C (1,650°F), and the residence time in the flame should be minimized.

To facilitate complete COC destruction, the temperature should be as high as possible (815 to 900°C, or 1,500 to 1,650°F), and the residence as long as possible (minimum of 1 second in the chamber between the injection point and the thermocouple used for temperature verification).

The desired temperature range is around 1,500 to 1,600°F. This is hot enough to allow thermal destruction of COCs (given enough residence time, 1 second or more), to prevent dioxin/furan formation, and low enough to prevent excessive thermal NO_x formation.

These specifications are independent of the COC load, as long as plenty of oxygen is supplied by the combustion air blower.

7.3.3 Off-Gas Polishing Need

The critical components in the off-gas are as follows:

- COCs
- Dioxins/furans
- NO_x
- SO_x
- CO/CO_2
- HCl
- Hydrogen fluoride (HF)
- Particulates

Chlorinated solvents may form gaseous HCl when oxidized. Acid gas scrubbing is often required to control HCl emissions. This is done by adding caustic (typically NaOH) in a wet quench/scrubber. However, creosote has a relatively low chlorine content. The very dilute HCl gas that would be produced during creosote oxidation is unlikely to result in nuisance conditions that would require an acid gas scrubber.

NO_x may be formed by oxidation of nitrogen species from air (free nitrogen), from the fuel, or from ammonia. However, most low-NO_x burners and oxidation chambers will run with less than 30 parts per million vapor (ppmv) NO_x emitted with the stack gas, and polishing should not be necessary.

Dioxins and furans form at temperatures between 250ºC and 450°C (480ºF and 840°F). The temperature and residence time should be controlled to minimize their formation. Dioxins/furans are destroyed at temperatures above 950°C (1,930°F) and also at lower temperatures if the residence time in the chamber is long enough. Gas polishing can be done either by catalytic oxidation or carbon adsorption.

The final criteria and the resulting flue gas treatment typically are determined by means of discussion with the air pollution authority in the area. We cannot assume certain criteria at this point. At this point, if gas polishing is required at all, the minimum flue gas treatment would be the following (Visalia required no treatment):

- Quenching
- Scrubbing of HCl

The emitted air would be cool and have low concentrations of HCl, HF, SO_x and COCs. NO_x concentration would not be significantly affected, but should be less than 30 ppmv anyway if a low-tech flue gas recirculating burner is used. With this setup, dioxins and furans would be destroyed in the oxidation chamber and prevented from forming by the rapid quenching of the flue gas.

If necessary, a more comprehensive vapor treatment can be designed, consisting of the following:

- Quenching
- Scrubbing of HCl
- Ammonia injection and catalytic NO_x removal
- Dioxin removal using either catalytic oxidation or carbon filtration
- High-efficiency particulate air (HEPA) filter or filter bag with associated baghouse to capture particulates (or an electrostatic precipitator)

One catalytic unit may accomplish both NO_x and dioxin removal. The best option we have found so far is the Zeronox D catalyst. A design with heat exchangers is needed to optimize the whole vapor treatment train. But since NO_x treatment should be avoided due to high cost and maintenance, this option can be ruled out.

Carbon filtration for dioxin removal can be performed above 100°C to prevent condensation of water vapors. Preliminary specifications from Calgon call for a unit with 11,000 pounds of activated charcoal with a minimum of 3 seconds residence time, when operated at 250°F at 7,500 standard cubic feet per minute (scfm).

In conclusion, the technology exists to limit dioxin and furan emissions during on-site recirculation of NAPL for energy reclamation. However, crucial permitting issues need to be evaluated before this solution can be chosen.

7.4 REVISION OF TARGET VOLUMES DURING DRILLING/INSTALLATION

For Scenarios 1 and 2, the E-MPA is not included as a priority for thermal treatment. However, since naphthalene was found in concentrations as high as 9 mg/L in well MW-4E, the presence of NAPL in the E-MPA is uncertain. A flexible approach to this problem is suggested for Scenarios 1 and 2:

- During installation of the steam injection wells on the east side of the MPA, soil samples will be collected in the C-, D-, and E-zones to assess the potential presence of NAPL.

- An extraction well will be installed close to MW-4E in the C-, D-, and E-zones, and soil samples will be collected to assess the potential presence of NAPL.

- If NAPL is found in the samples, another set of wells will be installed farther east, and additional samples will be collected to assess the potential presence of NAPL.

- If the outermost NAPL-containing well is a logical injection well (based on the overall pattern of injectors and extractors), then an extraction well will be placed farther east in order to minimize the potential for the spread of NAPL.

- If the outermost NAPL-containing well is a logical extraction well (based on the overall pattern of injectors and extractors), then an injection well will be placed farther east in order to push the NAPL back toward the extraction well.

For example, dissolved naphthalene concentrations in MW-4E were in the 9 mg/L range in November 2000, leading to the selection of this location for an extraction well. The observed groundwater quality will lead to the selection of this drilling location for soil sampling during drilling and well installation.

Should additional data become available on the groundwater and soil concentrations of COCs, this approach may be revised at a later design stage.

7.5 OPPORTUNITIES FOR PHASING CONSTRUCTION AND OPERATION

The three thermal treatment scenarios described in this conceptual design each would have an operational period of 7 years, with the construction of all wells and process equipment during an intensive 2-year period prior to operation. This would lead to a very high spending rate during the first years of the project, potentially exceeding the rate at which funds would become available for remediation.

The proposed scenarios would be feasible and possible provided that budgets allow for the high spending rate. However, there are other options for implementing thermal remediation at this site for which the present value and lifecycle costs would be more acceptable from a funding standpoint.

A screening of the options for a less aggressive spending rate and ways to reduce the present value cost of the thermal remediation was performed (Section 7.5.1). Sections 7.5.2 and 7.5.3 present an example phasing approach with a much lower initial yearly cost. The cost implications are briefly mentioned here and in more detail is provided in the cost estimate (USEPA 2001).

7.5.1 Reason for Discussing Longer Spending Period

The life cycle cost of Scenario 1 for thermal treatment is approximately $83.2 million. This money would be spent according to the following time line:

- Two years for design, bidding, and contract award ($2.3 million)
- Three years for procurement, mobilization, field construction and startup ($31.3 million)
- Four years for subsurface heating and intensive thermal treatment, vapor and groundwater extraction, NAPL/groundwater treatment, and groundwater monitoring (varies from $10.3 million [year 1] to $6.8 million [year 4], cumulative cost of $34.2 million)
- Three years for subsurface cool-down, including ongoing treatment of extracted liquids and vapors and groundwater monitoring (varies from $2.9 million [year 5] to $4.9 million [year 7], cumulative of $10.7 million)
- Twenty-three years of groundwater monitoring (cumulative $3.0 million, starts after completion of active thermal and cool-down)
- Periodic costs over 30-year period (cumulative $1.8 million, starts after completion of field construction)

The bulk of the cost (approximately $79 million, or 95 percent of the LCC) will be incurred during the first 12 years following EPA's decision to proceed with the design of the thermal treatment system. This would be an average spending of about $7 million per year, with the highest yearly spending during construction ($31.3 million over 3 years) and active thermal treatment (up to $10.3 million in a single year).

In reality, other options for managing the design, construction, and operations phases of the thermal remediation effort are available. These options include the following:

- Stretching the construction phase over more years for better match to the availability of funds. This would concern drilling, well installation, and the surface process equipment.

- Stretching out the drilling and installation phase and conducting interim aquifer tests for improved steam injection rate modeling. After limited well testing in each aquifer zone, the well-field design would be revisited. Potential savings would include a longer spending period and a potential for reducing the total drilling and construction effort.

- Treating different depth zones sequentially in order to reduce the overall equipment size and the cost of the initial construction phase.

After the initial screening, we selected the approach described in the next subsection as an example.

7.5.2 Description of Example Phasing Alternative

The Phasing Alternative consists of four steps, each projected to last 3 years, for a total heating period of 12 years:

1. Focus on depth interval from –190 to –270 feet of elevation. Thermal treatment of the E- and D-E-zones with extraction in D-, D-E-, and E-zones and limited hotspot extraction in the C-zone. During this period, steam would be injected in the E-zone aquifer over the area including the MPA and the N-MPA. Electrical heating would be conducted at a reduced rate in the upper two-thirds of the D-E aquitard. The affected volume of material in Step 1 is estimated to be 296,000 yd^3, or about 19 percent of the Scenario 1 volume. The necessary steam demand was calculated assuming that the target volume would be heated in a period of 360 days, followed by 2 years of continued operation at a reduced average rate. Since only the D-, D-E-, and D-zones would be affected by heating, the necessary extraction rate would be limited to 150 percent of the equivalent steam injection rate (estimated at 23 MM BTU/hr or 46 gpm) plus the pumping rate necessary to maintain hydraulic control in the D- and E-zone aquifers (51 gpm). The resulting design rate for the effluent treatment system would be 150 gpm, and similarly the vapor extraction rate was estimated at 100 scfm (there is no vadose zone in the

treatment interval). All the VEAs covering the ERT and temperature monitoring for Scenario 1 would be installed prior to Step 1 operations.

2. Focus on depth interval from –145 to –270 feet of elevation. While continuing injection and extraction in the E-zone, steam would also be injected into the D-zone, and electrical heating of the D-E aquitard would be discontinued. The extraction well system would be expanded to include areal coverage in the C-zone of the MPA and the N-MPA. Selected hotspot locations in the A- and B-zone aquifers may be used for liquid extraction. The affected volume of material in Step 2 is estimated to be 536,000 yd^3, or about 32 percent of the Scenario 1 volume. The necessary steam demand was calculated assuming that the added target volume would be heated in a period of 360 days, followed by 2 years of continued operation at a reduced average rate. Since only the D-, D-E-, D-, C-D-, and C-zones would be affected by heating, the necessary extraction rate would be limited to 150 percent of the equivalent steam injection rate (estimated at 27 MM BTU/hr or 54 gpm) plus the pumping rate necessary to maintain hydraulic control in the C-, D-, and E-zone aquifers (73 gpm). The resulting design rate for the effluent treatment system would be 150 gpm, and similarly the vapor extraction rate was estimated at 100 scfm. Thus, there is no change in the steam generation or effluent treatment system between Steps 1 and 2.

3. Focus on the depth interval from –40 to –270 feet of elevation, while reducing the treatment intensity in the E-zone. While continuing operation in the D- and E-zones at reduced rates, steam would be injected into the C-zone. The extraction well system would be expanded to include areal coverage in the B-, B-A-, and A-zones of the MPA and the CPA. No additional wells would be added in the N-MPA, since the target elevation for Scenario 1 would be deeper than –140 feet. The affected volume of material in Step 3 is estimated at 1,234,000 yd^3, or about 80 percent of the Scenario 1 volume. However, since heating would be slowed in the deeper zones, the volume being treated in Step 3 would be about 937,870 yd^3. The necessary steam demand was calculated assuming that the added target volume would be heated in a period of 360 days, followed by 2 years of continued operation at a reduced average rate. The necessary extraction rate would be limited to 150 percent of the equivalent steam injection rate (estimated at 50 MM BTU/hr or 100 gpm) plus the pumping rate necessary to maintain hydraulic control in the B-, C-, D-, and E-zone aquifers (117 gpm). The resulting design rate for the effluent treatment system would be 350 gpm, and similarly the vapor extraction rate was estimated at 350 scfm. So a treatment system upgrade would be necessary between years 6 and 7 of thermal treatment.

4. The target volume would be identical to that of Scenario 1, but the thermal treatment intensity in the C-, D-, and E-zones would be negligible. If deemed acceptable, steam injection may be discontinued in the D- and E-zones. The volume undergoing active treatment during Step 4 is estimated at 710,000 yd^3. The necessary steam demand was calculated assuming that the added target volume would be heated in a period of 360 days, followed by 2 years of continued operation at a reduced average rate. The necessary extraction rate would be limited to 150 percent of the equivalent steam injection rate (estimated at 41 MM BTU/hr or 82 gpm) plus the pumping rate necessary to maintain hydraulic control in all five aquifers (235 gpm). The resulting design rate for the effluent treatment system would be 350 gpm, and similarly the vapor extraction rate was estimated at 700 scfm. The only change in the effluent treatment system would be the addition of a 350-scfm vacuum extraction capacity.

The alternative scenario would extend the total project time as follows:

- Scenario 1 (base scenario) is based on 12 years of work to carry out design, construction, and active thermal treatment (including cool-down).

- The Phasing Alternative has a 19-year duration (7 years added to the base scenario).

Tables 7-2 through 7-8 provide the calculated operating parameters for the Phasing Alternative of Scenario 1. In order to simplify on-site work, we have selected the same steam delivery and extraction rates for Steps 1 and 2 (25 MM BTU/hr), and for Steps 3 and 4 (45 MM BTU/hr). This way, only one steam delivery system expansion is necessary (this will be before the beginning of the 7th year of thermal treatment).

Table 7-2 provides the treatment depths and areas for each step, the duration of each phase, and the volume and total energy demands calculated for each step. Electrical heating occurs only during Step 1. Each step is projected to last 3 years, so the total thermal treatment duration is 12 years, followed by 3 years of cool-down, identical to the design for Scenario 1.

Table 7-3 provides the data and calculation used to determine the treatment volume for each step. It also shows two different estimates of the steam demand for each step and the resulting recommendation for steam delivery. The recommendation is 25 MM BTU/hr for Steps 1 and 2, and 45 MM BTU/hr for Steps 3 and 4.

Table 7-4 summarizes the design parameters for which more detail is provided in Tables 7-5, 7-6, and 7-7. The steam delivery system and treatment system are unchanged for Steps 1 and 2 (the first 6 years of thermal treatment). The number of wells to be installed before onset of each step is also listed. The total number of wells for each step are as follows:

- Step 1: 50 wells including D-E electrodes and all VEAs (to cover the treatment volume)
- Step 2: 154 wells (104 added during Step 2 construction)
- Step 3: 263 wells (109 added during Step 3 construction)
- Step 4: 383 wells (120 added during Step 4 construction)

This provides for stretching of the drilling and well installation, so the added wells can be installed within the last 2 years of the previous operations step.

Table 7-5 provides the data used to estimate the liquid extraction rates and thereby the liquid treatment system capacity. The pump-and-treat rates are included only for those aquifer layers being treated in each step. For instance, Step 1 involves injection of steam into the E-zone and extraction from both the D- and E-zones. Thus, the necessary hydraulic control pumping rates (from the ICF Kaiser Alternative 4) for the D- and E-zones were added to the net extraction rate calculated for extracting 150 percent of the rate of water injected as steam. The resulting rates are 150 gpm for Steps 1 and 2, and 350 gpm for Steps 3 and 4. Thus, only one treatment system expansion is necessary (before year 7 of thermal treatment).

Table 7-6 provides the calculation results for estimating the vapor extraction rates. For the deep treatment in Steps 1 and 2, no atmospheric air is extracted, and the vapor extraction rate is equal to the air injection rate plus a contingency factor. For Steps 3 and 4, wells will span the vadose zone, and some atmospheric air will be extracted. The vapor rates increase to 350 and 700 scfm for Steps 3 and 4, respectively. The rate does not reach the 1,000 scfm designed for Scenario 1, since the steam injection rates (and thus the rate of air injection) are lower for the phased approach.

Table 7-7 provides the design parameters for the effluent treatment system for each of the four steps. All system components are substantially smaller than these for Scenario 1 treatment in 4 years. The installations and upgrades that will be necessary are as follows:

- Step 1: Install small system with 150-gpm liquid capacity and 100-scfm vapor capacity.

- Step 2: No upgrades.
- Step 3: Upgrade liquid capacity to 350 gpm and vapor capacity to 350 scfm.
- Step 4: Upgrade vapor capacity to 700 scfm.

For the following cool-down, the Step 4 treatment system capacity is sufficient.

Table 7-8 indicates the utility demands for each of the four steps. All the demands are substantially lower than those for Scenario 1. However, when the total usage is integrated over the 12 years of thermal treatment, the overall consumption of water, power, and gas is slightly higher than that for Scenario 1.

7.5.3 Cost Implications of Phasing Example

The major cost implications as compared to Scenario 1 are as follows:

- The drilling and well installation would be stretched out into four phases occurring during the following years of operation:
  - Years 3 to 4 (Step 1),
  - Year 7 (Step 2),
  - Years 9 to 10 (Step 3), and
  - Years 12 to 13 (Step 4).
- This reduces the present value of the drilling and construction costs.
- The size of the steam generation system would be reduced to one-fourth of the Scenario 1 system for Steps 1 and 2 (the first 6 years of thermal treatment), and to 45 percent of the Scenario 1 system for the last 6 years (Step 3 and 4). These systems would be substantially smaller and cheaper than the Scenario 1 system. The natural gas supply, the water supply, and the fuel consumption rates would be correspondingly lower.
- The fresh water supply rate would be reduced from 200 to 60 gpm (Steps 1 and 2) and 100 gpm (Steps 3 and 4).

- The yearly power demand would be reduced substantially (by 50 to 70 percent). However, the overall power usage would be somewhat higher than that for Scenario 1 because of the longer operations time and the continuous vacuum applied.

- The effluent treatment system size would be reduced substantially from a 475-gpm liquid capacity system to 150 gpm for Steps 1 and 2, and 350 gpm for Steps 3 and 4. The small system used for the initial 6 years (30 percent of the Scenario 1 capacity) would result in substantial savings on the initial construction phase.

- By using the step approach from deep to shallow, it is possible that the scope of Steps 3 and 4 drilling and well installation may be reduced, as steam migrates upward and leads to remediation in the zones above. Such savings would be realized using a combination of the ERT and temperature monitoring, observation of groundwater COC concentrations during extraction, and limited interim drill-back activities.

- The phased approach would prolong the thermal treatment period from 4 to 12 years at a lower intensity, resulting in more labor demand overall.

More detail on the cost implications is provided in the cost estimate (USEPA 2001).

Table 7-1
Estimates of GAC Consumption by Liquid Stream Treatment

Visalia data used for scaling				
Liquid pumping rate	400	gpm		
First 6 months average	23,333	lbs/month		
Second year average	16,667	lbs/month		
Third year average	8,333	lbs/month		
Pump-and treat usage	1,667	lbs/month		
McCormick-Baxter estimates	Scenario 1	Scenario 2	Scenario 3	
Pumping rate	475	575	700	gpm
Montly usage 1st yr	27,708	33,542	40,833	lbs/month
Montly usage 2nd yr	23,750	28,750	35,000	lbs/month
Montly usage 3rd yr	14,844	17,969	21,875	lbs/month
Montly usage 4th yr	9,896	11,979	14,583	lbs/month
Usage during cooldown yr 1	5,938	7,188	8,750	lbs/month
Usage during cooldown yr 2	3,958	4,792	5,833	lbs/month
Usage during cooldown yr 3	1,979	2,396	2,917	lbs/month
Estimated total, sacrificial	1,056,875	1,279,375	1,557,500	lbs
Changeout frequency, 10,000 lb primary vessels (times per year)				
Year 1	33	40	49	times
Year 2	29	35	42	times
Year 3	18	22	26	times
Year 4	12	14	18	times
Year 5	7	9	11	times
Year 6	5	6	7	times
Year 7	2	3	4	times
Estimated regeneration frequency (times per month)[1]				
Year 1	6	7	8	times
Year 2	5	6	7	times
Year 3	3	4	4	times
Year 4	2	2	3	times
Year 5	1.2	1.4	1.8	times
Year 6	0.8	1.0	1.2	times
Year 7	0.4	0.5	0.6	times
Estimated carbon usage using regeneration on-site[2]				
Year 1	33,250	40,250	49,000	lbs
Year 2	28,500	34,500	42,000	lbs
Year 3	17,813	21,563	26,250	lbs
Year 4	11,875	14,375	17,500	lbs
Year 5	7,125	8,625	10,500	lbs
Year 6	4,750	5,750	7,000	lbs
Year 7	2,375	2,875	3,500	lbs
Estimated total, regeneration on-site	105,688	127,938	155,750	lbs
1) Assumed that the vessels are regenerated when they are 50% loaded				
2) The carbon will be replaced after 20 regeneration cycles				

Table 7-2
Definition of Zones, Depths, Volumes, and Energy Demand for Phasing Alternative of Scenario 1

	Scenario 1	Step 1	Step 2	Step 3	Step 4	Unit	Comment
Thermal treatment depth	0-260	190-260	145-260	40-260	0-260		
Area affected	MPA,CPA,N-MPA	MPA,N-MPA	MPA,N-MPA	MPA,CPA	MPA,CPA		
Steam into aquifers	A,B,C,D,E	E	D,E	C,D,E	A,B,C,D,E		
Extraction in aquifers	A,B,C,D,E	D,E	C,D,E	A,B,C,D,E	A,B,C,D,E		Plus aquitards between aquifers
Duration of steam injection	4	3	3	3	3		
Duration of ERH	2	3	0	0	0		
Total volume heated	1,541,900	296,287	535,965	1,234,157	1,541,900	yd^3	
Total soil mass	2.29E+09	4.39E+08	7.95E+08	1.83E+09	2.29E+09	kg	
Total BTU need w/losses	2.61E+12	5.02E+11	9.08E+11	2.09E+12	2.61E+12	BTU	
Heat-up BTU need	4.04E+11	7.76E+10	1.40E+11	3.23E+11	4.04E+11	BTU	

Table 7-3
Estimation of Bulk Volume and Sand Fractions in Priority Treatment Zones

Zone/area	Area (ft^2)	Top (ft)	Btm (ft)	Depth (ft)	Volume (yd^3)	Scenario 1	Step 1	Step 2	Step 3	Step 4	
MPA	17,695	0	-120	120	78,651	78,651	0	0	78,651	78,651	yd^3
	28,419	0	-180	180	189,475	189,475	0	36,842	147,370	189,475	yd^3
	74,247	0	-260	260	715,028	715,028	192,508	316,263	605,024	715,028	yd^3
	19,398	-25	-260	235	168,848	168,848	50,295	82,628	158,070	168,848	yd^3
CPA	97,739	0	-80	80	289,620	289,620	0	0	144,810	289,620	yd^3
N-MPA	11,097	-30	-120	90	36,993	0	0	0	0	0	yd^3
	9,538	-30	-180	150	52,993	12,365	0	12,365	12,365	12,365	yd^3
	20,628	-30	-260	230	175,734	87,867	53,484	87,867	87,867	87,867	yd^3
Total volume					1,707,343	1,541,854	296,287	535,965	1,234,157	1,541,854	yd^3
Volume under active heating							296,287	535,965	937,870	709,603	yd^3
Projected steam injection demand based on volume							20	36	63	48	MM BTU/hr
Estimated steam injection rate based on heatup calculations							23	27	50	41	MM BTU/hr
Design steam injection rate for step							25	25	45	45	MM BTU/hr

Table 7-4
Summary of Design Parameters for the Four Steps

	Volume treated (yd3)	Steam rate (lbs/hr)	Liquid extraction rate (gpm)	Vapor extraction rate (scfm)	Injection wells (number)	Extraction wells (number)	Monitoring and NAPL wells (number)
Step 1	296,000	25,000	150	100	10	29	11
Step 2	536,000	25,000	150	100	45	88	21
Step 3	1,235,000	45,000	350	350	58	170	35
Step 4	1,540,000	45,000	350	700	165	170	48

Table 7-5
Summary of Liquid Extraction Rate Calculations for Phasing Alternative of Scenario 1

	Scenario 1	Step 1	Step 2	Step 3	Step 4	
Steam demand, 180 d heat-up	104	25	25	45	45	MM BTU/hr
Equivalent water injection rate, 180 d heat-up	187	46	54	100	82	gpm
Minimal water extraction rate, 150% of injected rate	280	75	75	135	135	gpm
Minimal net extraction rate from ICF Kaiser Alternative 4	235	51	73	117	235	gpm
Total liquid extraction rate needed	422	126	148	252	370	gpm
Estimated miscellaneous water usage	40	10	20	30	40	gpm
Total effluent treatment system size	462	136	168	282	410	gpm
Design rate	475	150	150	350	350	gpm

Table 7-6
Sizing of Vapor Extraction System for Phasing Alternative of Scenario 1

	Scenario 1	Step 1	Step 2	Step 3	Step 4	Unit
HPO co-injection	1	1	1	1	1	% air/steam
Steam rate	100,000	25,000	25,000	45,000	45,000	lbs/hr
Air injection rate	1,000	250	250	450	450	lbs/hr
Air injection rate	240	60	60	108	108	scfm
Minimium extraction rate	360	90	90	162	162	scfm
Area	268	0	0	100	268	1000 ft^2
Estimated infiltration rate	2	2	2	2	2	scfm/1000ft^2
Infiltration rate	536	0	0	200	536	scfm
Total air extraction rate	896	90	90	362	698	scfm
Design rate	1,000	100	100	350	700	scfm

Table 7-7
Sizes and Capacities of Major Effluent Treatment System Components for Phasing Alternative of Scenario 1

Component	Parameter	Scenario 1	Step 1	Step 2	Step 3	Step 4	Unit	Comment/assumption
Vapor phase liquid separator 1	Air flow rate	4,733	534	611	1,280	1,474	scfm air	Non-condensable gas plus 10% of injected steam as condensate
	Liquid flow rate	22	8	8	18	18	gpm condensate	Assuming max 5% of liquid extracted with vapor stream
Liquid phase heat exchanger	Liquid flow rate	435	150	150	350	350	gpm water	Maximum rate
	Cooling capacity	22	7	7	17	17	MM BTU/hr	Assumed 100 F cooling
Vapor phase heat exchanger/condensor	Cooling capacity	12	3	3	6	5	MM BTU/hr	0% of injected energy as steam and energy in 200F condensate
Vapor phase liquid separator 2	Air flow rate	1,000	100	100	350	700	scfm air	
	Liquid flow rate	23	6	7	12	11	gpm condensate	Based on maximum vapor phase cooling capacity
Vacuum pumps	Air flow rate	1,000	100	100	350	700	scfm	
	Vacuum	-10	-10	-10	-10	-10	psig	Need to apply vacuum
Vapor treatment units	Air flow rate	1,000	100	100	350	700	scfm	
Water surge tank	Retention time	1	1	1	1	1	hours	Need settling and separation time for solids and NAPL
	Minimum capacity	26,100	9,000	9,000	21,000	21,000	gallons	
Dissolved Air Floatation	Water flow rate	435	150	150	350	350	gpm	
	NAPL flow rate	11	4	4	9	9	gpm	Assumed max NAPL ratio of 2.5% of total water flow
Multimedia filters	Water flow rate	475	170	170	350	350	gpm	DAF flow rates plus process water
Water treatment unit (GAC)	Water flow rate	475	170	170	350	350	gpm	DAF flow rates plus process water
NAPL holding tanks	Capacity	21,000	21,000	21,000	21,000	21,000	gallons	Tanks added and emptied for disposal as needed
	Minimum number	2	2	2	2	2	#	Empty backup tank on-site

Table 7-8
Utility Demand for Phasing Alternative of Scenario 1

	Scenario 1	Step 1	Step 2	Step 3	Step 4	Unit	Comment
Fresh water demand	200	50	60	100	85	gpm	
ERH power	2,550	1,000	0	0	0	kW	DE ERH in Step 1
Process power	1,000	500	500	700	700	kW	Increases with vacuum extraction rate
Power demand	3,550	1,500	500	700	700	kW	
Gas firing rate	152,381	33,956	39,971	72,757	60,538	scfh	80% firing rate in average

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APPENDIX A

Evaluation of Heavy Metals Treatment Need

EVALUATION OF HEAVY METALS TREATMENT NEED

The premise for evaluating the need for treating the effluent water for heavy metals consists of the following:

- The treated water is re-injected into the E-zone through vertical wells.
- The concentrations of chemicals of concern (COCs) may not substantially exceed the concentrations currently in the E-zone.
- The 1997 groundwater data are valid for assessment of the heavy metals concentrations in all aquifer zones from A through E.

EVALUATION PROCESS

The evaluation consisted of the following steps:

1. Average concentrations of all heavy metals were calculated for each aquifer based on the tabulated 1997 groundwater samples in the remedial investigation (Table A-1, data from USEPA 1998).

2. Average pumping rate for each aquifer zone was estimated based on the steam injection and extraction rates predicted during heat-up, as follows (Scenario 3 is used for illustration, Table A-2):

   - Zone A: 66 gpm
   - Zone B: 107 gpm
   - Zone C: 159 gpm
   - Zone D: 64 gpm
   - Zone E: 183 gpm

3. The influent concentration to the treatment system was calculated by weighting all the concentrations with the appropriate flow rate. In this case, values from E-zone data were weighted high (since 183 gpm is a large fraction of the total flow rate), and values from the A-zone were weighted low (since 66 gpm is a small fraction of the total). Table A-2 provides the calculations.

4. A heavy metals concentration reduction by a factor of 2 was assumed for the effluent treatment system, based on the fact that solids and nonaqueous-phase liquids (NAPL) will be removed and that a substantial fraction of the heavy metals will be associated with those fractions.

5. A dilution factor of 2 was used since more than 2 pore volumes of steam condensate will be flushed through the site during thermal operation.

6. The heavy metals concentrations expected at the effluent end of the treatment system were estimated based on the average inlet concentrations and the stated reductions, and compared to the current levels in the E-zone aquifer (Table A-3).

For comparison, the estimated pumped concentrations from the EPA pump-and-treat scenario (USEPA 1998) are included in Table A-3.

The results are as follows for the thermal treatment scenarios:

- No treatment will be warranted for the COCs As, Cr, Cu, and Zn.

- Non-COCs that are likely to be injected into the E-zone at concentrations greater than the current levels include Al (estimated to be injected at 2.0 times the current level of 28 µg/L) and Fe (estimated to be injected at 1.3 times the current level of 326 µg/L).

In conclusion, it is likely that heavy metals treatment will not be necessary during thermal treatment. A more detailed evaluation may be conducted at a later design stage, if deemed necessary.

REFERENCE

U.S. Environmental Protection Agency (USEPA). 1998. *Soil and Groundwater Remedial Investigation Report, McCormick and Baxter Superfund Site, Stockton, California.* Prepared by ICF Kaiser Engineering, Inc. July 1998.

Table A-1
Heavy Metals Data From August 1997 Sampling Event

	A	B	C	D	E	
As	19.1	21.5	44.4	36.4	49.5	averages
ug/L	41	25.4	69	31	62	
	6	19.1	31	37	44.4	
	3	3	33.2	41.2	42	
	25	24				
	33.8	19				
	6	32				
		28				
	A	B	C	D	E	
Cr	7.15	<3	<3	<3	<3	averages
	3	2.9	3	3	3	
	21	3	3	3	3	
	10	9	2.9	2.9	3	
	3	3				
	2.9	3				
	3					
	A	B	C	D	E	
Cu	<3	<3	<3	<3	<3	average
	A	B	C	D	E	
Zn	393.0	34.2	99.7	31.7	41.7	average
	42	45.45	208	12	37	
	28	37	44	57	48	
	21	17	47	26	40	
	7	39				
	1090	42				
	1170	25				
Al	1022.3	88.6	313.0	<40	<25	averages
	332	78	1160			
	4980	28	23			
	736	41	39			
	40	72	30			
	23	170				
	23	208				
		23				
Fe	5037.0	1110.4	2993.3	447.5	326.0	averages
	11800	1410	9190	232	352	
	12400	752	692	609	234	
	2790	1180	1590	575	392	
	407	716	501	374		
	505	985				
	2320	1970				
		760				
Mn	464.5	186.0	238.8	373.8	196.7	averages
	1050	199	398	222	307	
	401	190	190	519	128	
	147	239	192	520	155	
	234	163	175	234		
	308	159				
	647	205				
		147				

Table A-2
Weighting of Heavy Metals Concentration by Expected Water Extraction Rate From Each Aquifer (Scenario 3 Rate Used)

As	Avg (ug/L)	gpm	Average in total flow stream		
A	19.1	66	38.0		
B	21.5	107			
C	44.4	159			
D	36.4	64			
E	49.5	183			
C(avg)/C(E zone)		0.77			
Zn	Avg (ug/L)	gpm	Average in total flow stream		
A	393.0	66	95.2		
B	34.2	107			
C	99.7	159			
D	31.7	64			
E	41.7	183			
C(avg)/C(E zone)		2.28			
Cu and Cr below 3 ug/L					
Al	Avg (ug/L)	gpm	Average in total flow stream		
A	1022.3	66	218.9		
B	88.6	107			
C	313.0	159			
D	0.0	64			
E	0.0	183			
Fe	Avg (ug/L)	gpm	Average in total flow stream		
A	5037.0	66	1753.9		
B	1110.4	107			
C	2993.3	159			
D	447.5	64			
E	326.0	183			
Mn	Avg (ug/L)	gpm	Average in total flow stream		
A	464.5	66	256.4		
B	186.0	107			
C	238.8	159			
D	373.8	64			
E	196.7	183			

Table A-3
Summary of Heavy Metals Concentrations Predictions in Effluent Water Streams at McCormick and Baxter (all concentrations are µg/L)

	COC metals					Non-COC metals[4]		
Source	**As**	**Cr**	**Cu**	**Zn**		**Al**	**Fe**	**Mn**
ICF Kaiser Pump-and-Treat Alt 4[1]	39	12	15	1066		828	6396	1032
August 1997 COC levels weighted with Scenario 3 extraction	38	<3	<3	95		219	1754	256
Average concentration in E zone, August 1997	49	<3	<3	42		28	326	197
Estimated removal efficiency in DAF and multi-media filters	50%	50%	50%	50%		50%	50%	50%
Estimated dilution factor due to steam flushing	2	2	2	2		2	2	2
Needed concentration reduction for E zone re-injection	0.1	NA	NA	0.4		2.0	1.3	0.3
Treatment needed	no	no	no	no[2]		yes/no[3]	yes/no[3]	no
1) The Zn level is high since P&T is dominated by A zone extraction (119 gpm of 235 gpm @1,100 ug/L)								
2) The preliminary recommendation of no Zn treatment needs to be investigated at a later design stage								
3) Treatment not needed since Al and Fe are not on the COC list								
4) Only the ones that would be critical based on ICF Kaiser P&T concentration estimates are shown								
Metals sceened to be well below the E zone background:	Sb							
	Ba							
	Be							
	Cd							
	Ca							
	Co							
	Pb							
	Mg							
	Hg							
	Ni							
	K							
	Se							
	Ag							
	Na							
	Tl							
	V							

APPENDIX B

Steam Injection Rate Modeling

STEAM INJECTION RATE MODELING

This appendix documents the choice of well spacing and heat-up rate for the thermal treatment at the McCormick and Baxter site. The intervals between the steam injection wells were chosen based on the following criteria:

- For thermal treatment of the chosen areas, steam will be injected in all of the depth intervals representing the treatment depths, except the upper A-zone in some locations where the A- and B-zone sands are sufficiently connected to allow for steam migration upward from the B-zone into the A-zone.

- Where a zone has a good definition of the outer bounds of the NAPL area, steam injection wells were placed outside the target zones, allowing for an outside-in steam migration.

- For zones in which nonaqueous-phase liquid (NAPL) is confirmed or suspected to be present outside the thermal treatment zone, the steam injection intervals are typically surrounded with extraction wells equipped with both liquid and vapor extraction capability.

- For thick sand zones that need steam flow in the bottom section, the injection screens are designed so they preferentially inject steam in the lower half of the aquifer interval. This is done by using short injection screens, typically screened from the middle of the aquifer to several feet into the underlying silt layer/aquitard.

- Where a sand zone is overlain by a thick silt/aquitard (such as the D-E aquitard in large areas of the site), it is desirable to allow steam injection in the bottom half of the aquitard into sand lenses that may be present. Often, it is not known where such lenses are, but the likelihood of sand sections is recognized. In such cases, steam injection wells in the deeper zone are completed with the top of the screened interval located in the overlying aquitard. As an example, E-zone steam wells may be screened from about –200 feet of elevation (the middle of the D-E aquitard) to the bottom of the E-zone aquifer. This will allow steam heat-up of any sand lenses that allow steam penetration in the lower D-E aquitard, without preventing sufficient heating in the E-zone, since the permeability in the E-zone aquifer is orders of magnitude higher than that of the D-E aquitard.

- For thinner aquifers in which the achievable steam injection rate may be limiting heat-up and performance, the injectors are screened across the entire aquifer, but not in the overlying aquitard, allowing for a higher injection pressure (due to a greater depth to the top of the screen) and the maximum achievable transmissivity of the aquifer interval.

The steam injection rates are critical for estimating the size of the steam generation equipment, for setting the well spacing, and for predicting the duration of thermal treatment. The procedure used to estimate the rates was as follows:

- The A through E zonation for the dominating aquifers was adapted, with assumption of average depths for each zone as provided by Mike Bailey of the U.S. Army Corps of Engineers (USACE) in a summary table (Bailey 2001).

- The sand fraction in each zone was estimated based on Bailey (2001) and used to make a rough assumption of the steam zone thickness during the initial steam migration and heat-up. Typically, it was assumed that the steam zone filled 50 percent of the average aquifer thickness, with a condensate zone surrounding the steam zone.

- Four-inch injection well screens in 10-inch boreholes were assumed, and the maximum injection pressures were defined as 0.5 psi per foot measured from the surface to the top of the injection screen.

- Permeability averages from Bailey (2000, based on data contained in USEPA 1998) were used for each aquifer zone. Three calculations were made for each depth interval, one in which the average conductivity was used, one in which one-third of the average was used, and one in which three times the average was used. This allows for a simple evaluation of how local heterogeneity may affect the steam injection rates across the site, assuming that the same injection pressure will be applied. Permeability values are provided in Table B-1.

- The simulations are simple radial, cylindrical calculations based on a numerical solution for one steam injection well, as described in Heron, Heron, and Udell (2000) and USACE (2000).

Table B-1 presents the achievable steam injection rates at the maximum allowable injection pressures for the scenarios described above. Table B-2 presents a typical set of input parameters.

Figures B-1 and B-2 show example model output used to construct Table B-1. Sixteen such model simulations were performed.

Average steam injection rates per well in each of the zones after about 180 days of injection were estimated as follows:

- Zone A: 900 lb/hr
- Zone B: 2,400 lb/hr
- Zone C: 4,800 lb/hr
- Zone D: 2,000 lb/hr
- Zone E: 12,800 lb/hr

For the E- and C-zone wells, a reduced injection pressure was used, since the maximum allowable pressure would lead to excessive injection rates (more than 25,000 lbs/hr per well).

For design purposes, the wells will allow for approximately 150 percent of the average injection rate listed above, leading to design injection ranges as follows:

- Zone F: 300 to 1,500 lb/hr
- Zone G: 800 to 4,000 lb/hr
- Zone H: 1,600 to 6,000 lb/hr
- Zone I: 600 to 3,000 lb/hr
- Zone J: 4,000 to 16,000 lb/hr

For the E-zone injection wells, the need to exceed the estimated injection rate is less important than it is for the upper zones, since the permeability is sufficiently high that all injection wells are expected to allow for injection at the design rate.

The radii of the steam zones are calculated simultaneously with the injection rates. For design purposes, the most important parameter is the optimal distance between injection and extraction wells for each depth zone. For this purpose, the time needed for steam breakthrough to the nearest extraction well was estimated by making the steam zone radius equal to the well spacing.

The criteria used to choose the well spacing were the following:

- The well spacing cannot significantly exceed the predicted radius of influence after 90 days of steam injection for the simulation using the average hydraulic conductivity values for that particular depth interval.

- The well spacing will allow for steam breakthrough within 360 days in the scenario using one-third of the average hydraulic conductivity.

Based on the results in Table B-1, the following maximum well spacings were achieved for each zone:

- Zone A: 52 feet
- Zone B: 83 feet
- Zone C: 112 feet
- Zone D: 69 feet
- Zone E: >300 feet

For practical purposes, it is desirable to group the depth zones so only two or three different well spacings are used. This allows for a logical well-field layout and minimizes the area occupied by wells and the piping from the wells to the steam and treatment systems, and it allows for access to the individual wells during operation. In addition, the E-zone injectors were predicted to allow for almost unlimited steam injection rates. For that purpose, a set of simulations was run with a lower injection pressure (840 kPa compared to the maximum allowable 928 kPa). This simulation showed that at injection rates of about 12,500 lb/hr per well, steam will break through to a well 180 feet away within 100 days of injection. Thus, the following well separations were chosen:

- Zone A: 60 feet
- Zone B: 60 feet
- Zone C: 120 feet
- Zone D: 60 feet
- Zone E: 180 feet

For Zone A, the well spacing is slightly greater than the 52 feet calculated above, but in this case we expect a positive effect by upward steam migration from the underlying zones. In conclusion, the 60-foot separation seems to be a good compromise.

The breakthrough times were estimated for each zone as follows, using the average hydraulic conductivity values:

- Zone A: 116 days (60-foot separation)
- Zone B: 30 days (60-foot separation)
- Zone C: 88 days (120-foot separation)
- Zone D: 44 days (60-foot separation)
- Zone E: 105 days (180-foot separation)

These times are for constant injection at the design pressures and may, therefore, be seen as reasonable predictions of the earliest steam breakthrough in areas where the hydraulic conductivity value is similar to the average value given by Bailey (2000). Due to less than 100 percent operation time for the steam injection, temporary pressure reductions for various reasons, less than average hydraulic conductivity values in many areas, and the intended reduction of steam injection rates in some wells to allow for a more uniform steam distribution, more realistic steam breakthrough times are listed as follows:

- Zone A: 100 to 180 days
- Zone B: 30 to 60 days
- Zone C: 90 to 180 days
- Zone D: 40 to 80 days
- Zone E: 100 to 180 days

During operations, the steam migration in certain zones may be reduced in order to control the direction of vertical pressure gradients, to minimize the risk of downward NAPL migration, and to achieve uniform heating with a minimal fuel demand during the heat-up phase. For design purposes and for sizing the steam supply and effluent treatment systems, the overall steam injection rate and pumping rates were fitted for a heat-up time of 180 days as an average across the site. This is a reasonable compromise among the following factors:

- The desire to heat and remediate the site rapidly (to shorten the overall operations time)

- The need to minimize the number of wells (to reduce drilling and hardware/instrumentation cost)

- The desire to have steam and treatment system sizes in practical and economic ranges (to minimize the capital cost of equipment)

- An allowance for contingencies in the actual field performance of each depth interval and the performance of each of the wells

In conclusion, the chosen well separation allow controlled heating of the five dominant aquifer zones, with steam breakthrough to extraction wells within 180 days after initiating steam injection. Contingencies were built in for poorer performance in some areas of the site.

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Bailey, M.M. 2001. Personal communication re: Summary of Sand Fractions in Distinct Depth Zones, McCormick and Baxter Superfund Site. Table.

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Heron, T., G. Heron, and K.S. Udell. 2000. "Tools for Designing Steam Enhanced Remediation Systems." Presentation at the May 2000 Battelle Conference on Chlorinated and Recalcitrant Compounds, Monterey, California. May 2000.

U.S. Army Corps of Engineers (USACE). 2000. *1999 NAPL Field Investigation Report, McCormick and Baxter Superfund Site, Stockton, California*. June 2000.

U.S. Environmental Protection Agency (USEPA). 1998. *Soil and Groundwater Remedial Investigation Report, McCormick and Baxter Superfund Site*, Stockton, California. 2 vols. Prepared by ICF Kaiser Engineering, Inc. July 1998.

