

**DEVELOPMENT OF DESIGN CURVES FOR RECIRCULATING WELL
TECHNOLOGY: MASSACHUSETTS MILITARY RESERVATION
CHEMICAL SPILL 10 PLUME**

by

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Submitted to the Department of Civil and Environmental Engineering
In Partial Fulfillment of the Requirements for the Degree of

MASTER OF ENGINEERING
IN CIVIL AND ENVIRONMENTAL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
June 1997

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ABSTRACT

The Massachusetts Military Reservation (MMR), located in Cape Cod, Massachusetts, has hosted numerous branches of the military since 1911. Intense land use and uncontrolled chemical releases have caused the contamination of groundwater known as the Chemical Spill 10 (CS-10) plume. Originally, the plan for the remediation of the CS-10 plume involved pump and treat technology. However, the Technical Review and Evaluation Team (TRET), opposed this technique, fearing ecological damage to local ponds. The TRET recommended the evaluation of recirculating well technology by conducting a pilot test in an area of high contamination. Recirculating wells are favored because they treat groundwater without the need and expense of pumping the groundwater to the surface for treatment, and cause little or no disturbance of the water table elevations.

The objective of this thesis was to develop recirculating well design curves specifically for the MMR. These design curves relate the recirculating well pumping rate to the resulting upstream capture zone. The graphs were based on the recirculating well designs of IEG Technologies Corporation and EG&G Environmental, Inc. and the specific soil characteristics of the MMR.

In order to accomplish this task, a three-dimensional, finite-element model was developed to estimate the upstream capture zone for various pumping rates. The site-specific recirculating well design curves were generated on the basis of these results. The results indicate that IEG's recirculating well retreats more groundwater, while EG&G's recirculating well captures more of the untreated groundwater plume.

In conclusion, the site-specific design graphs and dimensionless design graphs will aid in the design of future recirculating well systems at the MMR, because engineers will be able to estimate the upstream capture zone based on the pumping rate.

Thesis Supervisor: Peter Zeeb

Title: Lecturer of Civil and Environmental Engineering

ACKNOWLEDGMENTS

I would first like to say that this thesis would not have been possible without the love and support of my family. I want to thank my Mom, my Dad, and Clara. I am forever in their debt and I thank them for teaching me that to be a rich man you only need one thing...a family that loves you.

I would now like to thank my high school sweetheart and best friend, Lauri Chaves for all her love and support. I thank her with all my heart and I will never forget all the emotional support she gave me over the past year. I specially thank her for always being there to talk to me during the tough times. In addition she was never afraid to give me a kick in the butt when I needed it.

Next I must thank Dr. Peter Zeeb, my thesis advisor. I know he was very busy at work; therefore, I thank him for taking time out of his busy schedule to advise me. His professional guidance was instrumental in the success and completion of this thesis. Next, I would like to acknowledge Bruce Jacobs and Enrique López-Calva for their help and guidance through all the DYNSSYSTEM simulations.

I would like to send a very special thank you to Professor David Marks who always believed in me. I thank him for allowing me to become part of the M. Eng. program; thereby, forever changing my life. I would also like to thank Shawn Morrissey and Charlie Helliwell of the M. Eng. program for all their advice and willingness to listen.

Next, I would like to acknowledge my fellow recirculating well project members: Carl Kim, Tina Lin, and Mathew Smith. Without their dedication and hard work, the group project would not have been such a success. I would specially like to thank Tina Lin for teaching me the DYNSSYSTEM code, without her help I would have never been able to start my thesis.

Finally, I would like to all the M. Eng. students who shared in all the wild nights in Room 1-143. I would specially like to thank all the members of the late night crew: Dan Baker, Becky Kostek, Jill Manning, Juan Carlos Pérez, Seth Schneider, and last but not least the President of the late night crew Dave Lockwood. I enjoyed all laughs and thank everyone for making the tough times a little more enjoyable.