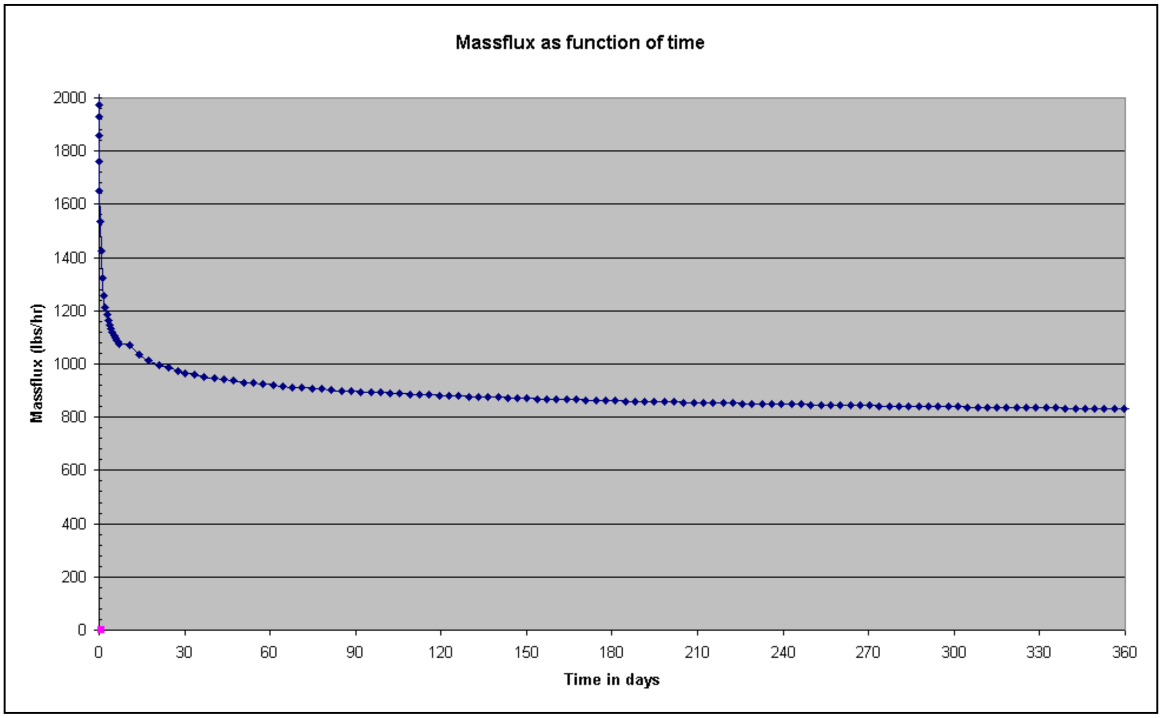


Figure B-1. Example Steam Injection Rate Simulation (A-zone, 8 darcy)

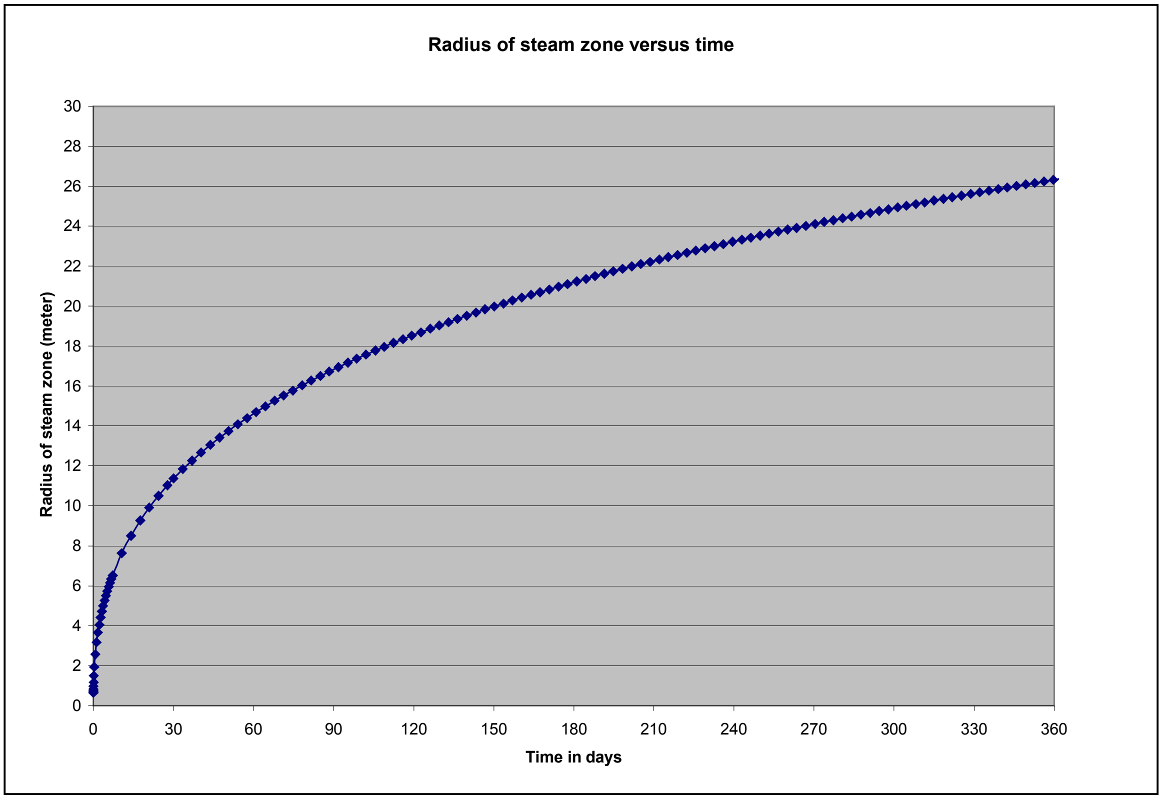


Figure B-2. Example Radius of Influence Simulation (A-zone, 8 darcy)

Table B-1
McCormick Baxter Well Spacing Calculation Based on Hydraulic Conductivity and Aquifer Thicknesses

				Hydr. Cond.						Steam	K sensitivity range (darcy)		
	Thickness	Top	Bottom	ft/day	darcy	TOS (ft)	Pinj (psig)	Pinj (Pa)	T(K)	zone (ft)*	Min	Avg	Max
A	30	15	45	23	8.1	25	12.5	187,439	388	15	2.7	8.1	24
A-B	5	45	50										
B	25	50	75	40	14.1	60	30	308,035	407	12.5	4.7	14	42
B-C	40	75	115										
C	20	115	135	43	15.2	125	62.5	531,997	427	10	5.1	15	46
C-D	10	135	145										
D	20	145	165	12	4.2	155	77.5	635,365	433	10	1.4	4.2	13
D-E	55	165	220										
E	30	230	260	136	48.0	240	120	928,239	448	15	16	48	144
E	30	230	260	136	48.0	240	107.2	840,000	444	15		48	

Injection rates, 30 days (lbs/hr)			Injection rates, 90 days (lbs/hr)			Injection rates, 180 days (lbs/hr)			Injection rates, 360 days (lbs/hr)		
Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
354	965	2,620	327	898	2,450	313	861	2,357	301	831	2,280
975	2,660	7,346	910	2,490	6,917	873	2,401	6,680	844	2,325	6,486
1,959	5,300	15,004	1,837	4,995	14,200	1,770	4,826	13,750	1,715	4,685	13,373
790	2,162	6,139	737	2,029	5,788	709	1,956	5,592	685	1,895	5,431
20,030	55,800	156,000	18,875	52,800	148,000	18,230	51,100	144,000	17,700	49,700	140,000
	14,160			13,300			12,860			12,480	

RO steam, 30 days (m)			RO steam, 90 days (m)			RO steam, 180 days (m)			RO steam, 360 days (m)		
Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
6.9	11.4	18.7	10.1	16.7	27.5	12.8	21.2	35.0	15.9	26.3	43.5
11.3	18.5	30.7	16.3	27.0	44.8	20.6	34.0	56.6	25.3	41.9	69.8
15.6	25.6	42.9	22.4	36.8	62.0	28.0	46.1	77.6	34.1	56.3	95.0
9.7	16.0	26.9	13.9	23.0	38.7	17.3	28.7	48.7	21.1	35.0	59.2
41.0	68.2	113.9	60.7	101.3	169.5	77.3	129.2	216.0	96.0	160.7	270.0
	34.9			51.7			65.8			81.8	

Well spacing, 90 day breakthru (ft)			Well spacing, 180 day breakthru (ft)			Well spacing, 360 day breakthru (ft)			Max well spacing	Chosen
Min (ft)	Avg (ft)	Max (ft)	Min (ft)	Avg (ft)	Max (ft)	Min (ft)	Avg (ft)	Max (ft)	recommended	spacing
33.1	54.8	90.2	42.0	69.5	114.8	52.1	86.2	142.6	53.4	60
53.4	88.5	146.9	67.5	111.5	185.6	83.0	137.4	228.9	85.7	60
73.4	120.7	203.3	91.8	151.1	254.4	111.8	184.6	311.5	116.2	120
45.6	75.4	126.9	56.7	94.1	159.7	69.2	114.8	194.1	72.3	60
199.0	332.1	555.7	253.4	423.6	708.2	314.8	526.9	885.2	NA	180
	169.5			215.7			268.2		169.5	

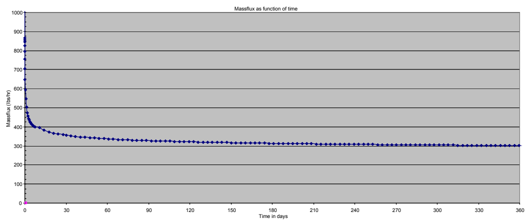
Table B-2
Example Input Parameters for Steam Injection Simulation

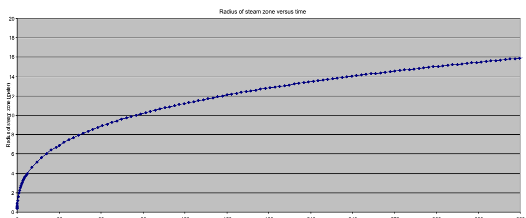
Parameter	Symbol	Unit	Value
Thickness of steamed layer	h	m	4.575
Particle density of soil	d_s	kg/m^3	2650
Porosity of steamed layer	p		0.35
Absolute permeability of soil	k_s	m^2	8.1E-12
Heat capacity of soil	cp_r	J/(kg K)	1152
Initial water saturation	S_w		1
Ambient pressure in aquifer	P_{amb}	Pa	147851
Density of water	d_w	kg/m^3	1000
Ambient water temperature	T_{amb}	K	295
Heat capacity of water	cp_w	J/(kg K)	4187
Overall heat capacity	cp_{sw}	J/(kg K)	2200
Overburden thermal conductivity	k	J/(s m K)	1.3
Overburden thermal diffusivity	a	m^2/s	0.00000018
Radius of injection well	r_w	m	0.0505
Maximum steam injection pressure	P_w	Pa	187439
Relative permeability of steam	k_{rs}		1
Steam viscosity	u_s	kg/(m s)	1.30E-05
Temperature of steam	T_s	K	391
Delta T	$T_s - T_{amb}$	K	96
Heat of condensation	´h	J/kg	2666000
Time since start of injection	t	s	
Steam mass flow rate	´m	kg/s	
Volume of steam zone	V	m^3	
Gas constant	R	J/(mole K)	8.314
Initial radius of steam zone	r_{si}	m	0.053025
Mole mass of water	M_w	kg/mole	0.018
Density of steam	d_{steam}	kg/m^3	1.1
Depth to top of injection screen	$D_{injscr.}$	m.b.g	7.625
Length of injection screen	$L_{inj,screen}$	m	4.5
Aquifer hydraulic head	D_{gwt}	m.b.g	3

Table B-3
Estimation of Steam Injection Rate and Steam Zone Growth

A-zone, 2.7 darcy

Parameter	Symbol	Unit	Value
Thickness of steamed layer	h	m	4.575
Particle density of soil	d_s	kg/m³	2650
Porosity of steamed layer	p		0.35
Absolute permeability of soil	k_s	m²	2.7E-12
Heat capacity of soil	cp_r	J/(kg K)	1152
Initial water saturation	S_w		1
Ambient pressure in aquifer	P_{amb}	Pa	14785
Density of water	d_w	kg/m³	1000
Ambient water temperature	T_{amb}	K	295
Heat capacity of water	cp_w	J/(kg K)	4187
Overall heat capacity	cp_{tw}	J/(kg K)	2200
Overburden thermal conductivity	k	J/(s m K)	1.3
Overburden thermal diffusivity	a	m²/s	0.0000001
Radius of injection well	r_w	m	0.0505
Maximum steam injection pressure	P_w	Pa	18743
Relative permeability of steam	k_{rs}		1
Steam viscosity	u_s	kg/(m s)	1.30E-05
Temperature of steam	T_s	K	391
Delta T	$T_s - T_{amb}$	K	96
Heat of condensation	'h	J/kg	266600
Time since start of injection	t	s	
Steam mass flow rate	'm	kg/s	
Volume of steam zone	V	m³	
Gas constant	R	J/(mole K)	8.314
Initial radius of steam zone	r_{si}	m	0.05302
Mole mass of water	M_w	kg/mole	0.018
Density of steam	d_{steam}	kg/m³	1.1
Depth to top of injection screen	$D_{injscr.}$	m.b.g	7.625
Length of injection screen	$L_{inj,screen}$	m	4.5
Aquifer hydraulic head	D_{gwt}	m.b.g	3



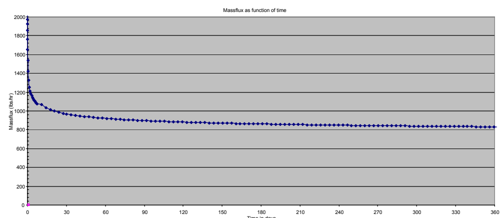


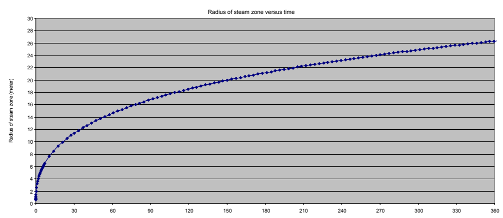
	t (s)	t (days)	'm	cp,ave	y	'mave	erf(y)xy2	A(t)	r(t)	Energy Injected	'm (lb/h)
1	60	0.00	4.46	3449770	0.00	4.46	0.967	0.4	0.4	7.17E+06	35518
2	120	0.00	0.11		0.00	2.29	0.986	0.5	0.4	7.34E+06	867
3	240	0.00	0.11		0.01	1.20	0.983	0.5	0.4	7.69E+06	857
4	480	0.01	0.11		0.01	0.65	0.980	0.5	0.4	8.37E+06	840
5	960	0.01	0.10		0.01	0.38	0.967	0.6	0.4	9.70E+06	826
6	1920	0.02	0.10		0.02	0.24	0.961	0.8	0.5	1.23E+07	797
7	3840	0.04	0.10		0.02	0.17	0.973	1.1	0.6	1.71E+07	768
8	7680	0.09	0.09		0.03	0.13	0.963	1.7	0.7	2.62E+07	704
9	15360	0.18	0.09		0.05	0.11	0.946	2.7	0.9	4.30E+07	649
10	30720	0.36	0.08		0.07	0.09	0.928	4.6	1.2	7.37E+07	595
11	61440	0.71	0.07		0.10	0.08	0.900	8.0	1.6	1.30E+08	546
12	104640	1.21	0.06		0.13	0.07	0.873	12.2	2.0	2.03E+08	502
13	147840	1.71	0.06		0.15	0.07	0.852	16.0	2.3	2.72E+08	473
14	191040	2.21	0.06		0.17	0.07	0.834	19.7	2.5	3.38E+08	456
15	234240	2.71	0.05		0.18	0.06	0.818	23.1	2.7	4.02E+08	444
16	277440	3.21	0.05		0.20	0.06	0.805	26.5	2.9	4.66E+08	435
17	320640	3.71	0.05		0.22	0.06	0.793	29.7	3.1	5.28E+08	428
18	363840	4.21	0.05		0.23	0.06	0.782	32.8	3.2	5.89E+08	422
19	407040	4.71	0.05		0.25	0.06	0.772	35.8	3.4	6.50E+08	417
74	450240	5.21	0.05		0.26	0.06	0.763	38.8	3.5	7.09E+08	412
75	493440	5.71	0.05		0.27	0.06	0.754	41.8	3.6	7.69E+08	408
76	536640	6.21	0.05		0.28	0.06	0.745	44.6	3.8	8.28E+08	405
77	579840	6.71	0.05		0.30	0.06	0.738	47.4	3.9	8.86E+08	402
78	623040	7.21	0.05		0.31	0.06	0.730	50.2	4.0	9.44E+08	399
79	919625	10.64	0.05		0.37	0.05	0.687	68.4	4.7	1.34E+09	386
80	1216210	14.08	0.05		0.43	0.05	0.654	84.9	5.2	1.72E+09	380
81	1512795	17.51	0.05		0.48	0.05	0.627	100.4	5.7	2.09E+09	374
82	1809380	20.94	0.05		0.52	0.05	0.604	114.9	6.0	2.46E+09	367
83	2105965	24.37	0.05		0.56	0.05	0.585	128.8	6.4	2.82E+09	362
84	2402550	27.81	0.05		0.60	0.05	0.567	142.0	6.7	3.18E+09	358
85	2599135	30.08	0.04		0.63	0.05	0.556	150.4	6.9	3.41E+11	354
86	2895720	33.52	0.04		0.66	0.05	0.542	162.9	7.2	3.76E+11	352
87	3192305	36.95	0.04		0.69	0.05	0.528	174.6	7.5	4.11E+11	349
88	3488890	40.38	0.04		0.73	0.05	0.516	186.5	7.7	4.46E+11	347
89	3785475	43.81	0.04		0.76	0.05	0.505	197.7	7.9	4.80E+11	345
90	4082060	47.25	0.04		0.78	0.05	0.495	208.7	8.1	5.14E+11	343
91	4378645	50.68	0.04		0.81	0.05	0.485	219.4	8.4	5.48E+11	341
92	4675230	54.11	0.04		0.84	0.05	0.476	229.6	8.6	5.82E+11	339
93	4971815	57.54	0.04		0.87	0.05	0.467	240.0	8.7	6.16E+11	338
94	5268400	60.98	0.04		0.89	0.05	0.459	249.9	8.9	6.49E+11	336
95	5564985	64.41	0.04		0.92	0.05	0.452	259.7	9.1	6.83E+11	335
96	5861570	67.84	0.04		0.94	0.05	0.445	269.2	9.3	7.16E+11	334
97	6158155	71.27	0.04		0.96	0.05	0.438	278.6	9.4	7.49E+11	333
98	6454740	74.71	0.04		0.99	0.05	0.431	287.8	9.6	7.82E+11	331
99	6751325	78.14	0.04		1.01	0.05	0.425	296.8	9.7	8.15E+11	330
100	7047910	81.57	0.04		1.03	0.05	0.419	305.7	9.9	8.48E+11	329
101	7344495	85.01	0.04		1.05	0.04	0.414	314.4	10.0	8.81E+11	328
102	7641080	88.44	0.04		1.07	0.04	0.408	323.0	10.1	9.13E+11	328
103	7937665	91.87	0.04		1.09	0.04	0.403	331.5	10.3	9.46E+11	327
104	8234250	95.30	0.04		1.11	0.04	0.398	339.8	10.4	9.78E+11	326
105	8530835	98.74	0.04		1.13	0.04	0.394	348.0	10.5	1.01E+12	325
106	8827420	102.17	0.04		1.15	0.04	0.389	356.1	10.6	1.04E+12	325
107	9124005	105.60	0.04		1.17	0.04	0.385	364.1	10.8	1.08E+12	324
108	9420590	109.03	0.04		1.19	0.04	0.380	372.0	10.9	1.11E+12	323
109	9717175	112.47	0.04		1.21	0.04	0.376	379.8	11.0	1.14E+12	323
110	10013760	115.90	0.04		1.23	0.04	0.372	387.4	11.1	1.17E+12	322
111	10310345	119.33	0.04		1.25	0.04	0.368	395.0	11.2	1.20E+12	321
112	10606930	122.77	0.04		1.26	0.04	0.365	402.5	11.3	1.24E+12	321
113	10903515	126.20	0.04		1.28	0.04	0.361	409.9	11.4	1.27E+12	320
114	11200100	129.63	0.04		1.30	0.04	0.358	417.2	11.5	1.30E+12	320
115	11496685	133.06	0.04		1.32	0.04	0.354	424.5	11.6	1.33E+12	319
116	11793270	136.50	0.04		1.33	0.04	0.351	431.6	11.7	1.36E+12	319
117	12089855	139.93	0.04		1.35	0.04	0.348	438.7	11.8	1.40E+12	318
118	12386440	143.36	0.04		1.37	0.04	0.345	445.7	11.9	1.43E+12	318
119	12683025	146.79	0.04		1.38	0.04	0.342	452.6	12.0	1.46E+12	317
120	12979610	150.23	0.04		1.40	0.04	0.339	459.5	12.1	1.49E+12	317
121	13276195	153.66	0.04		1.41	0.04	0.336	466.3	12.2	1.52E+12	316
122	13572780	157.09	0.04		1.43	0.04	0.333	473.0	12.3	1.55E+12	316
123	13869365	160.53	0.04		1.45	0.04	0.331	479.7	12.4	1.58E+12	315
124	14165950	163.96	0.04		1.46	0.04	0.328	486.3	12.4	1.62E+12	315
125	14462535	167.39	0.04		1.48	0.04	0.325	492.8	12.5	1.65E+12	315
126	14759120	170.82	0.04		1.49	0.04	0.323	499.3	12.6	1.68E+12	314
127	15055705	174.26	0.04		1.51	0.04	0.321	505.7	12.7	1.71E+12	314
128	15352290	177.69	0.04		1.52	0.04	0.318	512.1	12.8	1.74E+12	314
129	15648875	181.12	0.04		1.54	0.04	0.316	518.4	12.8	1.77E+12	313
130	15945460	184.55	0.04		1.55	0.04	0.314	524.6	12.9	1.80E+12	313
131	16242045	187.99	0.04		1.56	0.04	0.311	530.8	13.0	1.84E+12	313
132	16538630	191.42	0.04		1.58	0.04	0.309	537.0	13.1	1.87E+12	312
133	16835215	194.85	0.04		1.59	0.04	0.307	543.1	13.1	1.90E+12	312
134	17131800	198.28	0.04		1.61	0.04	0.305	549.1	13.2	1.93E+12	312
135	17428385	201.72	0.04		1.62	0.04	0.303	555.1	13.3	1.96E+12	311
136	17724970	205.15	0.04		1.63	0.04	0.301	561.1	13.4	1.99E+12	311
137	18021555	208.58	0.04		1.65	0.04	0.299	567.0	13.4	2.02E+12	311
138	18318140	212.02	0.04		1.66	0.04	0.297	572.9	13.5	2.05E+12	310
139	18614725	215.45	0.04		1.68	0.04	0.295	578.7	13.6	2.08E+12	310
140	18911310	218.88	0.04		1.69	0.04	0.293	584.5	13.6	2.11E+12	310
141	19207895	222.31	0.04		1.70	0.04	0.291	590.3	13.7	2.15E+12	310
142	19504480	225.75	0.04		1.71	0.04	0.290	596.0	13.8	2.18E+12	309
143	19801065	229.18	0.04		1.73	0.04	0.288	601.6	13.8	2.21E+12	309
144	20097650	232.61	0.04		1.74	0.04	0.286	607.3	13.9	2.24E+12	309
145	20394235	236.04	0.04		1.75	0.04	0.285	612.8	14.0	2.27E+12	308
146	20690820	239.48	0.04		1.77	0.04	0.283	618.4	14.0	2.30E+12	308
147	20987405	242.91	0.04		1.78	0.04	0.281	623.9	14.1	2.33E+12	308
148	21283990	246.34	0.04		1.79	0.04	0.280	629.4	14.2	2.36E+12	308
149	21580575	249.78	0.04		1.80	0.04	0.278	634.8	14.2	2.39E+12	308
150	21877160	253.21	0.04		1.82	0.04	0.277	640.2	14.3	2.42E+12	307
151	22173745	256.64	0.04		1.83	0.04	0.275	645.6	14.3	2.45E+12	307
152	22470330	260.07	0.04		1.84	0.04	0.274	650.9	14.4	2.48E+12	307
153	22766915	263.51	0.04		1.85	0.04	0.272	656.2	14.5	2.51E+12	307
154	23063500	266.94	0.04		1.86	0.04	0.271	661.5	14.5	2.54E+12	306
155	23360085	270.37	0.04		1.88	0.04	0.269	666.8	14.6	2.57E+12	306
156	23656670	273.80	0.04		1.89	0.04	0.268	672.0	14.6	2.61E+12	306
157	23953255	277.24	0.04		1.90	0.04	0.266	677.2	14.7	2.64E+12	306
158	24249840	280.67	0.04		1.91	0.04	0.265	682.3	14.7	2.67E+12	306
159	24546425	284.10	0.04		1.92	0.04	0.264	687.4	14.8	2.70E+12	305
160	24843010	287.53	0.04		1.94	0.04	0.262	692.5	14.8	2.73E+12	305
161	25139595	290.97	0.04		1.95	0.04	0.261	697.6	14.9	2.76E+12	305
162	25436180	294.40	0.04		1.96	0.04	0.260	702.6	15.0	2.79E+12	305
163	25732765	297.83	0.04		1.97	0.04	0.259	707.6	15.0	2.82E+12	305
164	26029350	301.27	0.04		1.98	0.04	0.257	712.6	15.1	2.85E+12	304
165	26325935	304.70	0.04		1.99	0.04	0.256	717.6	15.1	2.88E+12	304
166	26622520	308.13	0.04		2.00	0.04	0.255	722.5	15.2	2.91E+12	304
167	26919105	311.56	0.04		2.01	0.04	0.254	727.4	15.2	2.94E+12	304
168	27215690	315.00	0.04		2.03	0.04	0.253	732.3	15.3	2.97E+12	304
169	27512275	318.43	0.04		2.04	0.04	0.252	737.1	15.3	3.00E+12	303
170	27808860	321.86	0.04		2.05	0.04	0.250	741.9	15.4	3.03E+12	303
171	28105445	325.29	0.04		2.06	0.04	0.249	746.7	15.4	3.06E+12	303
172	28402030	328.73	0.04		2.07	0.04	0.248	751.5	15.5	3.09E+12	303
173	28698615	332.16	0.04		2.08	0.04	0.247	756.3	15.5	3.12E+12	303
174	28995200	335.59	0.04		2.09	0.04	0.246	761.0	15.6	3.15E+12	303
175	29291785	339.03	0.04		2.10	0.04	0.245	765.7	15.6	3.18E+12	302
176	29588370	342.46	0.04		2.11	0.04	0.244	770.4	15.7	3.21E+12	302
177	29884955	345.89	0.04		2.12	0.04	0.243	775.0	15.7	3.24E+12	302
178	30181540	349.32	0.04		2.13	0.04	0.242	779.7	15.8	3.27E+12	302
179	30478125	352.76	0.04		2.14	0.04	0.241	784.3	15.8	3.30E+12	302
180	30774710	356.19	0.04		2.15	0.04	0.240	788.9	15.8	3.33E+12	302
181	31071295	359.62	0.04		2.16	0.04	0.239	793.4	15.9	3.36E+12	301
182	31367880	363.05	0.04		2.17	0.04	0.238	798.0	15.9	3.39E+12	301
183	31664465	366.49	0.04		2.18	0.04	0.237	802.5	16.0	3.42E+12	301

Table B-4
Estimation of Steam Injection Rate and Steam Zone Growth

A-zone, 8.1 darcy

Parameter	Symbol	Unit	Value
Thickness of steamed layer	h	m	4.57
Particle density of soil	ρ_s	kg/m^3	[illegible]
Porosity of steamed layer	ϕ	-	[illegible]
Absolute permeability of soil	k	m^2	8.1E-12
Heat capacity of soil	c_{ps}	J/(kg K)	[illegible]
Initial water saturation	S_w		[illegible]
Ambient pressure in aquifer	P_{amb}	Pa	[illegible]
Density of water	ρ_w	kg/m^3	[illegible]
Ambient water temperature	T_{amb}	K	[illegible]
Heat capacity of water	c_{pw}	J/(kg K)	[illegible]
Overall heat capacity	$(\rho c)_t$	J/(m^3 K)	[illegible]
Overburden thermal conductivity	λ	J/(s m K)	[illegible]
Overburden thermal diffusivity	α	m^2/s	[illegible]
Radius of injection well	r_w	m	[illegible]
Maximum steam injection pressure	P_{inj}	Pa	[illegible]
Relative permeability of steam	k_{rs}		
Steam viscosity	μ_s	kg/(m s)	[illegible]
Temperature of steam	T_s	K	[illegible]
Delta T	$T_s - T_{amb}$	K	[illegible]
Heat of condensation	h_v	J/kg	[illegible]
Time since start of injection	t	s	
Steam mass flow rate	m	kg/s	
Volume of steam zone	V	m^3	
Gas constant	R	J/(mole K)	8.314
Initial radius of steam zone	r_0	m	[illegible]
Mole mass of water	M_w	kg/mole	[illegible]
Density of steam	ρ_{steam}	kg/m^3	[illegible]
Depth to top of injection screen	D_{top}	m b.g.s.	7.62
Length of injection screen	L_{screen}	m	[illegible]
Aquifer hydraulic head	H_{hyd}	m b.g.s.	



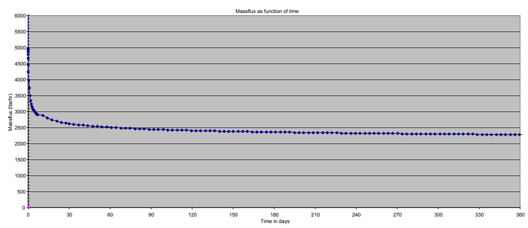


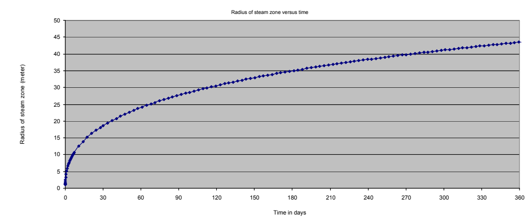
	t (s)	t (days)	´m	cp,sw	y	´mave	erf(y)*ey2	A(t)	r(t)	Energy Injected	´m (lb/h)
1	60	0.00	13.44	3449770	0.00	13.44	0.997	1	0.6	2.15E+09	106555
2	120	0.00	0.26		0.00	6.85	0.995	1	0.7	2.19E+09	2040
3	240	0.00	0.26		0.01	3.55	0.993	1	0.7	2.27E+09	2024
4	480	0.01	0.25		0.01	1.90	0.990	2	0.7	2.43E+09	2004
5	960	0.01	0.25		0.01	1.08	0.987	2	0.7	2.75E+09	1975
6	1920	0.02	0.24		0.02	0.66	0.981	2	0.8	3.38E+09	1928
7	3840	0.04	0.23		0.02	0.45	0.973	3	1.0	4.57E+09	1857
8	7680	0.09	0.22		0.03	0.33	0.963	4	1.2	6.85E+09	1762
9	15360	0.18	0.21		0.05	0.27	0.948	7	1.5	1.11E+10	1650
10	30720	0.36	0.19		0.07	0.23	0.928	12	1.9	1.90E+10	1535
11	61440	0.71	0.18		0.10	0.21	0.900	21	2.6	3.37E+10	1424
12	104640	1.21	0.17		0.13	0.19	0.873	32	3.2	5.30E+10	1324
13	147840	1.71	0.16		0.15	0.18	0.852	42	3.7	7.12E+10	1255
14	191040	2.21	0.15		0.17	0.17	0.834	52	4.1	8.88E+10	1214
15	234240	2.71	0.15		0.19	0.17	0.819	61	4.4	1.06E+11	1185
16	277440	3.21	0.15		0.20	0.17	0.805	70	4.7	1.23E+11	1164
17	320640	3.71	0.14		0.22	0.16	0.793	79	5.0	1.40E+11	1146
18	363840	4.21	0.14		0.23	0.16	0.782	87	5.3	1.56E+11	1131
19	407040	4.71	0.14		0.25	0.16	0.772	95	5.5	1.72E+11	1119
74	450240	5.21	0.14		0.26	0.16	0.763	103	5.7	1.88E+11	1108
75	493440	5.71	0.14		0.27	0.16	0.754	111	5.9	2.04E+11	1099
76	536640	6.21	0.14		0.28	0.15	0.745	119	6.1	2.20E+11	1090
77	579840	6.71	0.14		0.30	0.15	0.738	126	6.3	2.36E+11	1083
78	623040	7.21	0.14		0.31	0.15	0.730	134	6.5	2.52E+11	1076
79	919625	10.64	0.13		0.37	0.15	0.687	183	7.6	3.58E+11	1069
80	1216210	14.08	0.13		0.43	0.14	0.654	228	8.5	4.61E+11	1036
81	1512795	17.51	0.13		0.48	0.14	0.627	270	9.3	5.63E+11	1014
82	1809380	20.94	0.13		0.52	0.14	0.604	309	9.9	6.62E+11	998
83	2105965	24.37	0.12		0.56	0.14	0.585	347	10.5	7.60E+11	985
84	2402550	27.81	0.12		0.60	0.13	0.567	383	11.0	8.57E+11	974
85	2599135	30.08	0.12		0.63	0.13	0.556	406	11.4	9.21E+11	965
86	2895720	33.52	0.12		0.66	0.13	0.542	440	11.8	1.02E+12	960
87	3192305	36.95	0.12		0.69	0.13	0.528	473	12.3	1.11E+12	953
88	3488890	40.38	0.12		0.73	0.13	0.516	505	12.7	1.21E+12	947
89	3785475	43.81	0.12		0.76	0.13	0.505	535	13.1	1.30E+12	941
90	4082060	47.25	0.12		0.78	0.13	0.495	565	13.4	1.39E+12	936
91	4378645	50.68	0.12		0.81	0.13	0.485	595	13.8	1.49E+12	931
92	4675230	54.11	0.12		0.84	0.13	0.476	623	14.1	1.58E+12	927
93	4971815	57.54	0.12		0.87	0.13	0.467	651	14.4	1.67E+12	923
94	5268400	60.98	0.12		0.89	0.13	0.459	678	14.7	1.76E+12	920
95	5564985	64.41	0.12		0.92	0.12	0.452	705	15.0	1.85E+12	916
96	5861570	67.84	0.12		0.94	0.12	0.445	731	15.3	1.94E+12	913
97	6158155	71.27	0.11		0.96	0.12	0.438	757	15.5	2.04E+12	910
98	6454740	74.71	0.11		0.99	0.12	0.431	782	15.8	2.13E+12	908
99	6751325	78.14	0.11		1.01	0.12	0.425	807	16.0	2.22E+12	905
100	7047910	81.57	0.11		1.03	0.12	0.419	831	16.3	2.31E+12	903
101	7344495	85.01	0.11		1.05	0.12	0.414	855	16.5	2.40E+12	900
102	7641080	88.44	0.11		1.07	0.12	0.408	879	16.7	2.49E+12	898
103	7937665	91.87	0.11		1.09	0.12	0.403	902	16.9	2.58E+12	896
104	8234250	95.30	0.11		1.11	0.12	0.398	925	17.2	2.66E+12	894
105	8530835	98.74	0.11		1.13	0.12	0.394	948	17.4	2.75E+12	892
106	8827420	102.17	0.11		1.15	0.12	0.389	970	17.6	2.84E+12	890
107	9124005	105.60	0.11		1.17	0.12	0.385	992	17.8	2.93E+12	888
108	9420590	109.03	0.11		1.19	0.12	0.380	1014	18.0	3.02E+12	887
109	9717175	112.47	0.11		1.21	0.12	0.376	1035	18.1	3.11E+12	885
110	10013760	115.90	0.11		1.23	0.12	0.372	1056	18.3	3.20E+12	884
111	10310345	119.33	0.11		1.25	0.12	0.368	1077	18.5	3.28E+12	882
112	10606930	122.77	0.11		1.26	0.12	0.365	1098	18.7	3.37E+12	881
113	10903515	126.20	0.11		1.28	0.12	0.361	1118	18.9	3.46E+12	879
114	11200100	129.63	0.11		1.30	0.12	0.358	1138	19.0	3.55E+12	878
115	11496685	133.06	0.11		1.32	0.12	0.354	1158	19.2	3.63E+12	876
116	11793270	136.50	0.11		1.33	0.12	0.351	1178	19.4	3.72E+12	875
117	12089855	139.93	0.11		1.35	0.12	0.348	1197	19.5	3.81E+12	874
118	12386440	143.36	0.11		1.37	0.12	0.345	1217	19.7	3.90E+12	873
119	12683025	146.79	0.11		1.38	0.12	0.342	1236	19.8	3.98E+12	872
120	12979610	150.23	0.11		1.40	0.12	0.339	1255	20.0	4.07E+12	870
121	13276195	153.66	0.11		1.41	0.12	0.336	1273	20.1	4.16E+12	869
122	13572780	157.09	0.11		1.43	0.12	0.333	1292	20.3	4.24E+12	868
123	13869365	160.53	0.11		1.45	0.12	0.331	1310	20.4	4.33E+12	867
124	14165950	163.96	0.11		1.46	0.12	0.328	1328	20.6	4.41E+12	866
125	14462535	167.39	0.11		1.48	0.12	0.325	1346	20.7	4.50E+12	865
126	14759120	170.82	0.11		1.49	0.12	0.323	1364	20.8	4.59E+12	864
127	15055705	174.26	0.11		1.51	0.12	0.321	1382	21.0	4.67E+12	863
128	15352290	177.69	0.11		1.52	0.12	0.318	1399	21.1	4.76E+12	862
129	15648875	181.12	0.11		1.54	0.12	0.316	1417	21.2	4.85E+12	861
130	15945460	184.55	0.11		1.55	0.12	0.314	1434	21.4	4.93E+12	861
131	16242045	187.99	0.11		1.56	0.12	0.311	1451	21.5	5.02E+12	860
132	16538630	191.42	0.11		1.58	0.12	0.309	1468	21.6	5.10E+12	859
133	16835215	194.85	0.11		1.59	0.12	0.307	1485	21.7	5.19E+12	858
134	17131800	198.28	0.11		1.61	0.12	0.305	1502	21.9	5.27E+12	857
135	17428385	201.72	0.11		1.62	0.12	0.303	1518	22.0	5.36E+12	856
136	17724970	205.15	0.11		1.63	0.12	0.301	1535	22.1	5.44E+12	856
137	18021555	208.58	0.11		1.65	0.12	0.299	1551	22.2	5.53E+12	855
138	18318140	212.02	0.11		1.66	0.11	0.297	1567	22.3	5.61E+12	854
139	18614725	215.45	0.11		1.68	0.11	0.295	1583	22.4	5.70E+12	853
140	18911310	218.88	0.11		1.69	0.11	0.293	1599	22.6	5.78E+12	853
141	19207895	222.31	0.11		1.70	0.11	0.291	1615	22.7	5.87E+12	852
142	19504480	225.75	0.11		1.71	0.11	0.290	1631	22.8	5.95E+12	851
143	19801065	229.18	0.11		1.73	0.11	0.288	1647	22.9	6.04E+12	851
144	20097650	232.61	0.11		1.74	0.11	0.286	1662	23.0	6.12E+12	850
145	20394235	236.04	0.11		1.75	0.11	0.285	1678	23.1	6.21E+12	849
146	20690820	239.48	0.11		1.77	0.11	0.283	1693	23.2	6.29E+12	849
147	20987405	242.91	0.11		1.78	0.11	0.281	1708	23.3	6.38E+12	848
148	21283990	246.34	0.11		1.79	0.11	0.280	1723	23.4	6.46E+12	847
149	21580575	249.78	0.11		1.80	0.11	0.278	1738	23.5	6.55E+12	847
150	21877160	253.21	0.11		1.82	0.11	0.277	1753	23.6	6.63E+12	846
151	22173745	256.64	0.11		1.83	0.11	0.275	1768	23.7	6.72E+12	846
152	22470330	260.07	0.11		1.84	0.11	0.274	1783	23.8	6.80E+12	845
153	22766915	263.51	0.11		1.85	0.11	0.272	1797	23.9	6.88E+12	844
154	23063500	266.94	0.11		1.86	0.11	0.271	1812	24.0	6.97E+12	844
155	23360085	270.37	0.11		1.88	0.11	0.269	1827	24.1	7.05E+12	843
156	23656670	273.80	0.11		1.89	0.11	0.268	1841	24.2	7.14E+12	843
157	23953255	277.24	0.11		1.90	0.11	0.266	1855	24.3	7.22E+12	842
158	24249840	280.67	0.11		1.91	0.11	0.265	1869	24.4	7.30E+12	842
159	24546425	284.10	0.11		1.92	0.11	0.264	1884	24.5	7.39E+12	841
160	24843010	287.53	0.11		1.94	0.11	0.262	1898	24.6	7.47E+12	841
161	25139595	290.97	0.11		1.95	0.11	0.261	1912	24.7	7.56E+12	840
162	25436180	294.40	0.11		1.96	0.11	0.260	1926	24.8	7.64E+12	840
163	25732765	297.83	0.11		1.97	0.11	0.259	1939	24.8	7.72E+12	839
164	26029350	301.27	0.11		1.98	0.11	0.257	1953	24.9	7.81E+12	839
165	26325935	304.70	0.11		1.99	0.11	0.256	1967	25.0	7.89E+12	838
166	26622520	308.13	0.11		2.00	0.11	0.255	1980	25.1	7.97E+12	838
167	26919105	311.56	0.11		2.01	0.11	0.254	1994	25.2	8.06E+12	837
168	27215690	315.00	0.11		2.03	0.11	0.253	2008	25.3	8.14E+12	837
169	27512275	318.43	0.11		2.04	0.11	0.252	2021	25.4	8.22E+12	836
170	27808860	321.86	0.11		2.05	0.11	0.250	2034	25.4	8.31E+12	836
171	28105445	325.29	0.11		2.06	0.11	0.249	2048	25.5	8.39E+12	836
172	28402030	328.73	0.11		2.07	0.11	0.248	2061	25.6	8.47E+12	835
173	28698615	332.16	0.11		2.08	0.11	0.247	2074	25.7	8.56E+12	835
174	28995200	335.59	0.11		2.09	0.11	0.246	2087	25.8	8.64E+12	834
175	29291785	339.03	0.11		2.10	0.11	0.245	2100	25.8	8.72E+12	834
176	29588370	342.46	0.11		2.11	0.11	0.244	2113	25.9	8.81E+12	833
177	29884955	345.89	0.11		2.12	0.11	0.243	2126	26.0	8.89E+12	833
178	30181540	349.32	0.10		2.13	0.11	0.242	2139	26.1	8.97E+12	833
179	30478125	352.76	0.10		2.14	0.11	0.241	2151	26.2	9.06E+12	832
180	30774710	356.19	0.10		2.15	0.11	0.240	2164	26.2	9.14E+12	832
181	31071295	359.62	0.10		2.16	0.11	0.239	2177	26.3	9.22E+12	831
182	31367880	363.05	0.10		2.17	0.11	0.238	2189	26.4	9.30E+12	831
183	31664465	366.49	0.10		2.18	0.11	0.237	2202	26.5	9.39E+12	831

Table B-5
Estimation of Steam Injection Rate and Steam Zone Growth

A-zone, 24 darcy

Parameter	Symbol	Unit	Value
Thickness of steamed layer	h	m	4.575
Particle density of soil	d_s	kg/m³	2650
Porosity of steamed layer	p		0.35
Absolute permeability of soil	k_s	m²	2.4E-11
Heat capacity of soil	cp_r	J/(kg K)	1152
Initial water saturation	S_w		1
Ambient pressure in aquifer	P_{amb}	Pa	14785
Density of water	d_w	kg/m³	1000
Ambient water temperature	T_{amb}	K	295
Heat capacity of water	cp_w	J/(kg K)	4187
Overall heat capacity	cp_{sw}	J/(kg K)	2200
Overburden thermal conductivity	k	J/(s m K)	1.3
Overburden thermal diffusivity	a	m²/s	0.0000001
Radius of injection well	r_w	m	0.0508
Maximum steam injection pressure	P_w	Pa	187439
Relative permeability of steam	k_{rs}		1
Steam viscosity	u_s	kg/(m s)	1.30E-05
Temperature of steam	T_s	K	391
Delta T	$T_s - T_{amb}$	K	96
Heat of condensation	'h	J/kg	2666000
Time since start of injection	t	s	
Steam mass flow rate	'm	kg/s	
Volume of steam zone	V	m³	
Gas constant	R	J/(mole K)	8.314
Initial radius of steam zone	r_{si}	m	0.053025
Mole mass of water	M_w	kg/mole	0.018
Density of steam	d_{steam}	kg/m³	1.1
Depth to top of injection screen	$D_{injscr.}$	m.b.g	7.625
Length of injection screen	$L_{inj.screen}$	m	4.5
Aquifer hydraulic head	D_{gwt}	m.b.g	3



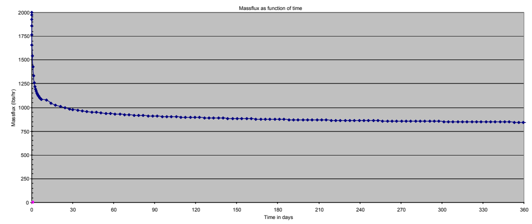


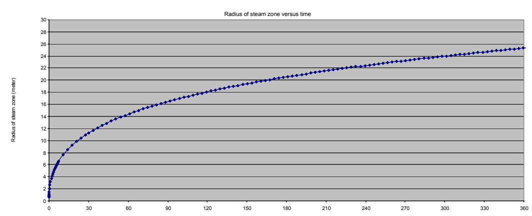
	t (s)	t (days)	hi	cp,sw	y	Vave	erfc(y)exp(y²)	A(t)	r(t)	Energy Injected	m (lb/h)
1	60	0.00	39.82	3449770	0.003	39.82	0.997	4	1.1	6.37E+09	315719
2	120	0.00	0.63		0.004	20.22	0.995	4	1.1	6.47E+09	4984
3	240	0.00	0.62		0.006	10.42	0.993	4	1.2	6.67E+09	4954
4	480	0.01	0.62		0.009	5.52	0.990	5	1.2	7.07E+09	4918
5	960	0.01	0.61		0.012	3.07	0.987	5	1.3	7.85E+09	4866
6	1920	0.02	0.60		0.017	1.84	0.981	6	1.4	9.40E+09	4783
7	3840	0.04	0.59		0.024	1.21	0.973	8	1.6	1.24E+10	4652
8	7680	0.09	0.56		0.034	0.89	0.963	12	1.9	1.82E+10	4466
9	15360	0.18	0.53		0.048	0.71	0.948	18	2.4	2.91E+10	4235
10	30720	0.36	0.50		0.068	0.61	0.928	31	3.1	4.97E+10	3981
11	61440	0.71	0.47		0.096	0.54	0.900	54	4.1	8.82E+10	3730
12	104640	1.21	0.44		0.126	0.50	0.873	83	5.1	1.39E+11	3495
13	147840	1.71	0.42		0.149	0.48	0.852	110	5.9	1.87E+11	3331
14	191040	2.21	0.41		0.170	0.46	0.834	136	6.6	2.34E+11	3232
15	234240	2.71	0.40		0.188	0.45	0.819	161	7.2	2.80E+11	3163
16	277440	3.21	0.39		0.205	0.44	0.805	185	7.7	3.25E+11	3109
17	320640	3.71	0.39		0.220	0.43	0.793	208	8.1	3.70E+11	3067
18	363840	4.21	0.38		0.234	0.43	0.782	231	8.6	4.14E+11	3031
19	407040	4.71	0.38		0.248	0.42	0.772	253	9.0	4.58E+11	3001
74	450240	5.21	0.38		0.261	0.42	0.763	274	9.3	5.01E+11	2974
75	493440	5.71	0.37		0.273	0.41	0.754	295	9.7	5.44E+11	2951
76	536640	6.21	0.37		0.284	0.41	0.745	316	10.0	5.86E+11	2930
77	579840	6.71	0.37		0.296	0.41	0.738	336	10.3	6.28E+11	2911
78	623040	7.21	0.36		0.306	0.40	0.730	357	10.7	6.70E+11	2894
79	919625	10.64	0.36		0.372	0.39	0.687	489	12.5	9.57E+11	2878
80	1216210	14.08	0.35		0.428	0.38	0.654	610	13.9	1.24E+12	2796
81	1512795	17.51	0.35		0.478	0.37	0.627	724	15.2	1.51E+12	2741
82	1809380	20.94	0.34		0.522	0.37	0.604	831	16.3	1.78E+12	2700
83	2105965	24.37	0.34		0.563	0.36	0.585	933	17.2	2.04E+12	2668
84	2402550	27.81	0.33		0.602	0.36	0.567	1031	18.1	2.31E+12	2641
85	2599135	30.08	0.33		0.626	0.36	0.556	1094	18.7	2.48E+12	2619
86	2895720	33.52	0.33		0.661	0.36	0.542	1186	19.4	2.74E+12	2606
87	3192305	36.95	0.33		0.694	0.35	0.528	1275	20.1	3.00E+12	2590
88	3488890	40.38	0.32		0.725	0.35	0.516	1362	20.8	3.26E+12	2572
89	3785475	43.81	0.32		0.755	0.35	0.505	1446	21.4	3.51E+12	2558
90	4082060	47.25	0.32		0.785	0.35	0.495	1527	22.0	3.76E+12	2545
91	4378645	50.68	0.32		0.813	0.34	0.485	1607	22.6	4.02E+12	2534
92	4675230	54.11	0.32		0.840	0.34	0.476	1685	23.2	4.27E+12	2523
93	4971815	57.54	0.32		0.866	0.34	0.467	1761	23.7	4.52E+12	2514
94	5268400	60.98	0.32		0.891	0.34	0.459	1836	24.2	4.77E+12	2505
95	5564985	64.41	0.31		0.916	0.34	0.452	1909	24.6	5.02E+12	2498
96	5861570	67.84	0.31		0.940	0.34	0.445	1980	25.1	5.27E+12	2488
97	6158155	71.27	0.31		0.964	0.34	0.438	2050	25.5	5.51E+12	2481
98	6454740	74.71	0.31		0.986	0.33	0.431	2119	26.0	5.76E+12	2474
99	6751325	78.14	0.31		1.009	0.33	0.425	2187	26.4	6.01E+12	2468
100	7047910	81.57	0.31		1.031	0.33	0.419	2254	26.8	6.25E+12	2461
101	7344495	85.01	0.31		1.052	0.33	0.414	2319	27.2	6.50E+12	2456
102	7641080	88.44	0.31		1.073	0.33	0.408	2384	27.5	6.74E+12	2450
103	7937665	91.87	0.31		1.094	0.33	0.403	2447	27.9	6.98E+12	2445
104	8234250	95.30	0.31		1.114	0.33	0.398	2510	28.3	7.23E+12	2439
105	8530835	98.74	0.31		1.134	0.33	0.394	2572	28.6	7.47E+12	2435
106	8827420	102.17	0.31		1.154	0.33	0.389	2633	28.9	7.71E+12	2430
107	9124005	105.60	0.31		1.173	0.33	0.385	2693	29.3	7.95E+12	2425
108	9420590	109.03	0.31		1.192	0.33	0.380	2752	29.6	8.20E+12	2421
109	9717175	112.47	0.30		1.210	0.33	0.376	2811	29.9	8.44E+12	2417
110	10013760	115.90	0.30		1.229	0.33	0.372	2868	30.2	8.68E+12	2413
111	10310345	119.33	0.30		1.247	0.32	0.368	2925	30.5	8.92E+12	2408
112	10606930	122.77	0.30		1.265	0.32	0.365	2982	30.8	9.16E+12	2405
113	10903515	126.20	0.30		1.282	0.32	0.361	3038	31.1	9.40E+12	2402
114	11200100	129.63	0.30		1.299	0.32	0.358	3093	31.4	9.64E+12	2398
115	11496685	133.06	0.30		1.317	0.32	0.354	3147	31.6	9.88E+12	2395
116	11793270	136.50	0.30		1.333	0.32	0.351	3201	31.9	1.01E+13	2392
117	12089855	139.93	0.30		1.350	0.32	0.348	3255	32.2	1.04E+13	2389
118	12386440	143.36	0.30		1.367	0.32	0.345	3308	32.4	1.06E+13	2386
119	12683025	146.79	0.30		1.383	0.32	0.342	3360	32.7	1.08E+13	2383
120	12979610	150.23	0.30		1.399	0.32	0.339	3412	32.9	1.11E+13	2380
121	13276195	153.66	0.30		1.415	0.32	0.336	3463	33.2	1.13E+13	2377
122	13572780	157.09	0.30		1.431	0.32	0.333	3514	33.4	1.15E+13	2374
123	13869365	160.53	0.30		1.446	0.32	0.331	3564	33.7	1.18E+13	2372
124	14165950	163.96	0.30		1.461	0.32	0.328	3614	33.9	1.20E+13	2369
125	14462535	167.39	0.30		1.477	0.32	0.325	3663	34.1	1.22E+13	2366
126	14759120	170.82	0.30		1.492	0.32	0.323	3712	34.4	1.25E+13	2364
127	15055705	174.26	0.30		1.507	0.32	0.321	3761	34.6	1.27E+13	2362
128	15352290	177.69	0.30		1.521	0.32	0.318	3809	34.8	1.30E+13	2359
129	15648875	181.12	0.30		1.536	0.32	0.316	3857	35.0	1.32E+13	2357
130	15945460	184.55	0.30		1.551	0.32	0.314	3904	35.2	1.34E+13	2355
131	16242045	187.99	0.30		1.565	0.32	0.311	3951	35.5	1.37E+13	2352
132	16538630	191.42	0.30		1.579	0.32	0.309	3997	35.7	1.39E+13	2350
133	16835215	194.85	0.30		1.593	0.31	0.307	4044	35.9	1.41E+13	2348
134	17131800	198.28	0.30		1.607	0.31	0.305	4090	36.1	1.44E+13	2346
135	17428385	201.72	0.30		1.621	0.31	0.303	4135	36.3	1.46E+13	2344
136	17724970	205.15	0.30		1.635	0.31	0.301	4180	36.5	1.48E+13	2342
137	18021555	208.58	0.30		1.648	0.31	0.299	4225	36.7	1.51E+13	2340
138	18318140	212.02	0.29		1.662	0.31	0.297	4269	36.9	1.53E+13	2338
139	18614725	215.45	0.29		1.675	0.31	0.295	4314	37.0	1.55E+13	2336
140	18911310	218.88	0.29		1.689	0.31	0.293	4357	37.2	1.58E+13	2335
141	19207895	222.31	0.29		1.702	0.31	0.291	4401	37.4	1.60E+13	2333
142	19504480	225.75	0.29		1.715	0.31	0.290	4444	37.6	1.62E+13	2331
143	19801065	229.18	0.29		1.728	0.31	0.288	4487	37.8	1.65E+13	2329
144	20097650	232.61	0.29		1.741	0.31	0.286	4530	38.0	1.67E+13	2328
145	20394235	236.04	0.29		1.754	0.31	0.285	4572	38.1	1.69E+13	2326
146	20690820	239.48	0.29		1.766	0.31	0.283	4614	38.3	1.72E+13	2324
147	20987405	242.91	0.29		1.779	0.31	0.281	4656	38.5	1.74E+13	2323
148	21283990	246.34	0.29		1.791	0.31	0.280	4697	38.7	1.76E+13	2321
149	21580575	249.78	0.29		1.804	0.31	0.278	4739	38.8	1.78E+13	2320
150	21877160	253.21	0.29		1.816	0.31	0.277	4780	39.0	1.81E+13	2318
151	22173745	256.64	0.29		1.828	0.31	0.275	4820	39.2	1.83E+13	2317
152	22470330	260.07	0.29		1.841	0.31	0.274	4861	39.3	1.85E+13	2315
153	22766915	263.51	0.29		1.853	0.31	0.272	4901	39.5	1.88E+13	2314
154	23063500	266.94	0.29		1.865	0.31	0.271	4941	39.7	1.90E+13	2312
155	23360085	270.37	0.29		1.877	0.31	0.269	4981	39.8	1.92E+13	2311
156	23656670	273.80	0.29		1.889	0.31	0.268	5021	40.0	1.95E+13	2309
157	23953255	277.24	0.29		1.900	0.31	0.266	5060	40.1	1.97E+13	2308
158	24249840	280.67	0.29		1.912	0.31	0.265	5099	40.3	1.99E+13	2307
159	24546425	284.10	0.29		1.924	0.31	0.264	5138	40.4	2.02E+13	2305
160	24843010	287.53	0.29		1.935	0.31	0.262	5176	40.6	2.04E+13	2304
161	25139595	290.97	0.29		1.947	0.31	0.261	5215	40.7	2.06E+13	2303
162	25436180	294.40	0.29		1.958	0.31	0.260	5253	40.9	2.08E+13	2302
163	25732765	297.83	0.29		1.970	0.31	0.259	5291	41.0	2.11E+13	2300
164	26029350	301.27	0.29		1.981	0.31	0.257	5329	41.2	2.13E+13	2299
165	26325935	304.70	0.29		1.992	0.31	0.256	5367	41.3	2.15E+13	2298
166	26622520	308.13	0.29		2.003	0.31	0.255	5404	41.5	2.18E+13	2297
167	26919105	311.56	0.29		2.015	0.31	0.254	5441	41.6	2.20E+13	2295
168	27215690	315.00	0.29		2.026	0.31	0.253	5478	41.8	2.22E+13	2294
169	27512275	318.43	0.29		2.037	0.31	0.252	5515	41.9	2.24E+13	2293
170	27808860	321.86	0.29		2.048	0.31	0.250	5552	42.0	2.27E+13	2292
171	28105445	325.29	0.29		2.059	0.31	0.249	5588	42.2	2.29E+13	2291
172	28402030	328.73	0.29		2.069	0.31	0.248	5625	42.3	2.31E+13	2290
173	28698615	332.16	0.29		2.080	0.31	0.247	5661	42.4	2.34E+13	2289
174	28995200	335.59	0.29		2.091	0.31	0.246	5697	42.6	2.36E+13	2288
175	29291785	339.03	0.29		2.101	0.30	0.245	5732	42.7	2.38E+13	2286
176	29588370	342.46	0.29		2.112	0.30	0.244	5768	42.8	2.40E+13	2285
177	29884955	345.89	0.29		2.123	0.30	0.243	5803	43.0	2.43E+13	2284
178	30181540	349.32	0.29		2.133	0.30	0.242	5839	43.1	2.45E+13	2283
179	30478125	352.76	0.29		2.144	0.30	0.241	5874	43.2	2.47E+13	2282
180	30774710	356.19	0.29		2.154	0.30	0.240	5909	43.4	2.50E+13	2281
181	31071295	359.62	0.29		2.164	0.30	0.239	5943	43.5	2.52E+13	2280
182	31367880	363.05	0.29		2.175	0.30	0.238	5978	43.6	2.54E+13	2279
183	31664465	366.49	0.29		2.185	0.30	0.237	6013	43.7	2.56E+13	2278

Table B-6
Estimation of Steam Injection Rate and Steam Zone Growth

B-zone, 4.7 darcy

Parameter	Symbol	Unit	Value
Thickness of steamed layer	h	m	3.75
Particle density of soil	ρ_s	kg/m³	2650
Porosity of steamed layer	ϕ	-	0.35
Absolute permeability of soil	k_0	m²	4.7E-12
Heat capacity of soil	c_{ps}	J/(kg K)	1152
Initial water saturation	S_w		1
Ambient pressure in aquifer	P_{amb}	Pa	255989
Density of water	ρ_w	kg/m³	1000
Ambient water temperature	T_{amb}	K	295
Heat capacity of water	c_{pw}	J/(kg K)	4187
Overall heat capacity	c_{ps}	J/(kg K)	2200
Overburden thermal conductivity	λ	J/(s m K)	1.3
Overburden thermal diffusivity	α	m²/s	0.0000001
Radius of injection well	r_w	m	0.0508
Maximum steam injection pressure	P_0	Pa	308035
Relative permeability of steam	k_{rs}	-	1
Steam viscosity	μ_s	kg/(m s)	1.31E-05
Temperature of steam	T_s	K	407
Delta T	$T_s - T_{amb}$	K	112
Heat of condensation	λ_s	J/kg	2666000
Time since start of injection	t	s	
Steam mass flow rate	$\dot{m}$	kg/s	
Volume of steam zone	V	m³	
Gas constant	R	J/(mole K)	8.314
Initial radius of steam zone	r_0	m	0.05302
Mole mass of water	M_w	kg/mole	0.018
Density of steam	ρ_{steam}	kg/m³	1.7
Depth to top of injection screen	D_{top}	ft bgs	18.3
Length of injection screen	L_{screen}	m	3.75
Aquifer hydraulic head	H_{gw}	ft bgs	3



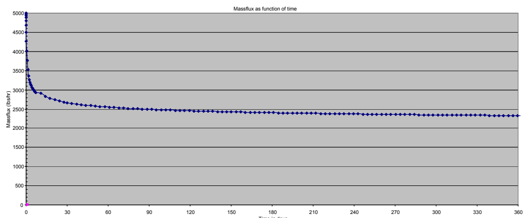


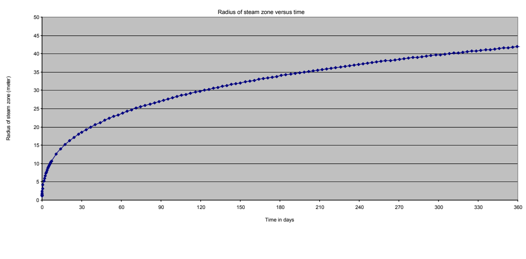
	t (s)	t (days)	´m	cp,sw	y	´mave	erf(y)*ey2	A(t)	r(t)	Energy Injected	´m (lb/h)
1	60	0.00	13.56	3449770	0.00	13.56	0.996	1	0.7	2.17E+09	107507
2	120	0.00	0.26		0.01	6.91	0.994	1	0.7	2.21E+09	2032
3	240	0.00	0.25		0.01	3.58	0.992	2	0.7	2.29E+09	2018
4	480	0.01	0.25		0.01	1.92	0.988	2	0.7	2.45E+09	2000
5	960	0.01	0.25		0.01	1.08	0.984	2	0.8	2.77E+09	1972
6	1920	0.02	0.24		0.02	0.66	0.977	2	0.9	3.39E+09	1926
7	3840	0.04	0.23		0.03	0.45	0.968	3	1.0	4.59E+09	1857
8	7680	0.09	0.22		0.04	0.34	0.955	5	1.2	6.87E+09	1764
9	15360	0.18	0.21		0.06	0.27	0.937	7	1.5	1.11E+10	1654
10	30720	0.36	0.19		0.08	0.23	0.913	12	2.0	1.91E+10	1539
11	61440	0.71	0.18		0.12	0.21	0.880	21	2.6	3.39E+10	1430
12	104640	1.21	0.17		0.15	0.19	0.848	33	3.2	5.32E+10	1330
13	147840	1.71	0.16		0.18	0.18	0.824	43	3.7	7.15E+10	1262
14	191040	2.21	0.15		0.21	0.18	0.803	53	4.1	8.92E+10	1221
15	234240	2.71	0.15		0.23	0.17	0.786	62	4.5	1.07E+11	1193
16	277440	3.21	0.15		0.25	0.17	0.771	71	4.8	1.24E+11	1171
17	320640	3.71	0.15		0.27	0.16	0.757	80	5.0	1.40E+11	1154
18	363840	4.21	0.14		0.29	0.16	0.745	88	5.3	1.57E+11	1139
19	407040	4.71	0.14		0.30	0.16	0.733	97	5.5	1.73E+11	1127
74	450240	5.21	0.14		0.32	0.16	0.722	105	5.8	1.89E+11	1116
75	493440	5.71	0.14		0.33	0.16	0.713	112	6.0	2.06E+11	1107
76	536640	6.21	0.14		0.35	0.15	0.703	120	6.2	2.21E+11	1099
77	579840	6.71	0.14		0.36	0.15	0.695	128	6.4	2.37E+11	1091
78	623040	7.21	0.14		0.37	0.15	0.687	135	6.6	2.53E+11	1084
79	919625	10.64	0.14		0.45	0.15	0.640	183	7.6	3.61E+11	1078
80	1216210	14.08	0.13		0.52	0.14	0.604	227	8.5	4.65E+11	1045
81	1512795	17.51	0.13		0.58	0.14	0.576	268	9.2	5.67E+11	1023
82	1809380	20.94	0.13		0.64	0.14	0.552	306	9.9	6.67E+11	1007
83	2105965	24.37	0.13		0.69	0.14	0.531	342	10.4	7.66E+11	994
84	2402550	27.81	0.12		0.73	0.13	0.513	377	10.9	8.65E+11	984
85	2599135	30.08	0.12		0.76	0.13	0.502	399	11.3	9.29E+11	975
86	2895720	33.52	0.12		0.81	0.13	0.487	431	11.7	1.03E+12	970
87	3192305	36.95	0.12		0.85	0.13	0.474	462	12.1	1.12E+12	963
88	3488890	40.38	0.12		0.88	0.13	0.461	492	12.5	1.22E+12	957
89	3785475	43.81	0.12		0.92	0.13	0.450	521	12.9	1.31E+12	952
90	4082060	47.25	0.12		0.96	0.13	0.440	549	13.2	1.41E+12	947
91	4378645	50.68	0.12		0.99	0.13	0.430	576	13.5	1.50E+12	942
92	4675230	54.11	0.12		1.02	0.13	0.421	603	13.9	1.59E+12	938
93	4971815	57.54	0.12		1.06	0.13	0.413	629	14.1	1.69E+12	934
94	5268400	60.98	0.12		1.09	0.13	0.405	654	14.4	1.78E+12	931
95	5564985	64.41	0.12		1.12	0.13	0.397	679	14.7	1.87E+12	928
96	5861570	67.84	0.12		1.15	0.13	0.391	704	15.0	1.96E+12	924
97	6158155	71.27	0.12		1.18	0.13	0.384	727	15.2	2.06E+12	922
98	6454740	74.71	0.12		1.20	0.12	0.378	751	15.5	2.15E+12	919
99	6751325	78.14	0.12		1.23	0.12	0.372	774	15.7	2.24E+12	916
100	7047910	81.57	0.12		1.26	0.12	0.366	796	15.9	2.33E+12	914
101	7344495	85.01	0.11		1.28	0.12	0.361	818	16.1	2.42E+12	912
102	7641080	88.44	0.11		1.31	0.12	0.356	840	16.3	2.51E+12	910
103	7937665	91.87	0.11		1.33	0.12	0.351	861	16.6	2.60E+12	907
104	8234250	95.30	0.11		1.36	0.12	0.346	882	16.8	2.69E+12	906
105	8530835	98.74	0.11		1.38	0.12	0.342	903	17.0	2.78E+12	904
106	8827420	102.17	0.11		1.41	0.12	0.337	924	17.1	2.87E+12	902
107	9124005	105.60	0.11		1.43	0.12	0.333	944	17.3	2.96E+12	900
108	9420590	109.03	0.11		1.45	0.12	0.329	964	17.5	3.05E+12	898
109	9717175	112.47	0.11		1.48	0.12	0.325	983	17.7	3.14E+12	897
110	10013760	115.90	0.11		1.50	0.12	0.322	1002	17.9	3.23E+12	895
111	10310345	119.33	0.11		1.52	0.12	0.318	1021	18.0	3.32E+12	894
112	10606930	122.77	0.11		1.54	0.12	0.315	1040	18.2	3.41E+12	892
113	10903515	126.20	0.11		1.56	0.12	0.311	1059	18.4	3.50E+12	891
114	11200100	129.63	0.11		1.59	0.12	0.308	1077	18.5	3.59E+12	890
115	11496685	133.06	0.11		1.61	0.12	0.305	1095	18.7	3.68E+12	888
116	11793270	136.50	0.11		1.63	0.12	0.302	1113	18.8	3.76E+12	887
117	12089855	139.93	0.11		1.65	0.12	0.299	1131	19.0	3.85E+12	886
118	12386440	143.36	0.11		1.67	0.12	0.296	1148	19.1	3.94E+12	885
119	12683025	146.79	0.11		1.69	0.12	0.293	1166	19.3	4.03E+12	884
120	12979610	150.23	0.11		1.71	0.12	0.291	1183	19.4	4.12E+12	882
121	13276195	153.66	0.11		1.73	0.12	0.288	1200	19.5	4.20E+12	881
122	13572780	157.09	0.11		1.75	0.12	0.286	1217	19.7	4.29E+12	880
123	13869365	160.53	0.11		1.76	0.12	0.283	1233	19.8	4.38E+12	879
124	14165950	163.96	0.11		1.78	0.12	0.281	1250	19.9	4.47E+12	878
125	14462535	167.39	0.11		1.80	0.12	0.278	1266	20.1	4.55E+12	877
126	14759120	170.82	0.11		1.82	0.12	0.276	1282	20.2	4.64E+12	876
127	15055705	174.26	0.11		1.84	0.12	0.274	1298	20.3	4.73E+12	875
128	15352290	177.69	0.11		1.86	0.12	0.272	1314	20.4	4.82E+12	875
129	15648875	181.12	0.11		1.87	0.12	0.270	1330	20.6	4.90E+12	874
130	15945460	184.55	0.11		1.89	0.12	0.267	1345	20.7	4.99E+12	873
131	16242045	187.99	0.11		1.91	0.12	0.265	1361	20.8	5.08E+12	872
132	16538630	191.42	0.11		1.93	0.12	0.263	1376	20.9	5.16E+12	871
133	16835215	194.85	0.11		1.94	0.12	0.262	1391	21.0	5.25E+12	870
134	17131800	198.28	0.11		1.96	0.12	0.260	1406	21.2	5.34E+12	870
135	17428385	201.72	0.11		1.98	0.12	0.258	1421	21.3	5.42E+12	869
136	17724970	205.15	0.11		1.99	0.12	0.256	1436	21.4	5.51E+12	868
137	18021555	208.58	0.11		2.01	0.12	0.254	1451	21.5	5.60E+12	867
138	18318140	212.02	0.11		2.03	0.12	0.252	1466	21.6	5.68E+12	867
139	18614725	215.45	0.11		2.04	0.12	0.251	1480	21.7	5.77E+12	866
140	18911310	218.88	0.11		2.06	0.12	0.249	1494	21.8	5.86E+12	865
141	19207895	222.31	0.11		2.08	0.12	0.248	1509	21.9	5.94E+12	864
142	19504480	225.75	0.11		2.09	0.12	0.246	1523	22.0	6.03E+12	864
143	19801065	229.18	0.11		2.11	0.12	0.244	1537	22.1	6.12E+12	863
144	20097650	232.61	0.11		2.12	0.12	0.243	1551	22.2	6.20E+12	862
145	20394235	236.04	0.11		2.14	0.12	0.241	1565	22.3	6.29E+12	862
146	20690820	239.48	0.11		2.15	0.12	0.240	1578	22.4	6.37E+12	861
147	20987405	242.91	0.11		2.17	0.12	0.238	1592	22.5	6.46E+12	861
148	21283990	246.34	0.11		2.18	0.12	0.237	1606	22.6	6.54E+12	860
149	21580575	249.78	0.11		2.20	0.12	0.236	1619	22.7	6.63E+12	859
150	21877160	253.21	0.11		2.22	0.12	0.234	1632	22.8	6.72E+12	859
151	22173745	256.64	0.11		2.23	0.12	0.233	1646	22.9	6.80E+12	858
152	22470330	260.07	0.11		2.25	0.11	0.231	1659	23.0	6.89E+12	858
153	22766915	263.51	0.11		2.26	0.11	0.230	1672	23.1	6.97E+12	857
154	23063500	266.94	0.11		2.27	0.11	0.229	1685	23.2	7.06E+12	856
155	23360085	270.37	0.11		2.29	0.11	0.228	1698	23.2	7.14E+12	856
156	23656670	273.80	0.11		2.30	0.11	0.226	1711	23.3	7.23E+12	855
157	23953255	277.24	0.11		2.32	0.11	0.225	1724	23.4	7.31E+12	855
158	24249840	280.67	0.11		2.33	0.11	0.224	1737	23.5	7.40E+12	854
159	24546425	284.10	0.11		2.35	0.11	0.223	1749	23.6	7.48E+12	854
160	24843010	287.53	0.11		2.36	0.11	0.222	1762	23.7	7.57E+12	853
161	25139595	290.97	0.11		2.38	0.11	0.220	1774	23.8	7.65E+12	853
162	25436180	294.40	0.11		2.39	0.11	0.219	1787	23.8	7.74E+12	852
163	25732765	297.83	0.11		2.40	0.11	0.218	1799	23.9	7.82E+12	852
164	26029350	301.27	0.11		2.42	0.11	0.217	1811	24.0	7.91E+12	851
165	26325935	304.70	0.11		2.43	0.11	0.216	1824	24.1	7.99E+12	851
166	26622520	308.13	0.11		2.44	0.11	0.215	1836	24.2	8.08E+12	850
167	26919105	311.56	0.11		2.46	0.11	0.214	1848	24.2	8.16E+12	850
168	27215690	315.00	0.11		2.47	0.11	0.213	1860	24.3	8.25E+12	849
169	27512275	318.43	0.11		2.48	0.11	0.212	1872	24.4	8.33E+12	849
170	27808860	321.86	0.11		2.50	0.11	0.211	1884	24.5	8.42E+12	848
171	28105445	325.29	0.11		2.51	0.11	0.210	1895	24.6	8.50E+12	848
172	28402030	328.73	0.11		2.52	0.11	0.209	1907	24.6	8.59E+12	848
173	28698615	332.16	0.11		2.54	0.11	0.208	1919	24.7	8.67E+12	847
174	28995200	335.59	0.11		2.55	0.11	0.207	1931	24.8	8.76E+12	847
175	29291785	339.03	0.11		2.56	0.11	0.206	1942	24.9	8.84E+12	847
176	29588370	342.46	0.11		2.58	0.11	0.205	1954	24.9	8.93E+12	846
177	29884955	345.89	0.11		2.59	0.11	0.204	1966	25.0	9.01E+12	846
178	30181540	349.32	0.11		2.60	0.11	0.203	1977	25.1	9.09E+12	845
179	30478125	352.76	0.11		2.62	0.11	0.203	1988	25.2	9.18E+12	845
180	30774710	356.19	0.11		2.63	0.11	0.202	2000	25.2	9.26E+12	845
181	31071295	359.62	0.11		2.64	0.11	0.201	2011	25.3	9.35E+12	844
182	31367880	363.05	0.11		2.65	0.11	0.200	2022	25.4	9.43E+12	844
183	31664465	366.49	0.11		2.67	0.11	0.199	2033	25.4	9.51E+12	843

Table B-7
Estimation of Steam Injection Rate and Steam Zone Growth

B-zone, 14 darcy

Parameter	Symbol	Unit	Value
Thickness of steamed layer	h	m	3.75
Particle density of soil	d_s	kg/m^3	2650
Porosity of steamed layer	p		0.35
Absolute permeability of soil	k_s	m^2	1.4E-11
Heat capacity of soil	cp_r	J/(kg K)	1152
Initial water saturation	S_w		1
Ambient pressure in aquifer	P_{amb}	Pa	255985
Density of water	d_w	kg/m^3	1000
Ambient water temperature	T_{amb}	K	295
Heat capacity of water	cp_w	J/(kg K)	4187
Overall heat capacity	cp_{sw}	J/(kg K)	2200
Overburden thermal conductivity	k	J/(s m K)	1.3
Overburden thermal diffusivity	a	m^2/s	0.0000001
Radius of injection well	r_w	m	0.0508
Maximum steam injection pressure	P_w	Pa	308035
Relative permeability of steam	k_{rs}		1
Steam viscosity	u_s	kg/(m s)	1.31E-05
Temperature of steam	T_s	K	407
Delta T	$T_s - T_{amb}$	K	112
Heat of condensation	'h	J/kg	2666000
Time since start of injection	t	s	
Steam mass flow rate	'm	kg/s	
Volume of steam zone	V	m^3	
Gas constant	R	J/(mole K)	8.314
Initial radius of steam zone	r_{si}	m	0.053025
Mole mass of water	M_w	kg/mole	0.018
Density of steam	d_{steam}	kg/m^3	1.7
Depth to top of injection screen	$D_{injscr.}$	m.b.g	18.3
Length of injection screen	$L_{inj.screen}$	m	3.75
Aquifer hydraulic head	D_{gwt}	m.b.g	3



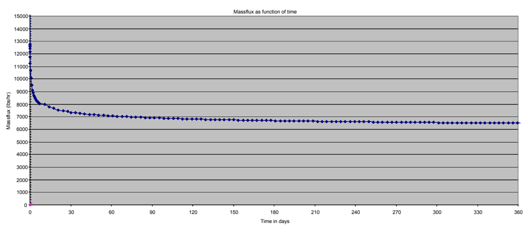


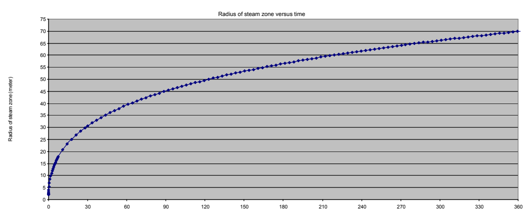
	t (s)	t (days)	'm	cp,sw	y	'mave	erf(y)*ey2	A(t)	r(t)	Energy Injected	'm (lb/h)
1	60	0.00	40.39	3449770	0.00	40.39	0.996	4	1.2	6.46E+09	320234
2	120	0.00	0.63		0.01	20.51	0.994	4	1.2	6.56E+09	4996
3	240	0.00	0.63		0.01	10.57	0.992	4	1.2	6.76E+09	4970
4	480	0.01	0.62		0.01	5.59	0.988	5	1.2	7.16E+09	4938
5	960	0.01	0.62		0.01	3.11	0.984	5	1.3	7.95E+09	4888
6	1920	0.02	0.61		0.02	1.86	0.977	6	1.4	9.50E+09	4808
7	3840	0.04	0.59		0.03	1.22	0.968	8	1.6	1.25E+10	4679
8	7680	0.09	0.57		0.04	0.90	0.955	12	2.0	1.83E+10	4496
9	15360	0.18	0.54		0.06	0.72	0.937	19	2.5	2.93E+10	4266
10	30720	0.36	0.51		0.08	0.61	0.913	32	3.2	5.01E+10	4014
11	61440	0.71	0.47		0.12	0.54	0.880	56	4.2	8.89E+10	3764
12	104640	1.21	0.45		0.15	0.50	0.848	86	5.2	1.40E+11	3530
13	147840	1.71	0.42		0.18	0.48	0.824	114	6.0	1.89E+11	3366
14	191040	2.21	0.41		0.21	0.46	0.803	140	6.7	2.37E+11	3267
15	234240	2.71	0.40		0.23	0.45	0.786	165	7.3	2.83E+11	3198
16	277440	3.21	0.40		0.25	0.44	0.771	190	7.8	3.29E+11	3145
17	320640	3.71	0.39		0.27	0.44	0.757	213	8.2	3.74E+11	3103
18	363840	4.21	0.39		0.29	0.43	0.745	236	8.7	4.18E+11	3067
19	407040	4.71	0.38		0.30	0.43	0.733	258	9.1	4.62E+11	3037
74	450240	5.21	0.38		0.32	0.42	0.722	280	9.4	5.06E+11	3011
75	493440	5.71	0.38		0.33	0.42	0.713	301	9.8	5.50E+11	2988
76	536640	6.21	0.37		0.35	0.41	0.703	321	10.1	5.93E+11	2967
77	579840	6.71	0.37		0.36	0.41	0.695	342	10.4	6.35E+11	2948
78	623040	7.21	0.37		0.37	0.41	0.687	362	10.7	6.78E+11	2931
79	919625	10.64	0.37		0.45	0.40	0.640	492	12.5	9.69E+11	2916
80	1216210	14.08	0.36		0.52	0.39	0.604	611	13.9	1.25E+12	2834
81	1512795	17.51	0.35		0.58	0.38	0.576	722	15.2	1.53E+12	2780
82	1809380	20.94	0.35		0.64	0.37	0.552	826	16.2	1.80E+12	2739
83	2105965	24.37	0.34		0.69	0.37	0.531	925	17.2	2.07E+12	2707
84	2402550	27.81	0.34		0.73	0.37	0.513	1019	18.0	2.34E+12	2681
85	2599135	30.08	0.34		0.76	0.36	0.502	1079	18.5	2.51E+12	2659
86	2895720	33.52	0.33		0.81	0.36	0.487	1167	19.3	2.78E+12	2646
87	3192305	36.95	0.33		0.85	0.36	0.474	1251	20.0	3.04E+12	2629
88	3488890	40.38	0.33		0.88	0.35	0.461	1333	20.6	3.30E+12	2613
89	3785475	43.81	0.33		0.92	0.35	0.450	1413	21.2	3.56E+12	2599
90	4082060	47.25	0.33		0.96	0.35	0.440	1490	21.8	3.82E+12	2587
91	4378645	50.68	0.32		0.99	0.35	0.430	1565	22.3	4.08E+12	2576
92	4675230	54.11	0.32		1.02	0.35	0.421	1638	22.8	4.33E+12	2565
93	4971815	57.54	0.32		1.06	0.35	0.413	1710	23.3	4.59E+12	2556
94	5268400	60.98	0.32		1.09	0.34	0.405	1779	23.8	4.84E+12	2547
95	5564985	64.41	0.32		1.12	0.34	0.397	1847	24.2	5.09E+12	2538
96	5861570	67.84	0.32		1.15	0.34	0.391	1914	24.7	5.35E+12	2531
97	6158155	71.27	0.32		1.18	0.34	0.384	1980	25.1	5.60E+12	2523
98	6454740	74.71	0.32		1.20	0.34	0.378	2044	25.5	5.85E+12	2517
99	6751325	78.14	0.32		1.23	0.34	0.372	2107	25.9	6.10E+12	2510
100	7047910	81.57	0.32		1.26	0.34	0.366	2169	26.3	6.35E+12	2504
101	7344495	85.01	0.32		1.28	0.34	0.361	2229	26.6	6.60E+12	2498
102	7641080	88.44	0.31		1.31	0.34	0.356	2289	27.0	6.85E+12	2493
103	7937665	91.87	0.31		1.33	0.34	0.351	2348	27.3	7.09E+12	2487
104	8234250	95.30	0.31		1.36	0.33	0.346	2406	27.7	7.34E+12	2482
105	8530835	98.74	0.31		1.38	0.33	0.342	2462	28.0	7.59E+12	2478
106	8827420	102.17	0.31		1.41	0.33	0.337	2519	28.3	7.83E+12	2473
107	9124005	105.60	0.31		1.43	0.33	0.333	2574	28.6	8.08E+12	2469
108	9420590	109.03	0.31		1.45	0.33	0.329	2628	28.9	8.33E+12	2464
109	9717175	112.47	0.31		1.48	0.33	0.325	2682	29.2	8.57E+12	2460
110	10013760	115.90	0.31		1.50	0.33	0.322	2735	29.5	8.82E+12	2456
111	10310345	119.33	0.31		1.52	0.33	0.318	2788	29.8	9.06E+12	2453
112	10606930	122.77	0.31		1.54	0.33	0.315	2839	30.1	9.31E+12	2449
113	10903515	126.20	0.31		1.56	0.33	0.311	2891	30.3	9.55E+12	2446
114	11200100	129.63	0.31		1.59	0.33	0.308	2941	30.6	9.79E+12	2442
115	11496685	133.06	0.31		1.61	0.33	0.305	2991	30.8	1.00E+13	2439
116	11793270	136.50	0.31		1.63	0.33	0.302	3040	31.1	1.03E+13	2436
117	12089855	139.93	0.31		1.65	0.33	0.299	3089	31.4	1.05E+13	2433
118	12386440	143.36	0.31		1.67	0.33	0.296	3137	31.6	1.08E+13	2430
119	12683025	146.79	0.31		1.69	0.33	0.293	3185	31.8	1.10E+13	2427
120	12979610	150.23	0.31		1.71	0.33	0.291	3232	32.1	1.12E+13	2424
121	13276195	153.66	0.31		1.73	0.32	0.288	3279	32.3	1.15E+13	2421
122	13572780	157.09	0.30		1.75	0.32	0.286	3325	32.5	1.17E+13	2418
123	13869365	160.53	0.30		1.76	0.32	0.283	3371	32.8	1.20E+13	2416
124	14165950	163.96	0.30		1.78	0.32	0.281	3416	33.0	1.22E+13	2413
125	14462535	167.39	0.30		1.80	0.32	0.278	3461	33.2	1.25E+13	2411
126	14759120	170.82	0.30		1.82	0.32	0.276	3506	33.4	1.27E+13	2408
127	15055705	174.26	0.30		1.84	0.32	0.274	3550	33.6	1.29E+13	2406
128	15352290	177.69	0.30		1.86	0.32	0.272	3594	33.8	1.32E+13	2404
129	15648875	181.12	0.30		1.87	0.32	0.270	3637	34.0	1.34E+13	2401
130	15945460	184.55	0.30		1.89	0.32	0.267	3680	34.2	1.37E+13	2399
131	16242045	187.99	0.30		1.91	0.32	0.265	3722	34.4	1.39E+13	2397
132	16538630	191.42	0.30		1.93	0.32	0.263	3765	34.6	1.41E+13	2395
133	16835215	194.85	0.30		1.94	0.32	0.262	3806	34.8	1.44E+13	2393
134	17131800	198.28	0.30		1.96	0.32	0.260	3848	35.0	1.46E+13	2391
135	17428385	201.72	0.30		1.98	0.32	0.258	3889	35.2	1.48E+13	2389
136	17724970	205.15	0.30		1.99	0.32	0.256	3930	35.4	1.51E+13	2387
137	18021555	208.58	0.30		2.01	0.32	0.254	3971	35.5	1.53E+13	2385
138	18318140	212.02	0.30		2.03	0.32	0.252	4011	35.7	1.56E+13	2383
139	18614725	215.45	0.30		2.04	0.32	0.251	4051	35.9	1.58E+13	2381
140	18911310	218.88	0.30		2.06	0.32	0.249	4090	36.1	1.60E+13	2379
141	19207895	222.31	0.30		2.08	0.32	0.248	4130	36.2	1.63E+13	2378
142	19504480	225.75	0.30		2.09	0.32	0.246	4169	36.4	1.65E+13	2376
143	19801065	229.18	0.30		2.11	0.32	0.244	4207	36.6	1.67E+13	2374
144	20097650	232.61	0.30		2.12	0.32	0.243	4246	36.8	1.70E+13	2373
145	20394235	236.04	0.30		2.14	0.32	0.241	4284	36.9	1.72E+13	2371
146	20690820	239.48	0.30		2.15	0.32	0.240	4322	37.1	1.75E+13	2369
147	20987405	242.91	0.30		2.17	0.32	0.238	4360	37.2	1.77E+13	2368
148	21283990	246.34	0.30		2.19	0.32	0.237	4397	37.4	1.79E+13	2366
149	21580575	249.78	0.30		2.20	0.32	0.236	4434	37.6	1.82E+13	2365
150	21877160	253.21	0.30		2.22	0.32	0.234	4471	37.7	1.84E+13	2363
151	22173745	256.64	0.30		2.23	0.32	0.233	4508	37.9	1.86E+13	2362
152	22470330	260.07	0.30		2.25	0.31	0.231	4544	38.0	1.89E+13	2360
153	22766915	263.51	0.30		2.26	0.31	0.230	4581	38.2	1.91E+13	2359
154	23063500	266.94	0.30		2.27	0.31	0.229	4617	38.3	1.93E+13	2357
155	23360085	270.37	0.30		2.29	0.31	0.228	4652	38.5	1.96E+13	2356
156	23656670	273.80	0.30		2.30	0.31	0.226	4688	38.6	1.98E+13	2355
157	23953255	277.24	0.30		2.32	0.31	0.225	4723	38.8	2.00E+13	2353
158	24249840	280.67	0.30		2.33	0.31	0.224	4759	38.9	2.03E+13	2352
159	24546425	284.10	0.30		2.35	0.31	0.223	4794	39.1	2.05E+13	2351
160	24843010	287.53	0.30		2.36	0.31	0.222	4828	39.2	2.07E+13	2349
161	25139595	290.97	0.30		2.38	0.31	0.220	4863	39.3	2.10E+13	2348
162	25436180	294.40	0.30		2.39	0.31	0.219	4897	39.5	2.12E+13	2347
163	25732765	297.83	0.30		2.40	0.31	0.218	4931	39.6	2.14E+13	2346
164	26029350	301.27	0.30		2.42	0.31	0.217	4965	39.7	2.17E+13	2344
165	26325935	304.70	0.30		2.43	0.31	0.216	4999	39.9	2.19E+13	2343
166	26622520	308.13	0.30		2.44	0.31	0.215	5033	40.0	2.21E+13	2342
167	26919105	311.56	0.30		2.46	0.31	0.214	5066	40.1	2.24E+13	2341
168	27215690	315.00	0.30		2.47	0.31	0.213	5099	40.3	2.26E+13	2340
169	27512275	318.43	0.29		2.48	0.31	0.212	5132	40.4	2.28E+13	2339
170	27808860	321.86	0.29		2.50	0.31	0.211	5165	40.5	2.31E+13	2337
171	28105445	325.29	0.29		2.51	0.31	0.210	5198	40.7	2.33E+13	2336
172	28402030	328.73	0.29		2.52	0.31	0.209	5230	40.8	2.35E+13	2335
173	28698615	332.16	0.29		2.54	0.31	0.208	5263	40.9	2.38E+13	2334
174	28995200	335.59	0.29		2.55	0.31	0.207	5295	41.0	2.40E+13	2333
175	29291785	339.03	0.29		2.56	0.31	0.206	5327	41.2	2.42E+13	2332
176	29588370	342.46	0.29		2.58	0.31	0.205	5359	41.3	2.45E+13	2331
177	29884955	345.89	0.29		2.59	0.31	0.204	5391	41.4	2.47E+13	2330
178	30181540	349.32	0.29		2.60	0.31	0.203	5422	41.5	2.49E+13	2329
179	30478125	352.76	0.29		2.62	0.31	0.203	5454	41.7	2.52E+13	2328
180	30774710	356.19	0.29		2.63	0.31	0.202	5485	41.8	2.54E+13	2327
181	31071295	359.62	0.29		2.64	0.31	0.201	5516	41.9	2.56E+13	2326
182	31367880	363.05	0.29		2.65	0.31	0.200	5547	42.0	2.59E+13	2325
183	31664465	366.49	0.29		2.67	0.31	0.199	5578	42.1	2.61E+13	2324

Table B-8
Estimation of Steam Injection Rate and Steam Zone Growth

B-zone, 42 darcy

Parameter	Symbol	Unit	Value
Thickness of steamed layer	h	m	3.75
Particle density of soil	ρs	kg/m³	2650
Porosity of steamed layer	φ	-	0.35
Absolute permeability of soil	k0	m²	4.2E-11
Heat capacity of soil	cps	J/(kg K)	1152
Initial water saturation	Sw	-	1
Ambient pressure in aquifer	Pamb	Pa	255985
Density of water	ρw	kg/m³	1000
Ambient water temperature	Tamb	K	295
Heat capacity of water	cpw	J/(kg K)	4187
Overall heat capacity	Mcp	J/(kg K)	2200
Overburden thermal conductivity	λ	J/(s m K)	1.3
Overburden thermal diffusivity	κ	m²/s	0.0000001
Radius of injection well	rw	m	0.0508
Maximum steam injection pressure	Ps	Pa	308039
Relative permeability of steam	krs	-	1
Steam viscosity	μs	kg/(m s)	1.31E-05
Temperature of steam	Ts	K	407
Delta T	Ts - Tamb	K	112
Heat of condensation	hv	J/kg	2166000
Time since start of injection	t	s	
Steam mass flow rate	m	kg/s	
Volume of steam zone	V	m³	
Gas constant	R	J/(mole K)	8.314
Initial radius of steam zone	r0	m	0.05308
Mole mass of water	Mw	kg/mole	0.018
Density of steam	ρsteam	kg/m³	1.7
Depth to top of injection screen	Dtop	m bg	18.3
Length of injection screen	Lscreen	m	3.75
Aquifer hydraulic head	hw	m bg	