TABLE OF CONTENTS

ABSTRACT.....	2
ACKNOWLEDGMENTS	3
LIST OF FIGURES	6
LIST OF TABLES.....	8
LIST OF APPENDICES.....	9
1. INTRODUCTION.....	10
1.1 PROBLEM DEFINITION.....	10
1.2 TEAM OBJECTIVE.....	10
1.3 INDIVIDUAL OBJECTIVE.....	11
1.4 SCOPE.....	12
2. BACKGROUND AND SITE DESCRIPTION.....	13
2.1 MMR BACKGROUND AND SITE DESCRIPTION	13
2.1.1 Location.....	13
2.1.2 History of Operation	16
2.1.3 Surrounding Land Use	16
2.1.4 Climate	17
2.1.5 Geology and Geography	17
2.1.6 Hydrogeology.....	19
2.2 CS-10 BACKGROUND AND SITE DESCRIPTION.....	21
2.2.1 Location and Land Use	21
2.2.2 History of Operation	21
2.2.2.1 BOMARC Activities	21
2.2.2.2 UTES Activities.....	24
2.2.3 CS-10 Plume	25
3. RECIRCULATING WELL TECHNOLOGY REVIEW	27
3.1 ADVANTAGES AND DISADVANTAGES OF RECIRCULATING WELLS.....	29
3.1.1 Advantages over Pump and Treat Systems.....	29
3.1.2 Advantages over Air Sparging.....	30
3.1.3 Disadvantages of Recirculating Wells	30
3.2 DESIGN AND USE AT MMR	32
3.2.1 IEG Technologies Corporation	32
3.2.2 EG&G Environmental, Inc.....	37
4. METHOD OF DESIGNING RECIRCULATING WELLS	41
4.1 HERRLING APPROACH	41
4.1.1 Sphere of Influence and Capture Zone	42
4.1.1.1 Recirculating Well Flow Field.....	42
4.1.1.2 Diagrams for the Dimensioning of Recirculating Wells.....	44
4.1.2 Shortfalls of the Herrling Approach.....	49
4.2 NUMERICAL MODEL APPROACH.....	49
4.2.1 DYNYSYSTEM™ Description.....	50
4.2.2 Model Development and Procedure.....	50

4.2.2.1 Capture Zone Simulation.....	53
4.2.2.2 Effect of the Water Elevation Simulation.....	53
4.2.2.3 Recirculating Particle Simulation.....	54
4.2.3 Flow and Transport Simulation for IEG Technologies Corporation Well.....	55
4.2.4 Flow and Transport Simulation for EG&G Environmental, Inc. Well.....	57
4.2.5 Discussion of Simulations.....	59
5. RESULTS AND DISCUSSION	65
5.1 COMPARISON BETWEEN MODEL RESULTS AND HERRLING CHARTS	65
5.1.1 IEG Technologies Corporation	65
5.1.2 EG&G Environmental, Inc.....	66
5.1.3 Discussion of Comparison	67
5.2 EFFECT OF WATER TABLE ELEVATION SIMULATION	68
5.3 DESIGN CURVES	69
5.3.1 Capture Zone Simulation	69
5.3.1.1 IEG Technologies Corporation	69
5.3.1.2 EG&G Environmental, Inc.	71
5.3.2 Recirculated Particle Simulation.....	72
5.3.2.1 IEG Technologies Corporation	73
5.3.2.2 EG&G Environmental, Inc.	75
5.3.3 Discussion of Results and Optimization.....	76
6. CONCLUSION	78
7. FUTURE WORK	79
8. REFERENCES.....	80