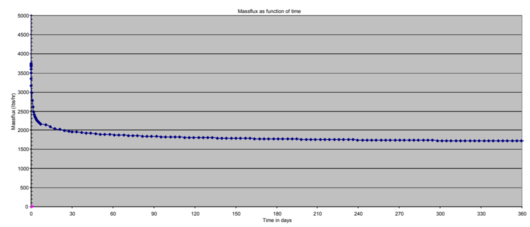


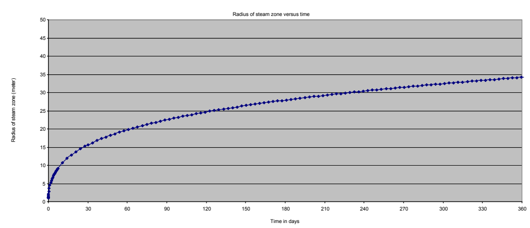
	t (s)	t (days)	˙m	cp,sw	y	˙mave	erf(y)*ey2	A(t)	r(t)	Energy Injected	˙m (lb/h)
1	60	0.00	121.16	3449770	0.00	121.16	0.996	13	2.0	1.94E+10	960702
2	120	0.00	1.61		0.01	61.38	0.994	13	2.0	1.96E+10	12749
3	240	0.00	1.60		0.01	31.49	0.992	13	2.1	2.01E+10	12697
4	480	0.01	1.59		0.01	16.54	0.988	14	2.1	2.12E+10	12634
5	960	0.01	1.58		0.01	9.06	0.984	16	2.2	2.32E+10	12539
6	1920	0.02	1.56		0.02	5.31	0.977	18	2.4	2.72E+10	12383
7	3840	0.04	1.53		0.03	3.42	0.968	23	2.7	3.50E+10	12128
8	7680	0.09	1.48		0.04	2.45	0.955	33	3.3	5.02E+10	11749
9	15360	0.18	1.42		0.06	1.93	0.937	52	4.1	7.92E+10	11251
10	30720	0.36	1.35		0.08	1.64	0.913	87	5.3	1.34E+11	10680
11	61440	0.71	1.27		0.12	1.46	0.880	150	6.9	2.39E+11	10091
12	104640	1.21	1.20		0.15	1.35	0.848	232	8.6	3.77E+11	9527
13	147840	1.71	1.15		0.18	1.29	0.824	307	9.9	5.10E+11	9125
14	191040	2.21	1.12		0.21	1.25	0.803	379	11.0	6.39E+11	8882
15	234240	2.71	1.10		0.23	1.23	0.786	447	11.9	7.65E+11	8709
16	277440	3.21	1.08		0.25	1.20	0.771	513	12.8	8.90E+11	8577
17	320640	3.71	1.07		0.27	1.18	0.757	577	13.6	1.01E+12	8470
18	363840	4.21	1.06		0.29	1.17	0.745	639	14.3	1.13E+12	8382
19	407040	4.71	1.05		0.30	1.16	0.733	700	14.9	1.26E+12	8306
74	450240	5.21	1.04		0.32	1.15	0.722	759	15.5	1.37E+12	8239
75	493440	5.71	1.03		0.33	1.14	0.713	817	16.1	1.49E+12	8181
76	536640	6.21	1.03		0.35	1.13	0.703	874	16.7	1.61E+12	8129
77	579840	6.71	1.02		0.36	1.12	0.695	930	17.2	1.73E+12	8082
78	623040	7.21	1.01		0.37	1.11	0.687	985	17.7	1.85E+12	8039
79	919625	10.64	1.01		0.45	1.08	0.640	1344	20.7	2.64E+12	8000
80	1216210	14.08	0.98		0.52	1.05	0.604	1671	23.1	3.42E+12	7793
81	1512795	17.51	0.97		0.58	1.04	0.576	1976	25.1	4.18E+12	7654
82	1809380	20.94	0.95		0.64	1.02	0.552	2263	26.8	4.94E+12	7551
83	2105965	24.37	0.94		0.69	1.01	0.531	2536	28.4	5.68E+12	7469
84	2402550	27.81	0.93		0.73	1.00	0.513	2796	29.8	6.42E+12	7402
85	2599135	30.08	0.93		0.76	1.00	0.502	2962	30.7	6.91E+12	7346
86	2895720	33.52	0.92		0.81	0.99	0.487	3205	31.9	7.63E+12	7312
87	3192305	36.95	0.92		0.85	0.98	0.474	3440	33.1	8.36E+12	7268
88	3488890	40.38	0.91		0.88	0.98	0.461	3667	34.2	9.08E+12	7228
89	3785475	43.81	0.91		0.92	0.97	0.450	3888	35.2	9.80E+12	7193
90	4082060	47.25	0.90		0.96	0.97	0.440	4102	36.1	1.05E+13	7161
91	4378645	50.68	0.90		0.99	0.96	0.430	4310	37.0	1.12E+13	7131
92	4675230	54.11	0.90		1.02	0.96	0.421	4513	37.9	1.19E+13	7105
93	4971815	57.54	0.89		1.06	0.95	0.413	4711	38.7	1.26E+13	7080
94	5268400	60.98	0.89		1.09	0.95	0.405	4904	39.5	1.33E+13	7057
95	5564985	64.41	0.89		1.12	0.95	0.397	5094	40.3	1.40E+13	7036
96	5861570	67.84	0.88		1.15	0.94	0.391	5279	41.0	1.47E+13	7016
97	6158155	71.27	0.88		1.18	0.94	0.384	5461	41.7	1.54E+13	6997
98	6454740	74.71	0.88		1.20	0.94	0.378	5639	42.4	1.61E+13	6979
99	6751325	78.14	0.88		1.23	0.94	0.372	5814	43.0	1.68E+13	6963
100	7047910	81.57	0.88		1.26	0.93	0.366	5986	43.6	1.75E+13	6947
101	7344495	85.01	0.87		1.28	0.93	0.361	6155	44.3	1.82E+13	6932
102	7641080	88.44	0.87		1.31	0.93	0.356	6321	44.8	1.89E+13	6918
103	7937665	91.87	0.87		1.33	0.93	0.351	6484	45.4	1.96E+13	6904
104	8234250	95.30	0.87		1.36	0.92	0.346	6645	46.0	2.03E+13	6891
105	8530835	98.74	0.87		1.38	0.92	0.342	6803	46.5	2.10E+13	6879
106	8827420	102.17	0.87		1.41	0.92	0.337	6960	47.1	2.16E+13	6867
107	9124005	105.60	0.86		1.43	0.92	0.333	7113	47.6	2.23E+13	6856
108	9420590	109.03	0.86		1.45	0.92	0.329	7265	48.1	2.30E+13	6845
109	9717175	112.47	0.86		1.48	0.91	0.325	7415	48.6	2.37E+13	6834
110	10013760	115.90	0.86		1.50	0.91	0.322	7563	49.1	2.44E+13	6824
111	10310345	119.33	0.86		1.52	0.91	0.318	7709	49.5	2.51E+13	6814
112	10606930	122.77	0.86		1.54	0.91	0.315	7853	50.0	2.57E+13	6805
113	10903515	126.20	0.86		1.56	0.91	0.311	7995	50.4	2.64E+13	6796
114	11200100	129.63	0.86		1.59	0.91	0.308	8136	50.9	2.71E+13	6787
115	11496685	133.06	0.85		1.61	0.91	0.305	8274	51.3	2.78E+13	6778
116	11793270	136.50	0.85		1.63	0.90	0.302	8412	51.7	2.84E+13	6770
117	12089855	139.93	0.85		1.65	0.90	0.299	8548	52.2	2.91E+13	6762
118	12386440	143.36	0.85		1.67	0.90	0.296	8682	52.6	2.98E+13	6754
119	12683025	146.79	0.85		1.69	0.90	0.293	8815	53.0	3.05E+13	6746
120	12979610	150.23	0.85		1.71	0.90	0.291	8947	53.4	3.11E+13	6739
121	13276195	153.66	0.85		1.73	0.90	0.288	9077	53.7	3.18E+13	6732
122	13572780	157.09	0.85		1.75	0.90	0.286	9206	54.1	3.25E+13	6725
123	13869365	160.53	0.85		1.76	0.90	0.283	9334	54.5	3.31E+13	6718
124	14165950	163.96	0.85		1.78	0.90	0.281	9460	54.9	3.38E+13	6712
125	14462535	167.39	0.85		1.80	0.89	0.278	9585	55.2	3.45E+13	6705
126	14759120	170.82	0.84		1.82	0.89	0.276	9709	55.6	3.52E+13	6699
127	15055705	174.26	0.84		1.84	0.89	0.274	9832	55.9	3.58E+13	6693
128	15352290	177.69	0.84		1.86	0.89	0.272	9954	56.3	3.65E+13	6687
129	15648875	181.12	0.84		1.87	0.89	0.270	10075	56.6	3.72E+13	6681
130	15945460	184.55	0.84		1.89	0.89	0.267	10195	57.0	3.78E+13	6675
131	16242045	187.99	0.84		1.91	0.89	0.265	10313	57.3	3.85E+13	6669
132	16538630	191.42	0.84		1.93	0.89	0.263	10431	57.6	3.91E+13	6664
133	16835215	194.85	0.84		1.94	0.89	0.262	10548	57.9	3.98E+13	6659
134	17131800	198.28	0.84		1.96	0.89	0.260	10663	58.2	4.05E+13	6653
135	17428385	201.72	0.84		1.98	0.89	0.258	10778	58.6	4.11E+13	6648
136	17724970	205.15	0.84		1.99	0.88	0.256	10892	58.9	4.18E+13	6643
137	18021555	208.58	0.84		2.01	0.88	0.254	11005	59.2	4.25E+13	6638
138	18318140	212.02	0.84		2.03	0.88	0.252	11118	59.5	4.31E+13	6633
139	18614725	215.45	0.84		2.04	0.88	0.251	11229	59.8	4.38E+13	6629
140	18911310	218.88	0.84		2.06	0.88	0.249	11339	60.1	4.44E+13	6624
141	19207895	222.31	0.83		2.08	0.88	0.248	11449	60.4	4.51E+13	6619
142	19504480	225.75	0.83		2.09	0.88	0.246	11558	60.6	4.58E+13	6615
143	19801065	229.18	0.83		2.11	0.88	0.244	11666	60.9	4.64E+13	6610
144	20097650	232.61	0.83		2.12	0.88	0.243	11774	61.2	4.71E+13	6606
145	20394235	236.04	0.83		2.14	0.88	0.241	11880	61.5	4.77E+13	6602
146	20690820	239.48	0.83		2.15	0.88	0.240	11986	61.8	4.84E+13	6598
147	20987405	242.91	0.83		2.17	0.88	0.238	12091	62.0	4.91E+13	6593
148	21283990	246.34	0.83		2.19	0.88	0.237	12196	62.3	4.97E+13	6589
149	21580575	249.78	0.83		2.20	0.88	0.236	12300	62.6	5.04E+13	6585
150	21877160	253.21	0.83		2.22	0.87	0.234	12403	62.8	5.10E+13	6582
151	22173745	256.64	0.83		2.23	0.87	0.233	12505	63.1	5.17E+13	6578
152	22470330	260.07	0.83		2.25	0.87	0.231	12607	63.3	5.23E+13	6574
153	22766915	263.51	0.83		2.26	0.87	0.230	12708	63.6	5.30E+13	6570
154	23063500	266.94	0.83		2.27	0.87	0.229	12809	63.8	5.36E+13	6566
155	23360085	270.37	0.83		2.29	0.87	0.228	12909	64.1	5.43E+13	6563
156	23656670	273.80	0.83		2.30	0.87	0.226	13008	64.3	5.50E+13	6559
157	23953255	277.24	0.83		2.32	0.87	0.225	13107	64.6	5.56E+13	6556
158	24249840	280.67	0.83		2.33	0.87	0.224	13205	64.8	5.63E+13	6552
159	24546425	284.10	0.83		2.35	0.87	0.223	13302	65.1	5.69E+13	6549
160	24843010	287.53	0.83		2.36	0.87	0.222	13399	65.3	5.76E+13	6545
161	25139595	290.97	0.83		2.38	0.87	0.220	13496	65.5	5.82E+13	6542
162	25436180	294.40	0.82		2.39	0.87	0.219	13592	65.8	5.89E+13	6539
163	25732765	297.83	0.82		2.40	0.87	0.218	13687	66.0	5.95E+13	6536
164	26029350	301.27	0.82		2.42	0.87	0.217	13782	66.2	6.02E+13	6532
165	26325935	304.70	0.82		2.43	0.87	0.216	13876	66.4	6.08E+13	6529
166	26622520	308.13	0.82		2.44	0.87	0.215	13970	66.7	6.15E+13	6526
167	26919105	311.56	0.82		2.46	0.87	0.214	14063	66.9	6.21E+13	6523
168	27215690	315.00	0.82		2.47	0.87	0.213	14156	67.1	6.28E+13	6520
169	27512275	318.43	0.82		2.48	0.86	0.212	14249	67.3	6.34E+13	6517
170	27808860	321.86	0.82		2.50	0.86	0.211	14340	67.5	6.41E+13	6514
171	28105445	325.29	0.82		2.51	0.86	0.210	14432	67.8	6.47E+13	6511
172	28402030	328.73	0.82		2.52	0.86	0.209	14523	68.0	6.54E+13	6508
173	28698615	332.16	0.82		2.54	0.86	0.208	14613	68.2	6.60E+13	6506
174	28995200	335.59	0.82		2.55	0.86	0.207	14703	68.4	6.67E+13	6503
175	29291785	339.03	0.82		2.56	0.86	0.206	14793	68.6	6.73E+13	6500
176	29588370	342.46	0.82		2.58	0.86	0.205	14882	68.8	6.80E+13	6497
177	29884955	345.89	0.82		2.59	0.86	0.204	14970	69.0	6.86E+13	6495
178	30181540	349.32	0.82		2.60	0.86	0.203	15059	69.2	6.93E+13	6492
179	30478125	352.76	0.82		2.62	0.86	0.203	15146	69.4	6.99E+13	6489
180	30774710	356.19	0.82		2.63	0.86	0.202	15234	69.6	7.06E+13	6487
181	31071295	359.62	0.82		2.64	0.86	0.201	15321	69.8	7.12E+13	6484
182	31367880	363.05	0.82		2.65	0.86	0.200	15407	70.0	7.19E+13	6482
183	31664465	366.49	0.82		2.67	0.86	0.199	15493	70.2	7.25E+13	6479

Table B-9
Estimation of Steam Injection Rate and Steam Zone Growth

C-zone, 5.1 darcy

Parameter	Symbol	Unit	Value
Thickness of steamed layer	h	m	3.05
Particle density of soil	d_s	kg/m^3	2650
Porosity of steamed layer	p		0.35
Absolute permeability of soil	k_s	m^2	5.1E-12
Heat capacity of soil	cp_r	J/(kg K)	1152
Initial water saturation	S_w		1
Ambient pressure in aquifer	P_{amb}	Pa	456816
Density of water	d_w	kg/m^3	1000
Ambient water temperature	T_{amb}	K	295
Heat capacity of water	cp_w	J/(kg K)	4187
Overall heat capacity	cp_{sw}	J/(kg K)	2200
Overburden thermal conductivity	k	J/(s m K)	1.3
Overburden thermal diffusivity	a	m^2/s	0.0000001
Radius of injection well	r_w	m	0.0505
Maximum steam injection pressure	P_w	Pa	531997
Relative permeability of steam	k_{rs}		1
Steam viscosity	u_s	kg/(m s)	1.31E-05
Temperature of steam	T_s	K	427
Delta T	$T_s - T_{amb}$	K	132
Heat of condensation	˙h	J/kg	2666000
Time since start of injection	t	s	
Steam mass flow rate	˙m	kg/s	
Volume of steam zone	V	m^3	
Gas constant	R	J/(mole K)	8.314
Initial radius of steam zone	r_{si}	m	0.053025
Mole mass of water	M_w	kg/mole	0.018
Density of steam	d_{steam}	kg/m^3	2.8
Depth to top of injection screen	$D_{injscr.}$	m.b.g	38.125
Length of injection screen	$L_{inj,screen}$	m	3
Aquifer hydraulic head	D_{gwt}	m.b.g	3



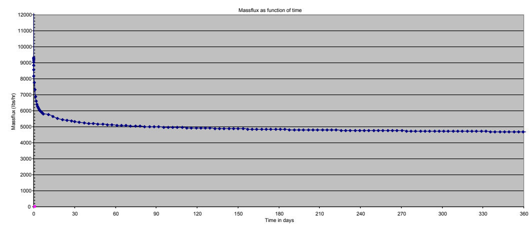


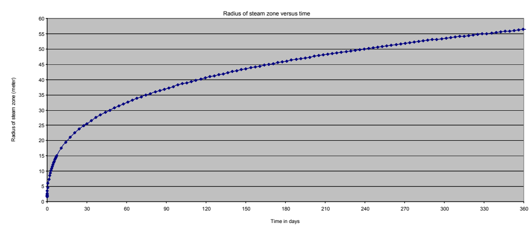
	t (s)	t (days)	˙m	cp,sw	y	˙mave	erf(y)*ey2	A(t)	r(t)	Energy Injected	˙m (lb/h)
1	60	0.00	28.89	3449770	0.00	28.89	0.995	3	1.0	4.62E+09	229045
2	120	0.00	0.47		0.01	14.68	0.993	3	1.0	4.70E+09	3738
3	240	0.00	0.47		0.01	7.57	0.990	3	1.0	4.85E+09	3720
4	480	0.01	0.47		0.01	4.02	0.986	4	1.1	5.14E+09	3695
5	960	0.01	0.46		0.02	2.24	0.980	4	1.1	5.73E+09	3656
6	1920	0.02	0.45		0.03	1.35	0.972	5	1.2	6.89E+09	3592
7	3840	0.04	0.44		0.04	0.89	0.961	6	1.4	9.15E+09	3490
8	7680	0.09	0.42		0.05	0.66	0.945	9	1.7	1.35E+10	3345
9	15360	0.18	0.40		0.07	0.53	0.923	15	2.2	2.16E+10	3166
10	30720	0.36	0.37		0.10	0.45	0.894	25	2.8	3.70E+10	2972
11	61440	0.71	0.35		0.14	0.40	0.856	43	3.7	6.57E+10	2781
12	104640	1.21	0.33		0.19	0.37	0.818	65	4.6	1.04E+11	2605
13	147840	1.71	0.31		0.22	0.35	0.790	86	5.2	1.40E+11	2482
14	191040	2.21	0.30		0.25	0.34	0.767	105	5.8	1.75E+11	2408
15	234240	2.71	0.30		0.28	0.33	0.747	124	6.3	2.09E+11	2356
16	277440	3.21	0.29		0.31	0.33	0.730	142	6.7	2.42E+11	2317
17	320640	3.71	0.29		0.33	0.32	0.715	159	7.1	2.76E+11	2285
18	363840	4.21	0.28		0.35	0.32	0.701	175	7.5	3.08E+11	2259
19	407040	4.71	0.28		0.37	0.31	0.688	191	7.8	3.41E+11	2237
74	450240	5.21	0.28		0.39	0.31	0.676	207	8.1	3.73E+11	2217
75	493440	5.71	0.28		0.41	0.31	0.665	222	8.4	4.05E+11	2200
76	536640	6.21	0.28		0.43	0.31	0.655	237	8.7	4.37E+11	2185
77	579840	6.71	0.27		0.44	0.30	0.646	252	8.9	4.68E+11	2171
78	623040	7.21	0.27		0.46	0.30	0.637	266	9.2	5.00E+11	2159
79	919625	10.64	0.27		0.56	0.29	0.587	359	10.7	7.14E+11	2147
80	1216210	14.08	0.26		0.64	0.28	0.549	443	11.9	9.22E+11	2087
81	1512795	17.51	0.26		0.72	0.28	0.520	520	12.9	1.13E+12	2047
82	1809380	20.94	0.25		0.78	0.28	0.495	592	13.7	1.33E+12	2017
83	2105965	24.37	0.25		0.85	0.27	0.474	660	14.5	1.53E+12	1994
84	2402550	27.81	0.25		0.90	0.27	0.456	724	15.2	1.72E+12	1975
85	2599135	30.08	0.25		0.94	0.27	0.445	766	15.6	1.85E+12	1959
86	2895720	33.52	0.25		0.99	0.27	0.430	825	16.2	2.05E+12	1949
87	3192305	36.95	0.24		1.04	0.26	0.417	883	16.8	2.24E+12	1936
88	3488890	40.38	0.24		1.09	0.26	0.405	939	17.3	2.43E+12	1925
89	3785475	43.81	0.24		1.13	0.26	0.394	992	17.8	2.62E+12	1915
90	4082060	47.25	0.24		1.18	0.26	0.384	1044	18.2	2.81E+12	1906
91	4378645	50.68	0.24		1.22	0.26	0.374	1095	18.7	3.00E+12	1898
92	4675230	54.11	0.24		1.26	0.26	0.366	1144	19.1	3.19E+12	1890
93	4971815	57.54	0.24		1.30	0.25	0.358	1191	19.5	3.38E+12	1883
94	5268400	60.98	0.24		1.34	0.25	0.350	1238	19.8	3.57E+12	1877
95	5564985	64.41	0.24		1.37	0.25	0.343	1283	20.2	3.75E+12	1871
96	5861570	67.84	0.24		1.41	0.25	0.337	1328	20.6	3.94E+12	1865
97	6158155	71.27	0.23		1.45	0.25	0.331	1371	20.9	4.12E+12	1860
98	6454740	74.71	0.23		1.48	0.25	0.325	1414	21.2	4.31E+12	1855
99	6751325	78.14	0.23		1.51	0.25	0.319	1456	21.5	4.49E+12	1850
100	7047910	81.57	0.23		1.55	0.25	0.314	1497	21.8	4.68E+12	1846
101	7344495	85.01	0.23		1.58	0.25	0.309	1537	22.1	4.86E+12	1841
102	7641080	88.44	0.23		1.61	0.25	0.304	1576	22.4	5.04E+12	1837
103	7937665	91.87	0.23		1.64	0.25	0.300	1615	22.7	5.23E+12	1834
104	8234250	95.30	0.23		1.67	0.25	0.296	1653	22.9	5.41E+12	1830
105	8530835	98.74	0.23		1.70	0.25	0.292	1691	23.2	5.59E+12	1826
106	8827420	102.17	0.23		1.73	0.25	0.288	1727	23.4	5.77E+12	1823
107	9124005	105.60	0.23		1.76	0.24	0.284	1764	23.7	5.95E+12	1820
108	9420590	109.03	0.23		1.79	0.24	0.280	1800	23.9	6.14E+12	1817
109	9717175	112.47	0.23		1.82	0.24	0.277	1835	24.2	6.32E+12	1814
110	10013760	115.90	0.23		1.84	0.24	0.273	1870	24.4	6.50E+12	1811
111	10310345	119.33	0.23		1.87	0.24	0.270	1904	24.6	6.68E+12	1808
112	10606930	122.77	0.23		1.90	0.24	0.267	1938	24.8	6.86E+12	1806
113	10903515	126.20	0.23		1.92	0.24	0.264	1971	25.0	7.04E+12	1803
114	11200100	129.63	0.23		1.95	0.24	0.261	2004	25.3	7.22E+12	1801
115	11496685	133.06	0.23		1.97	0.24	0.258	2037	25.5	7.40E+12	1798
116	11793270	136.50	0.23		2.00	0.24	0.255	2069	25.7	7.58E+12	1796
117	12089855	139.93	0.23		2.03	0.24	0.253	2101	25.9	7.75E+12	1794
118	12386440	143.36	0.23		2.05	0.24	0.250	2132	26.0	7.93E+12	1791
119	12683025	146.79	0.23		2.07	0.24	0.248	2163	26.2	8.11E+12	1789
120	12979610	150.23	0.23		2.10	0.24	0.245	2194	26.4	8.29E+12	1787
121	13276195	153.66	0.23		2.12	0.24	0.243	2224	26.6	8.47E+12	1785
122	13572780	157.09	0.22		2.15	0.24	0.241	2255	26.8	8.65E+12	1783
123	13869365	160.53	0.22		2.17	0.24	0.238	2284	27.0	8.82E+12	1781
124	14165950	163.96	0.22		2.19	0.24	0.236	2314	27.1	9.00E+12	1779
125	14462535	167.39	0.22		2.21	0.24	0.234	2343	27.3	9.18E+12	1778
126	14759120	170.82	0.22		2.24	0.24	0.232	2372	27.5	9.35E+12	1776
127	15055705	174.26	0.22		2.26	0.24	0.230	2401	27.6	9.53E+12	1774
128	15352290	177.69	0.22		2.28	0.24	0.228	2429	27.8	9.71E+12	1772
129	15648875	181.12	0.22		2.30	0.24	0.226	2457	28.0	9.88E+12	1771
130	15945460	184.55	0.22		2.33	0.24	0.225	2485	28.1	1.01E+13	1769
131	16242045	187.99	0.22		2.35	0.24	0.223	2512	28.3	1.02E+13	1768
132	16538630	191.42	0.22		2.37	0.24	0.221	2540	28.4	1.04E+13	1766
133	16835215	194.85	0.22		2.39	0.24	0.219	2567	28.6	1.06E+13	1765
134	17131800	198.28	0.22		2.41	0.24	0.218	2594	28.7	1.08E+13	1763
135	17428385	201.72	0.22		2.43	0.24	0.216	2620	28.9	1.09E+13	1762
136	17724970	205.15	0.22		2.45	0.24	0.214	2647	29.0	1.11E+13	1760
137	18021555	208.58	0.22		2.47	0.24	0.213	2673	29.2	1.13E+13	1759
138	18318140	212.02	0.22		2.49	0.23	0.211	2699	29.3	1.15E+13	1757
139	18614725	215.45	0.22		2.51	0.23	0.210	2725	29.4	1.16E+13	1756
140	18911310	218.88	0.22		2.53	0.23	0.208	2750	29.6	1.18E+13	1755
141	19207895	222.31	0.22		2.55	0.23	0.207	2776	29.7	1.20E+13	1754
142	19504480	225.75	0.22		2.57	0.23	0.206	2801	29.9	1.22E+13	1752
143	19801065	229.18	0.22		2.59	0.23	0.204	2826	30.0	1.23E+13	1751
144	20097650	232.61	0.22		2.61	0.23	0.203	2851	30.1	1.25E+13	1750
145	20394235	236.04	0.22		2.63	0.23	0.202	2875	30.2	1.27E+13	1749
146	20690820	239.48	0.22		2.65	0.23	0.200	2900	30.4	1.29E+13	1747
147	20987405	242.91	0.22		2.67	0.23	0.199	2924	30.5	1.30E+13	1746
148	21283990	246.34	0.22		2.69	0.23	0.198	2948	30.6	1.32E+13	1745
149	21580575	249.78	0.22		2.71	0.23	0.197	2972	30.8	1.34E+13	1744
150	21877160	253.21	0.22		2.72	0.23	0.195	2996	30.9	1.36E+13	1743
151	22173745	256.64	0.22		2.74	0.23	0.194	3020	31.0	1.37E+13	1742
152	22470330	260.07	0.22		2.76	0.23	0.193	3043	31.1	1.39E+13	1741
153	22766915	263.51	0.22		2.78	0.23	0.192	3066	31.2	1.41E+13	1740
154	23063500	266.94	0.22		2.80	0.23	0.191	3090	31.4	1.43E+13	1739
155	23360085	270.37	0.22		2.82	0.23	0.190	3113	31.5	1.44E+13	1738
156	23656670	273.80	0.22		2.83	0.23	0.189	3135	31.6	1.46E+13	1737
157	23953255	277.24	0.22		2.85	0.23	0.187	3158	31.7	1.48E+13	1736
158	24249840	280.67	0.22		2.87	0.23	0.186	3181	31.8	1.49E+13	1735
159	24546425	284.10	0.22		2.89	0.23	0.185	3203	31.9	1.51E+13	1734
160	24843010	287.53	0.22		2.90	0.23	0.184	3226	32.0	1.53E+13	1733
161	25139595	290.97	0.22		2.92	0.23	0.183	3248	32.1	1.55E+13	1732
162	25436180	294.40	0.22		2.94	0.23	0.182	3270	32.3	1.56E+13	1731
163	25732765	297.83	0.22		2.95	0.23	0.182	3292	32.4	1.58E+13	1730
164	26029350	301.27	0.22		2.97	0.23	0.181	3314	32.5	1.60E+13	1729
165	26325935	304.70	0.22		2.99	0.23	0.180	3335	32.6	1.62E+13	1728
166	26622520	308.13	0.22		3.01	0.23	0.179	3357	32.7	1.63E+13	1727
167	26919105	311.56	0.22		3.02	0.23	0.178	3378	32.8	1.65E+13	1727
168	27215690	315.00	0.22		3.04	0.23	0.177	3400	32.9	1.67E+13	1726
169	27512275	318.43	0.22		3.05	0.23	0.176	3421	33.0	1.68E+13	1725
170	27808860	321.86	0.22		3.07	0.23	0.175	3442	33.1	1.70E+13	1724
171	28105445	325.29	0.22		3.09	0.23	0.174	3463	33.2	1.72E+13	1723
172	28402030	328.73	0.22		3.10	0.23	0.174	3484	33.3	1.74E+13	1722
173	28698615	332.16	0.22		3.12	0.23	0.173	3504	33.4	1.75E+13	1722
174	28995200	335.59	0.22		3.14	0.23	0.172	3525	33.5	1.77E+13	1721
175	29291785	339.03	0.22		3.15	0.23	0.171	3546	33.6	1.79E+13	1720
176	29588370	342.46	0.22		3.17	0.23	0.170	3566	33.7	1.80E+13	1719
177	29884955	345.89	0.22		3.18	0.23	0.170	3586	33.8	1.82E+13	1719
178	30181540	349.32	0.22		3.20	0.23	0.169	3607	33.9	1.84E+13	1718
179	30478125	352.76	0.22		3.22	0.23	0.168	3627	34.0	1.86E+13	1717
180	30774710	356.19	0.22		3.23	0.23	0.167	3647	34.1	1.87E+13	1716
181	31071295	359.62	0.22		3.25	0.23	0.166	3667	34.2	1.89E+13	1716
182	31367880	363.05	0.22		3.26	0.23	0.166	3687	34.2	1.91E+13	1715
183	31664465	366.49	0.22		3.28	0.23	0.165	3706	34.3	1.92E+13	1714

Table B-10
Estimation of Steam Injection Rate and Steam Zone Growth

C-zone, 15 darcy

Parameter	Symbol	Unit	Value
Thickness of steamed layer	h	m	3.05
Particle density of soil	d_s	kg/m^3	2650
Porosity of steamed layer	p		0.35
Absolute permeability of soil	k_a	m^2	1.5E-11
Heat capacity of soil	cp_r	J/(kg K)	1152
Initial water saturation	S_w		1
Ambient pressure in aquifer	P_{amb}	Pa	456816
Density of water	d_w	kg/m^3	1000
Ambient water temperature	T_{amb}	K	295
Heat capacity of water	cp_w	J/(kg K)	4187
Overall heat capacity	cp_{sw}	J/(kg K)	2200
Overburden thermal conductivity	k	J/(s m K)	1.3
Overburden thermal diffusivity	a	m^2/s	0.0000001[illegible]
Radius of injection well	r_w	m	0.0505
Maximum steam injection pressure	P_w	Pa	531997
Relative permeability of steam	k_{rs}		1
Steam viscosity	u_s	kg/(m s)	1.31E-05
Temperature of steam	T_s	K	427
Delta T	$T_s - T_{amb}$	K	132
Heat of condensation	'h	J/kg	2666000
Time since start of injection	t	s	
Steam mass flow rate	'm	kg/s	
Volume of steam zone	V	m^3	
Gas constant	R	J/(mole K)	8.314
Initial radius of steam zone	r_{si}	m	0.053025
Mole mass of water	M_w	kg/mole	0.018
Density of steam	d_{steam}	kg/m^3	2.8
Depth to top of injection screen	$D_{injscr.}$	m.b.g	38.125
Length of injection screen	$L_{inj,screen}$	m	3
Aquifer hydraulic head	D_{gwt}	m.b.g	3



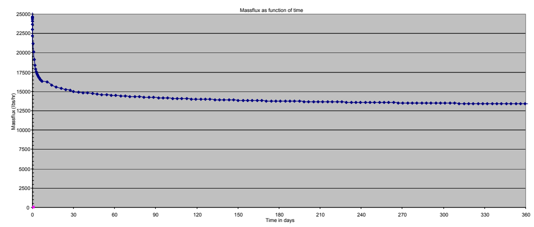


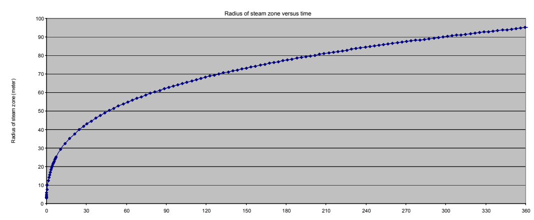
	t (s)	t (days)	'm	cp,sw	y	'mave	erf(y)*ey2	A(t)	r(t)	Energy Injected	'm (lb/h)
1	60	0.00	84.96	3449770	0.00	84.96	0.995	9	1.7	1.36E+10	673661
2	120	0.00	1.17		0.01	43.07	0.993	10	1.7	1.38E+10	9313
3	240	0.00	1.17		0.01	22.12	0.990	10	1.8	1.42E+10	9278
4	480	0.01	1.16		0.01	11.64	0.986	10	1.8	1.49E+10	9232
5	960	0.01	1.16		0.02	6.40	0.980	12	1.9	1.64E+10	9161
6	1920	0.02	1.14		0.03	3.77	0.972	14	2.1	1.93E+10	9040
7	3840	0.04	1.12		0.04	2.44	0.961	17	2.4	2.50E+10	8843
8	7680	0.09	1.08		0.05	1.76	0.945	25	2.8	3.60E+10	8551
9	15360	0.18	1.03		0.07	1.40	0.923	39	3.5	5.71E+10	8172
10	30720	0.36	0.98		0.10	1.19	0.894	65	4.5	9.71E+10	7742
11	61440	0.71	0.92		0.14	1.05	0.856	112	6.0	1.73E+11	7303
12	104640	1.21	0.87		0.19	0.98	0.818	172	7.4	2.73E+11	6886
13	147840	1.71	0.83		0.22	0.93	0.790	227	8.5	3.68E+11	6591
14	191040	2.21	0.81		0.25	0.91	0.767	279	9.4	4.61E+11	6413
15	234240	2.71	0.79		0.28	0.89	0.747	328	10.2	5.53E+11	6287
16	277440	3.21	0.78		0.31	0.87	0.730	375	10.9	6.43E+11	6190
17	320640	3.71	0.77		0.33	0.86	0.715	421	11.6	7.31E+11	6113
18	363840	4.21	0.76		0.35	0.84	0.701	465	12.2	8.19E+11	6048
19	407040	4.71	0.76		0.37	0.84	0.688	508	12.7	9.06E+11	5993
74	450240	5.21	0.75		0.39	0.83	0.676	550	13.2	9.93E+11	5945
75	493440	5.71	0.74		0.41	0.82	0.665	591	13.7	1.08E+12	5903
76	536640	6.21	0.74		0.43	0.81	0.655	631	14.2	1.16E+12	5865
77	579840	6.71	0.74		0.44	0.81	0.646	670	14.6	1.25E+12	5831
78	623040	7.21	0.73		0.46	0.80	0.637	709	15.0	1.33E+12	5800
79	919625	10.64	0.73		0.56	0.78	0.587	959	17.5	1.91E+12	5771
80	1216210	14.08	0.71		0.64	0.76	0.549	1185	19.4	2.47E+12	5622
81	1512795	17.51	0.70		0.72	0.75	0.520	1394	21.1	3.02E+12	5522
82	1809380	20.94	0.69		0.78	0.74	0.495	1589	22.5	3.56E+12	5448
83	2105965	24.37	0.68		0.85	0.73	0.474	1773	23.8	4.10E+12	5389
84	2402550	27.81	0.67		0.90	0.72	0.456	1948	24.9	4.63E+12	5341
85	2599135	30.08	0.67		0.94	0.72	0.445	2059	25.6	4.98E+12	5301
86	2895720	33.52	0.67		0.99	0.71	0.430	2222	26.6	5.51E+12	5277
87	3192305	36.95	0.66		1.04	0.71	0.417	2378	27.5	6.03E+12	5245
88	3488890	40.38	0.66		1.09	0.70	0.405	2529	28.4	6.55E+12	5217
89	3785475	43.81	0.65		1.13	0.70	0.394	2675	29.2	7.07E+12	5192
90	4082060	47.25	0.65		1.18	0.70	0.384	2816	29.9	7.59E+12	5169
91	4378645	50.68	0.65		1.22	0.69	0.374	2953	30.7	8.10E+12	5148
92	4675230	54.11	0.65		1.26	0.69	0.366	3086	31.3	8.61E+12	5129
93	4971815	57.54	0.64		1.30	0.69	0.358	3216	32.0	9.12E+12	5111
94	5268400	60.98	0.64		1.34	0.69	0.350	3343	32.6	9.63E+12	5095
95	5564985	64.41	0.64		1.37	0.68	0.343	3467	33.2	1.01E+13	5080
96	5861570	67.84	0.64		1.41	0.68	0.337	3588	33.8	1.06E+13	5065
97	6158155	71.27	0.64		1.45	0.68	0.331	3706	34.3	1.11E+13	5052
98	6454740	74.71	0.64		1.48	0.68	0.325	3822	34.9	1.16E+13	5039
99	6751325	78.14	0.63		1.51	0.67	0.319	3936	35.4	1.21E+13	5028
100	7047910	81.57	0.63		1.55	0.67	0.314	4047	35.9	1.26E+13	5016
101	7344495	85.01	0.63		1.58	0.67	0.309	4157	36.4	1.31E+13	5006
102	7641080	88.44	0.63		1.61	0.67	0.304	4264	36.8	1.36E+13	4996
103	7937665	91.87	0.63		1.64	0.67	0.300	4370	37.3	1.41E+13	4986
104	8234250	95.30	0.63		1.67	0.67	0.296	4473	37.7	1.46E+13	4977
105	8530835	98.74	0.63		1.70	0.67	0.292	4576	38.2	1.51E+13	4968
106	8827420	102.17	0.63		1.73	0.66	0.288	4676	38.6	1.56E+13	4959
107	9124005	105.60	0.62		1.76	0.66	0.284	4775	39.0	1.61E+13	4951
108	9420590	109.03	0.62		1.79	0.66	0.280	4873	39.4	1.66E+13	4943
109	9717175	112.47	0.62		1.82	0.66	0.277	4969	39.8	1.71E+13	4936
110	10013760	115.90	0.62		1.84	0.66	0.273	5064	40.1	1.76E+13	4929
111	10310345	119.33	0.62		1.87	0.66	0.270	5158	40.5	1.81E+13	4922
112	10606930	122.77	0.62		1.90	0.66	0.267	5250	40.9	1.86E+13	4915
113	10903515	126.20	0.62		1.92	0.66	0.264	5341	41.2	1.91E+13	4908
114	11200100	129.63	0.62		1.95	0.65	0.261	5431	41.6	1.96E+13	4902
115	11496685	133.06	0.62		1.97	0.65	0.258	5520	41.9	2.00E+13	4896
116	11793270	136.50	0.62		2.00	0.65	0.255	5608	42.2	2.05E+13	4890
117	12089855	139.93	0.62		2.03	0.65	0.253	5695	42.6	2.10E+13	4884
118	12386440	143.36	0.62		2.05	0.65	0.250	5781	42.9	2.15E+13	4879
119	12683025	146.79	0.61		2.07	0.65	0.248	5866	43.2	2.20E+13	4873
120	12979610	150.23	0.61		2.10	0.65	0.245	5950	43.5	2.25E+13	4868
121	13276195	153.66	0.61		2.12	0.65	0.243	6033	43.8	2.30E+13	4863
122	13572780	157.09	0.61		2.15	0.65	0.241	6115	44.1	2.34E+13	4858
123	13869365	160.53	0.61		2.17	0.65	0.238	6196	44.4	2.39E+13	4853
124	14165950	163.96	0.61		2.19	0.65	0.236	6277	44.7	2.44E+13	4848
125	14462535	167.39	0.61		2.21	0.65	0.234	6357	45.0	2.49E+13	4844
126	14759120	170.82	0.61		2.24	0.65	0.232	6435	45.3	2.54E+13	4839
127	15055705	174.26	0.61		2.26	0.64	0.230	6514	45.5	2.59E+13	4835
128	15352290	177.69	0.61		2.28	0.64	0.228	6591	45.8	2.63E+13	4831
129	15648875	181.12	0.61		2.30	0.64	0.226	6668	46.1	2.68E+13	4826
130	15945460	184.55	0.61		2.33	0.64	0.225	6744	46.3	2.73E+13	4822
131	16242045	187.99	0.61		2.35	0.64	0.223	6819	46.6	2.78E+13	4818
132	16538630	191.42	0.61		2.37	0.64	0.221	6894	46.8	2.83E+13	4814
133	16835215	194.85	0.61		2.39	0.64	0.219	6968	47.1	2.87E+13	4811
134	17131800	198.28	0.61		2.41	0.64	0.218	7041	47.3	2.92E+13	4807
135	17428385	201.72	0.61		2.43	0.64	0.216	7114	47.6	2.97E+13	4803
136	17724970	205.15	0.61		2.45	0.64	0.214	7186	47.8	3.02E+13	4800
137	18021555	208.58	0.60		2.47	0.64	0.213	7258	48.1	3.07E+13	4796
138	18318140	212.02	0.60		2.49	0.64	0.211	7329	48.3	3.11E+13	4793
139	18614725	215.45	0.60		2.51	0.64	0.210	7399	48.5	3.16E+13	4789
140	18911310	218.88	0.60		2.53	0.64	0.208	7469	48.8	3.21E+13	4786
141	19207895	222.31	0.60		2.55	0.64	0.207	7539	49.0	3.26E+13	4783
142	19504480	225.75	0.60		2.57	0.64	0.206	7608	49.2	3.30E+13	4779
143	19801065	229.18	0.60		2.59	0.64	0.204	7676	49.4	3.35E+13	4776
144	20097650	232.61	0.60		2.61	0.63	0.203	7744	49.6	3.40E+13	4773
145	20394235	236.04	0.60		2.63	0.63	0.202	7811	49.9	3.45E+13	4770
146	20690820	239.48	0.60		2.65	0.63	0.200	7878	50.1	3.50E+13	4767
147	20987405	242.91	0.60		2.67	0.63	0.199	7945	50.3	3.54E+13	4764
148	21283990	246.34	0.60		2.69	0.63	0.198	8011	50.5	3.59E+13	4761
149	21580575	249.78	0.60		2.71	0.63	0.197	8076	50.7	3.64E+13	4758
150	21877160	253.21	0.60		2.72	0.63	0.195	8141	50.9	3.68E+13	4756
151	22173745	256.64	0.60		2.74	0.63	0.194	8206	51.1	3.73E+13	4753
152	22470330	260.07	0.60		2.76	0.63	0.193	8270	51.3	3.78E+13	4750
153	22766915	263.51	0.60		2.78	0.63	0.192	8334	51.5	3.83E+13	4747
154	23063500	266.94	0.60		2.80	0.63	0.191	8397	51.7	3.87E+13	4745
155	23360085	270.37	0.60		2.82	0.63	0.190	8460	51.9	3.92E+13	4742
156	23656670	273.80	0.60		2.83	0.63	0.189	8523	52.1	3.97E+13	4740
157	23953255	277.24	0.60		2.85	0.63	0.187	8585	52.3	4.02E+13	4737
158	24249840	280.67	0.60		2.87	0.63	0.186	8647	52.5	4.06E+13	4735
159	24546425	284.10	0.60		2.89	0.63	0.185	8708	52.6	4.11E+13	4732
160	24843010	287.53	0.60		2.90	0.63	0.184	8770	52.8	4.16E+13	4730
161	25139595	290.97	0.60		2.92	0.63	0.183	8830	53.0	4.20E+13	4727
162	25436180	294.40	0.60		2.94	0.63	0.182	8891	53.2	4.25E+13	4725
163	25732765	297.83	0.60		2.95	0.63	0.182	8951	53.4	4.30E+13	4723
164	26029350	301.27	0.60		2.97	0.63	0.181	9010	53.5	4.35E+13	4720
165	26325935	304.70	0.60		2.99	0.63	0.180	9070	53.7	4.39E+13	4718
166	26622520	308.13	0.59		3.01	0.63	0.179	9129	53.9	4.44E+13	4716
167	26919105	311.56	0.59		3.02	0.63	0.178	9187	54.1	4.49E+13	4714
168	27215690	315.00	0.59		3.04	0.62	0.177	9246	54.2	4.53E+13	4712
169	27512275	318.43	0.59		3.05	0.62	0.176	9304	54.4	4.58E+13	4709
170	27808860	321.86	0.59		3.07	0.62	0.175	9362	54.6	4.63E+13	4707
171	28105445	325.29	0.59		3.09	0.62	0.174	9419	54.7	4.67E+13	4705
172	28402030	328.73	0.59		3.10	0.62	0.174	9476	54.9	4.72E+13	4703
173	28698615	332.16	0.59		3.12	0.62	0.173	9533	55.1	4.77E+13	4701
174	28995200	335.59	0.59		3.14	0.62	0.172	9589	55.2	4.82E+13	4699
175	29291785	339.03	0.59		3.15	0.62	0.171	9646	55.4	4.86E+13	4697
176	29588370	342.46	0.59		3.17	0.62	0.170	9702	55.6	4.91E+13	4695
177	29884955	345.89	0.59		3.18	0.62	0.170	9757	55.7	4.96E+13	4693
178	30181540	349.32	0.59		3.20	0.62	0.169	9813	55.9	5.00E+13	4691
179	30478125	352.76	0.59		3.22	0.62	0.168	9868	56.0	5.05E+13	4689
180	30774710	356.19	0.59		3.23	0.62	0.167	9923	56.2	5.10E+13	4688
181	31071295	359.62	0.59		3.25	0.62	0.166	9977	56.3	5.14E+13	4686
182	31367880	363.05	0.59		3.26	0.62	0.166	10031	56.5	5.19E+13	4684
183	31664465	366.49	0.59		3.28	0.62	0.165	10086	56.6	5.24E+13	4682

Table B-11
Estimation of Steam Injection Rate and Steam Zone Growth

C-zone, 46 darcy

Parameter	Symbol	Unit	Value
Thickness of steamed layer	[illegible]	m	3.05
Particle density of soil	[illegible]	kg/m³	2650
Porosity of steamed layer	[illegible]	-	0.35
Absolute permeability of soil	[illegible]	m²	4.6E-11
Heat capacity of soil	[illegible]	J/(kg K)	1152
Initial water saturation	[illegible]	-	1
Ambient pressure in aquifer	[illegible]	Pa	456816
Density of water	[illegible]	kg/m³	1000
Ambient water temperature	[illegible]	K	295
Heat capacity of water	[illegible]	J/(kg K)	4187
Overall heat capacity	[illegible]	J/(kg K)	2200
Overburden thermal conductivity	[illegible]	J/(s m K)	1.3
Overburden thermal diffusivity	[illegible]	m²/s	0.0000001
Radius of injection well	[illegible]	m	0.0508
Maximum steam injection pressure	[illegible]	Pa	531997
Relative permeability of steam	[illegible]	-	1
Steam viscosity	[illegible]	kg/(m s)	1.31E-05
Temperature of steam	[illegible]	K	427
Delta T	[illegible]	K	132
Heat of condensation	[illegible]	J/kg	2666000
Time since start of injection	[illegible]	s	
Steam mass flow rate	[illegible]	kg/s	
Volume of steam zone	[illegible]	m³	
Gas constant	[illegible]	J/(mole K)	8.314
Initial radius of steam zone	[illegible]	m	0.053025
Mole mass of water	[illegible]	kg/mole	0.018
Density of steam	[illegible]	kg/m³	2.8
Depth to top of injection screen	[illegible]	m.s.g.	38.125
Length of injection screen	[illegible]	m	
Aquifer hydraulic head	[illegible]	m.s.g.	