LIST OF FIGURES

Figure 2-1: Site Location Map.....	14
Figure 2-2: MMR Site Map	15
Figure 2-3: Upper Cape Cod Geologic Map.....	18
Figure 2-4: Upper Cape Cod Water Table Contour Map	20
Figure 2-5: UTES/BOMARC CS-10 Operable Units.....	22
Figure 2-6: Extent of CS-10 Plume	26
Figure 3-1: Recirculating Well Technology Conceptual Flow Diagram.....	28
Figure 3-2: IEG Recirculating Well Technology Conceptual Flow Diagram	34
Figure 3-3: IEG Circulation Cell Dimension Notations	36
Figure 3-4: EG&G Recirculating Well Technology Conceptual Flow Diagram	38
Figure 3-5: EG&G Circulation Cell Dimension Notations	40
Figure 4-1: Vertical Longitudinal Cross Section of the Flow Field Produced	43
Figure 4-2: Notation for the Upstream Capture Zone.....	45
Figure 4-3: Herrling Charts.....	46
Figure 4-4: Herrling Chart for Stagnation Point.....	48
Figure 4-5: Finite Element Grid.....	51
Figure 4-6: IEG Technologies Corporation Model Vertical Discretization	56
Figure 4-7: EG&G Environmental, Inc. Model Vertical Discretization.....	58
Figure 4-8: IEG’s Model Particle Starting Position.....	60
Figure 4-9: EG&G’s Model Particle Starting Position.....	61
Figure 4-10: IEG’s Upstream Capture Zone.....	62
Figure 4-11: EG&G’s Upstream Capture Zone	63
Figure 5-1: IEG Technologies Corporation Recirculating Well Schematic	70
Figure 5-2: IEG Upstream Capture Width vs. Pumping Rate	70
Figure 5-3: IEG Dimensionless Upstream Capture Width vs. Pumping Rate.....	70
Figure 5-4: EG&G Environmental, Inc. Recirculating Well Schematic	71
Figure 5-5: EG&G Upstream Capture Width vs. Pumping Rate.....	72
Figure 5-6: EG&G Dimensionless Upstream Capture Width vs. Pumping Rate	72
Figure 5-7: IEG Percent of Groundwater Flow vs. Pumping Rate	74
Figure 5-8: IEG Flow of Groundwater into Well vs. Pumping Rate.....	74

Figure 5-9: EG&G Percent of Groundwater Flow vs. Pumping Rate76
Figure 5-10: EG&G Flow of Groundwater into Well vs. Pumping Rate76

LIST OF TABLES

Table 3-1: IEG Installation Summary	31
Table 3-2: EG&G Installation Summary	32
Table 3-3: IEG Circulation Cell Dimensions.....	35
Table 3-4: EG&G Circulation Cell Dimensions.....	39
Table 4-1: IEG Technologies Corporation Model Input.....	55
Table 4-2: EG&G Environmental, Inc. Model Input.....	57
Table 5-1: Summary of Results for IEG Technologies Corporation	66
Table 5-2: Summary of Predicted for EG&G Environmental, Inc.	67
Table 5-3: IEG Capture Zone with different Water Table Elevations	68
Table 5-4: EG&G Capture Zone with different Water Table Elevations.....	68
Table 5-5: IEG Upstream Capture Width vs. Pumping Rate.....	69
Table 5-6: EG&G Upstream Capture Width vs. Pumping Rate	71
Table 5-7: IEG Percent of Recycled Flow vs. Pumping Rate.....	73
Table 5-8: EG&G Percent of Recycled Flow vs. Pumping Rate	75

LIST APPENDICES

APPENDIX A: MODEL INPUT AND COMMAND FILES FOR IEG TECHNOLOGIES CORPORATION.....	84
APPENDIX A.1 COMMAND FILE FOR DYNFLOW	85
APPENDIX A.2 COMMAND FILE FOR DYNTRACK CAPTURE ZONE SIMULATIONS.....	87
APPENDIX A.3 PROPERTY FILE USED FOR DYNTRACK	93
APPENDIX A.4 COMMAND FILE FOR DYNTRACK RETREATMENT SIMULATIONS.....	94
APPENDIX A.5 DYNPLOT GRAPHICAL OUTPUT OF CAPTURE ZONE FOR DESIGN PUMPING RATE	98
APPENDIX A.6 DYNPLOT GRAPHICAL OUTPUT OF CAPTURE ZONE FOR DIFFERENT PUMPING RATES.....	102
APPENDIX A.7 DYNPLOT GRAPHICAL OUTPUT OF RECIRCULATING ZONE FOR DIFFERENT PUMPING RATES	113
APPENDIX B: MODEL INPUT AND COMMAND FILES FOR EG&G ENVIRONMENTAL, INC.....	125
APPENDIX B.1 COMMAND FILE FOR DYNFLOW	126
APPENDIX B.2 COMMAND FILE FOR DYNTRACK CAPTURE ZONE SIMULATIONS.....	128
APPENDIX B.3 PROPERTY FILE USED FOR DYNTRACK	135
APPENDIX B.4 COMMAND FILE FOR DYNTRACK RETREATMENT SIMULATIONS.....	136
APPENDIX B.5 DYNPLOT GRAPHICAL OUTPUT OF CAPTURE ZONE FOR DESIGN PUMPING RATE	139
APPENDIX B.6 DYNPLOT GRAPHICAL OUTPUT OF CAPTURE ZONE FOR DIFFERENT PUMPING RATES.....	143
APPENDIX B.7 DYNPLOT GRAPHICAL OUTPUT OF RECIRCULATING ZONE FOR DIFFERENT PUMPING RATES	154

1. INTRODUCTION

The Massachusetts Military Reservation (MMR), located in Cape Cod, Massachusetts, has hosted numerous branches of the military since 1911. The training and maintenance activities associated with MMR have adversely affected the regional Cape Cod ecological system by releasing a number of hazardous compounds into the environment. Section 120 of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 provides guidelines for the remediation of hazardous constituents released from federal facilities. CERCLA also authorizes the United States Environmental Protection Agency (USEPA) to include sites formerly owned or operated by another federal agency to be placed on the National Priorities List (NPL) (CMMD, 1996). The NPL is a list of hazardous waste sites ranked in order from high potential for adverse health effects to low potential for adverse health effects. MMR was added to the NPL in 1989 and is currently being investigated under the Installation Restoration Program (IRP) section of the Environmental Restoration Program.

1.1 Problem Definition

In January 1996, the 60 percent remedial design for all plumes by Operational Technology (OpTech) called for 100 percent containment using pump and treat technology. Residents, however, opposed this technique, fearing ecological damage to local ponds due to the lowering of water levels caused by extracting large quantities of groundwater. Hence, the Technical Review and Evaluation Team (TRET) deemed the design unacceptable. The TRET recommended the evaluation of recirculating well technology. Recirculating wells are favored because they treat groundwater without the need and expense of pumping the groundwater to the surface for treatment, and cause little or no disturbance of the water table elevations.

1.2 Team Objective

Because this technology is relatively new, a team of four Master of Engineering students from the Department of Civil and Environmental Engineering at the Massachusetts Institute of Technology will evaluate the performance of IEG Technologies Corporation and EG&G Environmental, Inc. recirculating well equipment. Pilot installations of these two well designs

were installed for the Unit Training Equipment Site/Boeing Michigan Aerospace Research Center (UTES/BOMARC) plume in December 1996. First, the team will complete a general study of the recirculating well technology including a review of applications of this technology. Second, the team will model the remediation process of this technology in order to evaluate the design parameters. Third, the team will investigate the geotechnical issues associated with recirculating wells. Finally, the team will determine the feasibility and cost-effectiveness of using recirculating well technology for the remediation of CS-10 versus OpTech's proposed pump and treat design.

1.3 Individual Objective

This thesis is part of a group evaluation of recirculating well technology. The objective of this thesis is to develop recirculating well design curves specifically for the MMR. These design curves will relate the recirculating well pumping rate to the resulting upstream capture zone. The graphs will be based on the recirculating well designs of IEG Technologies Corporation and EG&G Environmental, Inc. and the specific soil characteristics of the MMR. The design graphs will aid in the design of future recirculating well systems at the MMR, because engineers will be able to estimate the upstream capture zone based on the pumping rate.

Recirculating well design curves were first developed by Herrling (Herrling et al., 1991). Herrling's recirculating well design graphs can be used as a first approximation of the upstream capture for recirculating wells with screens fixed at the top and bottom of the aquifer. Although EG&G Environmental, Inc. recirculating wells consist of two screened intervals, the screens are placed at the top and bottom of the plume rather than at the top and bottom of the aquifer. In contrast, IEG Technologies Corporation recirculating wells consist of three screened intervals which are placed at the top, middle, and bottom of the plume. Because of these differences, site-specific design graphs will be developed for the use of engineers at MMR.