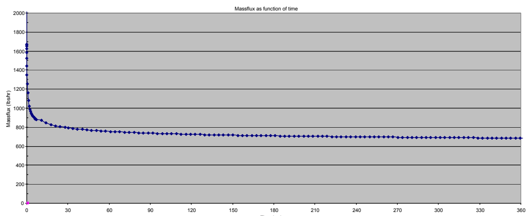


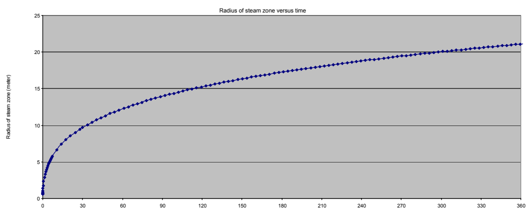
	t (s)	t (days)	´m	cp,sw	y	´mave	erf(y)*ey2	A(t)	r(t)	Energy Injected	´m (lb/h)
1	60	0.00	260.53	3449770	0.00	260.53	0.995	29	3.0	4.17E+10	2065893
2	120	0.00	3.11		0.01	131.82	0.993	29	3.1	4.22E+10	24648
3	240	0.00	3.10		0.01	67.46	0.990	30	3.1	4.32E+10	24572
4	480	0.01	3.09		0.01	35.27	0.986	32	3.2	4.51E+10	24478
5	960	0.01	3.07		0.02	19.17	0.980	35	3.3	4.91E+10	24333
6	1920	0.02	3.04		0.03	11.10	0.972	40	3.6	5.68E+10	24087
7	3840	0.04	2.99		0.04	7.05	0.961	50	4.0	7.21E+10	23677
8	7680	0.09	2.91		0.05	4.98	0.945	71	4.7	1.02E+11	23047
9	15360	0.18	2.80		0.07	3.89	0.923	109	5.9	1.59E+11	22194
10	30720	0.36	2.67		0.10	3.28	0.894	180	7.6	2.69E+11	21186
11	61440	0.71	2.54		0.14	2.91	0.856	310	9.9	4.76E+11	20123
12	104640	1.21	2.41		0.19	2.70	0.818	476	12.3	7.54E+11	19086
13	147840	1.71	2.31		0.22	2.59	0.790	629	14.1	1.02E+12	18342
14	191040	2.21	2.26		0.25	2.51	0.767	773	15.7	1.28E+12	17887
15	234240	2.71	2.22		0.28	2.46	0.747	911	17.0	1.53E+12	17565
16	277440	3.21	2.18		0.31	2.42	0.730	1043	18.2	1.79E+12	17317
17	320640	3.71	2.16		0.33	2.38	0.715	1172	19.3	2.04E+12	17118
18	363840	4.21	2.14		0.35	2.35	0.701	1296	20.3	2.28E+12	16951
19	407040	4.71	2.12		0.37	2.33	0.688	1417	21.2	2.53E+12	16809
74	450240	5.21	2.10		0.39	2.31	0.676	1534	22.1	2.77E+12	16685
75	493440	5.71	2.09		0.41	2.29	0.665	1650	22.9	3.01E+12	16575
76	536640	6.21	2.08		0.43	2.27	0.655	1762	23.7	3.25E+12	16477
77	579840	6.71	2.07		0.44	2.25	0.646	1872	24.4	3.49E+12	16389
78	623040	7.21	2.06		0.46	2.24	0.637	1981	25.1	3.72E+12	16308
79	919625	10.64	2.05		0.56	2.18	0.587	2685	29.2	5.34E+12	16234
80	1216210	14.08	2.00		0.64	2.13	0.549	3323	32.5	6.92E+12	15846
81	1512795	17.51	1.97		0.72	2.10	0.520	3912	35.3	8.48E+12	15585
82	1809380	20.94	1.94		0.78	2.08	0.495	4464	37.7	1.00E+13	15391
83	2105965	24.37	1.92		0.85	2.05	0.474	4986	39.8	1.15E+13	15237
84	2402550	27.81	1.91		0.90	2.04	0.456	5482	41.8	1.30E+13	15111
85	2599135	30.08	1.89		0.94	2.02	0.445	5798	42.9	1.40E+13	15004
86	2895720	33.52	1.88		0.99	2.01	0.430	6259	44.6	1.55E+13	14942
87	3192305	36.95	1.87		1.04	2.00	0.417	6702	46.2	1.70E+13	14858
88	3488890	40.38	1.86		1.09	1.99	0.405	7130	47.6	1.85E+13	14783
89	3785475	43.81	1.86		1.13	1.98	0.394	7544	49.0	1.99E+13	14716
90	4082060	47.25	1.85		1.18	1.97	0.384	7945	50.3	2.14E+13	14656
91	4378645	50.68	1.84		1.22	1.96	0.374	8335	51.5	2.29E+13	14601
92	4675230	54.11	1.83		1.26	1.95	0.366	8714	52.7	2.43E+13	14550
93	4971815	57.54	1.83		1.30	1.94	0.358	9084	53.8	2.58E+13	14504
94	5268400	60.98	1.82		1.34	1.94	0.350	9444	54.8	2.72E+13	14461
95	5564985	64.41	1.82		1.37	1.93	0.343	9796	55.8	2.86E+13	14420
96	5861570	67.84	1.81		1.41	1.92	0.337	10140	56.8	3.01E+13	14383
97	6158155	71.27	1.81		1.45	1.92	0.331	10477	57.7	3.15E+13	14347
98	6454740	74.71	1.81		1.48	1.91	0.325	10807	58.6	3.29E+13	14314
99	6751325	78.14	1.80		1.51	1.91	0.319	11130	59.5	3.44E+13	14283
100	7047910	81.57	1.80		1.55	1.90	0.314	11447	60.4	3.58E+13	14253
101	7344495	85.01	1.79		1.58	1.90	0.309	11759	61.2	3.72E+13	14225
102	7641080	88.44	1.79		1.61	1.90	0.304	12065	62.0	3.86E+13	14198
103	7937665	91.87	1.79		1.64	1.89	0.300	12366	62.7	4.00E+13	14172
104	8234250	95.30	1.78		1.67	1.89	0.296	12662	63.5	4.14E+13	14148
105	8530835	98.74	1.78		1.70	1.88	0.292	12953	64.2	4.28E+13	14124
106	8827420	102.17	1.78		1.73	1.88	0.288	13240	64.9	4.42E+13	14102
107	9124005	105.60	1.78		1.76	1.88	0.284	13522	65.6	4.56E+13	14080
108	9420590	109.03	1.77		1.79	1.87	0.280	13800	66.3	4.71E+13	14059
109	9717175	112.47	1.77		1.82	1.87	0.277	14074	66.9	4.85E+13	14039
110	10013760	115.90	1.77		1.84	1.87	0.273	14345	67.6	4.98E+13	14020
111	10310345	119.33	1.77		1.87	1.86	0.270	14612	68.2	5.12E+13	14002
112	10606930	122.77	1.76		1.90	1.86	0.267	14875	68.8	5.26E+13	13984
113	10903515	126.20	1.76		1.92	1.86	0.264	15135	69.4	5.40E+13	13966
114	11200100	129.63	1.76		1.95	1.86	0.261	15392	70.0	5.54E+13	13950
115	11496685	133.06	1.76		1.97	1.85	0.258	15646	70.6	5.68E+13	13933
116	11793270	136.50	1.76		2.00	1.85	0.255	15896	71.1	5.82E+13	13918
117	12089855	139.93	1.75		2.03	1.85	0.253	16144	71.7	5.96E+13	13903
118	12386440	143.36	1.75		2.05	1.85	0.250	16389	72.2	6.10E+13	13888
119	12683025	146.79	1.75		2.07	1.84	0.248	16631	72.7	6.24E+13	13873
120	12979610	150.23	1.75		2.10	1.84	0.245	16871	73.3	6.37E+13	13859
121	13276195	153.66	1.75		2.12	1.84	0.243	17108	73.8	6.51E+13	13846
122	13572780	157.09	1.74		2.15	1.84	0.241	17342	74.3	6.65E+13	13832
123	13869365	160.53	1.74		2.17	1.84	0.238	17574	74.8	6.79E+13	13820
124	14165950	163.96	1.74		2.19	1.83	0.236	17804	75.3	6.93E+13	13807
125	14462535	167.39	1.74		2.21	1.83	0.234	18032	75.7	7.06E+13	13795
126	14759120	170.82	1.74		2.24	1.83	0.232	18257	76.2	7.20E+13	13783
127	15055705	174.26	1.74		2.26	1.83	0.230	18480	76.7	7.34E+13	13771
128	15352290	177.69	1.74		2.28	1.83	0.228	18701	77.1	7.47E+13	13760
129	15648875	181.12	1.73		2.30	1.82	0.226	18920	77.6	7.61E+13	13748
130	15945460	184.55	1.73		2.33	1.82	0.225	19137	78.0	7.75E+13	13738
131	16242045	187.99	1.73		2.35	1.82	0.223	19352	78.5	7.89E+13	13727
132	16538630	191.42	1.73		2.37	1.82	0.221	19566	78.9	8.02E+13	13716
133	16835215	194.85	1.73		2.39	1.82	0.219	19777	79.3	8.16E+13	13706
134	17131800	198.28	1.73		2.41	1.82	0.218	19987	79.7	8.30E+13	13696
135	17428385	201.72	1.73		2.43	1.81	0.216	20195	80.2	8.43E+13	13686
136	17724970	205.15	1.72		2.45	1.81	0.214	20401	80.6	8.57E+13	13677
137	18021555	208.58	1.72		2.47	1.81	0.213	20605	81.0	8.70E+13	13667
138	18318140	212.02	1.72		2.49	1.81	0.211	20808	81.4	8.84E+13	13658
139	18614725	215.45	1.72		2.51	1.81	0.210	21010	81.8	8.98E+13	13649
140	18911310	218.88	1.72		2.53	1.81	0.208	21209	82.1	9.11E+13	13640
141	19207895	222.31	1.72		2.55	1.81	0.207	21408	82.5	9.25E+13	13631
142	19504480	225.75	1.72		2.57	1.80	0.206	21605	82.9	9.38E+13	13623
143	19801065	229.18	1.72		2.59	1.80	0.204	21800	83.3	9.52E+13	13614
144	20097650	232.61	1.72		2.61	1.80	0.203	21994	83.7	9.66E+13	13606
145	20394235	236.04	1.71		2.63	1.80	0.202	22186	84.0	9.79E+13	13598
146	20690820	239.48	1.71		2.65	1.80	0.200	22377	84.4	9.93E+13	13590
147	20987405	242.91	1.71		2.67	1.80	0.199	22567	84.7	1.01E+14	13582
148	21283990	246.34	1.71		2.69	1.80	0.198	22756	85.1	1.02E+14	13574
149	21580575	249.78	1.71		2.71	1.80	0.197	22943	85.4	1.03E+14	13567
150	21877160	253.21	1.71		2.72	1.79	0.195	23129	85.8	1.05E+14	13559
151	22173745	256.64	1.71		2.74	1.79	0.194	23314	86.1	1.06E+14	13552
152	22470330	260.07	1.71		2.76	1.79	0.193	23497	86.5	1.07E+14	13545
153	22766915	263.51	1.71		2.78	1.79	0.192	23680	86.8	1.09E+14	13538
154	23063500	266.94	1.71		2.80	1.79	0.191	23861	87.1	1.10E+14	13531
155	23360085	270.37	1.71		2.82	1.79	0.190	24041	87.5	1.11E+14	13524
156	23656670	273.80	1.70		2.83	1.79	0.189	24220	87.8	1.13E+14	13517
157	23953255	277.24	1.70		2.85	1.79	0.187	24398	88.1	1.14E+14	13510
158	24249840	280.67	1.70		2.87	1.79	0.186	24575	88.4	1.15E+14	13504
159	24546425	284.10	1.70		2.89	1.79	0.185	24750	88.7	1.17E+14	13497
160	24843010	287.53	1.70		2.90	1.78	0.184	24925	89.1	1.18E+14	13491
161	25139595	290.97	1.70		2.92	1.78	0.183	25098	89.4	1.20E+14	13484
162	25436180	294.40	1.70		2.94	1.78	0.182	25271	89.7	1.21E+14	13478
163	25732765	297.83	1.70		2.95	1.78	0.182	25443	90.0	1.22E+14	13472
164	26029350	301.27	1.70		2.97	1.78	0.181	25613	90.3	1.24E+14	13466
165	26325935	304.70	1.70		2.99	1.78	0.180	25783	90.6	1.25E+14	13460
166	26622520	308.13	1.70		3.01	1.78	0.179	25952	90.9	1.26E+14	13454
167	26919105	311.56	1.70		3.02	1.78	0.178	26119	91.2	1.28E+14	13448
168	27215690	315.00	1.70		3.04	1.78	0.177	26286	91.5	1.29E+14	13442
169	27512275	318.43	1.69		3.05	1.78	0.176	26452	91.7	1.30E+14	13436
170	27808860	321.86	1.69		3.07	1.77	0.175	26617	92.0	1.32E+14	13431
171	28105445	325.29	1.69		3.09	1.77	0.174	26781	92.3	1.33E+14	13425
172	28402030	328.73	1.69		3.10	1.77	0.174	26945	92.6	1.34E+14	13420
173	28698615	332.16	1.69		3.12	1.77	0.173	27107	92.9	1.36E+14	13414
174	28995200	335.59	1.69		3.14	1.77	0.172	27269	93.1	1.37E+14	13409
175	29291785	339.03	1.69		3.15	1.77	0.171	27430	93.4	1.38E+14	13404
176	29588370	342.46	1.69		3.17	1.77	0.170	27590	93.7	1.40E+14	13398
177	29884955	345.89	1.69		3.18	1.77	0.170	27749	94.0	1.41E+14	13393
178	30181540	349.32	1.69		3.20	1.77	0.169	27907	94.2	1.42E+14	13388
179	30478125	352.76	1.69		3.22	1.77	0.168	28065	94.5	1.44E+14	13383
180	30774710	356.19	1.69		3.23	1.77	0.167	28222	94.8	1.45E+14	13378
181	31071295	359.62	1.69		3.25	1.77	0.166	28378	95.0	1.46E+14	13373
182	31367880	363.05	1.69		3.26	1.77	0.166	28534	95.3	1.48E+14	13368
183	31664465	366.49	1.69		3.28	1.76	0.165	28688	95.5	1.49E+14	13363

Table B-12
Estimation of Steam Injection Rate and Steam Zone Growth

D-zone, 1.4 darcy

Parameter	Symbol	Unit	Value
Thickness of steamed layer	h	m	3.05
Particle density of soil	d_s	kg/m^3	2650
Porosity of steamed layer	p		0.35
Absolute permeability of soil	k_s	m^2	1.4E-12
Heat capacity of soil	cp_r	J/(kg K)	1152
Initial water saturation	S_w		1
Ambient pressure in aquifer	P_{amb}	Pa	549500
Density of water	d_w	kg/m^3	1000
Ambient water temperature	T_{amb}	K	295
Heat capacity of water	cp_w	J/(kg K)	4187
Overall heat capacity	cp_{sw}	J/(kg K)	2200
Overburden thermal conductivity	k	J/(s m K)	1.3
Overburden thermal diffusivity	a	m^2/s	0.0000001
Radius of injection well	r_w	m	0.0509
Maximum steam injection pressure	P_w	Pa	635360
Relative permeability of steam	k_{rs}		1
Steam viscosity	u_s	kg/(m s)	1.31E-05
Temperature of steam	T_s	K	433
Delta T	$T_s - T_{amb}$	K	138
Heat of condensation	´h	J/kg	2666000
Time since start of injection	t	s	
Steam mass flow rate	´m	kg/s	
Volume of steam zone	V	m^3	
Gas constant	R	J/(mole K)	8.314
Initial radius of steam zone	r_{si}	m	0.053029
Mole mass of water	M_w	kg/mole	0.018
Density of steam	d_{steam}	kg/m^3	3.3
Depth to top of injection screen	$D_{injscr.}$	m.b.g	47.275
Length of injection screen	$L_{inj.screen}$	m	3
Aquifer hydraulic head	D_{gwt}	m.b.g	3



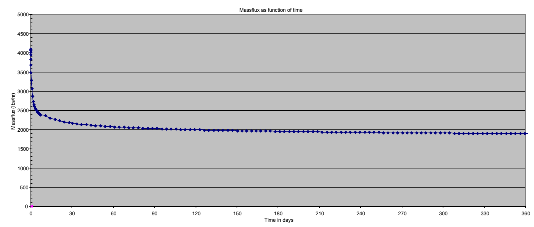


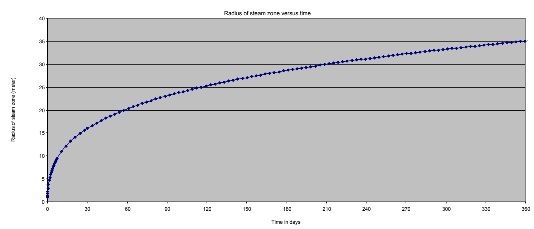
	t (s)	t (days)	´m	cp,sw	y	´mave	erf(y)*ey2	A(t)	r(t)	Energy Injected	´m (lb/h)
1	60	0.00	10.68	3449770	0.00	10.68	0.995	1	0.6	1.71E+09	84673
2	120	0.00	0.21		0.01	5.44	0.993	1	0.6	1.74E+09	1674
3	240	0.00	0.21		0.01	2.83	0.990	1	0.6	1.81E+09	1663
4	480	0.01	0.21		0.01	1.52	0.986	1	0.6	1.94E+09	1648
5	960	0.01	0.20		0.02	0.86	0.980	1	0.7	2.20E+09	1623
6	1920	0.02	0.20		0.03	0.53	0.972	2	0.8	2.72E+09	1584
7	3840	0.04	0.19		0.04	0.36	0.961	2	0.9	3.70E+09	1523
8	7680	0.09	0.18		0.05	0.27	0.945	4	1.1	5.56E+09	1443
9	15360	0.18	0.17		0.07	0.22	0.923	6	1.4	9.04E+09	1349
10	30720	0.36	0.16		0.10	0.19	0.894	10	1.8	1.55E+10	1252
11	61440	0.71	0.15		0.14	0.17	0.856	17	2.3	2.75E+10	1161
12	104640	1.21	0.14		0.19	0.15	0.818	26	2.9	4.32E+10	1079
13	147840	1.71	0.13		0.22	0.15	0.790	34	3.3	5.80E+10	1022
14	191040	2.21	0.12		0.25	0.14	0.767	42	3.6	7.24E+10	989
15	234240	2.71	0.12		0.28	0.14	0.747	49	3.9	8.64E+10	966
16	277440	3.21	0.12		0.31	0.14	0.730	56	4.2	1.00E+11	948
17	320640	3.71	0.12		0.33	0.13	0.715	62	4.5	1.14E+11	934
18	363840	4.21	0.12		0.35	0.13	0.701	69	4.7	1.27E+11	922
19	407040	4.71	0.12		0.37	0.13	0.688	75	4.9	1.40E+11	912
74	450240	5.21	0.11		0.39	0.13	0.676	81	5.1	1.54E+11	904
75	493440	5.71	0.11		0.41	0.13	0.665	87	5.3	1.67E+11	896
76	536640	6.21	0.11		0.43	0.13	0.655	93	5.4	1.79E+11	889
77	579840	6.71	0.11		0.44	0.12	0.646	98	5.6	1.92E+11	883
78	623040	7.21	0.11		0.46	0.12	0.637	104	5.7	2.05E+11	878
79	919625	10.64	0.11		0.56	0.12	0.587	140	6.7	2.92E+11	873
80	1216210	14.08	0.11		0.64	0.12	0.549	172	7.4	3.76E+11	846
81	1512795	17.51	0.10		0.72	0.11	0.520	202	8.0	4.59E+11	828
82	1809380	20.94	0.10		0.78	0.11	0.495	229	8.5	5.40E+11	815
83	2105965	24.37	0.10		0.85	0.11	0.474	255	9.0	6.21E+11	805
84	2402550	27.81	0.10		0.90	0.11	0.456	280	9.4	7.00E+11	797
85	2599135	30.08	0.10		0.94	0.11	0.445	296	9.7	7.52E+11	790
86	2895720	33.52	0.10		0.99	0.11	0.430	319	10.1	8.31E+11	786
87	3192305	36.95	0.10		1.04	0.11	0.417	341	10.4	9.08E+11	780
88	3488890	40.38	0.10		1.09	0.11	0.405	362	10.7	9.86E+11	775
89	3785475	43.81	0.10		1.13	0.11	0.394	383	11.0	1.06E+12	771
90	4082060	47.25	0.10		1.18	0.10	0.384	403	11.3	1.14E+12	767
91	4378645	50.68	0.10		1.22	0.10	0.374	422	11.6	1.22E+12	763
92	4675230	54.11	0.10		1.26	0.10	0.366	441	11.8	1.29E+12	760
93	4971815	57.54	0.10		1.30	0.10	0.358	459	12.1	1.37E+12	757
94	5268400	60.98	0.10		1.34	0.10	0.350	477	12.3	1.44E+12	754
95	5564985	64.41	0.09		1.37	0.10	0.343	494	12.5	1.52E+12	752
96	5861570	67.84	0.09		1.41	0.10	0.337	511	12.7	1.59E+12	749
97	6158155	71.27	0.09		1.45	0.10	0.331	527	13.0	1.67E+12	747
98	6454740	74.71	0.09		1.48	0.10	0.325	544	13.2	1.74E+12	745
99	6751325	78.14	0.09		1.51	0.10	0.319	560	13.3	1.81E+12	743
100	7047910	81.57	0.09		1.55	0.10	0.314	575	13.5	1.89E+12	741
101	7344495	85.01	0.09		1.58	0.10	0.309	590	13.7	1.96E+12	739
102	7641080	88.44	0.09		1.61	0.10	0.304	605	13.9	2.04E+12	737
103	7937665	91.87	0.09		1.64	0.10	0.300	620	14.0	2.11E+12	736
104	8234250	95.30	0.09		1.67	0.10	0.296	635	14.2	2.18E+12	734
105	8530835	98.74	0.09		1.70	0.10	0.292	649	14.4	2.25E+12	733
106	8827420	102.17	0.09		1.73	0.10	0.288	663	14.5	2.33E+12	731
107	9124005	105.60	0.09		1.76	0.10	0.284	677	14.7	2.40E+12	730
108	9420590	109.03	0.09		1.79	0.10	0.280	691	14.8	2.47E+12	728
109	9717175	112.47	0.09		1.82	0.10	0.277	704	15.0	2.55E+12	727
110	10013760	115.90	0.09		1.84	0.10	0.273	717	15.1	2.62E+12	726
111	10310345	119.33	0.09		1.87	0.10	0.270	730	15.2	2.69E+12	725
112	10606930	122.77	0.09		1.90	0.10	0.267	743	15.4	2.76E+12	724
113	10903515	126.20	0.09		1.92	0.10	0.264	756	15.5	2.83E+12	722
114	11200100	129.63	0.09		1.95	0.10	0.261	768	15.6	2.91E+12	721
115	11496685	133.06	0.09		1.97	0.10	0.258	781	15.8	2.98E+12	720
116	11793270	136.50	0.09		2.00	0.10	0.255	793	15.9	3.05E+12	719
117	12089855	139.93	0.09		2.03	0.10	0.253	805	16.0	3.12E+12	718
118	12386440	143.36	0.09		2.05	0.10	0.250	817	16.1	3.19E+12	717
119	12683025	146.79	0.09		2.07	0.10	0.248	829	16.2	3.26E+12	716
120	12979610	150.23	0.09		2.10	0.10	0.245	841	16.4	3.34E+12	716
121	13276195	153.66	0.09		2.12	0.10	0.243	852	16.5	3.41E+12	715
122	13572780	157.09	0.09		2.15	0.10	0.241	864	16.6	3.48E+12	714
123	13869365	160.53	0.09		2.17	0.10	0.238	875	16.7	3.55E+12	713
124	14165950	163.96	0.09		2.19	0.10	0.236	886	16.8	3.62E+12	712
125	14462535	167.39	0.09		2.21	0.10	0.234	897	16.9	3.69E+12	711
126	14759120	170.82	0.09		2.24	0.10	0.232	908	17.0	3.76E+12	711
127	15055705	174.26	0.09		2.26	0.10	0.230	919	17.1	3.83E+12	710
128	15352290	177.69	0.09		2.28	0.10	0.228	930	17.2	3.90E+12	709
129	15648875	181.12	0.09		2.30	0.10	0.226	940	17.3	3.97E+12	709
130	15945460	184.55	0.09		2.33	0.10	0.225	951	17.4	4.04E+12	708
131	16242045	187.99	0.09		2.35	0.10	0.223	961	17.5	4.12E+12	707
132	16538630	191.42	0.09		2.37	0.09	0.221	972	17.6	4.19E+12	706
133	16835215	194.85	0.09		2.39	0.09	0.219	982	17.7	4.26E+12	706
134	17131800	198.28	0.09		2.41	0.09	0.218	992	17.8	4.33E+12	705
135	17428385	201.72	0.09		2.43	0.09	0.216	1002	17.9	4.40E+12	705
136	17724970	205.15	0.09		2.45	0.09	0.214	1012	17.9	4.47E+12	704
137	18021555	208.58	0.09		2.47	0.09	0.213	1022	18.0	4.54E+12	703
138	18318140	212.02	0.09		2.49	0.09	0.211	1032	18.1	4.61E+12	703
139	18614725	215.45	0.09		2.51	0.09	0.210	1042	18.2	4.68E+12	702
140	18911310	218.88	0.09		2.53	0.09	0.208	1052	18.3	4.75E+12	702
141	19207895	222.31	0.09		2.55	0.09	0.207	1061	18.4	4.82E+12	701
142	19504480	225.75	0.09		2.57	0.09	0.206	1071	18.5	4.89E+12	701
143	19801065	229.18	0.09		2.59	0.09	0.204	1080	18.5	4.96E+12	700
144	20097650	232.61	0.09		2.61	0.09	0.203	1090	18.6	5.03E+12	700
145	20394235	236.04	0.09		2.63	0.09	0.202	1099	18.7	5.10E+12	699
146	20690820	239.48	0.09		2.65	0.09	0.200	1109	18.8	5.17E+12	698
147	20987405	242.91	0.09		2.67	0.09	0.199	1118	18.9	5.24E+12	698
148	21283990	246.34	0.09		2.69	0.09	0.198	1127	18.9	5.31E+12	698
149	21580575	249.78	0.09		2.71	0.09	0.197	1136	19.0	5.37E+12	697
150	21877160	253.21	0.09		2.72	0.09	0.195	1145	19.1	5.44E+12	697
151	22173745	256.64	0.09		2.74	0.09	0.194	1154	19.2	5.51E+12	696
152	22470330	260.07	0.09		2.76	0.09	0.193	1163	19.2	5.58E+12	696
153	22766915	263.51	0.09		2.78	0.09	0.192	1172	19.3	5.65E+12	695
154	23063500	266.94	0.09		2.80	0.09	0.191	1181	19.4	5.72E+12	695
155	23360085	270.37	0.09		2.82	0.09	0.190	1189	19.5	5.79E+12	694
156	23656670	273.80	0.09		2.83	0.09	0.189	1198	19.5	5.86E+12	694
157	23953255	277.24	0.09		2.85	0.09	0.187	1207	19.6	5.93E+12	693
158	24249840	280.67	0.09		2.87	0.09	0.186	1215	19.7	6.00E+12	693
159	24546425	284.10	0.09		2.89	0.09	0.185	1224	19.7	6.07E+12	693
160	24843010	287.53	0.09		2.90	0.09	0.184	1232	19.8	6.14E+12	692
161	25139595	290.97	0.09		2.92	0.09	0.183	1241	19.9	6.21E+12	692
162	25436180	294.40	0.09		2.94	0.09	0.182	1249	19.9	6.27E+12	691
163	25732765	297.83	0.09		2.95	0.09	0.182	1257	20.0	6.34E+12	691
164	26029350	301.27	0.09		2.97	0.09	0.181	1265	20.1	6.41E+12	691
165	26325935	304.70	0.09		2.99	0.09	0.180	1274	20.1	6.48E+12	690
166	26622520	308.13	0.09		3.01	0.09	0.179	1282	20.2	6.55E+12	690
167	26919105	311.56	0.09		3.02	0.09	0.178	1290	20.3	6.62E+12	690
168	27215690	315.00	0.09		3.04	0.09	0.177	1298	20.3	6.69E+12	689
169	27512275	318.43	0.09		3.05	0.09	0.176	1306	20.4	6.76E+12	689
170	27808860	321.86	0.09		3.07	0.09	0.175	1314	20.4	6.82E+12	688
171	28105445	325.29	0.09		3.09	0.09	0.174	1322	20.5	6.89E+12	688
172	28402030	328.73	0.09		3.10	0.09	0.174	1330	20.6	6.96E+12	688
173	28698615	332.16	0.09		3.12	0.09	0.173	1338	20.6	7.03E+12	687
174	28995200	335.59	0.09		3.14	0.09	0.172	1346	20.7	7.10E+12	687
175	29291785	339.03	0.09		3.15	0.09	0.171	1353	20.8	7.17E+12	687
176	29588370	342.46	0.09		3.17	0.09	0.170	1361	20.8	7.24E+12	686
177	29884955	345.89	0.09		3.18	0.09	0.170	1369	20.9	7.30E+12	686
178	30181540	349.32	0.09		3.20	0.09	0.169	1377	20.9	7.37E+12	686
179	30478125	352.76	0.09		3.22	0.09	0.168	1384	21.0	7.44E+12	685
180	30774710	356.19	0.09		3.23	0.09	0.167	1392	21.0	7.51E+12	685
181	31071295	359.62	0.09		3.25	0.09	0.166	1399	21.1	7.58E+12	685
182	31367880	363.05	0.09		3.26	0.09	0.166	1407	21.2	7.65E+12	685
183	31664465	366.49	0.09		3.28	0.09	0.165	1414	21.2	7.71E+12	684

Table B-13
Estimation of Steam Injection Rate and Steam Zone Growth

D-zone, 4.2 darcy

Parameter	Symbol	Unit	Value
Thickness of steamed layer	h	m	3.05
Particle density of soil	d_s	kg/m^3	2650
Porosity of steamed layer	p		0.35
Absolute permeability of soil	k_s	m^2	4.2E-12
Heat capacity of soil	cp_r	J/(kg K)	1152
Initial water saturation	S_w		1
Ambient pressure in aquifer	P_{amb}	Pa	549500
Density of water	d_w	kg/m^3	1000
Ambient water temperature	T_{amb}	K	295
Heat capacity of water	cp_w	J/(kg K)	4187
Overall heat capacity	cp_{sw}	J/(kg K)	2200
Overburden thermal conductivity	k	J/(s m K)	1.3
Overburden thermal diffusivity	a	m^2/s	0.0000001
Radius of injection well	r_w	m	0.0505
Maximum steam injection pressure	P_w	Pa	635369
Relative permeability of steam	k_{rs}		1
Steam viscosity	u_s	kg/(m s)	1.31E-05
Temperature of steam	T_s	K	433
Delta T	$T_s - T_{amb}$	K	138
Heat of condensation	´h	J/kg	2666000
Time since start of injection	t	s	
Steam mass flow rate	´m	kg/s	
Volume of steam zone	V	m^3	
Gas constant	R	J/(mole K)	8.314
Initial radius of steam zone	r_{si}	m	0.053025
Mole mass of water	M_w	kg/mole	0.018
Density of steam	d_{steam}	kg/m^3	3.3
Depth to top of injection screen	$D_{injscr.}$	m.b.g	47.275
Length of injection screen	$L_{inj,screen}$	m	3
Aquifer hydraulic head	D_{gwt}	m.b.g	3



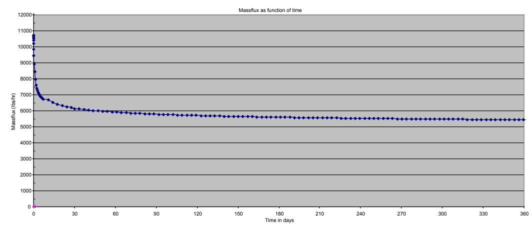


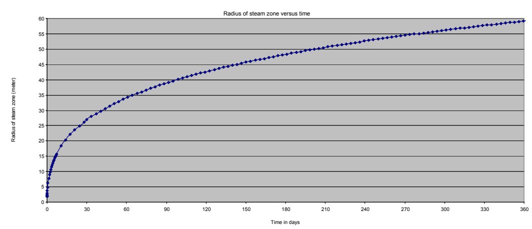
	t (s)	t (days)	´m	cp,sw	y	´mave	erf(y)*ey2	A(t)	r(t)	Energy Injected	´m (lb/h)
1	60	0.00	32.03	3449770	0.00	32.03	0.995	3	1.0	5.12E+09	254018
2	120	0.00	0.52		0.01	16.28	0.993	3	1.0	5.21E+09	4108
3	240	0.00	0.52		0.01	8.40	0.990	4	1.1	5.37E+09	4088
4	480	0.01	0.51		0.01	4.45	0.986	4	1.1	5.70E+09	4062
5	960	0.01	0.51		0.02	2.48	0.980	4	1.2	6.35E+09	4020
6	1920	0.02	0.50		0.03	1.49	0.972	5	1.3	7.62E+09	3950
7	3840	0.04	0.48		0.04	0.99	0.961	7	1.5	1.01E+10	3839
8	7680	0.09	0.46		0.05	0.73	0.945	10	1.8	1.49E+10	3682
9	15360	0.18	0.44		0.07	0.58	0.923	16	2.2	2.39E+10	3487
10	30720	0.36	0.41		0.10	0.50	0.894	26	2.9	4.08E+10	3275
11	61440	0.71	0.39		0.14	0.44	0.856	45	3.8	7.24E+10	3066
12	104640	1.21	0.36		0.19	0.41	0.818	69	4.7	1.14E+11	2872
13	147840	1.71	0.35		0.22	0.39	0.790	90	5.4	1.54E+11	2738
14	191040	2.21	0.34		0.25	0.38	0.767	111	5.9	1.93E+11	2657
15	234240	2.71	0.33		0.28	0.37	0.747	130	6.4	2.30E+11	2600
16	277440	3.21	0.32		0.31	0.36	0.730	149	6.9	2.67E+11	2557
17	320640	3.71	0.32		0.33	0.36	0.715	167	7.3	3.04E+11	2522
18	363840	4.21	0.31		0.35	0.35	0.701	184	7.7	3.40E+11	2493
19	407040	4.71	0.31		0.37	0.35	0.688	201	8.0	3.76E+11	2469
74	450240	5.21	0.31		0.39	0.34	0.676	217	8.3	4.12E+11	2447
75	493440	5.71	0.31		0.41	0.34	0.665	233	8.6	4.47E+11	2428
76	536640	6.21	0.30		0.43	0.34	0.655	249	8.9	4.82E+11	2412
77	579840	6.71	0.30		0.44	0.33	0.646	264	9.2	5.17E+11	2396
78	623040	7.21	0.30		0.46	0.33	0.637	279	9.4	5.51E+11	2383
79	919625	10.64	0.30		0.56	0.32	0.587	377	11.0	7.88E+11	2370
80	1216210	14.08	0.29		0.64	0.31	0.549	465	12.2	1.02E+12	2304
81	1512795	17.51	0.28		0.72	0.31	0.520	546	13.2	1.24E+12	2260
82	1809380	20.94	0.28		0.78	0.30	0.495	622	14.1	1.46E+12	2227
83	2105965	24.37	0.28		0.85	0.30	0.474	693	14.9	1.68E+12	2201
84	2402550	27.81	0.27		0.90	0.30	0.456	761	15.6	1.90E+12	2180
85	2599135	30.08	0.27		0.94	0.30	0.445	804	16.0	2.04E+12	2163
86	2895720	33.52	0.27		0.99	0.29	0.430	867	16.6	2.26E+12	2152
87	3192305	36.95	0.27		1.04	0.29	0.417	928	17.2	2.47E+12	2138
88	3488890	40.38	0.27		1.09	0.29	0.405	986	17.7	2.68E+12	2126
89	3785475	43.81	0.27		1.13	0.29	0.394	1043	18.2	2.90E+12	2115
90	4082060	47.25	0.27		1.18	0.29	0.384	1097	18.7	3.11E+12	2105
91	4378645	50.68	0.26		1.22	0.28	0.374	1151	19.1	3.31E+12	2096
92	4675230	54.11	0.26		1.26	0.28	0.366	1202	19.6	3.52E+12	2087
93	4971815	57.54	0.26		1.30	0.28	0.358	1252	20.0	3.73E+12	2080
94	5268400	60.98	0.26		1.34	0.28	0.350	1301	20.3	3.94E+12	2073
95	5564985	64.41	0.26		1.37	0.28	0.343	1349	20.7	4.14E+12	2066
96	5861570	67.84	0.26		1.41	0.28	0.337	1396	21.1	4.35E+12	2060
97	6158155	71.27	0.26		1.45	0.28	0.331	1442	21.4	4.55E+12	2054
98	6454740	74.71	0.26		1.48	0.28	0.325	1486	21.7	4.76E+12	2049
99	6751325	78.14	0.26		1.51	0.28	0.319	1530	22.1	4.96E+12	2043
100	7047910	81.57	0.26		1.55	0.27	0.314	1573	22.4	5.16E+12	2038
101	7344495	85.01	0.26		1.58	0.27	0.309	1615	22.7	5.37E+12	2034
102	7641080	88.44	0.26		1.61	0.27	0.304	1657	23.0	5.57E+12	2029
103	7937665	91.87	0.26		1.64	0.27	0.300	1698	23.2	5.77E+12	2025
104	8234250	95.30	0.25		1.67	0.27	0.296	1738	23.5	5.97E+12	2021
105	8530835	98.74	0.25		1.70	0.27	0.292	1777	23.8	6.17E+12	2017
106	8827420	102.17	0.25		1.73	0.27	0.288	1816	24.0	6.37E+12	2014
107	9124005	105.60	0.25		1.76	0.27	0.284	1854	24.3	6.58E+12	2010
108	9420590	109.03	0.25		1.79	0.27	0.280	1892	24.5	6.78E+12	2007
109	9717175	112.47	0.25		1.82	0.27	0.277	1929	24.8	6.98E+12	2004
110	10013760	115.90	0.25		1.84	0.27	0.273	1965	25.0	7.17E+12	2000
111	10310345	119.33	0.25		1.87	0.27	0.270	2002	25.2	7.37E+12	1997
112	10606930	122.77	0.25		1.90	0.27	0.267	2037	25.5	7.57E+12	1994
113	10903515	126.20	0.25		1.92	0.27	0.264	2072	25.7	7.77E+12	1992
114	11200100	129.63	0.25		1.95	0.27	0.261	2107	25.9	7.97E+12	1989
115	11496685	133.06	0.25		1.97	0.27	0.258	2141	26.1	8.17E+12	1986
116	11793270	136.50	0.25		2.00	0.27	0.255	2175	26.3	8.37E+12	1984
117	12089855	139.93	0.25		2.03	0.27	0.253	2209	26.5	8.56E+12	1981
118	12386440	143.36	0.25		2.05	0.27	0.250	2242	26.7	8.76E+12	1979
119	12683025	146.79	0.25		2.07	0.26	0.248	2274	26.9	8.96E+12	1976
120	12979610	150.23	0.25		2.10	0.26	0.245	2307	27.1	9.15E+12	1974
121	13276195	153.66	0.25		2.12	0.26	0.243	2339	27.3	9.35E+12	1972
122	13572780	157.09	0.25		2.15	0.26	0.241	2370	27.5	9.55E+12	1970
123	13869365	160.53	0.25		2.17	0.26	0.238	2402	27.6	9.74E+12	1968
124	14165950	163.96	0.25		2.19	0.26	0.236	2433	27.8	9.94E+12	1966
125	14462535	167.39	0.25		2.21	0.26	0.234	2463	28.0	1.01E+13	1964
126	14759120	170.82	0.25		2.24	0.26	0.232	2494	28.2	1.03E+13	1962
127	15055705	174.26	0.25		2.26	0.26	0.230	2524	28.3	1.05E+13	1960
128	15352290	177.69	0.25		2.28	0.26	0.228	2554	28.5	1.07E+13	1958
129	15648875	181.12	0.25		2.30	0.26	0.226	2583	28.7	1.09E+13	1956
130	15945460	184.55	0.25		2.33	0.26	0.225	2612	28.8	1.11E+13	1954
131	16242045	187.99	0.25		2.35	0.26	0.223	2641	29.0	1.13E+13	1953
132	16538630	191.42	0.25		2.37	0.26	0.221	2670	29.1	1.15E+13	1951
133	16835215	194.85	0.25		2.39	0.26	0.219	2699	29.3	1.17E+13	1949
134	17131800	198.28	0.25		2.41	0.26	0.218	2727	29.5	1.19E+13	1948
135	17428385	201.72	0.25		2.43	0.26	0.216	2755	29.6	1.21E+13	1946
136	17724970	205.15	0.25		2.45	0.26	0.214	2783	29.8	1.23E+13	1944
137	18021555	208.58	0.25		2.47	0.26	0.213	2810	29.9	1.25E+13	1943
138	18318140	212.02	0.24		2.49	0.26	0.211	2838	30.0	1.27E+13	1941
139	18614725	215.45	0.24		2.51	0.26	0.210	2865	30.2	1.29E+13	1940
140	18911310	218.88	0.24		2.53	0.26	0.208	2892	30.3	1.31E+13	1939
141	19207895	222.31	0.24		2.55	0.26	0.207	2918	30.5	1.32E+13	1937
142	19504480	225.75	0.24		2.57	0.26	0.206	2945	30.6	1.34E+13	1936
143	19801065	229.18	0.24		2.59	0.26	0.204	2971	30.7	1.36E+13	1934
144	20097650	232.61	0.24		2.61	0.26	0.203	2997	30.9	1.38E+13	1933
145	20394235	236.04	0.24		2.63	0.26	0.202	3023	31.0	1.40E+13	1932
146	20690820	239.48	0.24		2.65	0.26	0.200	3049	31.1	1.42E+13	1930
147	20987405	242.91	0.24		2.67	0.26	0.199	3074	31.3	1.44E+13	1929
148	21283990	246.34	0.24		2.69	0.26	0.198	3100	31.4	1.46E+13	1928
149	21580575	249.78	0.24		2.71	0.26	0.197	3125	31.5	1.48E+13	1927
150	21877160	253.21	0.24		2.72	0.26	0.195	3150	31.7	1.50E+13	1925
151	22173745	256.64	0.24		2.74	0.26	0.194	3175	31.8	1.52E+13	1924
152	22470330	260.07	0.24		2.76	0.26	0.193	3200	31.9	1.54E+13	1923
153	22766915	263.51	0.24		2.78	0.26	0.192	3224	32.0	1.56E+13	1922
154	23063500	266.94	0.24		2.80	0.26	0.191	3249	32.2	1.57E+13	1921
155	23360085	270.37	0.24		2.82	0.26	0.190	3273	32.3	1.59E+13	1920
156	23656670	273.80	0.24		2.83	0.26	0.189	3297	32.4	1.61E+13	1918
157	23953255	277.24	0.24		2.85	0.26	0.187	3321	32.5	1.63E+13	1917
158	24249840	280.67	0.24		2.87	0.26	0.186	3344	32.6	1.65E+13	1916
159	24546425	284.10	0.24		2.89	0.26	0.185	3368	32.7	1.67E+13	1915
160	24843010	287.53	0.24		2.90	0.26	0.184	3392	32.9	1.69E+13	1914
161	25139595	290.97	0.24		2.92	0.25	0.183	3415	33.0	1.71E+13	1913
162	25436180	294.40	0.24		2.94	0.25	0.182	3438	33.1	1.73E+13	1912
163	25732765	297.83	0.24		2.95	0.25	0.182	3461	33.2	1.75E+13	1911
164	26029350	301.27	0.24		2.97	0.25	0.181	3484	33.3	1.77E+13	1910
165	26325935	304.70	0.24		2.99	0.25	0.180	3507	33.4	1.79E+13	1909
166	26622520	308.13	0.24		3.01	0.25	0.179	3530	33.5	1.80E+13	1908
167	26919105	311.56	0.24		3.02	0.25	0.178	3552	33.6	1.82E+13	1907
168	27215690	315.00	0.24		3.04	0.25	0.177	3575	33.7	1.84E+13	1906
169	27512275	318.43	0.24		3.05	0.25	0.176	3597	33.8	1.86E+13	1906
170	27808860	321.86	0.24		3.07	0.25	0.175	3619	33.9	1.88E+13	1905
171	28105445	325.29	0.24		3.09	0.25	0.174	3641	34.0	1.90E+13	1904
172	28402030	328.73	0.24		3.10	0.25	0.174	3663	34.1	1.92E+13	1903
173	28698615	332.16	0.24		3.12	0.25	0.173	3685	34.2	1.94E+13	1902
174	28995200	335.59	0.24		3.13	0.25	0.172	3707	34.3	1.96E+13	1901
175	29291785	339.03	0.24		3.15	0.25	0.171	3728	34.4	1.97E+13	1900
176	29588370	342.46	0.24		3.17	0.25	0.170	3750	34.5	1.99E+13	1899
177	29884955	345.89	0.24		3.18	0.25	0.170	3771	34.6	2.01E+13	1899
178	30181540	349.32	0.24		3.20	0.25	0.169	3792	34.7	2.03E+13	1898
179	30478125	352.76	0.24		3.22	0.25	0.168	3814	34.8	2.05E+13	1897
180	30774710	356.19	0.24		3.23	0.25	0.167	3835	34.9	2.07E+13	1896
181	31071295	359.62	0.24		3.25	0.25	0.166	3856	35.0	2.09E+13	1895
182	31367880	363.05	0.24		3.26	0.25	0.166	3876	35.1	2.11E+13	1895
183	31664465	366.49	0.24		3.28	0.25	0.165	3897	35.2	2.13E+13	1894