1.4 Scope

This thesis describes the development of recirculating well design graphs specifically for the MMR. Chapter 2 provides a detailed site description, including the location, history, and physical and environmental conditions of both the MMR and the UTES/BOMARC (CS-10) site.

Chapter 3 describes recirculating well technology. Included in this section is a discussion of its advantages, disadvantages, and the specific recirculating well designs used at the MMR.

In Chapter 4, the method of designing recirculating wells is presented. First, an introduction to the design protocol is discussed. Then, a review of Herrling's article on the design of recirculating wells is presented. Finally, the design approach used to develop the recirculating well design graphs for the MMR is explained.

In Chapter 5, recirculating well design graphs for the MMR are presented. Specifically, design graphs that relate the recirculating well pumping rate to the resulting upstream capture zones are shown. Included in this chapter is a discussion of the significance of the design curves in optimizing the remediation design.

Chapter 6 and 7 concludes the thesis with a discussion of the implication of the design curves and additional work that would enhance the results.

2. BACKGROUND AND SITE DESCRIPTION

This section includes background information and site descriptions of the MMR, and more specifically the CS-10 plume. In order to investigate a remediation technology for the CS-10 plume, it is vital to have an understanding of the location, history, and the physical and environmental conditions of both the MMR and the CS-10 plume.

2.1 MMR Background and Site Description

This section describes the physical and environmental conditions of MMR. The focus of this section includes location, history of operation, surrounding land use, climate, geography, geology, and hydrogeology of the MMR.

2.1.1 Location

The MMR lies in the upper western portion of Cape Cod, Massachusetts. It occupies approximately 22,000 acres (35 square miles) within the towns of Bourne, Sandwich, Mashpee, and Falmouth in Barnstable County (see Figure 2-1).

The MMR is divided into four principal areas (see Figure 2-2):

- Maneuver Range and Impact Area - A 14,000 acre site occupying the northern 70 percent of MMR and used for training and maneuvers.
- Cantonment Area - A 5,000-acre area located in the southern portion of MMR. This area includes administration, operational, maintenance, housing, and support facilities for the base.
- Airfield - A 4,000 acre area located along the south eastern edge of the MMR. This area contains the runways and support facilities for aircraft.
- Massachusetts National Cemetery - A 750-acre area located along the western edge of the MMR. This area contains the Veterans Administration (VA) cemetery and support facilities.