Table B-14
Estimation of Steam Injection Rate and Steam Zone Growth

D-zone, 13 darcy

Parameter	Symbol	Unit	Value
Thickness of steamed layer	h	m	3.05
Particle density of soil	d_s	kg/m³	2650
Porosity of steamed layer	p		0.35
Absolute permeability of soil	k_s	m²	1.3E-11
Heat capacity of soil	cp_r	J/(kg K)	1152
Initial water saturation	S_w		1
Ambient pressure in aquifer	P_{amb}	Pa	549500
Density of water	d_w	kg/m³	1000
Ambient water temperature	T_{amb}	K	295
Heat capacity of water	cp_w	J/(kg K)	4187
Overall heat capacity	cp_{sw}	J/(kg K)	2200
Overburden thermal conductivity	k	J/(s m K)	1.3
Overburden thermal diffusivity	a	m²/s	0.0000001
Radius of injection well	r_w	m	0.0505
Maximum steam injection pressure	P_w	Pa	635365
Relative permeability of steam	k_{rs}		1
Steam viscosity	μ_s	kg/(m s)	1.31E-05
Temperature of steam	T_s	K	433
Delta T	$T_s - T_{amb}$	K	138
Heat of condensation	Δh	J/kg	2666000
Time since start of injection	t	s	
Steam mass flow rate	'm	kg/s	
Volume of steam zone	V	m³	
Gas constant	R	J/(mole K)	8.314
Initial radius of steam zone	r_{si}	m	0.053025
Mole mass of water	M_w	kg/mole	0.018
Density of steam	d_{steam}	kg/m³	3.3
Depth to top of injection screen	$D_{injscr.}$	m.b.g	47.275
Length of injection screen	$L_{inj,screen}$	m	3
Aquifer hydraulic head	D_{gwt}	m.b.g	3



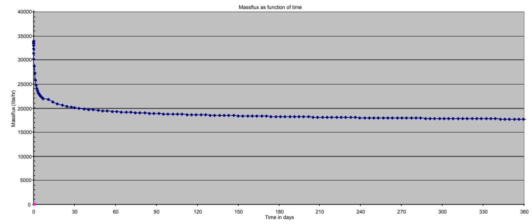


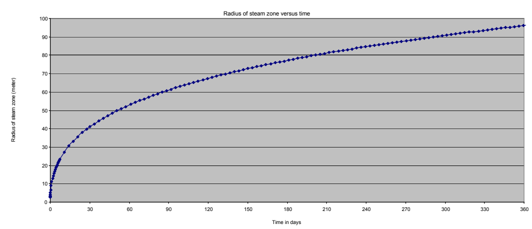
	t (s)	t (days)	Ys	rp,sw	y	rwave	erfc(Yw)2	A(t)	r(t)	Energy Injected	'm (lb/h)
1	60	0.00	99.15	3e+0770	0.00	99.15	0.995	10	1.6	1.55E+10	786246
2	120	0.00	1.35		0.01	50.20	0.993	11	1.6	1.61E+10	10710
3	240	0.00	1.35		0.01	25.60	0.990	11	1.6	1.65E+10	10670
4	480	0.01	1.34		0.01	13.07	0.986	12	1.6	1.74E+10	10619
5	960	0.01	1.33		0.02	7.45	0.980	13	2.0	1.91E+10	10535
6	1920	0.02	1.31		0.03	4.38	0.972	15	2.2	2.24E+10	10404
7	3840	0.04	1.28		0.04	2.63	0.961	19	2.5	2.90E+10	10182
8	7680	0.09	1.24		0.05	2.04	0.945	29	3.0	4.17E+10	9853
9	15360	0.18	1.19		0.07	1.61	0.923	43	3.7	6.61E+10	9424
10	30720	0.36	1.13		0.10	1.37	0.894	71	4.8	1.12E+11	8935
11	61440	0.71	1.06		0.14	1.22	0.856	123	6.3	1.99E+11	8439
12	104640	1.21	1.00		0.18	1.13	0.818	189	7.8	3.15E+11	7958
13	147840	1.71	0.96		0.22	1.06	0.790	250	8.9	4.26E+11	7620
14	191040	2.21	0.94		0.25	1.01	0.767	307	9.9	5.33E+11	7415
15	234240	2.71	0.92		0.28	1.02	0.747	361	10.7	6.35E+11	7271
16	277440	3.21	0.90		0.31	1.00	0.730	413	11.5	7.43E+11	7160
17	320640	3.71	0.89		0.33	0.99	0.715	463	12.1	8.46E+11	7071
18	363840	4.21	0.88		0.35	0.98	0.701	512	12.8	9.47E+11	6997
19	407040	4.71	0.87		0.37	0.97	0.689	560	13.3	1.05E+12	6934
74	450240	5.21	0.87		0.39	0.96	0.678	606	13.9	1.15E+12	6879
75	493440	5.71	0.86		0.41	0.95	0.665	651	14.4	1.25E+12	6830
76	536640	6.21	0.86		0.43	0.94	0.655	695	14.9	1.35E+12	6787
77	579840	6.71	0.85		0.44	0.93	0.646	738	15.3	1.44E+12	6748
78	623040	7.21	0.85		0.46	0.93	0.637	781	15.8	1.54E+12	6712
79	919625	10.64	0.84		0.56	0.90	0.587	1056	18.3	2.21E+12	6679
80	1216210	14.08	0.82		0.64	0.88	0.549	1305	20.4	2.86E+12	6508
81	1512795	17.51	0.81		0.72	0.87	0.520	1535	22.1	3.49E+12	6393
82	1809380	20.94	0.80		0.78	0.85	0.495	1750	23.6	4.12E+12	6308
83	2105965	24.37	0.79		0.85	0.85	0.474	1953	24.9	4.74E+12	6241
84	2402550	27.81	0.78		0.90	0.84	0.456	2146	26.1	5.36E+12	6185
85	2699135	31.24	0.77		0.96	0.83	0.440	2329	26.9	5.97E+12	6139
86	2995720	34.67	0.77		0.99	0.83	0.430	2448	27.9	6.58E+12	6112
87	3192305	36.95	0.77		1.04	0.82	0.417	2621	28.9	6.98E+12	6075
88	3488890	40.38	0.76		1.09	0.82	0.405	2787	29.8	7.59E+12	6042
89	3785475	43.81	0.76		1.13	0.81	0.394	2946	30.6	8.18E+12	6013
90	4082060	47.25	0.76		1.18	0.81	0.384	3104	31.4	8.79E+12	5987
91	4378645	50.68	0.75		1.22	0.80	0.374	3250	32.2	9.38E+12	5963
92	4675230	54.11	0.75		1.26	0.80	0.366	3402	32.9	9.97E+12	5941
93	4971815	57.54	0.75		1.30	0.80	0.358	3545	33.6	1.06E+13	5921
94	5268400	60.98	0.74		1.34	0.79	0.350	3685	34.2	1.11E+13	5902
95	5564985	64.41	0.74		1.37	0.79	0.343	3821	34.9	1.17E+13	5884
96	5861570	67.84	0.74		1.41	0.79	0.337	3955	35.5	1.23E+13	5868
97	6158155	71.27	0.74		1.45	0.79	0.331	4085	36.1	1.29E+13	5853
98	6454740	74.71	0.74		1.48	0.78	0.325	4213	36.6	1.35E+13	5838
99	6751325	78.14	0.73		1.51	0.78	0.319	4339	37.2	1.41E+13	5824
100	7047910	81.57	0.73		1.55	0.78	0.314	4462	37.7	1.46E+13	5812
101	7344495	85.01	0.73		1.58	0.78	0.309	4582	38.2	1.52E+13	5799
102	7641080	88.44	0.73		1.61	0.78	0.304	4701	38.7	1.58E+13	5788
103	7937665	91.87	0.73		1.64	0.77	0.300	4817	39.2	1.64E+13	5776
104	8234250	95.30	0.73		1.67	0.77	0.296	4932	39.6	1.70E+13	5766
105	8530835	98.74	0.72		1.70	0.77	0.292	5045	40.1	1.75E+13	5756
106	8827420	102.17	0.72		1.73	0.77	0.288	5156	40.5	1.81E+13	5746
107	9124005	105.60	0.72		1.76	0.77	0.284	5265	40.9	1.87E+13	5737
108	9420590	109.03	0.72		1.79	0.77	0.280	5373	41.3	1.92E+13	5728
109	9717175	112.47	0.72		1.82	0.76	0.277	5479	41.8	1.98E+13	5719
110	10013760	115.90	0.72		1.84	0.76	0.273	5584	42.1	2.04E+13	5711
111	10310345	119.33	0.72		1.87	0.76	0.270	5687	42.5	2.10E+13	5703
112	10606930	122.77	0.72		1.90	0.76	0.267	5789	42.9	2.15E+13	5695
113	10903515	126.20	0.72		1.92	0.76	0.264	5890	43.3	2.21E+13	5687
114	11200100	129.63	0.72		1.95	0.76	0.261	5989	43.7	2.27E+13	5680
115	11496685	133.06	0.72		1.97	0.76	0.258	6087	44.0	2.32E+13	5673
116	11793270	136.50	0.71		2.00	0.75	0.255	6184	44.4	2.38E+13	5666
117	12089855	139.93	0.71		2.02	0.75	0.253	6280	44.7	2.43E+13	5660
118	12386440	143.36	0.71		2.05	0.75	0.250	6374	45.0	2.49E+13	5653
119	12683025	146.79	0.71		2.07	0.75	0.248	6468	45.4	2.55E+13	5647
120	12979610	150.23	0.71		2.10	0.75	0.245	6561	45.7	2.60E+13	5641
121	13276195	153.66	0.71		2.12	0.75	0.243	6652	46.0	2.66E+13	5635
122	13572780	157.09	0.71		2.15	0.75	0.241	6743	46.3	2.72E+13	5629
123	13869365	160.53	0.71		2.17	0.75	0.238	6833	46.6	2.77E+13	5624
124	14165950	163.96	0.71		2.19	0.75	0.236	6921	46.9	2.83E+13	5618
125	14462535	167.39	0.71		2.21	0.75	0.234	7009	47.2	2.88E+13	5613
126	14759120	170.82	0.71		2.24	0.75	0.232	7097	47.5	2.94E+13	5608
127	15055705	174.26	0.71		2.26	0.75	0.230	7183	47.8	3.00E+13	5603
128	15352290	177.69	0.71		2.28	0.75	0.228	7268	48.1	3.05E+13	5598
129	15648875	181.12	0.71		2.30	0.74	0.226	7353	48.4	3.11E+13	5593
130	15945460	184.55	0.70		2.33	0.74	0.225	7437	48.6	3.16E+13	5589
131	16242045	187.99	0.70		2.35	0.74	0.223	7520	48.9	3.22E+13	5584
132	16538630	191.42	0.70		2.37	0.74	0.221	7602	49.2	3.27E+13	5579
133	16835215	194.85	0.70		2.39	0.74	0.219	7684	49.4	3.33E+13	5575
134	17131800	198.28	0.70		2.41	0.74	0.218	7765	49.7	3.39E+13	5570
135	17428385	201.72	0.70		2.43	0.74	0.216	7845	50.0	3.44E+13	5566
136	17724970	205.15	0.70		2.45	0.74	0.214	7925	50.2	3.50E+13	5562
137	18021555	208.58	0.70		2.47	0.74	0.213	8004	50.5	3.55E+13	5558
138	18318140	212.02	0.70		2.49	0.74	0.211	8082	50.7	3.61E+13	5554
139	18614725	215.45	0.70		2.51	0.74	0.210	8160	51.0	3.66E+13	5550
140	18911310	218.88	0.70		2.53	0.74	0.208	8237	51.2	3.72E+13	5546
141	19207895	222.31	0.70		2.55	0.74	0.207	8314	51.4	3.77E+13	5542
142	19504480	225.75	0.70		2.57	0.74	0.206	8390	51.7	3.83E+13	5539
143	19801065	229.18	0.70		2.59	0.74	0.204	8466	51.9	3.88E+13	5535
144	20097650	232.61	0.70		2.61	0.74	0.203	8540	52.1	3.94E+13	5531
145	20394235	236.04	0.70		2.63	0.73	0.202	8615	52.4	3.99E+13	5528
146	20690820	239.48	0.70		2.65	0.73	0.200	8689	52.6	4.05E+13	5524
147	20987405	242.91	0.70		2.67	0.73	0.199	8762	52.8	4.10E+13	5521
148	21283990	246.34	0.70		2.69	0.73	0.198	8835	53.0	4.16E+13	5518
149	21580575	249.78	0.70		2.71	0.73	0.197	8907	53.2	4.21E+13	5514
150	21877160	253.21	0.70		2.72	0.73	0.195	8979	53.5	4.27E+13	5511
151	22173745	256.64	0.69		2.74	0.73	0.194	9050	53.7	4.32E+13	5508
152	22470330	260.07	0.69		2.76	0.73	0.193	9121	53.9	4.38E+13	5505
153	22766915	263.51	0.69		2.78	0.73	0.192	9192	54.1	4.43E+13	5502
154	23063500	266.94	0.69		2.80	0.73	0.191	9261	54.3	4.49E+13	5499
155	23360085	270.37	0.69		2.82	0.73	0.190	9331	54.5	4.54E+13	5496
156	23656670	273.80	0.69		2.83	0.73	0.189	9400	54.7	4.60E+13	5493
157	23953255	277.24	0.69		2.85	0.73	0.187	9469	54.9	4.65E+13	5490
158	24249840	280.67	0.69		2.87	0.73	0.186	9537	55.1	4.71E+13	5487
159	24546425	284.10	0.69		2.89	0.73	0.185	9605	55.3	4.76E+13	5484
160	24843010	287.53	0.69		2.90	0.73	0.184	9672	55.5	4.82E+13	5482
161	25139595	290.97	0.69		2.92	0.73	0.183	9739	55.7	4.87E+13	5479
162	25436180	294.40	0.69		2.94	0.73	0.182	9806	55.9	4.93E+13	5476
163	25732765	297.83	0.69		2.95	0.73	0.182	9872	56.0	4.98E+13	5473
164	26029350	301.27	0.69		2.97	0.73	0.181	9938	56.2	5.04E+13	5471
165	26325935	304.70	0.69		2.99	0.73	0.180	10003	56.4	5.09E+13	5468
166	26622520	308.13	0.69		3.01	0.72	0.179	10069	56.6	5.14E+13	5466
167	26919105	311.56	0.69		3.02	0.72	0.178	10133	56.8	5.20E+13	5463
168	27215690	315.00	0.69		3.04	0.72	0.177	10198	57.0	5.25E+13	5461
169	27512275	318.43	0.69		3.05	0.72	0.176	10262	57.1	5.31E+13	5458
170	27808860	321.86	0.69		3.07	0.72	0.175	10325	57.3	5.36E+13	5456
171	28105445	325.29	0.69		3.09	0.72	0.174	10389	57.5	5.42E+13	5453
172	28402030	328.73	0.69		3.10	0.72	0.174	10452	57.7	5.47E+13	5451
173	28698615	332.16	0.69		3.12	0.72	0.173	10515	57.8	5.53E+13	5449
174	28995200	335.59	0.69		3.14	0.72	0.172	10577	58.0	5.58E+13	5446
175	29291785	339.03	0.69		3.15	0.72	0.171	10639	58.2	5.63E+13	5444
176	29588370	342.46	0.69		3.17	0.72	0.170	10701	58.4	5.69E+13	5442
177	29884955	345.89	0.69		3.18	0.72	0.170	10762	58.5	5.74E+13	5440
178	30181540	349.32	0.69		3.20	0.72	0.169	10823	58.7	5.80E+13	5437
179	30478125	352.76	0.69		3.22	0.72	0.168	10884	58.9	5.85E+13	5435
180	30774710	356.19	0.69		3.23	0.72	0.167	10945	59.0	5.90E+13	5433
181	31071295	359.62	0.68		3.25	0.72	0.166	11005	59.2	5.96E+13	5431
182	31367880	363.05	0.68		3.26	0.72	0.166	11065	59.3	6.01E+13	5429
183	31664465	366.49	0.68		3.28	0.72	0.165	11125	59.5	6.07E+13	5427

Table B-15
Estimation of Steam Injection Rate and Steam Zone Growth

E-zone, 16 darcy

Parameter	Symbol	Unit	Value
Thickness of steamed layer	h	m	4.5
Particle density of soil	d_s	kg/m^3	2650
Porosity of steamed layer	p		0.35
Absolute permeability of soil	k_s	m^2	1.6E-11
Heat capacity of soil	cp_r	J/(kg K)	1152
Initial water saturation	S_w		1
Ambient pressure in aquifer	P_{amb}	Pa	81212
Density of water	d_w	kg/m^3	1000
Ambient water temperature	T_{amb}	K	295
Heat capacity of water	cp_w	J/(kg K)	4187
Overall heat capacity	cp_{sw}	J/(kg K)	2200
Overburden thermal conductivity	k	J/(s m K)	1.3
Overburden thermal diffusivity	a	m^2/s	0.0000001
Radius of injection well	r_w	m	0.0508
Maximum steam injection pressure	P_w	Pa	92823
Relative permeability of steam	k_{rs}		1
Steam viscosity	u_s	kg/(m s)	1.31E-05
Temperature of steam	T_s	K	448
Delta T	$T_s - T_{amb}$	K	153
Heat of condensation	´h	J/kg	266600
Time since start of injection	t	s	
Steam mass flow rate	´m	kg/s	
Volume of steam zone	V	m^3	
Gas constant	R	J/(mole K)	8.314
Initial radius of steam zone	r_{si}	m	0.05302
Mole mass of water	M_w	kg/mole	0.018
Density of steam	d_{steam}	kg/m^3	4.6
Depth to top of injection screen	$D_{injscr.}$	m.b.g	73.2
Length of injection screen	$L_{inj.screen}$	m	4.5
Aquifer hydraulic head	D_{gwt}	m.b.g	3



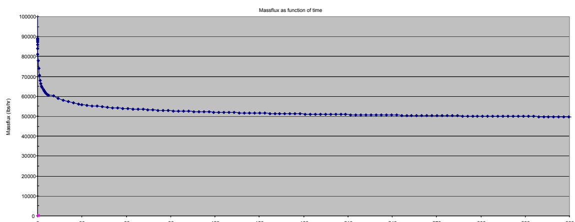


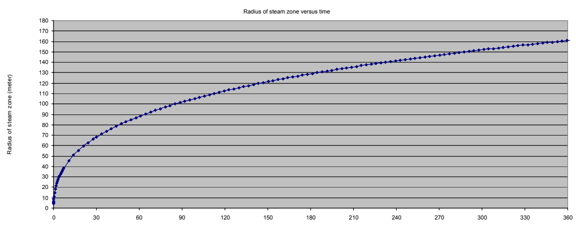
t (s)	t (days)	´m	cp,sw	y	´mave	erf(y)*ey2	A(t)	r(t)	Energy Injected	´m (lb/h)	
1	60	0.00	345.30	3449770	0.00	345.30	0.997	22	2.6	5.52E+10	2738094
2	120	0.00	4.27		0.00	174.79	0.995	22	2.7	5.59E+10	33834
3	240	0.00	4.25		0.01	89.52	0.993	23	2.7	5.73E+10	33691
4	480	0.01	4.23		0.01	46.87	0.990	24	2.8	6.00E+10	33530
5	960	0.01	4.20		0.01	25.54	0.986	27	2.9	6.54E+10	33301
6	1920	0.02	4.15		0.02	14.84	0.981	31	3.1	7.60E+10	32929
7	3840	0.04	4.08		0.02	9.46	0.973	40	3.6	9.68E+10	32323
8	7680	0.09	3.96		0.03	6.71	0.962	56	4.2	1.37E+11	31407
9	15360	0.18	3.81		0.05	5.26	0.947	87	5.3	2.15E+11	30183
10	30720	0.36	3.63		0.07	4.44	0.926	145	6.8	3.64E+11	28752
11	61440	0.71	3.44		0.10	3.94	0.899	252	9.0	6.45E+11	27253
12	104640	1.21	3.25		0.13	3.66	0.871	391	11.1	1.02E+12	25797
13	147840	1.71	3.12		0.15	3.50	0.849	520	12.9	1.38E+12	24752
14	191040	2.21	3.04		0.17	3.40	0.832	643	14.3	1.73E+12	24114
15	234240	2.71	2.98		0.19	3.32	0.816	761	15.6	2.07E+12	23661
16	277440	3.21	2.94		0.21	3.26	0.803	875	16.7	2.41E+12	23313
17	320640	3.71	2.90		0.22	3.21	0.790	986	17.7	2.75E+12	23032
18	363840	4.21	2.87		0.24	3.17	0.779	1095	18.7	3.08E+12	22797
19	407040	4.71	2.85		0.25	3.14	0.769	1200	19.5	3.41E+12	22596
74	450240	5.21	2.83		0.26	3.11	0.759	1304	20.4	3.73E+12	22421
75	493440	5.71	2.81		0.28	3.08	0.750	1406	21.2	4.05E+12	22266
76	536640	6.21	2.79		0.29	3.06	0.742	1506	21.9	4.38E+12	22127
77	579840	6.71	2.77		0.30	3.04	0.734	1604	22.6	4.70E+12	22002
78	623040	7.21	2.76		0.31	3.02	0.727	1701	23.3	5.01E+12	21888
79	919625	10.64	2.75		0.38	2.93	0.684	2338	27.3	7.19E+12	21784
80	1216210	14.08	2.68		0.44	2.87	0.650	2925	30.5	9.30E+12	21233
81	1512795	17.51	2.63		0.49	2.82	0.623	3475	33.3	1.14E+13	20861
82	1809380	20.94	2.60		0.53	2.79	0.600	3996	35.7	1.34E+13	20585
83	2105965	24.37	2.57		0.57	2.75	0.580	4493	37.8	1.55E+13	20365
84	2402550	27.81	2.55		0.61	2.73	0.563	4970	39.8	1.75E+13	20185
85	2599135	30.08	2.53		0.64	2.71	0.552	5275	41.0	1.88E+13	20032
86	2895720	33.52	2.52		0.67	2.69	0.537	5724	42.7	2.08E+13	19943
87	3192305	36.95	2.50		0.71	2.68	0.524	6158	44.3	2.28E+13	19823
88	3488890	40.38	2.49		0.74	2.66	0.512	6579	45.8	2.47E+13	19716
89	3785475	43.81	2.47		0.77	2.64	0.500	6988	47.2	2.67E+13	19620
90	4082060	47.25	2.46		0.80	2.63	0.490	7387	48.5	2.86E+13	19533
91	4378645	50.68	2.45		0.83	2.62	0.480	7776	49.7	3.06E+13	19454
92	4675230	54.11	2.44		0.85	2.61	0.471	8156	50.9	3.25E+13	19382
93	4971815	57.54	2.44		0.88	2.60	0.463	8528	52.1	3.44E+13	19315
94	5268400	60.98	2.43		0.91	2.59	0.455	8891	53.2	3.64E+13	19253
95	5564985	64.41	2.42		0.93	2.58	0.447	9248	54.2	3.83E+13	19195
96	5861570	67.84	2.41		0.96	2.57	0.440	9597	55.3	4.02E+13	19141
97	6158155	71.27	2.41		0.98	2.56	0.433	9940	56.2	4.21E+13	19091
98	6454740	74.71	2.40		1.00	2.56	0.427	10277	57.2	4.40E+13	19043
99	6751325	78.14	2.40		1.03	2.55	0.421	10608	58.1	4.59E+13	18998
100	7047910	81.57	2.39		1.05	2.54	0.415	10934	59.0	4.78E+13	18955
101	7344495	85.01	2.39		1.07	2.54	0.409	11254	59.8	4.97E+13	18914
102	7641080	88.44	2.38		1.09	2.53	0.404	11570	60.7	5.15E+13	18876
103	7937665	91.87	2.38		1.11	2.52	0.399	11881	61.5	5.34E+13	18839
104	8234250	95.30	2.37		1.13	2.52	0.394	12187	62.3	5.53E+13	18804
105	8530835	98.74	2.37		1.15	2.51	0.389	12489	63.0	5.72E+13	18770
106	8827420	102.17	2.36		1.17	2.51	0.385	12787	63.8	5.90E+13	18738
107	9124005	105.60	2.36		1.19	2.50	0.380	13080	64.5	6.09E+13	18707
108	9420590	109.03	2.36		1.21	2.50	0.376	13371	65.2	6.28E+13	18677
109	9717175	112.47	2.35		1.23	2.49	0.372	13657	65.9	6.46E+13	18649
110	10013760	115.90	2.35		1.25	2.49	0.368	13940	66.6	6.65E+13	18621
111	10310345	119.33	2.34		1.27	2.49	0.364	14219	67.3	6.83E+13	18595
112	10606930	122.77	2.34		1.29	2.48	0.361	14496	67.9	7.02E+13	18569
113	10903515	126.20	2.34		1.30	2.48	0.357	14769	68.6	7.20E+13	18544
114	11200100	129.63	2.34		1.32	2.47	0.353	15039	69.2	7.39E+13	18520
115	11496685	133.06	2.33		1.34	2.47	0.350	15306	69.8	7.57E+13	18497
116	11793270	136.50	2.33		1.36	2.47	0.347	15570	70.4	7.76E+13	18474
117	12089855	139.93	2.33		1.37	2.46	0.344	15832	71.0	7.94E+13	18453
118	12386440	143.36	2.32		1.39	2.46	0.341	16090	71.6	8.12E+13	18431
119	12683025	146.79	2.32		1.41	2.46	0.338	16347	72.1	8.31E+13	18411
120	12979610	150.23	2.32		1.42	2.45	0.335	16600	72.7	8.49E+13	18391
121	13276195	153.66	2.32		1.44	2.45	0.332	16851	73.2	8.67E+13	18371
122	13572780	157.09	2.31		1.45	2.45	0.329	17100	73.8	8.86E+13	18352
123	13869365	160.53	2.31		1.47	2.44	0.327	17347	74.3	9.04E+13	18334
124	14165950	163.96	2.31		1.49	2.44	0.324	17591	74.8	9.22E+13	18316
125	14462535	167.39	2.31		1.50	2.44	0.321	17833	75.3	9.41E+13	18298
126	14759120	170.82	2.31		1.52	2.44	0.319	18073	75.8	9.59E+13	18281
127	15055705	174.26	2.30		1.53	2.43	0.316	18311	76.3	9.77E+13	18264
128	15352290	177.69	2.30		1.55	2.43	0.314	18547	76.8	9.95E+13	18248
129	15648875	181.12	2.30		1.56	2.43	0.312	18781	77.3	1.01E+14	18232
130	15945460	184.55	2.30		1.58	2.43	0.310	19013	77.8	1.03E+14	18217
131	16242045	187.99	2.30		1.59	2.42	0.307	19243	78.2	1.05E+14	18201
132	16538630	191.42	2.29		1.61	2.42	0.305	19471	78.7	1.07E+14	18187
133	16835215	194.85	2.29		1.62	2.42	0.303	19697	79.2	1.09E+14	18172
134	17131800	198.28	2.29		1.63	2.42	0.301	19922	79.6	1.10E+14	18158
135	17428385	201.72	2.29		1.65	2.41	0.299	20145	80.1	1.12E+14	18144
136	17724970	205.15	2.29		1.66	2.41	0.297	20366	80.5	1.14E+14	18130
137	18021555	208.58	2.28		1.68	2.41	0.295	20586	80.9	1.16E+14	18117
138	18318140	212.02	2.28		1.69	2.41	0.293	20804	81.4	1.18E+14	18103
139	18614725	215.45	2.28		1.70	2.41	0.291	21021	81.8	1.19E+14	18090
140	18911310	218.88	2.28		1.72	2.40	0.289	21236	82.2	1.21E+14	18078
141	19207895	222.31	2.28		1.73	2.40	0.288	21449	82.6	1.23E+14	18065
142	19504480	225.75	2.28		1.74	2.40	0.286	21661	83.0	1.25E+14	18053
143	19801065	229.18	2.28		1.76	2.40	0.284	21872	83.4	1.27E+14	18041
144	20097650	232.61	2.27		1.77	2.40	0.282	22081	83.8	1.28E+14	18029
145	20394235	236.04	2.27		1.78	2.40	0.281	22288	84.2	1.30E+14	18018
146	20690820	239.48	2.27		1.80	2.39	0.279	22495	84.6	1.32E+14	18006
147	20987405	242.91	2.27		1.81	2.39	0.277	22700	85.0	1.34E+14	17995
148	21283990	246.34	2.27		1.82	2.39	0.276	22904	85.4	1.36E+14	17984
149	21580575	249.78	2.27		1.83	2.39	0.274	23106	85.7	1.37E+14	17973
150	21877160	253.21	2.27		1.85	2.39	0.273	23307	86.1	1.39E+14	17963
151	22173745	256.64	2.26		1.86	2.39	0.271	23507	86.5	1.41E+14	17952
152	22470330	260.07	2.26		1.87	2.39	0.270	23706	86.9	1.43E+14	17942
153	22766915	263.51	2.26		1.88	2.39	0.268	23904	87.2	1.45E+14	17932
154	23063500	266.94	2.26		1.90	2.38	0.267	24100	87.6	1.46E+14	17922
155	23360085	270.37	2.26		1.91	2.38	0.266	24295	87.9	1.48E+14	17912
156	23656670	273.80	2.26		1.92	2.38	0.264	24489	88.3	1.50E+14	17902
157	23953255	277.24	2.26		1.93	2.38	0.263	24682	88.6	1.52E+14	17893
158	24249840	280.67	2.26		1.94	2.37	0.262	24874	89.0	1.53E+14	17883
159	24546425	284.10	2.25		1.95	2.37	0.260	25065	89.3	1.55E+14	17874
160	24843010	287.53	2.25		1.97	2.37	0.259	25255	89.6	1.57E+14	17865
161	25139595	290.97	2.25		1.98	2.37	0.258	25443	90.0	1.59E+14	17856
162	25436180	294.40	2.25		1.99	2.37	0.256	25631	90.3	1.61E+14	17847
163	25732765	297.83	2.25		2.00	2.37	0.255	25818	90.6	1.62E+14	17838
164	26029350	301.27	2.25		2.01	2.37	0.254	26003	91.0	1.64E+14	17830
165	26325935	304.70	2.25		2.03	2.36	0.253	26188	91.3	1.66E+14	17821
166	26622520	308.13	2.25		2.04	2.36	0.252	26372	91.6	1.68E+14	17813
167	26919105	311.56	2.25		2.05	2.36	0.250	26554	91.9	1.69E+14	17805
168	27215690	315.00	2.24		2.06	2.36	0.249	26736	92.2	1.71E+14	17796
169	27512275	318.43	2.24		2.07	2.36	0.248	26917	92.5	1.73E+14	17788
170	27808860	321.86	2.24		2.08	2.36	0.247	27097	92.9	1.75E+14	17780
171	28105445	325.29	2.24		2.09	2.36	0.246	27276	93.2	1.77E+14	17772
172	28402030	328.73	2.24		2.10	2.35	0.245	27455	93.5	1.78E+14	17765
173	28698615	332.16	2.24		2.11	2.35	0.244	27632	93.8	1.80E+14	17757
174	28995200	335.59	2.24		2.13	2.35	0.243	27808	94.1	1.82E+14	17749
175	29291785	339.03	2.24		2.14	2.35	0.242	27984	94.4	1.84E+14	17742
176	29588370	342.46	2.24		2.15	2.35	0.241	28159	94.7	1.85E+14	17734
177	29884955	345.89	2.24		2.16	2.35	0.240	28333	94.9	1.87E+14	17727
178	30181540	349.32	2.23		2.17	2.35	0.239	28506	95.2	1.89E+14	17720
179	30478125	352.76	2.23		2.18	2.35	0.238	28678	95.5	1.91E+14	17713
180	30774710	356.19	2.23		2.19	2.35	0.237	28850	95.8	1.93E+14	17706
181	31071295	359.62	2.23		2.20	2.35	0.236	29021	96.1	1.94E+14	17699
182	31367880	363.05	2.23		2.21	2.34	0.235	29191	96.4	1.96E+14	17692
183	31664465	366.48	2.23		2.22	2.34	0.234	29360	96.7	1.98E+14	17685

Table B-16
Estimation of Steam Injection Rate and Steam Zone Growth

E-zone, 48 darcy, 928 kPa

Parameter	Symbol	Unit	Value
Thickness of steamed layer	h	m	4.5
Particle density of soil	d_s	kg/m^3	2650
Porosity of steamed layer	p		0.35
Absolute permeability of soil	k_s	m^2	4.8E-11
Heat capacity of soil	cp_r	J/(kg K)	1152
Initial water saturation	S_w		1
Ambient pressure in aquifer	P_{amb}	Pa	812120
Density of water	d_w	kg/m^3	1000
Ambient water temperature	T_{amb}	K	295
Heat capacity of water	cp_w	J/(kg K)	4187
Overall heat capacity	cp_{rw}	J/(kg K)	2200
Overburden thermal conductivity	k	J/(s m K)	1.3
Overburden thermal diffusivity	a	m^2/s	0.0000001
Radius of injection well	r_w	m	0.0505
Maximum steam injection pressure	P_w	Pa	928239
Relative permeability of steam	k_{rs}		1
Steam viscosity	u_s	kg/(m s)	1.31E-05
Temperature of steam	T_s	K	448
Delta T	$T_s - T_{amb}$	K	153
Heat of condensation	´h	J/kg	2666000
Time since start of injection	t	s	
Steam mass flow rate	´m	kg/s	
Volume of steam zone	V	m^3	
Gas constant	R	J/(mole K)	8.314
Initial radius of steam zone	r_{si}	m	0.053025
Mole mass of water	M_w	kg/mole	0.018
Density of steam	d_{steam}	kg/m^3	4.6
Depth to top of injection screen	$D_{inject.}$	m.b.g	73.2
Length of injection screen	$L_{inj.screen}$	m	4.5
Aquifer hydraulic head	D_{gwt}	m.b.g	3



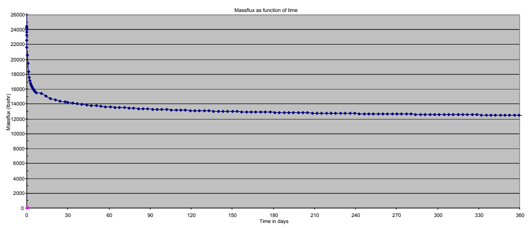


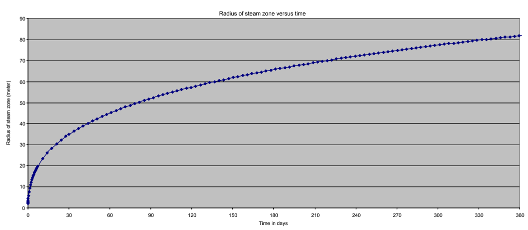
	t (s)	t (days)	´m	cp,sw	y	´mave	erf(y)*ey2	A(t)	r(t)	Energy Injected	´m (lb/h)
1	60	0.00	1035.91	3449770	0.00	1035.91	0.997	65	4.5	1.66E+11	8214281
2	120	0.00	11.24		0.00	523.58	0.995	67	4.6	1.68E+11	89105
3	240	0.00	11.20		0.01	267.39	0.993	69	4.7	1.71E+11	88790
4	480	0.01	11.15		0.01	139.27	0.990	73	4.8	1.78E+11	88446
5	960	0.01	11.09		0.01	75.18	0.986	79	5.0	1.92E+11	87963
6	1920	0.02	10.99		0.02	43.09	0.981	90	5.4	2.21E+11	87184
7	3840	0.04	10.83		0.02	26.96	0.973	113	6.0	2.76E+11	85895
8	7680	0.09	10.58		0.03	18.77	0.962	157	7.1	3.84E+11	83893
9	15360	0.18	10.23		0.05	14.50	0.947	240	8.7	5.94E+11	81124
10	30720	0.36	9.81		0.07	12.15	0.926	397	11.2	9.95E+11	77768
11	61440	0.71	9.35		0.10	10.75	0.899	689	14.8	1.76E+12	74148
12	104640	1.21	8.90		0.13	9.99	0.871	1067	18.4	2.79E+12	70552
13	147840	1.71	8.57		0.15	9.57	0.849	1421	21.3	3.77E+12	67933
14	191040	2.21	8.36		0.17	9.30	0.832	1759	23.7	4.74E+12	66321
15	234240	2.71	8.22		0.19	9.10	0.816	2085	25.8	5.68E+12	65171
16	277440	3.21	8.11		0.21	8.94	0.803	2400	27.6	6.62E+12	64284
17	320640	3.71	8.02		0.22	8.82	0.790	2707	29.3	7.54E+12	63566
18	363840	4.21	7.94		0.24	8.72	0.779	3007	30.9	8.45E+12	62965
19	407040	4.71	7.88		0.25	8.63	0.769	3299	32.4	9.36E+12	62450
74	450240	5.21	7.82		0.26	8.55	0.759	3586	33.8	1.03E+13	62001
75	493440	5.71	7.77		0.28	8.48	0.750	3868	35.1	1.12E+13	61604
76	536640	6.21	7.72		0.29	8.42	0.742	4145	36.3	1.20E+13	61248
77	579840	6.71	7.68		0.30	8.36	0.734	4417	37.5	1.29E+13	60927
78	623040	7.21	7.65		0.31	8.32	0.727	4685	38.6	1.38E+13	60633
79	919625	10.64	7.61		0.38	8.09	0.684	6452	45.3	1.98E+13	60364
80	1216210	14.08	7.43		0.44	7.93	0.650	8083	50.7	2.57E+13	58943
81	1512795	17.51	7.31		0.49	7.81	0.623	9614	55.3	3.15E+13	57983
82	1809380	20.94	7.22		0.53	7.71	0.600	11064	59.3	3.72E+13	57264
83	2105965	24.37	7.15		0.57	7.63	0.580	12449	62.9	4.29E+13	56695
84	2402550	27.81	7.09		0.61	7.57	0.563	13778	66.2	4.85E+13	56226
85	2599135	30.08	7.04		0.64	7.53	0.552	14631	68.2	5.22E+13	55829
86	2895720	33.52	7.01		0.67	7.47	0.537	15882	71.1	5.77E+13	55596
87	3192305	36.95	6.97		0.71	7.43	0.524	17094	73.8	6.32E+13	55282
88	3488890	40.38	6.94		0.74	7.39	0.512	18270	76.2	6.87E+13	55003
89	3785475	43.81	6.90		0.77	7.35	0.500	19414	78.6	7.42E+13	54753
90	4082060	47.25	6.88		0.80	7.31	0.490	20529	80.8	7.96E+13	54527
91	4378645	50.68	6.85		0.83	7.28	0.480	21616	82.9	8.50E+13	54320
92	4675230	54.11	6.83		0.85	7.25	0.471	22679	84.9	9.04E+13	54131
93	4971815	57.54	6.80		0.88	7.23	0.463	23718	86.9	9.58E+13	53956
94	5268400	60.98	6.78		0.91	7.20	0.455	24735	88.7	1.01E+14	53794
95	5564985	64.41	6.76		0.93	7.18	0.447	25733	90.5	1.06E+14	53643
96	5861570	67.84	6.75		0.96	7.16	0.440	26711	92.2	1.12E+14	53501
97	6158155	71.27	6.73		0.98	7.14	0.433	27671	93.8	1.17E+14	53368
98	6454740	74.71	6.71		1.00	7.12	0.427	28614	95.4	1.22E+14	53243
99	6751325	78.14	6.70		1.03	7.10	0.421	29542	97.0	1.28E+14	53125
100	7047910	81.57	6.69		1.05	7.08	0.415	30454	98.4	1.33E+14	53013
101	7344495	85.01	6.67		1.07	7.06	0.409	31351	99.9	1.38E+14	52906
102	7641080	88.44	6.66		1.09	7.05	0.404	32235	101.3	1.44E+14	52805
103	7937665	91.87	6.65		1.11	7.03	0.399	33106	102.6	1.49E+14	52709
104	8234250	95.30	6.64		1.13	7.02	0.394	33964	104.0	1.54E+14	52616
105	8530835	98.74	6.62		1.15	7.01	0.389	34811	105.2	1.59E+14	52528
106	8827420	102.17	6.61		1.17	6.99	0.385	35645	106.5	1.65E+14	52443
107	9124005	105.60	6.60		1.19	6.98	0.380	36469	107.7	1.70E+14	52362
108	9420590	109.03	6.59		1.21	6.97	0.376	37282	108.9	1.75E+14	52284
109	9717175	112.47	6.58		1.23	6.96	0.372	38086	110.1	1.80E+14	52209
110	10013760	115.90	6.58		1.25	6.94	0.368	38879	111.2	1.85E+14	52137
111	10310345	119.33	6.57		1.27	6.93	0.364	39663	112.3	1.91E+14	52067
112	10606930	122.77	6.56		1.29	6.92	0.361	40437	113.4	1.96E+14	51999
113	10903515	126.20	6.55		1.30	6.91	0.357	41203	114.5	2.01E+14	51934
114	11200100	129.63	6.54		1.32	6.90	0.353	41961	115.5	2.06E+14	51871
115	11496685	133.06	6.53		1.34	6.89	0.350	42710	116.6	2.11E+14	51810
116	11793270	136.50	6.53		1.36	6.88	0.347	43451	117.6	2.16E+14	51751
117	12089855	139.93	6.52		1.37	6.88	0.344	44185	118.6	2.22E+14	51694
118	12386440	143.36	6.51		1.39	6.87	0.341	44911	119.5	2.27E+14	51638
119	12683025	146.79	6.51		1.41	6.86	0.338	45630	120.5	2.32E+14	51584
120	12979610	150.23	6.50		1.42	6.85	0.335	46342	121.4	2.37E+14	51531
121	13276195	153.66	6.49		1.44	6.84	0.332	47047	122.4	2.42E+14	51480
122	13572780	157.09	6.49		1.45	6.83	0.329	47745	123.3	2.47E+14	51430
123	13869365	160.53	6.48		1.47	6.83	0.327	48437	124.1	2.52E+14	51381
124	14165950	163.96	6.47		1.49	6.82	0.324	49123	125.0	2.58E+14	51334
125	14462535	167.39	6.47		1.50	6.81	0.321	49803	125.9	2.63E+14	51288
126	14759120	170.82	6.46		1.52	6.81	0.319	50476	126.7	2.68E+14	51243
127	15055705	174.26	6.46		1.53	6.80	0.316	51144	127.6	2.73E+14	51199
128	15352290	177.69	6.45		1.55	6.79	0.314	51806	128.4	2.78E+14	51156
129	15648875	181.12	6.45		1.56	6.78	0.312	52463	129.2	2.83E+14	51114
130	15945460	184.55	6.44		1.58	6.78	0.310	53114	130.0	2.88E+14	51073
131	16242045	187.99	6.44		1.59	6.77	0.307	53761	130.8	2.93E+14	51033
132	16538630	191.42	6.43		1.61	6.77	0.305	54402	131.6	2.98E+14	50993
133	16835215	194.85	6.43		1.62	6.76	0.303	55038	132.3	3.03E+14	50955
134	17131800	198.28	6.42		1.63	6.75	0.301	55669	133.1	3.08E+14	50917
135	17428385	201.72	6.42		1.65	6.75	0.299	56295	133.8	3.13E+14	50881
136	17724970	205.15	6.41		1.66	6.74	0.297	56917	134.6	3.18E+14	50844
137	18021555	208.58	6.41		1.68	6.74	0.295	57534	135.3	3.24E+14	50809
138	18318140	212.02	6.40		1.69	6.73	0.293	58146	136.0	3.29E+14	50774
139	18614725	215.45	6.40		1.70	6.73	0.291	58755	136.7	3.34E+14	50740
140	18911310	218.88	6.39		1.72	6.72	0.289	59359	137.4	3.39E+14	50707
141	19207895	222.31	6.39		1.73	6.72	0.288	59958	138.1	3.44E+14	50674
142	19504480	225.75	6.39		1.74	6.71	0.286	60554	138.8	3.49E+14	50642
143	19801065	229.18	6.38		1.76	6.71	0.284	61146	139.5	3.54E+14	50610
144	20097650	232.61	6.38		1.77	6.70	0.282	61733	140.2	3.59E+14	50579
145	20394235	236.04	6.37		1.78	6.70	0.281	62317	140.8	3.64E+14	50549
146	20690820	239.48	6.37		1.80	6.69	0.279	62897	141.5	3.69E+14	50519
147	20987405	242.91	6.37		1.81	6.69	0.277	63473	142.1	3.74E+14	50489
148	21283990	246.34	6.36		1.82	6.68	0.276	64046	142.8	3.79E+14	50460
149	21580575	249.78	6.36		1.83	6.68	0.274	64615	143.4	3.84E+14	50432
150	21877160	253.21	6.36		1.85	6.67	0.273	65180	144.0	3.89E+14	50404
151	22173745	256.64	6.35		1.86	6.67	0.271	65743	144.6	3.94E+14	50376
152	22470330	260.07	6.35		1.87	6.67	0.270	66301	145.2	3.99E+14	50349
153	22766915	263.51	6.35		1.88	6.66	0.268	66856	145.9	4.04E+14	50322
154	23063500	266.94	6.34		1.90	6.66	0.267	67409	146.5	4.09E+14	50296
155	23360085	270.37	6.34		1.91	6.65	0.266	67957	147.0	4.14E+14	50270
156	23656670	273.80	6.34		1.92	6.65	0.264	68503	147.6	4.19E+14	50244
157	23953255	277.24	6.33		1.93	6.65	0.263	69045	148.2	4.24E+14	50219
158	24249840	280.67	6.33		1.94	6.64	0.262	69585	148.8	4.29E+14	50194
159	24546425	284.10	6.33		1.96	6.64	0.260	70121	149.4	4.34E+14	50170
160	24843010	287.53	6.32		1.97	6.63	0.259	70655	149.9	4.39E+14	50146
161	25139595	290.97	6.32		1.98	6.63	0.258	71185	150.5	4.44E+14	50122
162	25436180	294.40	6.32		1.99	6.63	0.256	71713	151.1	4.49E+14	50099
163	25732765	297.83	6.32		2.00	6.62	0.255	72238	151.6	4.54E+14	50075
164	26029350	301.27	6.31		2.01	6.62	0.254	72760	152.2	4.59E+14	50053
165	26325935	304.70	6.31		2.03	6.62	0.253	73279	152.7	4.64E+14	50030
166	26622520	308.13	6.31		2.04	6.61	0.252	73796	153.2	4.69E+14	50008
167	26919105	311.56	6.30		2.05	6.61	0.250	74310	153.8	4.74E+14	49986
168	27215690	315.00	6.30		2.06	6.61	0.249	74821	154.3	4.79E+14	49964
169	27512275	318.43	6.30		2.07	6.60	0.248	75330	154.8	4.84E+14	49943
170	27808860	321.86	6.30		2.08	6.60	0.247	75837	155.3	4.89E+14	49922
171	28105445	325.29	6.29		2.09	6.60	0.246	76340	155.9	4.94E+14	49901
172	28402030	328.73	6.29		2.10	6.59	0.245	76842	156.4	4.99E+14	49881
173	28698615	332.16	6.29		2.11	6.59	0.244	77340	156.9	5.04E+14	49860
174	28995200	335.59	6.29		2.13	6.59	0.243	77837	157.4	5.09E+14	49840
175	29291785	339.03	6.28		2.14	6.58	0.242	78331	157.9	5.14E+14	49820
176	29588370	342.46	6.28		2.15	6.58	0.241	78823	158.4	5.19E+14	49801
177	29884955	345.89	6.28		2.16	6.58	0.240	79312	158.9	5.24E+14	49782
178	30181540	349.32	6.28		2.17	6.57	0.238	79799	159.3	5.29E+14	49762
179	30478125	352.76	6.27		2.18	6.57	0.238	80284	159.8	5.34E+14	49743
180	30774710	356.19	6.27		2.19	6.57	0.237	80767	160.3	5.39E+14	49725
181	31071295	359.62	6.27		2.20	6.57	0.236	81248	160.8	5.44E+14	49706
182	31367880	363.05	6.27		2.21	6.56	0.235	81726	161.3	5.49E+14	49688
183	31664465	366.49	6.26		2.22	6.56	0.234	82202	161.7	5.54E+14	49670

Table B-17
Estimation of Steam Injection Rate and Steam Zone Growth

E-zone, 48 darcy, 840 kPa

Parameter	Symbol	Unit	Value
Thickness of steamed layer	h	m	4.5
Particle density of soil	d_s	kg/m³	2650
Porosity of steamed layer	p		0.35
Absolute permeability of soil	k_s	m²	4.8E-11
Heat capacity of soil	cp_r	J/(kg K)	1152
Initial water saturation	S_w		1
Ambient pressure in aquifer	P_{amb}	Pa	812120
Density of water	d_w	kg/m³	1000
Ambient water temperature	T_{amb}	K	295
Heat capacity of water	cp_w	J/(kg K)	4187
Overall heat capacity	cp_{rw}	J/(kg K)	2200
Overburden thermal conductivity	k	J/(s m K)	1.3
Overburden thermal diffusivity	a	m²/s	0.0000001
Radius of injection well	r_w	m	0.0505
Maximum steam injection pressure	P_w	Pa	840000
Relative permeability of steam	k_{rs}		1
Steam viscosity	u_s	kg/(m s)	1.31E-05
Temperature of steam	T_s	K	444
Delta T	$T_s - T_{amb}$	K	149
Heat of condensation	´h	J/kg	2666000
Time since start of injection	t	s	
Steam mass flow rate	´m	kg/s	
Volume of steam zone	V	m³	
Gas constant	R	J/(mole K)	8.314
Initial radius of steam zone	r_{si}	m	0.053025
Mole mass of water	M_w	kg/mole	0.018
Density of steam	d_{steam}	kg/m³	4.2
Depth to top of injection screen	$D_{injscr.}$	m.b.g	73.2
Length of injection screen	$L_{inj.screen}$	m	4.5
Aquifer hydraulic head	D_{gwt}	m.b.g	3



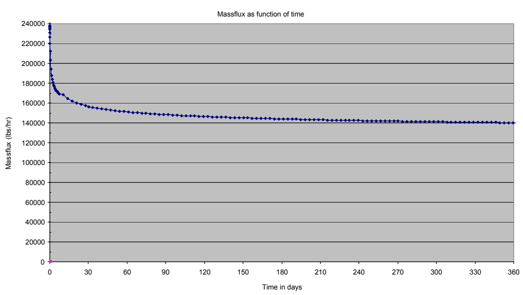


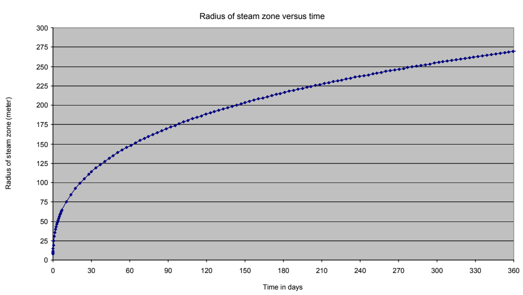
	t (s)	t (days)	´m	cp,sw	y	´mave	erf(y)*ey2	A(t)	r(t)	Energy Injected	´m (lb/h)
1	60	0.00	238.30	3449770	0.00	238.30	0.997	15	2.2	3.81E+10	1889572
2	120	0.00	3.08		0.00	120.69	0.995	16	2.2	3.86E+10	24413
3	240	0.00	3.07		0.01	61.88	0.993	16	2.3	3.96E+10	24304
4	480	0.01	3.05		0.01	32.46	0.990	17	2.4	4.15E+10	24179
5	960	0.01	3.03		0.01	17.74	0.986	19	2.5	4.54E+10	24000
6	1920	0.02	2.99		0.02	10.37	0.981	22	2.7	5.31E+10	23710
7	3840	0.04	2.93		0.02	6.65	0.973	29	3.0	6.81E+10	23240
8	7680	0.09	2.84		0.03	4.75	0.962	41	3.6	9.72E+10	22538
9	15360	0.18	2.73		0.05	3.74	0.947	63	4.5	1.53E+11	21611
10	30720	0.36	2.59		0.07	3.16	0.926	106	5.8	2.59E+11	20539
11	61440	0.71	2.45		0.10	2.81	0.899	185	7.7	4.60E+11	19428
12	104640	1.21	2.31		0.13	2.60	0.871	286	9.5	7.26E+11	18357
13	147840	1.71	2.22		0.15	2.49	0.849	380	11.0	9.82E+11	17592
14	191040	2.21	2.16		0.17	2.42	0.832	469	12.2	1.23E+12	17126
15	234240	2.71	2.12		0.19	2.36	0.816	556	13.3	1.47E+12	16796
16	277440	3.21	2.09		0.21	2.32	0.803	639	14.3	1.71E+12	16542
17	320640	3.71	2.06		0.22	2.28	0.790	720	15.1	1.95E+12	16337
18	363840	4.21	2.04		0.24	2.25	0.779	799	15.9	2.19E+12	16166
19	407040	4.71	2.02		0.25	2.23	0.769	876	16.7	2.42E+12	16020
74	450240	5.21	2.00		0.26	2.21	0.759	951	17.4	2.65E+12	15893
75	493440	5.71	1.99		0.28	2.19	0.750	1025	18.1	2.88E+12	15781
76	536640	6.21	1.98		0.29	2.17	0.742	1098	18.7	3.11E+12	15680
77	579840	6.71	1.97		0.30	2.16	0.734	1169	19.3	3.33E+12	15589
78	623040	7.21	1.96		0.31	2.14	0.727	1240	19.9	3.56E+12	15507
79	919625	10.64	1.95		0.38	2.08	0.684	1703	23.3	5.10E+12	15431
80	1216210	14.08	1.90		0.44	2.03	0.650	2130	26.0	6.60E+12	15031
81	1512795	17.51	1.86		0.49	2.00	0.623	2530	28.4	8.07E+12	14762
82	1809380	20.94	1.84		0.53	1.97	0.600	2908	30.4	9.52E+12	14562
83	2105965	24.37	1.82		0.57	1.95	0.580	3269	32.3	1.10E+13	14403
84	2402550	27.81	1.80		0.61	1.93	0.563	3615	33.9	1.24E+13	14273
85	2599135	30.08	1.79		0.64	1.92	0.552	3837	34.9	1.33E+13	14163
86	2895720	33.52	1.78		0.67	1.91	0.537	4162	36.4	1.47E+13	14098
87	3192305	36.95	1.77		0.71	1.89	0.524	4477	37.7	1.61E+13	14011
88	3488890	40.38	1.76		0.74	1.88	0.512	4782	39.0	1.75E+13	13934
89	3785475	43.81	1.75		0.77	1.87	0.500	5079	40.2	1.89E+13	13864
90	4082060	47.25	1.74		0.80	1.86	0.490	5369	41.3	2.03E+13	13802
91	4378645	50.68	1.73		0.83	1.85	0.480	5651	42.4	2.16E+13	13745
92	4675230	54.11	1.73		0.85	1.85	0.471	5926	43.4	2.30E+13	13693
93	4971815	57.54	1.72		0.88	1.84	0.463	6196	44.4	2.44E+13	13644
94	5268400	60.98	1.72		0.91	1.83	0.455	6459	45.3	2.57E+13	13600
95	5564985	64.41	1.71		0.93	1.82	0.447	6718	46.2	2.71E+13	13558
96	5861570	67.84	1.70		0.96	1.82	0.440	6971	47.1	2.84E+13	13519
97	6158155	71.27	1.70		0.98	1.81	0.433	7220	47.9	2.98E+13	13482
98	6454740	74.71	1.70		1.00	1.81	0.427	7464	48.7	3.11E+13	13448
99	6751325	78.14	1.69		1.03	1.80	0.421	7704	49.5	3.24E+13	13415
100	7047910	81.57	1.69		1.05	1.80	0.415	7940	50.3	3.38E+13	13385
101	7344495	85.01	1.68		1.07	1.79	0.409	8172	51.0	3.51E+13	13355
102	7641080	88.44	1.68		1.09	1.79	0.404	8401	51.7	3.64E+13	13327
103	7937665	91.87	1.68		1.11	1.78	0.399	8626	52.4	3.78E+13	13301
104	8234250	95.30	1.67		1.13	1.78	0.394	8848	53.1	3.91E+13	13276
105	8530835	98.74	1.67		1.15	1.78	0.389	9067	53.7	4.04E+13	13251
106	8827420	102.17	1.67		1.17	1.77	0.385	9283	54.3	4.17E+13	13228
107	9124005	105.60	1.67		1.19	1.77	0.380	9496	55.0	4.30E+13	13206
108	9420590	109.03	1.66		1.21	1.77	0.376	9706	55.6	4.44E+13	13184
109	9717175	112.47	1.66		1.23	1.76	0.372	9913	56.2	4.57E+13	13164
110	10013760	115.90	1.66		1.25	1.76	0.368	10118	56.7	4.70E+13	13144
111	10310345	119.33	1.66		1.27	1.76	0.364	10321	57.3	4.83E+13	13125
112	10606930	122.77	1.65		1.29	1.75	0.361	10521	57.9	4.96E+13	13106
113	10903515	126.20	1.65		1.30	1.75	0.357	10719	58.4	5.09E+13	13088
114	11200100	129.63	1.65		1.32	1.75	0.353	10915	58.9	5.22E+13	13071
115	11496685	133.06	1.65		1.34	1.75	0.350	11108	59.5	5.35E+13	13054
116	11793270	136.50	1.64		1.36	1.74	0.347	11299	60.0	5.48E+13	13038
117	12089855	139.93	1.64		1.37	1.74	0.344	11489	60.5	5.61E+13	13023
118	12386440	143.36	1.64		1.39	1.74	0.341	11676	61.0	5.74E+13	13007
119	12683025	146.79	1.64		1.41	1.74	0.338	11862	61.4	5.87E+13	12992
120	12979610	150.23	1.64		1.42	1.73	0.335	12046	61.9	6.00E+13	12978
121	13276195	153.66	1.63		1.44	1.73	0.332	12227	62.4	6.13E+13	12964
122	13572780	157.09	1.63		1.45	1.73	0.329	12408	62.8	6.26E+13	12950
123	13869365	160.53	1.63		1.47	1.73	0.327	12586	63.3	6.39E+13	12937
124	14165950	163.96	1.63		1.49	1.73	0.324	12763	63.7	6.52E+13	12924
125	14462535	167.39	1.63		1.50	1.72	0.321	12938	64.2	6.64E+13	12911
126	14759120	170.82	1.63		1.52	1.72	0.319	13112	64.6	6.77E+13	12899
127	15055705	174.26	1.63		1.53	1.72	0.316	13285	65.0	6.90E+13	12887
128	15352290	177.69	1.62		1.55	1.72	0.314	13455	65.4	7.03E+13	12875
129	15648875	181.12	1.62		1.56	1.72	0.312	13625	65.8	7.16E+13	12864
130	15945460	184.55	1.62		1.58	1.71	0.310	13793	66.2	7.29E+13	12853
131	16242045	187.99	1.62		1.59	1.71	0.307	13959	66.6	7.41E+13	12842
132	16538630	191.42	1.62		1.61	1.71	0.305	14125	67.0	7.54E+13	12831
133	16835215	194.85	1.62		1.62	1.71	0.303	14289	67.4	7.67E+13	12820
134	17131800	198.28	1.62		1.63	1.71	0.301	14451	67.8	7.80E+13	12810
135	17428385	201.72	1.61		1.65	1.71	0.299	14613	68.2	7.93E+13	12800
136	17724970	205.15	1.61		1.66	1.70	0.297	14773	68.6	8.05E+13	12790
137	18021555	208.58	1.61		1.68	1.70	0.295	14932	68.9	8.18E+13	12781
138	18318140	212.02	1.61		1.69	1.70	0.293	15090	69.3	8.31E+13	12771
139	18614725	215.45	1.61		1.70	1.70	0.291	15247	69.7	8.44E+13	12762
140	18911310	218.88	1.61		1.72	1.70	0.289	15402	70.0	8.56E+13	12753
141	19207895	222.31	1.61		1.73	1.70	0.288	15557	70.4	8.69E+13	12744
142	19504480	225.75	1.61		1.74	1.70	0.286	15710	70.7	8.82E+13	12735
143	19801065	229.18	1.60		1.76	1.69	0.284	15863	71.0	8.94E+13	12726
144	20097650	232.61	1.60		1.77	1.69	0.282	16014	71.4	9.07E+13	12718
145	20394235	236.04	1.60		1.78	1.69	0.281	16165	71.7	9.20E+13	12709
146	20690820	239.48	1.60		1.80	1.69	0.279	16314	72.0	9.32E+13	12701
147	20987405	242.91	1.60		1.81	1.69	0.277	16462	72.4	9.45E+13	12693
148	21283990	246.34	1.60		1.82	1.69	0.276	16610	72.7	9.58E+13	12685
149	21580575	249.78	1.60		1.83	1.69	0.274	16757	73.0	9.70E+13	12678
150	21877160	253.21	1.60		1.85	1.69	0.273	16902	73.3	9.83E+13	12670
151	22173745	256.64	1.60		1.86	1.68	0.271	17047	73.6	9.96E+13	12662
152	22470330	260.07	1.60		1.87	1.68	0.270	17191	74.0	1.01E+14	12655
153	22766915	263.51	1.60		1.88	1.68	0.268	17334	74.3	1.02E+14	12648
154	23063500	266.94	1.59		1.90	1.68	0.267	17476	74.6	1.03E+14	12640
155	23360085	270.37	1.59		1.91	1.68	0.266	17617	74.9	1.05E+14	12633
156	23656670	273.80	1.59		1.92	1.68	0.264	17758	75.2	1.06E+14	12626
157	23953255	277.24	1.59		1.93	1.68	0.263	17898	75.5	1.07E+14	12620
158	24249840	280.67	1.59		1.94	1.68	0.262	18036	75.8	1.08E+14	12613
159	24546425	284.10	1.59		1.96	1.68	0.260	18175	76.0	1.10E+14	12606
160	24843010	287.53	1.59		1.97	1.67	0.259	18312	76.3	1.11E+14	12600
161	25139595	290.97	1.59		1.98	1.67	0.258	18448	76.6	1.12E+14	12593
162	25436180	294.40	1.59		1.99	1.67	0.256	18584	76.9	1.13E+14	12587
163	25732765	297.83	1.59		2.00	1.67	0.255	18719	77.2	1.15E+14	12580
164	26029350	301.27	1.59		2.01	1.67	0.254	18854	77.5	1.16E+14	12574
165	26325935	304.70	1.58		2.03	1.67	0.253	18987	77.7	1.17E+14	12568
166	26622520	308.13	1.58		2.04	1.67	0.252	19120	78.0	1.18E+14	12562
167	26919105	311.56	1.58		2.05	1.67	0.250	19253	78.3	1.20E+14	12556
168	27215690	315.00	1.58		2.06	1.67	0.249	19384	78.5	1.21E+14	12550
169	27512275	318.43	1.58		2.07	1.67	0.248	19515	78.8	1.22E+14	12544
170	27808860	321.86	1.58		2.08	1.66	0.247	19646	79.1	1.23E+14	12539
171	28105445	325.29	1.58		2.09	1.66	0.246	19775	79.3	1.25E+14	12533
172	28402030	328.73	1.58		2.10	1.66	0.245	19904	79.6	1.26E+14	12527
173	28698615	332.16	1.58		2.11	1.66	0.244	20033	79.8	1.27E+14	12522
174	28995200	335.59	1.58		2.13	1.66	0.243	20160	80.1	1.28E+14	12516
175	29291785	339.03	1.58		2.14	1.66	0.242	20287	80.3	1.30E+14	12511
176	29588370	342.46	1.58		2.15	1.66	0.241	20414	80.6	1.31E+14	12506
177	29884955	345.89	1.58		2.16	1.66	0.240	20540	80.8	1.32E+14	12500
178	30181540	349.32	1.58		2.17	1.66	0.238	20665	81.1	1.33E+14	12495
179	30478125	352.76	1.58		2.18	1.66	0.238	20790	81.3	1.35E+14	12490
180	30774710	356.19	1.57		2.19	1.66	0.237	20914	81.6	1.36E+14	12485
181	31071295	359.62	1.57		2.20	1.66	0.236	21038	81.8	1.37E+14	12480
182	31367880	363.05	1.57		2.21	1.65	0.235	21161	82.1	1.38E+14	12475
183	31664465	366.49	1.57		2.22	1.65	0.234	21283	82.3	1.40E+14	12470

Table B-18
Estimation of Steam Injection Rate and Steam Zone Growth

E-zone, 144 darcy

Parameter	Symbol	Unit	Value
Thickness of steamed layer	h	m	4.5
Particle density of soil	d_s	kg/m^3	2650
Porosity of steamed layer	p		0.35
Absolute permeability of soil	k_s	m^2	1.44E-10
Heat capacity of soil	cp_r	J/(kg K)	1152
Initial water saturation	S_w		1
Ambient pressure in aquifer	P_{amb}	Pa	812126
Density of water	d_w	kg/m^3	1000
Ambient water temperature	T_{amb}	K	295
Heat capacity of water	cp_w	J/(kg K)	4187
Overall heat capacity	cp_{sw}	J/(kg K)	2200
Overburden thermal conductivit	k	J/(s m K)	1.3
Overburden thermal diffusivity	a	m^2/s	0.00000018
Radius of injection well	r_w	m	0.0505
Maximum steam injection press	P_w	Pa	928239
Relative permeability of steam	k_{rs}		1
Steam viscosity	u_s	kg/(m s)	1.31E-05
Temperature of steam	T_s	K	448
Delta T	$T_s - T_{amb}$	K	153
Heat of condensation	´h	J/kg	2666000
Time since start of injection	t	s	
Steam mass flow rate	´m	kg/s	
Volume of steam zone	V	m^3	
Gas constant	R	J/(mole K)	8.314
Initial radius of steam zone	r_{si}	m	0.053025
Mole mass of water	M_w	kg/mole	0.018
Density of steam	d_{steam}	kg/m^3	4.6
Depth to top of injection screen	$D_{injscr.}$	m.b.g	73.2
Length of injection screen	$L_{inj,screen}$	m	4.5
Aquifer hydraulic head	D_{gwt}	m.b.g	3





	t (s)	t (days)	´m	cp,sw	y	´mave	erf(y)*ey2	A(t)	r(t)	Energy Injected	´m (lb/h)
1	60	0.00	3107.74	3449770	0.00	3107.74	0.997	194	7.9	4.97E+11	24642843
2	120	0.00	30.04		0.00	1568.89	0.995	200	8.0	5.02E+11	238222
3	240	0.00	29.95		0.01	799.42	0.993	207	8.1	5.12E+11	237498
4	480	0.01	29.85		0.01	414.64	0.990	216	8.3	5.31E+11	236729
5	960	0.01	29.72		0.01	222.18	0.986	233	8.6	5.69E+11	235674
6	1920	0.02	29.51		0.02	125.84	0.981	264	9.2	6.44E+11	233976
7	3840	0.04	29.15		0.02	77.50	0.973	325	10.2	7.93E+11	231138
8	7680	0.09	28.58		0.03	53.04	0.962	443	11.9	1.09E+12	226634
9	15360	0.18	27.77		0.05	40.41	0.947	669	14.6	1.65E+12	220220
10	30720	0.36	26.76		0.07	33.58	0.926	1097	18.7	2.75E+12	212205
11	61440	0.71	25.64		0.10	29.61	0.899	1897	24.6	4.85E+12	203327
12	104640	1.21	24.51		0.13	27.50	0.871	2939	30.6	7.67E+12	194328
13	147840	1.71	23.67		0.15	26.38	0.849	3918	35.3	1.04E+13	187683
14	191040	2.21	23.15		0.17	25.65	0.832	4854	39.3	1.31E+13	183564
15	234240	2.71	22.78		0.19	25.12	0.816	5756	42.8	1.57E+13	180611
16	277440	3.21	22.49		0.21	24.71	0.803	6631	45.9	1.83E+13	178328
17	320640	3.71	22.26		0.22	24.38	0.790	7484	48.8	2.08E+13	176475
18	363840	4.21	22.06		0.24	24.11	0.779	8316	51.4	2.34E+13	174923
19	407040	4.71	21.89		0.25	23.87	0.769	9130	53.9	2.59E+13	173592
74	450240	5.21	21.75		0.26	23.67	0.759	9929	56.2	2.84E+13	172429
75	493440	5.71	21.62		0.28	23.49	0.750	10712	58.4	3.09E+13	171399
76	536640	6.21	21.50		0.29	23.33	0.742	11483	60.4	3.34E+13	170475
77	579840	6.71	21.39		0.30	23.18	0.734	12241	62.4	3.58E+13	169640
78	623040	7.21	21.30		0.31	23.05	0.727	12988	64.3	3.83E+13	168878
79	919625	10.64	21.21		0.38	22.46	0.684	17915	75.5	5.51E+13	168178
80	1216210	14.08	20.74		0.44	22.04	0.650	22469	84.6	7.15E+13	164479
81	1512795	17.51	20.43		0.49	21.72	0.623	26747	92.3	8.76E+13	161970
82	1809380	20.94	20.19		0.53	21.47	0.600	30806	99.0	1.04E+14	160090
83	2105965	24.37	20.00		0.57	21.26	0.580	34683	105.1	1.19E+14	158599
84	2402550	27.81	19.85		0.61	21.09	0.563	38406	110.5	1.35E+14	157368
85	2599135	30.08	19.71		0.64	20.99	0.552	40796	113.9	1.45E+14	156325
86	2895720	33.52	19.64		0.67	20.85	0.537	44305	118.7	1.61E+14	155714
87	3192305	36.95	19.53		0.71	20.73	0.524	47703	123.2	1.76E+14	154886
88	3488890	40.38	19.44		0.74	20.62	0.512	51004	127.4	1.92E+14	154152
89	3785475	43.81	19.36		0.77	20.52	0.500	54214	131.3	2.07E+14	153494
90	4082060	47.25	19.28		0.80	20.43	0.490	57343	135.1	2.22E+14	152898
91	4378645	50.68	19.21		0.83	20.35	0.480	60396	138.6	2.38E+14	152355
92	4675230	54.11	19.15		0.85	20.27	0.471	63380	142.0	2.53E+14	151856
93	4971815	57.54	19.09		0.88	20.20	0.463	66299	145.2	2.68E+14	151395
94	5268400	60.98	19.04		0.91	20.13	0.455	69157	148.3	2.83E+14	150967
95	5564985	64.41	18.99		0.93	20.07	0.447	71960	151.3	2.98E+14	150568
96	5861570	67.84	18.94		0.96	20.02	0.440	74709	154.2	3.13E+14	150194
97	6158155	71.27	18.90		0.98	19.96	0.433	77408	156.9	3.28E+14	149843
98	6454740	74.71	18.86		1.00	19.91	0.427	80060	159.6	3.43E+14	149513
99	6751325	78.14	18.82		1.03	19.86	0.421	82667	162.2	3.58E+14	149200
100	7047910	81.57	18.78		1.05	19.82	0.415	85232	164.7	3.72E+14	148904
101	7344495	85.01	18.74		1.07	19.77	0.409	87757	167.1	3.87E+14	148623
102	7641080	88.44	18.71		1.09	19.73	0.404	90244	169.5	4.02E+14	148355
103	7937665	91.87	18.68		1.11	19.69	0.399	92694	171.7	4.17E+14	148100
104	8234250	95.30	18.65		1.13	19.66	0.394	95108	174.0	4.31E+14	147856
105	8530835	98.74	18.62		1.15	19.62	0.389	97490	176.1	4.46E+14	147623
106	8827420	102.17	18.59		1.17	19.58	0.385	99839	178.2	4.61E+14	147399
107	9124005	105.60	18.56		1.19	19.55	0.380	102158	180.3	4.76E+14	147184
108	9420590	109.03	18.54		1.21	19.52	0.376	104447	182.3	4.90E+14	146977
109	9717175	112.47	18.51		1.23	19.49	0.372	106708	184.3	5.05E+14	146779
110	10013760	115.90	18.49		1.25	19.46	0.368	108941	186.2	5.19E+14	146587
111	10310345	119.33	18.46		1.27	19.43	0.364	111148	188.1	5.34E+14	146402
112	10606930	122.77	18.44		1.29	19.40	0.361	113329	189.9	5.49E+14	146224
113	10903515	126.20	18.42		1.30	19.38	0.357	115486	191.7	5.63E+14	146051
114	11200100	129.63	18.40		1.32	19.35	0.353	117619	193.5	5.78E+14	145884
115	11496685	133.06	18.38		1.34	19.32	0.350	119730	195.2	5.92E+14	145722
116	11793270	136.50	18.36		1.36	19.30	0.347	121817	196.9	6.07E+14	145565
117	12089855	139.93	18.34		1.37	19.28	0.344	123884	198.5	6.21E+14	145413
118	12386440	143.36	18.32		1.39	19.25	0.341	125929	200.2	6.36E+14	145265
119	12683025	146.79	18.30		1.41	19.23	0.338	127955	201.8	6.50E+14	145122
120	12979610	150.23	18.28		1.42	19.21	0.335	129960	203.4	6.65E+14	144982
121	13276195	153.66	18.27		1.44	19.19	0.332	131947	204.9	6.79E+14	144846
122	13572780	157.09	18.25		1.45	19.17	0.329	133915	206.4	6.94E+14	144714
123	13869365	160.53	18.23		1.47	19.15	0.327	135864	207.9	7.08E+14	144585
124	14165950	163.96	18.22		1.49	19.13	0.324	137797	209.4	7.22E+14	144460
125	14462535	167.39	18.20		1.50	19.11	0.321	139712	210.8	7.37E+14	144337
126	14759120	170.82	18.19		1.52	19.09	0.319	141611	212.3	7.51E+14	144218
127	15055705	174.26	18.17		1.53	19.07	0.316	143493	213.7	7.66E+14	144101
128	15352290	177.69	18.16		1.55	19.06	0.314	145359	215.1	7.80E+14	143987
129	15648875	181.12	18.14		1.56	19.04	0.312	147211	216.4	7.94E+14	143876
130	15945460	184.55	18.13		1.58	19.02	0.310	149047	217.8	8.09E+14	143767
131	16242045	187.99	18.12		1.59	19.01	0.307	150868	219.1	8.23E+14	143661
132	16538630	191.42	18.10		1.61	18.99	0.305	152675	220.4	8.37E+14	143556
133	16835215	194.85	18.09		1.62	18.97	0.303	154468	221.7	8.52E+14	143454
134	17131800	198.28	18.08		1.63	18.96	0.301	156247	223.0	8.66E+14	143355
135	17428385	201.72	18.07		1.65	18.94	0.299	158013	224.2	8.80E+14	143257
136	17724970	205.15	18.05		1.66	18.93	0.297	159766	225.5	8.94E+14	143161
137	18021555	208.58	18.04		1.68	18.91	0.295	161506	226.7	9.09E+14	143067
138	18318140	212.02	18.03		1.69	18.90	0.293	163234	227.9	9.23E+14	142975
139	18614725	215.45	18.02		1.70	18.88	0.291	164949	229.1	9.37E+14	142884
140	18911310	218.88	18.01		1.72	18.87	0.289	166652	230.3	9.51E+14	142796
141	19207895	222.31	18.00		1.73	18.86	0.288	168344	231.4	9.66E+14	142709
142	19504480	225.75	17.99		1.74	18.84	0.286	170024	232.6	9.80E+14	142623
143	19801065	229.18	17.98		1.76	18.83	0.284	171692	233.7	9.94E+14	142539
144	20097650	232.61	17.97		1.77	18.82	0.282	173350	234.9	1.01E+15	142457
145	20394235	236.04	17.96		1.78	18.81	0.281	174997	236.0	1.02E+15	142376
146	20690820	239.48	17.95		1.80	18.79	0.279	176633	237.1	1.04E+15	142296
147	20987405	242.91	17.94		1.81	18.78	0.277	178258	238.2	1.05E+15	142218
148	21283990	246.34	17.93		1.82	18.77	0.276	179874	239.2	1.07E+15	142141
149	21580575	249.78	17.92		1.83	18.76	0.274	181479	240.3	1.08E+15	142065
150	21877160	253.21	17.91		1.85	18.75	0.273	183075	241.4	1.09E+15	141990
151	22173745	256.64	17.90		1.86	18.73	0.271	184660	242.4	1.11E+15	141917
152	22470330	260.07	17.89		1.87	18.72	0.270	186236	243.4	1.12E+15	141845
153	22766915	263.51	17.88		1.88	18.71	0.268	187803	244.5	1.14E+15	141774
154	23063500	266.94	17.87		1.90	18.70	0.267	189361	245.5	1.15E+15	141704
155	23360085	270.37	17.86		1.91	18.69	0.266	190909	246.5	1.16E+15	141635
156	23656670	273.80	17.85		1.92	18.68	0.264	192449	247.5	1.18E+15	141567
157	23953255	277.24	17.84		1.93	18.67	0.263	193980	248.4	1.19E+15	141500
158	24249840	280.67	17.84		1.94	18.66	0.262	195502	249.4	1.21E+15	141434
159	24546425	284.10	17.83		1.96	18.65	0.260	197016	250.4	1.22E+15	141369
160	24843010	287.53	17.82		1.97	18.64	0.259	198522	251.3	1.23E+15	141305
161	25139595	290.97	17.81		1.98	18.63	0.258	200019	252.3	1.25E+15	141242
162	25436180	294.40	17.80		1.99	18.62	0.256	201508	253.2	1.26E+15	141180
163	25732765	297.83	17.80		2.00	18.61	0.255	202990	254.1	1.28E+15	141118
164	26029350	301.27	17.79		2.01	18.60	0.254	204463	255.1	1.29E+15	141057
165	26325935	304.70	17.78		2.03	18.59	0.253	205929	256.0	1.30E+15	140998
166	26622520	308.13	17.77		2.04	18.58	0.252	207387	256.9	1.32E+15	140939
167	26919105	311.56	17.77		2.05	18.57	0.250	208838	257.8	1.33E+15	140880
168	27215690	315.00	17.76		2.06	18.57	0.249	210281	258.7	1.35E+15	140823
169	27512275	318.43	17.75		2.07	18.56	0.248	211718	259.5	1.36E+15	140766
170	27808860	321.86	17.75		2.08	18.55	0.247	213147	260.4	1.38E+15	140710
171	28105445	325.29	17.74		2.09	18.54	0.246	214569	261.3	1.39E+15	140655
172	28402030	328.73	17.73		2.10	18.53	0.245	215984	262.2	1.40E+15	140600
173	28698615	332.16	17.72		2.11	18.52	0.244	217392	263.0	1.42E+15	140546
174	28995200	335.59	17.72		2.13	18.51	0.243	218794	263.9	1.43E+15	140492
175	29291785	339.03	17.71		2.14	18.51	0.242	220189	264.7	1.45E+15	140440
176	29588370	342.46	17.70		2.15	18.50	0.241	221577	265.5	1.46E+15	140388
177	29884955	345.89	17.70		2.16	18.49	0.240	222959	266.4	1.47E+15	140336
178	30181540	349.32	17.69		2.17	18.48	0.238	224334	267.2	1.49E+15	140285
179	30478125	352.76	17.69		2.18	18.47	0.238	225704	268.0	1.50E+15	140235
180	30774710	356.19	17.68		2.19	18.47	0.237	227067	268.8	1.52E+15	140185
181	31071295	359.62	17.67		2.20	18.46	0.236	228424	269.6	1.53E+15	140136
182	31367880	363.05	17.67		2.21	18.45	0.235	229774	270.4	1.54E+15	140087
183	31664465	366.49	17.66		2.22	18.44	0.234	231119	271.2	1.56E+15	140039

APPENDIX C

Safe Injection Pressures Under Old Mormon Slough

SAFE INJECTION PRESSURES UNDER OLD MORMON SLOUGH

Due to the low elevation of the slough bottom and the presence of water in the slough, it is not safe to inject steam at shallow depths below the slough. This brief analysis was performed in order to determine the shallowest safe and practical steam injection depth, and also the shallowest safe electrical heating depth.

The analysis is based on the following physical situation:

- To inject steam, the injection pressure must exceed the hydrostatic pressure at the top of the well screen (otherwise there is not a pressure gradient away from the well screen, and fluids cannot be injected).
- The rule of thumb for estimating the maximum safe injection pressure of 0.5 psi per foot of overburden was used to set the maximal steam pressure at a given depth.
- Electrical heating may produce steam locally at depth without producing a significantly elevated pressure compared to hydrostatic.
- The soil liquefaction pressure is equal to the overburden pressure minus the hydrostatic pressure at a given depth.
- If the steam injection pressure exceeds the soil liquefaction pressure, steam injection is considered unsafe and likely to result in soil lifting and shallow steam escape.
- If the soil liquefaction pressure is negative, electrical heating is considered unsafe and likely to result in soil lifting and shallow steam escape.
- For steam injection to be practical at a given depth, the available injection pressure must exceed the static water pressure by at least 5 psi in order to allow substantial injection rates.

At most locations below grade, the soil overburden pressure is greater than the groundwater hydrostatic pressure. This would be a positive "liquefaction pressure." However, at shallow depths below the slough, the overburden pressure is less than the hydrostatic pressure; the most extreme case is at the mudline, where the overburden pressure is zero, yet the hydrostatic pressure is equal to about 10 feet of water. If a steam bubble moves into a region of negative liquefaction pressure, it is very likely to liquefy the soil as it moves upward.

The results are provided in Table C-1 and Figure C-1. The conclusions are as follows:

1. Steam should not be injected directly into the A- or B-zone aquifers under the slough (shallowest safe injection location under the slough is at an elevation of –90 feet).

2. The A-B aquitard and the B-zone aquifer can safely be heated by electrical heating using electrodes placed under the slough (deeper than an elevation of –40 feet).

These are the principles used to design the heating pattern for the shallow N-MPA for Scenarios 2 and 3.

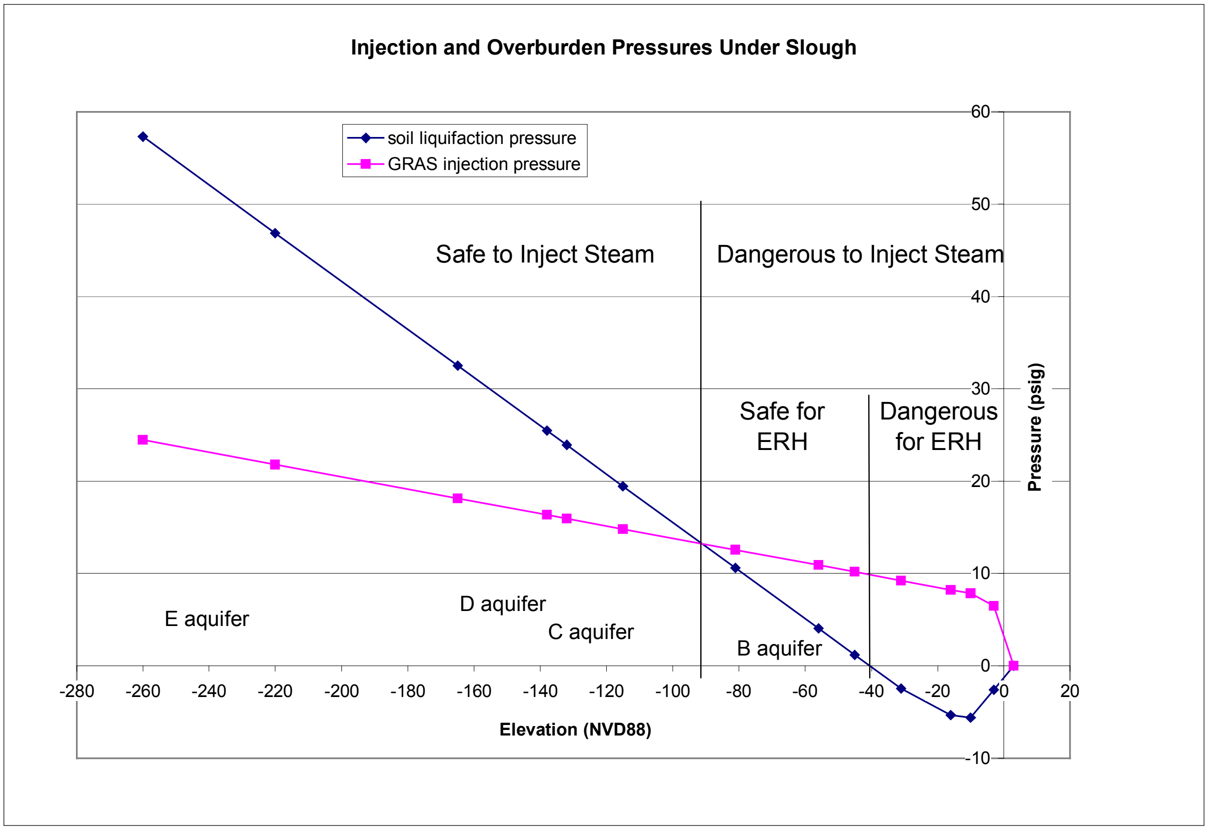


Figure C-1. Schematic of the injection and overburden pressures under Old Mormon Slough with indication of safe injection depths for steam and electrical heating (ERH).

Table C-1
Calculations Used to Estimate Safe Depths for Steam Injection and Electrical Heating Under Old Mormon Slough

location description	overlying soil density (lb/cu ft)	elevation NVD88 (ft)	hydrostatic pressure (psig)	overburden pressure (psig)	ovb - hyd pressure differential (psid)	GRAS pressure differential (psid)
MHHW	N/A	3	0	0	0	0
MLLW	N/A	-3	2.6	0	-2.6	6.5
mud line	N/A	-10	5.6	0	-5.6	7.8
bottom of mud	70	-16	8.2	2.9	-5.3	8.2
bottom of slough deposits	90	-31	14.7	12.3	-2.4	9.2
bottom of A aquifer	100	-45	20.8	22.0	1.2	10.2
bottom of A-B aquitard	100	-56	25.6	29.7	4.1	10.9
bottom of B aquifer	100	-81	36.4	47.0	10.6	12.6
bottom of B-C aquitard	100	-115	51.2	70.6	19.5	14.8
bottom of C aquifer	100	-132	58.5	82.4	23.9	15.9
bottom of C-D aquitard	100	-138	61.1	86.6	25.5	16.3
bottom of D aquifer	100	-165	72.8	105.3	32.5	18.1
bottom of D-E aquitard	100	-220	96.7	143.5	46.9	21.8
bottom of E aquifer	100	-260	114.0	171.3	57.3	24.5
MHHW = Mean higher high water						
GRAS = Generally Regarded As Safe						
GRAS Assumptions - It is generally safe to inject steam at a site if:						
1) five feet of vadose zone is present (uncapped)						
2) the injection pressure is limited to 0.5 psig per foot of depth						
3) GRAS pressure differential also assumes that an additional 5 psid is required for proper steam flow						

APPENDIX D

Electrical Resistivity Tomography

ELECTRICAL RESISTIVITY TOMOGRAPHY

Electrical resistivity tomography (ERT) has revolutionized the monitoring of subsurface processes and has allowed the acquisition of three-dimensional images of the subsurface. ERT produces a cross section of the distribution of information between measuring points, the distribution having, in some cases, nearly as much certainty as the measuring points themselves. In ERT, this distribution is of resistivity, and the measuring points are electrodes placed at various intervals around a target area. After numerous measurements are made from current transmitted and received from all possible combinations of electrodes, a resistivity distribution is reconstructed using a finite element mesh model to produce a two-dimensional cross section of the area underground. Data collected in two or more planes at once can generate three-dimensional images.

ELECTRICAL PROPERTIES OF ROCKS

Resistivity is a physical property of a material describing how much that material resists the flow of electric current. It is measured in ohm-meters. Conductivity is the inverse of resistivity, and it is measured in 1/ohm, or siemens, per meter (m). The better the current flows through an object, the higher its conductivity, and the lower its resistivity.

In mineral grains, there are two ways in which current flows: through electrons, which is called electronic conductivity; and through ions, which is called electrolytic conductivity. However, the pore fluids in rocks are actually what drive the rock's resistivity, as mineral grains are poor conductors of any type. A rock's resistivity is therefore determined by the following factors:

- Porosity
- Permeability
- Saturation
- Resistivity of the pore fluid

In monitoring steam-enhanced remediation, ERT detects changes in resistivity that reflect saturation changes, which are caused by the movement of steam through the subsurface and the corresponding temperature changes therein. The porosity of soil and rock remains constant before and during steaming. According to Archie's law, bulk resistivity is an inverse power function of both porosity and saturation (Archie 1942).

$$\rho_t = F * \rho_w / S_w = 0.62/\phi^{2.15} * \rho_w/S_w^{\ 2}$$

Where:

ρ_t = bulk resistivity of partially saturated clay-free sediments
F = formation factor, a function of porosity
ρ_w = pore fluid resistivity
S_w = saturation
ϕ = porosity

This equation is graphed in Figure D-1. With water resistivity assumed to be 1 ohm-m, the general trend is for bulk resistivity to decrease as saturation increases. A medium that is more than 80 percent saturated at any porosity may have more than an order of magnitude increase in resistivity when its saturation decreases to less than 20 percent.

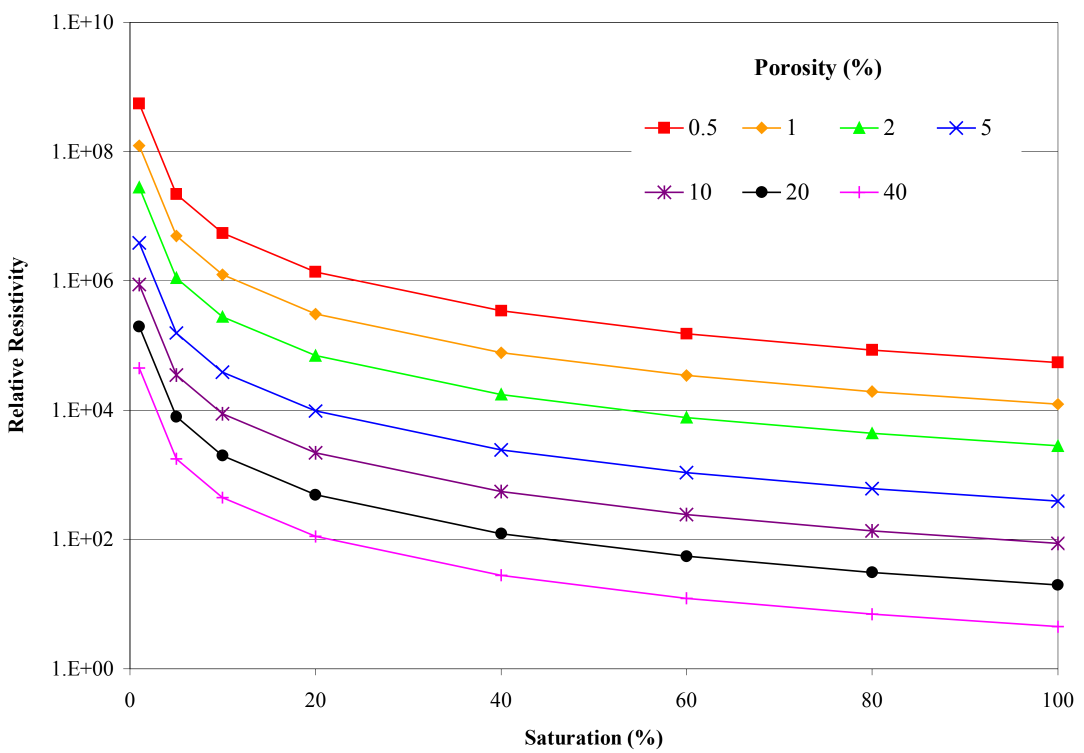


Figure D-1: Resistivity in ohm-m versus saturation in percent for a range of porosities. Water resistivity is assumed to be 1 ohm-m.