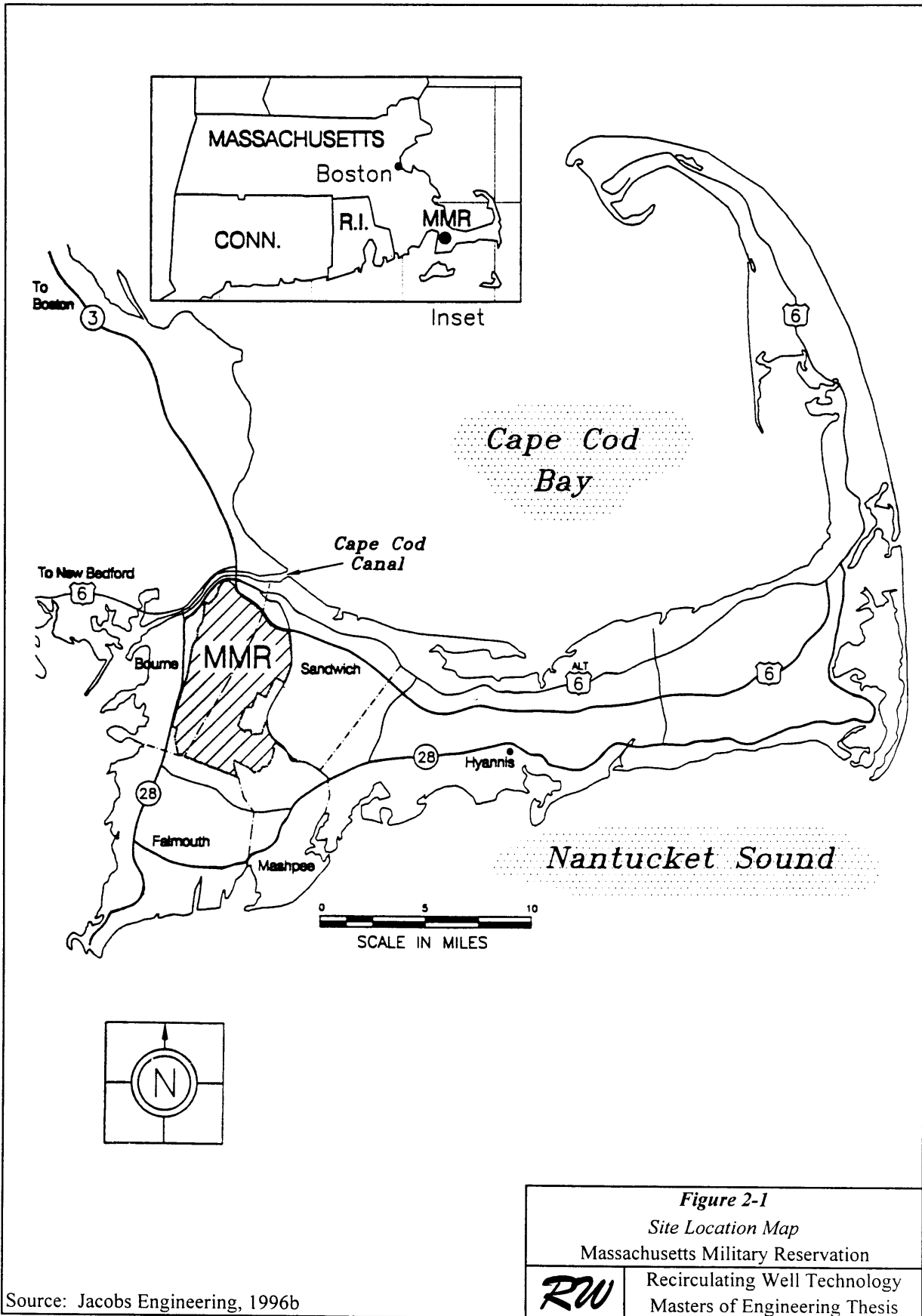
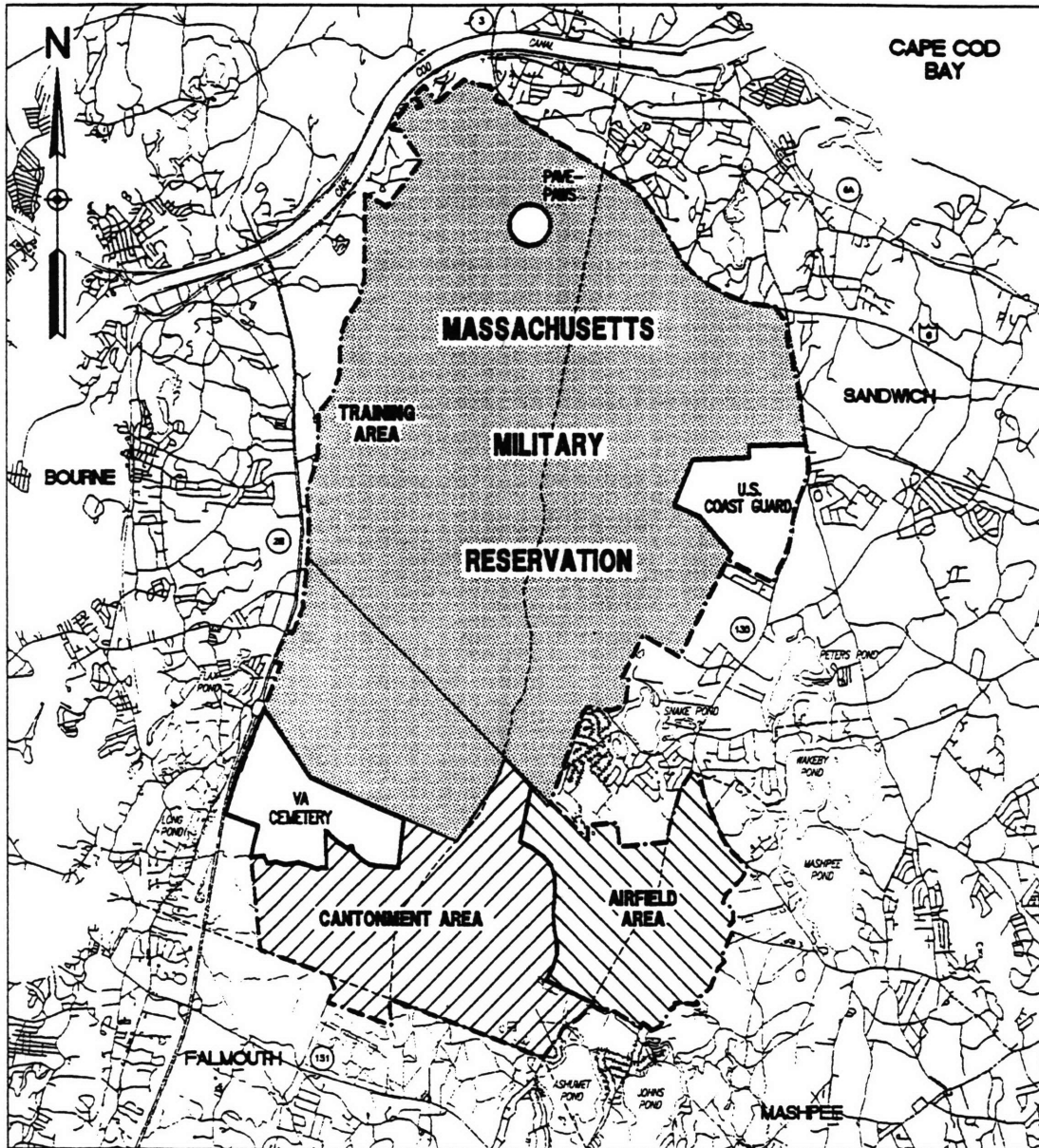