Pore fluid resistivity also decreases as temperature increases, due largely to the fact that ion mobility increases with temperature. The resistivity of a saturated rock is an exponential function of the reciprocal of temperature (Llera et al. 1990). A simplified relationship is indicated by the following equation:

$$\rho_t = \alpha/\phi^{2.15} * e^{k/T}$$

Where:

α = a function of water resistivity, viscosity, hydration, ionic radius, concentration, elementary charge, Faraday's constant, and valency
k = a function of Boltzmann's constant and activation energy of viscous flow
T = absolute temperature
ϕ = porosity

A plot of resistivity versus temperature is shown in Figure D-2 for a wide range of porosities. The values for pore fluid resistivity (ρ_w) may be substituted into Archie's law to determine how the bulk resistivity changes with temperature.

There is an apparent risk that resistivity increases due to dewatering during steaming of a saturated zone and resistivity decreases due to the high temperatures of steam will ultimately produce no change in resistivity. Typically, this problem is avoided because one regime will dominate over the other, such that even small changes in resistivity (e.g., 20 percent) lie within the sensitivity range for ERT detection. The dominant regime may change over time. For instance, a steamed volume may initially experience a period of heat-up, followed by intense drying out, both of which would be detected by ERT.

WHAT IS ERT?

ERT (electrical resistivity tomography, also known as electrical impedance tomography) is an adaptation of the more standard surface DC resistance surveys that involve electrodes buried just under the ground surface. ERT adds a level of complexity not only by changing the array configuration to that of a cross-borehole style, but also by incorporating a finite element mesh analysis and sophisticated algorithms for inversion of the collected data. This ultimately results in much better resolution than surface surveys, greater spatial coverage, and accuracy that extends to greater depth.

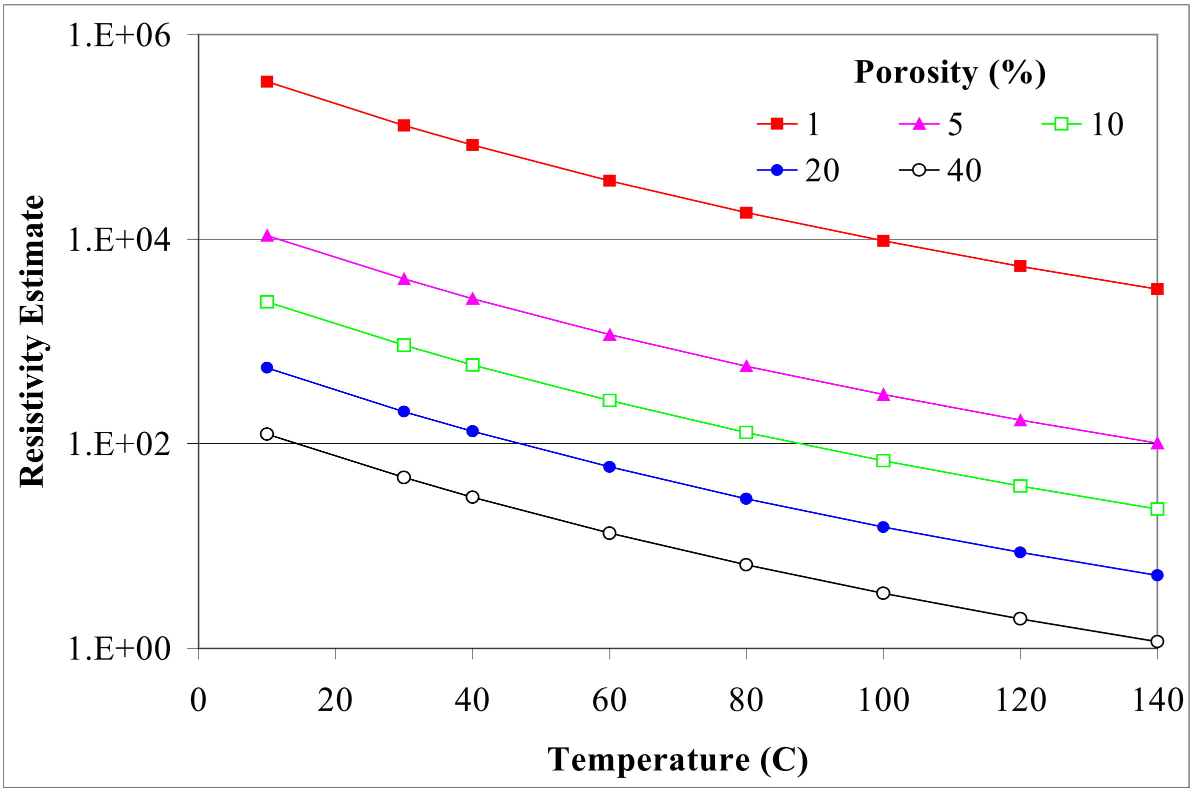


Figure D-2: Resistivity in ohm-m versus temperature in degrees Celsius.

An ERT survey is set up by emplacing colinear electrodes, called vertical electrode arrays (VEAs), into boreholes surrounding the area to be imaged. Each VEA is typically grouted into place, resulting in a permanently placed array. These electrodes are each independently wired to the surface data collection system. To collect data, one pair of adjacent electrodes acts as a transmitter of electric current, while pairs of electrodes in the same hole and in neighboring holes act as receivers. Data are collected between every possible combination of transmitter-receiver pairs between all neighboring boreholes. Data are then inverted using an algorithm to calculate the resistivity structure that best fits the measured voltages (see the following subsection, ERT Data Reduction). The resistivity cross sections produced are subsurface image planes that can be viewed in a two-dimensional fence diagram between wells, or as combined into a three-dimensional structure, depending on which optimally displays the target. During interpretation of these images, the resistivity signature is correlated to known processes, such as steam location, for tracking the steam migration.

The result is a near realtime geophysical technology for environmental monitoring and site characterization. Data collection is automated and relatively fast, typically taking less than 1 day to collect and image a site containing many VEAs. The expected resolution of ERT is around half of the vertical electrode spacing (typically 2 to 3 ft [0.6 to 0.9 m]). Surface electrodes may be added to improve near-surface resolution.

ERT has two advantages over most other geophysical methods. First, it is probably the only geophysical method applied to environmental sites where the data are routinely collected and interpreted fully three-dimensionally. The ERT methodology lends itself to the collection of large data sets using automated, relatively inexpensive equipment. Most other geophysical methods that would be used for monitoring have a limitation on the quantity of data that can be collected in a short period of time and, in general, are labor intensive with equipment that is currently available. The second advantage of ERT is that the electrodes are permanently placed in the subsurface, ensuring a high level of repeatability of the measurements, making the method suited for monitoring subsurface changes over time.

ERT DATA REDUCTION

Using an inverse algorithm, the resistivity structure that best fits the measured voltages is calculated. This method uses a finite element mesh design with typically two elements between electrodes. Thus the accuracy of images generated by ERT is said to be usually one-half of the electrode spacing. The inversion code calculates a model of the smoothest resistivity distribution that fits the data within estimated standard deviations using an inversion of the solution. More information is provided in LaBrecque and Yang (2000) and in LaBrecque et al. (1995).

The inversion produces a solution that is non-unique, meaning that several different interpretations could result from the collection of one data set. This is usually not a problem if experienced geophysicists are interpreting the data and if as many known factors are accounted for, facilitating the distinction between true anomalies and spurious artifacts. A strong difference inversion code makes use of the high degree of repeatability of ERT data, thereby reducing the amount of inversion artifacts.

ERT CASE STUDIES

ERT has become an effective technology for in situ monitoring of many processes, such as water movement in the vadose zone (Yang 1999), air-sparging, joule (electrical) heating, remediation processes (Ramirez et al. 1993; LaBrecque et al. 1998) and steam injection (Newmark et al. 1994; Southern California Edison 2000). Two examples are presented in the following subsections.

Thermal Remediation Monitoring at Portsmouth, Ohio

A pilot study was conducted at the X-701B Area at the Portsmouth Gaseous Diffusion Plant. During the study, steam and air were injected into the subsurface through wells, and water and vapor were extracted. The steam delivered energy to the target area, heating it to steam temperature, thereby accelerating the removal of nonaqueous-phase liquids.

The treatment area was located at the west end of a trichloroethene (TCE) plume emanating from a holding pond. TCE moved through permeable fine sands, silts, and clays of the Minford and Gallia Members and along the upper interface of a nearly impermeable shale layer, the Sunbury Shale. The contamination was present within the top of the Sunbury Shale. TCE levels in the upper Sunbury were as high as 1,600 mg/kg, generally 10 to 100 times those in the overlying layers. Steam was injected via shallow wells, into permeable, unconsolidated sediments (Gallia and Minford), heating these layers advectively. The Sunbury Shale was heated by conductive movement of heat from these overlying layers. ERT was used to monitor the movement of heat throughout the site.

This project presented a number of challenges in terms of ERT data collection and processing. Large amounts of electric power are used at the site, creating very high noise levels. In addition, much of the site was covered with large metal containers of low-level radioactive waste. This created a source of “cultural interference” and made access difficult. The site also contained a large number of metal well casings and pipes. Next, the contrasts in background resistivity were very large. The background ERT image showed highly conductive zones in the Sunbury Shale and Berea Sandstone. These corresponded to pyritic zones within the two formations. As a result, the upper 2 m (7 ft) of the Sunbury displayed a nearly 100-fold gradient in resistivity. It should be noted that the primary zone of interest was a thin permeable zone immediately on top of the Sunbury Shale.

Figure D-3 shows a two-dimensional sequence of percent change images over 1 month between the same two ERT boreholes (6 and 7). Steam injection commenced a few days prior to February 18, 1999, from the right side of the plane. Here, the results are displayed as percent differences from the background of conductivity, which is the inverse of resistivity. The only area changing is that which is affected by the steam. The difference inversion clearly shows this progression of the steam heated zone along the base of the Gallia. Over time, the temperature of the surrounding formations began to increase due to the conductive flow of heat from the steam zone and the upward migration of steam into the upper Gallia.

Midway through the project, ERT images revealed a linear belt of cooler water in the target zone. Substantial water flow through this channel prevented steam migration into the channel. The images were used to identify ideal locations for supplementary steam injection wells. After these wells were installed and steam was injected, the heating of the target zone was completed.

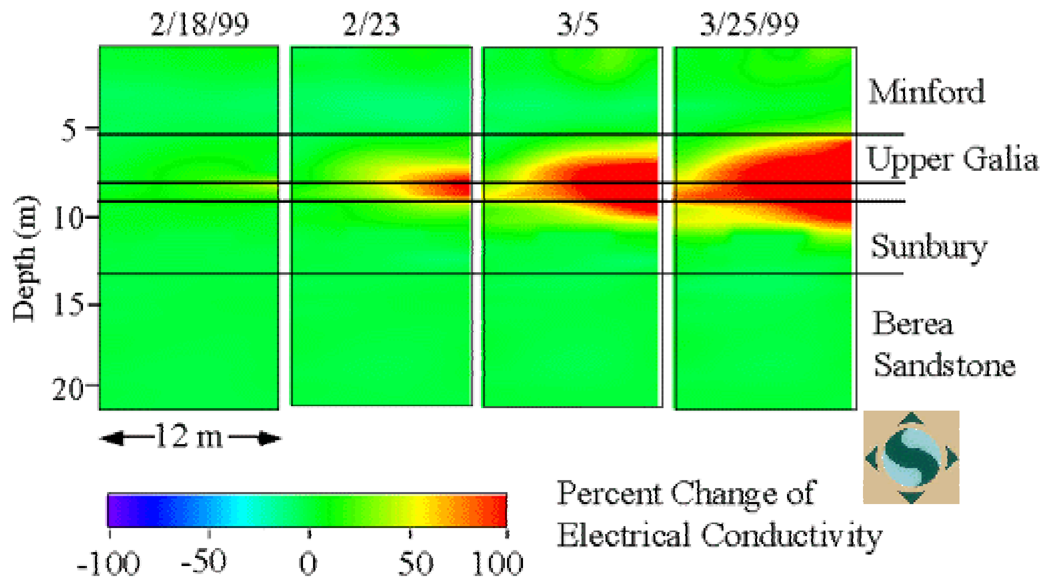


Figure D-3: Percent difference of electrical conductivity between boreholes ERT06 and ERT07 at the Portsmouth X701-B site. Depth in meters.

Monitoring Infiltration at the Socorro-Tech Vadose Zone Facility, New Mexico

Researchers from Sandia National Laboratories, the New Mexico Institute of Technology, the University of Arizona, and SteamTech Environmental Services collaborated on an interdisciplinary research project to develop a hybrid hydrologic-geophysical inverse technique (HHGIT) for vadose zone characterization. This project was funded by the U.S. Department of Energy's (DOE's) Environmental Management Science Program. SteamTech developed a three-dimensional stochastic inversion program for ERT data interpretation and a three-dimensional cokriging algorithm to estimate three-dimensional moisture content distribution from ERT data and neutron-derived moisture contents. SteamTech also provided ERT monitoring for the infiltration experiment at the Socorro-Tech Vadose Zone (STVZ) facility.

The STVZ site is located on the campus of New Mexico Tech in Socorro, New Mexico. Soil deposits at the site exhibit contrasting textures and sedimentary structures typical of deposits found in various DOE waste sites in western United States. The test site was installed in relatively unconsolidated, heterogeneous, fluvial deposits consisting of gravel, sand, and clays of fairly high hydraulic permeability. The near-surface layer consists of poorly consolidated sand and gravel. There are multiple interbedded clay, sand, and gravel layers between 2 and 6 m. The rest of the site consists of fine sands with variable contents of clay and iron oxides.

In addition to the ERT survey conducted at this site, dense arrays of hydrologic probes such as time-domain reflectometer (TDR) probes and tensiometers, along with arrays of surface and subsurface ERT electrodes, were installed at the STVZ site. Neutron probe measurements and EM-39 conductivity logs were obtained through 13 polyvinyl chloride (PVC) access tubes. Cross-borehole ground penetrating radar (XBGPR) surveys were carried out along a northeast-southwest transect through five PVC access tubes. There were a total of 8 VEAs and 36 surface electrodes installed at the site. ERT data provided the capability to construct three-dimensional images of the subsurface electrical conductivity, from which estimates of the subsurface geology, temporal moisture content distributions, and advancement of wetting front could be derived.

The experimental site was 10.5 m (34 ft) long, 10.5 m wide, and 13 m (43 ft) deep. A square infiltration pad of 3 x 3 m (10 x 10 ft), made out of 900 18-gauge medical needles, was installed in the center of the site. The infiltration began on March 11, 1999, with a constant flux of 2.7 cm/day (1.2 inches/day).

The three-dimensional conductivity percent difference images, shown in Figure D-4, provide a clear picture of the water movement in the vadose zone. A 30 percent cutoff for volume rendering was used for image construction. The downward growth and lateral development of the wetted area can be seen clearly from these difference images.

IMPROVEMENTS TO INVERSION CODE AND ELECTRODE DESIGN

Inversion Code

One of the difficulties in comparing images created using Occam's inversion is that the resolution of the image is dependent on the noise in the data. This problem is exacerbated in situations such as the one at Portsmouth where there are thin, strongly contrasting layers. The resolution is typically not great enough to see the smaller features.

However, the recent development of a new modeling code has helped reduce these problems (Yang and LaBrecque 2000). Prior inversion codes inverted the electrical potential data of each data set, including the background, and then difference images were created afterward. ERT data are very unique among the electrical methods due in part to the fact that they exhibit a high degree of measurement precision, or repeatability. In the new difference inversion code, the differences in data sets are inverted, rather than the data sets themselves. The data are fit more closely than in previous algorithms, and systematic errors tend to cancel out. The result is faster convergence and better resolution in the images.

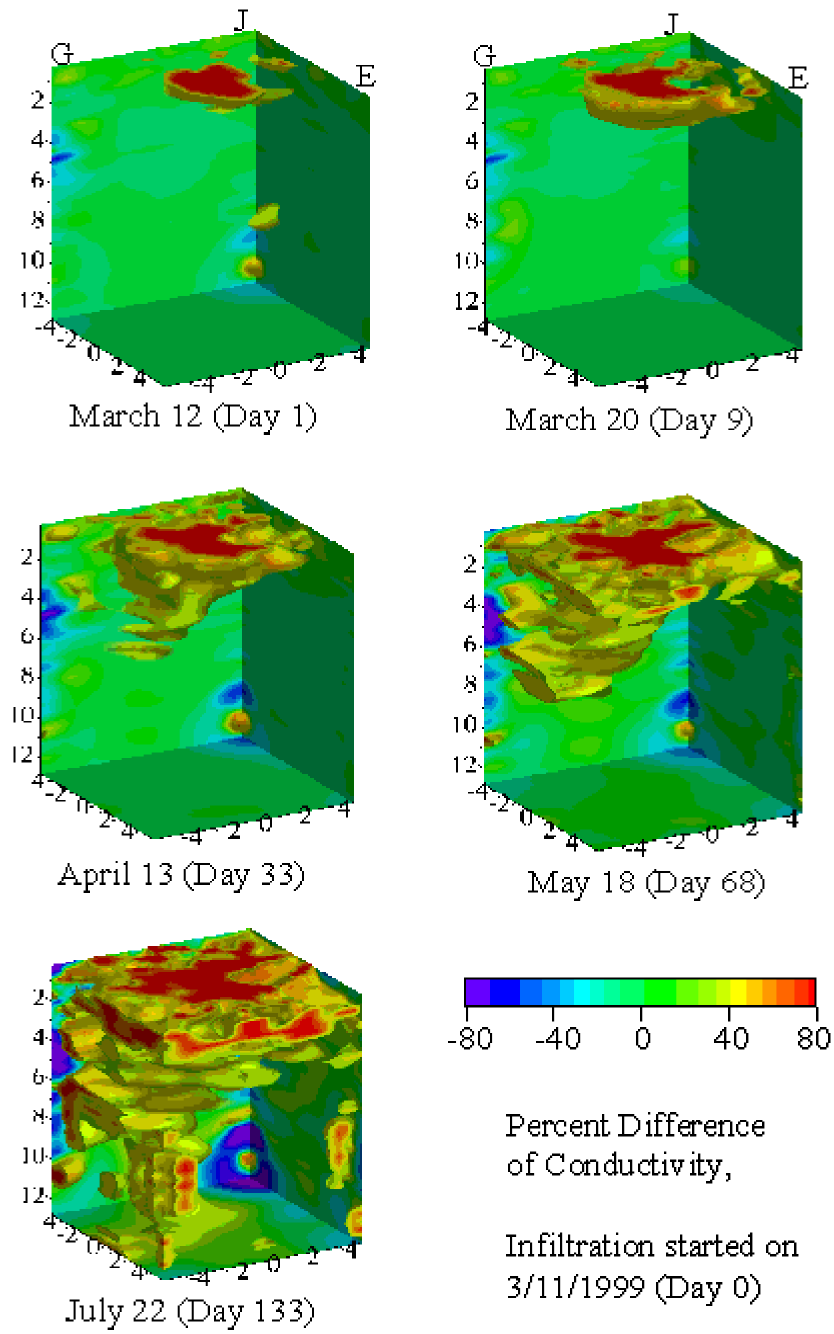


Figure D-4: Percent change of electrical conductivity at the STVZ site. The cut-off for the volume rendering is 30 percent.

The artifacts that result from using Occam's inversion in an environment of thin, strongly contrasting layers are shown in the top images of Figure D-5. These top images are data from the Portsmouth Gaseous Diffusion Plant; these resemble data from operations at the Visalia Pole Treatment Yard (Southern California Edison 2000). There is a general trend of a resistivity anomaly growing in size over time, but with the presence of other extraneous artifacts that could confuse a valid interpretation. Along the bottom are the same data as those at the top, but inverted using the difference inversion code. These bottom images show the clean, easily interpreted tomographs resulting from the difference inversion, which are the same images shown in color in Figure D-3.

The difference code of Yang and LaBrecque is a published code, with property rights belonging to SteamTech and Lawrence Livermore National Laboratory. This code may be made public in the future. There are most likely other difference codes available today that are similar to that of Yang and LaBrecque.

Electrode Design

Ensuring collection of good quality data with a high level of repeatability means removing systematic errors wherever possible. One place where errors can be easily remedied is in electrode design. Errors can result from electrodes that are designed inconsistently, have intermittent connections, or sometimes have short circuited or lost their connections entirely. These problems can be eradicated by designing electrodes as identically as possible, especially making sure the surface area of metal exposed is exactly the same for each electrode. Also, creating a robust wire connection to each electrode and protecting it from corroding substances, are essential for preventing the loss of electrical connection. Short circuits can be prevented by making sure there are no nicks on any of the connection wires and that any conductive bodies, such as cable shielding, are not emplaced along with the VEA.

DISTRIBUTED TEMPERATURE MEASUREMENT

Taking the temperature at various points along a borehole underground is very useful and complementary to ERT to further delineate the nature of the subsurface during thermal remediation. One method for taking temperature measurements is the use of thermocouples. Each thermocouple consists of a pair of Teflon™-coated wires of dissimilar metals stripped back and welded together at the end in the borehole, with the free ends running up to the surface. The temperature received at the weld junction produces a voltage difference at the free ends, thus enabling temperature to be read at the surface for each weld location down-hole. Though the data are generally considered accurate, the disadvantages of using thermocouples are that the construction can be laborious, data collection is time consuming, and the probes can corrode, resulting in loss of data.

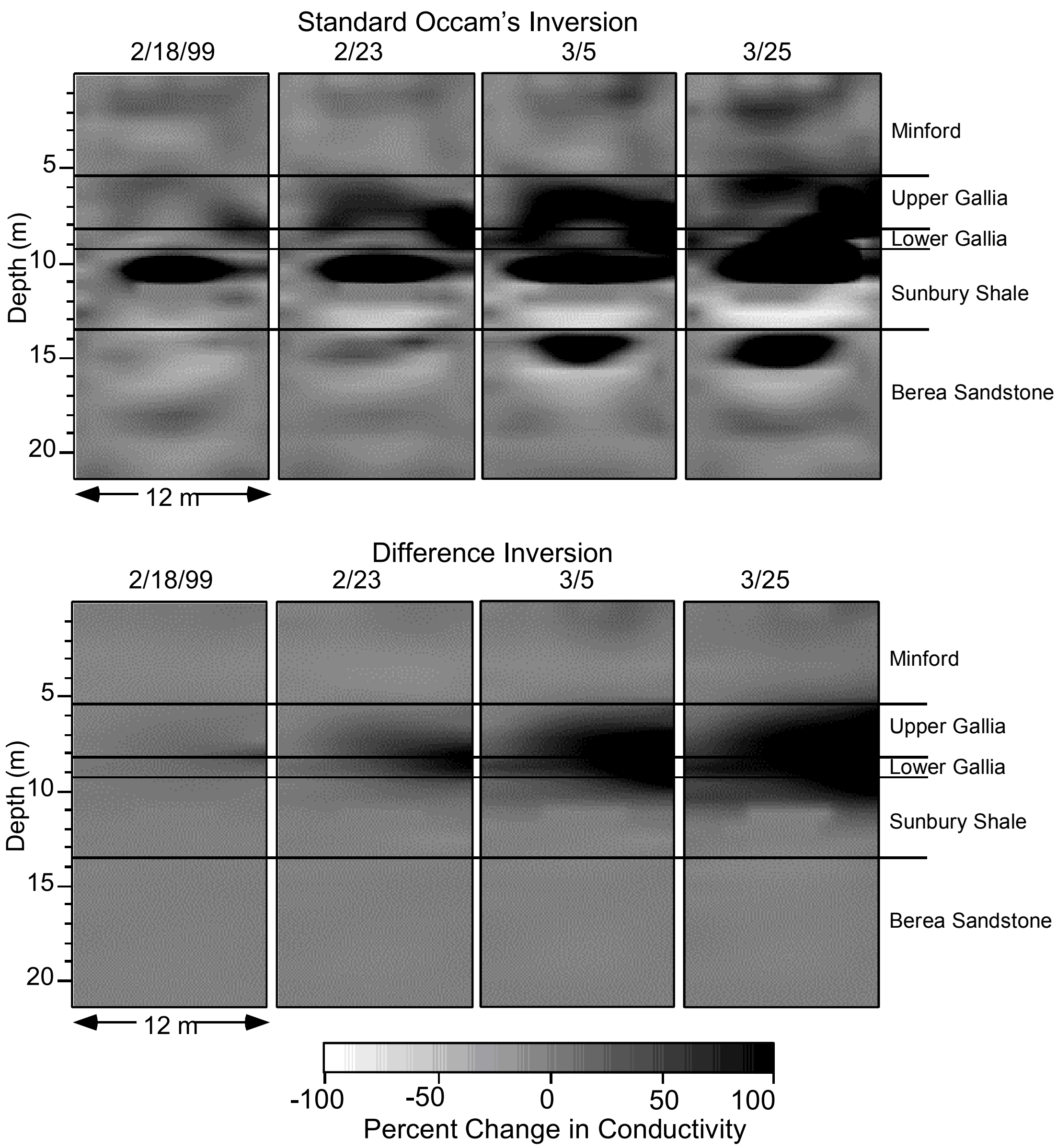


Figure D-5: Comparison of Occam's inversion (top) to difference inversion using percent difference conductivity images from Portsmouth X701-B site. Darker areas represent increased conductivity.

Another method for taking underground temperature that has been in the oil field industry for some time is the use of fiber optics. The method, known as distributed temperature sensing (DTS), makes use of an optical fiber that runs down-hole in the area where temperature readings are to be taken. An optical pulse sent down the fiber undergoes scattering, the strongest of which is called Rayleigh, which is the type used in telecommunications. Secondary to that is the Raman scattering, consisting of the Stokes and anti-Stokes components. The Stokes component has a longer wavelength and does not vary with temperature, while the anti-Stokes component, at a shorter wavelength, is temperature variant. The ratio of these signals, as measured in the backscatter, is used to determine the temperature at known intervals, which are determined by the length of the optical pulse. Typically, this laser pulse is 10 nanoseconds, resulting in a measurement interval of 1 m (Normann, Weiss, and Krumhansl 2001).

In a DTS installation, it is important above all else to keep water away from the fiber. Exposure to water, or any other source of hydrogen, enables free hydrogen to get inside the fiber and create hydroxyl group molecules, which causes irreversible damage to the fiber and decreases its lifespan. For this reason, fibers should be installed using high-pressure air or heat-transfer fluid.

One continuous length of fiber can measure temperature at 1-m intervals up to 5 km. Therefore, individual wells can be outfitted with fibers, each ending at the surface, or if there are a lot of wells needed at a site for temperature measurement, several can be daisy-chained together with one single length of optical fiber.

DTS is a proven technology for taking underground temperature readings in oil field and geothermal applications. Conditions during thermal remediation are not unlike the conditions experienced in these applications, making DTS a promising method for subsurface monitoring.

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APPENDIX E

Slough Dewatering Evaluation

SLOUGH DEWATERING EVALUATION

PURPOSE

Technical discussions regarding three thermal treatment scenarios for the McCormick and Baxter site raised concerns about the potential for mobilization of non-aqueous phase liquids (NAPLs) into Old Mormon Slough. Addition discussions focused on the ability to place injection and extraction wells in targeted subsurface treatment zones under the slough. Damming and dewatering of the slough was discussed at the EPA/USACE kick-off meeting on March 7, 2001, as a method to address these concerns. URS Corporation (URS) was asked to evaluate the capital and operation and maintenance (O&M) costs for this effort for presentation at a later date. This appendix is a summary of the information presented by URS at Meeting #1 on April 5, 2001.

URS evaluated the capital costs of constructing a sheetpile dam across Old Mormon Slough and building a dewatering system to remove water from an approximately 2,800-foot section of the slough for up to 5 years. The following information was developed for the April 5, 2001, presentation.

CAPITAL COST OF TEMPORARY DAM IN OLD MORMON SLOUGH

URS evaluated the capital cost of constructing a temporary sheetpile dam across Old Mormon Slough, which is documented in Table E-1. A review of existing documents for the site yielded a prior assessment by the Pacific Northwest National Laboratory (PNNL 1998), which was compared to URS' independent evaluation. The order-of-magnitude capital cost estimated by URS ranged from $703,000 to $943, 000. The PNNL estimate was $859,000.

CAPITAL COST OF DEWATERING SYSTEM

URS developed an order-of-magnitude cost estimate for constructing a dewatering system to remove water from the inside face of the temporary sheetpile dam (estimated to be 56 million gallons [MG]) and to keep the slough dewatered for 5 years (4 years of active thermal treatment in the McCormick and Baxter site and the first year of cool-down). Estimates by PNNL (1998) were used for inflow to the slough from groundwater recharge (0.84 MG per day), and URS estimated that stormwater inflow from surface runoff and permitted/unpermitted discharge pipes in the slough contributed an average of 0.2 MG per day. Long-term dewatering efforts are assumed to be 1 MG per day or a total of 365 MG per year. The order-of-magnitude capital cost of the dewatering system is estimated by URS to be $333,000 (Table E-2).

O&M COST FOR SLOUGH DEWATERING

URS estimated the labor, equipment, and material costs of dewatering the slough for 5 years (Table E-3). This estimate is for pump operation and maintenance only; no water treatment costs prior to discharge were included in this evaluation. The total cost for 5 years of dewatering system O&M is estimated to be $2,350,000.

WATER TREATMENT COST FOR SLOUGH DEWATERING

Water treatment requirements and costs, if any, are a key factor in determining if dewatering the slough is feasible for the site. The removal of water from inside the dam poses a risk of remobilizing contaminants of concern during dewatering and during the thermal treatment. Technical input received during the kick-off meeting suggested that direct pumping from one side of the dam to the other would not be allowed, and the discharge would likely require a National Pollutant Discharge Elimination System (NPDES) permit. The level of treatment that would be required is not known at this time, and detailed evaluations would be required to determine the actual costs of a suitable treatment system.

Based on the estimated costs of the dam and dewatering system construction, URS assumed that the costs of direct discharge, reflecting dewatering infrastructure and equipment O&M costs, are $0.0019 per gallon (total capital and O&M costs divided by the total volume of water discharged from initial drawdown of the slough and 5 years of continuous dewatering) or about $1,900 per MG discharged. Costs increase as the level of treatment increases. For comparative purposes, URS assumed costs of $3,000 per MG for minimal physical treatment (settling, filtration) prior to discharge. The addition of physical and chemical treatment (targeting NAPL and select contaminants of concern) is expected to increase costs to $10,000 per MG. Treated discharge quality equivalent to a publicly owned treatment work (POTW) was assumed to be $60,000 per MG. Subsequent discussions with the city of Stockton suggest these costs would be more than $104,000 per MG under the commercial fee structure for its treatment system; however, the local system does not have the capacity to accept this discharge volume.

Table E-4 is a comparison of the estimated costs for each level of treatment prior to discharge, including initial dewatering of the slough (56 MG) and 5 years of continuous dewatering (1,825 MG). The cost of pumping only (no treatment) is estimated to be $3.6 million; addition of physical treatment (settling, filtration) increases costs to $5.6 million. Additional treatment increases costs to levels of between $18.8 million (minimal treatment such as settling, oil-water separation, and filtration) and $112.9 million (treatment comparable to a POTW).

CONCLUSIONS

The information presented in this appendix was discussed in Meeting #1 (April 5, 2001). The potential capital and O&M costs for dewatering the slough are considered too high when compared to the incremental costs of addressing concerns about injection/extraction well placement and NAPL remobilization by other means. Dewatering of the slough will not receive further consideration in the conceptual design analysis.

REFERENCE

Pacific Northwest National Laboratory (PNNL). *Surface Water—Sediment Feasibility Study Report for the McCormick and Baxter Superfund Site, Stockton, California.* July 1998.

Appendix E
Slough Dewatering Evaluation

Table E-1: Capital Cost of Temporary Dam in Old Mormon Slough

Description: Evaluate the capital and operation/maintenance (O&M) costs of dewatering Old Mormon Slough for up to 5 years during active thermal remediation by steam and six-phase heating of subsurface soil and groundwater zones at the McCormick & Baxter site. Assume construction of a temporary sheetpile dam, a long-term dewatering system, and operation for 4 years. The average depth of the slough is approximately 15 feet, and the width is 180 feet to 200 feet at the proposed dam location. The dam will isolate a 2,800 linear foot section of the slough.

Prepared by: Harry Ehlers, URS Corporation
Date: June 21, 2001

Capital Costs

		URS Estimate				PNNL Estimate			
Cost Item	**Description/Basis for Costs**	**Units**	**Quantity**	**Unit Cost**	**Cost Item Price**	**Units**	**Quantity**	**Unit Cost**	**Cost Item Price**
1.0	Mobilization/demobilization (10 - 15% of construction)	LS	1	$45,000 - $85,000	$45,000 - $85,000	LS	1	$73,000	$73,000
2.0	Sheetpile Wall, Installed Complete (URS: 40 feet deep, 250 feet wide; key into shore, 20 feet above sediment and 20 feet below sediment; PNNL - 60 feet deep, 230 feet wide)	SF	10,000	$25 - $30	$250,000 - $300,000	SF	13,800	$20	$276,000
3.0	Geotextile & 30-mil Liner (URS: place at inside face of the sheetpile, 30 feet wide, 250 feet long)	SF	7,500	$2.50 - $3.50	$18,750 - $26,250	LS	1	$35,000	$35,000
4.0	Rock, 6-inch or larger (URS: place on inside face of sheetpile)	CY	1,480	$15 - $25	$22,225 - $37,040	--	--	--	--
5.0	Demolition, remove sheetpile (URS: 40 feet deep, 250 feet wide; PNNL: 60 feet deep, 230 feet wide)	SF	10,000	$15 - $20	$150,000 - $200,000	SF	13,800	$13	$179,400
				Subtotal	$485,975 - $648,290			Subtotal	$563,400
	Engineering (URS: $35,000 - $50,000; PNNL, 15% of subtotal)				$35,000 - $50,000				$73,000
				Subtotal	$520,975 - $698,290				$636,400
				Construction contingency (30%)	$156,300 - $209,500				$190,920
				Owner's cost (administration, construction management - 5%)	$26,000 - $35,000				$31,820
				Capital Cost	**$703,300 - $942,800**			**Capital Cost**	**$859,140**

Appendix E
Slough Dewatering Evaluation

Table E-2: Capital Cost of Dewatering System **Prepared by:** Harry Ehlers, URS Corporation
Date: June 21, 2001

Description: Evaluate the capital and operation/maintenance (O&M) costs of dewatering Old Mormon Slough for up to 5 years during active thermal remediation by steam and six-phase heating of subsurface soil and groundwater zones at the McCormick & Baxter site. Assume construction of a temporary dewatering system and long-term dewatering system operation for 4 years. The average depth of the slough is approximately 15 feet, and the width is 180 feet to 200 feet at the proposed dam location. Assumptions are as follow:

1. The dam will isolate a 2,800 linear foot section of the slough, 15 feet deep, average 180 feet wide. Calculate as square channel - 7.56 million cubic feet or 56.0 million gallons.
2. Use recharge estimates by PNNL - 0.84 million gallons per day; add 0.2 million stormwater runoff from surrounding area, permitted and unpermitted stormwater discharges to Old Mormon Slough.

3.0 Assume total dewatering effort of 1.0 million gallons per day or 365 million gallons per year.

4. Assume dewatering occurs for 5 years - 4 years of active thermal treatment and one year of the cool-down period; operate 24 hours per day, 7 days per week.
5. No water treatment is included in this estimate; see Table E-4.

Capital Costs

Cost Item	Description/Basis for Costs	URS Estimate Units	 Quantity	 Unit Cost	 Cost Item Price
1.0	Pump Building, temporary structure, 40 by 60 feet, Sprung or Rubb type, with office	SF	2,400	$20	$48,000
2.0	Concrete slab, 40 by 60 feet, 6-inch, moderate reinforcement	SF	2,400	$5	$12,000
3.0	Equipment pads, 200 square ft, 12-inch, heavy reinforcement	SF	200	$10	$2,000
4.0	Intake structure in slough	LS	1	$20,000	$20,000
5.0	Pipe, 8-inch DIP	LF	300	$60	$18,000
6.0	Discharge structure to slough, downstream of temporary dam	LS	1	$10,000	$10,000
6.0	Misc. fittings, valves	LS	1	$2,000	$2,000
7.0	Pump & motor, duplex, 700 gpm, with controls and misc piping	LS	1	$80,000	$80,000
8.0	Demolition of dewatering system	LS	1	$20,000	$20,000
8.0	Mobilization/demobilization	LS	1	$10,000	$10,000
				Subtotal	$222,000
	Engineering (15% of subtotal)				$33,300.0
	Construction management (10% of subtotal)				$22,200.0
	Contingency (scope and bid, 25% of subtotal)				$55,500.0
				Capital cost	**$333,000**

Appendix E
Slough Dewatering Evaluation

Table E-3: O&M Cost for Slough Dewatering

Prepared by: Harry Ehlers, URS Corporation
Date: June 21, 2001

Description: Evaluate operation/maintenance (O&M) costs of dewatering Old Mormon Slough for up to 5 years during active thermal remediation by steam and six-phase heating of subsurface soil and groundwater zones at the McCormick & Baxter site. Assumptions are as follow:

1. Initial dewatering of slough - assume 56.0 million gallons (MG).
2. Assume total dewatering effort of 1.0 million gallons per day or 365 million gallons per year.
3. Assume dewatering occurs for 5 years - 4 years of active thermal treatment and one year of the cool-down period; operate 24 hours per day, 7 days per week.
4. Assume a O&M lead (equipment operator), $60 per hour, and laborer, $45 per hour; assume operations are concurrent with thermal treatment operations, allocate 0.25 full-time operator for each shift, 0.5 laborer per shift - composite crew rate is $37.50 per hour.

Operation and Maintenance (O&M) Costs

		URS Estimate			
Cost Item	**ion/Basis for Costs**	**Units**	**Quantity**	**Unit Cost**	**Cost Item Price**
1.0	Labor, composite crew, 3 shifts per day, 7 days/week, 365 days/ week, 5 years.	MHR	43,800	$37.50	$1,642,500
2.0	Small tools, disposables, 2% of labor	LS	1	$32,850	$32,850
3.0	Equipment repair & parts, 10% of equipment cost ($130,000) each year, 5 years	LS	1	$65,000	$65,000
				Subtotal	$1,740,350
		Construction management (10% of subtotal)			$174,035.0
		Contingency (scope and bid, 25% of subtotal)			$435,087.5
				O&M cost, 5 years	**$2,349,473**

Appendix E
Slough Dewatering Evaluation

Table E-4: Water Treatment Cost for Slough Dewatering

Prepared by: Harry Ehlers, URS Corporation
Date: June 21, 2001

Description: The pumping costs for dewatering of Old Mormon Slough are estimated to be $3.54 million for 5 years of operation ($0.86 million for dam [PNNL], $0.33 million for dewatering system, and $2.35 million for 5 years of O&M), handling 1 MG per day or 1,825 million gallons of water over the operating period. This is an equivalent per gallon cost of $0.0019 per gallon or $1,900 per million gallon. This does not include treatment of the water to reduce suspended sediment loads or to remove contaminants entrained in the water by dewatering or the thermal treatment operations. For comparison purposes, a range of treatment costs are shown in the table to show the potential costs of handling and treating this water:

Cost Item	Quantity (MG)	Pumping ($1,900 per MG)[1]	Phys. Only ($3,000 per MG)[2]	Phys/Chem ($10,000 per MG)[3]	POTW ($60,000 per MG)[4]
Initial dewatering of Old Mormon Slough	56	$106,400	$168,000	$560,000	$3,360,000
5-years of dewatering from slough	1,825	$3,467,500	$5,475,000	$18,250,000	$109,500,000
	Dewatering total by method	$3,573,900	$5,643,000	$18,810,000	$112,860,000

Notes:
1. Pumping cost, $0.0019 per gallon or $1,900 per million gallons.
2. Minimum physical treatment - filtration or sedimentation, no chemical or biological treatment - assume $0.003 per gallon or $3,000 per million gallons
3. Minimum physical/chemical treatment - assume $0.01 per gallon or $10,000 per million gallons.
4. Moderate physical/chemical treatment, such as publicly owned treatment works (POTW) - $0.06 per gallon or $60,000 per million gallons

APPENDIX F

Memorandum: Evaluation of Angled Drilling Under Old Mormon Slough
McCormick and Baxter Superfund Site, Stockton, California

URS Memorandum

Date: July 16, 2001

To: Steve Carroll, SteamTech/Denver CO
Jack Spear, URS/Cranford NJ

From: Harry Ehlers

Subject: **Evaluation of Angled Drilling under Old Mormon Slough**
McCormick & Baxter Superfund Site, Stockton, CA

Purpose

Technical discussions regarding three thermal treatment scenarios for the McCormick & Baxter site raised concerns about the potential for mobilization of non-aqueous phase liquids (NAPLs) into Old Mormon Slough. Additional discussions focused on the ability to place injection and extraction wells in targeted subsurface treatment zones located under the slough. Use of angled borings to position the wells was discussed at the project kick-off meeting on March 7, 2001. This memorandum summarizes information obtained regarding the feasibility of using angled wells to reach the depths targeted by Steam Tech for subsurface injection and extraction.

Background

The three thermal treatment scenarios include treatment of the North – Main Processing Area (N-MPA), which extends under Old Mormon Slough. Each scenario includes installation of steam injection wells and electrical resistance heating electrodes at depths below the B-C aquitard, at depths of –120 feet or more below mean sea level (MSL). The angles required for installation of these wells are generally less than 30 degrees from vertical, with several approaching 40 degrees. The maximum length of these borings are under 300 linear feet.

Discussion

Drilling contractors were contacted by Steam Tech and URS personnel to determine if the boring angles anticipated for the under-slough wells and electrodes posed a concern for construction or operation. Lane Christiansen (Fontana, CA) provided budgetary numbers for injection/extraction well construction, including the angled borings. Boart Longyear (Dayton, NV) also provided technical feedback to Steam Tech regarding construction techniques and maximum angles for conventional drilling equipment.

Based on these discussion, rotary (mud or air) and sonic drilling equipment appear capable of installing these wells at the angles anticipated for the thermal treatment scenarios. Horizontal boring equipment, typically used for trenchless utility and horizontal well installation, were not considered appropriate for the planned installations. Phone memos regarding this input are enclosed as attachments to this memorandum.

"Steve Carroll"
<carroll@steamtech.c
om>

07/02/01 09:22 AM

To: Harry_Ehlers@URSCorp.com
cc:
Subject: RE: angled drilling at McCormick and Baxter site

Good Morning Harry,

further to our telephone conversation of Friday afternoon, I have made some enquiries and found that San Francisco - Sacramento area environmental drilling contractors typically had doubts about drilling to depths of 300 feet at the angles of interest. On the face of it, this might require some changes to the design, possibly with additional, deeper, drilling from a barge in the slough.

I am assured by Patrick Langan (775-246-0296) of Boart Longyear in Dayton, NV, that they would anticipate no difficulty in drilling to these depths at angles as low as 45 degrees using rotary or sonic rigs with down-hole casing advance and that 4 or 6-inch casing and screen could be installed. You may wish to talk to him.

Let me know if I can be of any assistance.

Steve Carroll

(661) 322 6552 Fax
(908) 653-1313 Fax

June 12, 2001

John E. Spear
URS Corporation
12 Commerce Drive
Cranford, NJ 07016-1101

Tim Cechini
Lane Christiansen
Fontana, CA

Re: McCormick and Baxter Superfund Site
Stockton, CA
Drilling Pricing

Dear Tim:

As we discussed in early May we need budget pricing for the drilling and installation of wells at the referenced site. We are working on an Engineers estimate for the Feasibility of this option under contract with the USACOE.

The pricing could be broken down in the following unit prices:

Extraction Well pumps 725.00
well 450
Temp 450
1625

Unit Price

1. Drilling wells, 12" dia. (288 Wells) 36,851 LFT 135.00/ft
   These are extraction and injection wells with 6" casing/screens all Stainless Steel.
   Note that 15 of these wells will be drilled off barge in the Old Mormon Slough.
   Also 15 of these wells will be drilled at an angle from the bank under the Slough.
2. Install URS furnished Electrodes 44 EA 450.00/each
   These electrodes will go in the bottom of some of the 288 wells drilled above.
3. Install URS furnished Extraction Pumps 124 EA 725.00/each
4. Install URS furnished Thermocouples ave 40.00/lft → 38 EA 9000.00/each
   These thermocouples (VEA's) will be installed in 4" dia holes and grouted solid. Total drilling for these 38 will be 8,560 vertical feet.
5. 12" Protective Case and Well head up to flange 288 EA 250/well
6. Install URS furnished Down Hole Instruments 288 EA 450.00/each
7. Well Development 288 EA 1000.00/each
   288 Extraction and Injection wells. Monitoring wells below.
8. Pump tests 4 EA 6,300.00/test

9. Monitoring wells (39 each with 4" SS Piping/Screens) 5,580 LFT 100/H
Complete including drilling, developing, piping, locking caps,

All wells above would include packing, grout etc required in ea. Well.

If you have any questions please call me in my NJ office at 908-653-3154 or 908-653-1300. My fax number in NJ is 908-653-1313.

Cordially,

John E. Spear