Figure 2-1
Site Location Map
 Massachusetts Military Reservation

RW	Recirculating Well Technology Masters of Engineering Thesis
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Source: Jacobs Engineering, 1996b



LEGEND

- TOWN BOUNDARY
- INSTALLATION BOUNDARY
- 6 6A US/STATE HIGHWAY

- TRAINING AREA
- CANTONMENT AREA
- AIRFIELD AREA
- OTHER USE

0 4000 8000 FEET
1" = 8000'

Figure 2-2
MMR Site Map
Massachusetts Military Reservation

RW	Recirculating Well Technology Masters of Engineering Thesis
-----------	--

Source: The Commonwealth of Massachusetts Military Division, 1996

2.1.2 History of Operation

While military activity at MMR began in 1911, most military activity occurred after 1935 by the U.S. Army, U.S. Navy (USN), U.S. Coast Guard (USCG), U.S. Air Force (USAF), Massachusetts Army National Guard (ARNG), U.S. Air National Guard (ANG), and the Veterans Administration (VA). The level of activity at MMR has varied over its history. The most intense U.S. Army activity occurred during World War II (WWII) and the demobilization period after WWII. During this period, the Cantonment Area housed thousands of troops and operated a large motor pool. The USN carried on advances in naval aviation flight training during the last two years of WWII. The USAF maintained an intensive airborne surveillance operation from 1955 to 1970 (CDM Federal, 1993).

Currently, the ARNG and U.S. Army Reserve conduct a variety of training activities at the MMR. The USCG air station at MMR provides medium-range search and recovery support of the 1st Coast Guard District and Atlantic Area. The ANG air station at MMR operates and maintains a squadron of F-15 fighter aircraft to protect the northeastern United States from armed attack. The USAF operates the Precision Acquisition Vehicle Entry - Phase Array Warning System (PAVE-PAWS) for missile and space vehicle tracking. The Veterans Administration also maintains the Massachusetts National Cemetery at the MMR (CDM Federal, 1993).

2.1.3 Surrounding Land Use

Land uses in the area surrounding MMR include recreational activities such as golfing, swimming, boating and hunting. Two adjacent ponds, John's Pond and Ashumet Pond, support swimming, fishing, boating and water skiing. The Shawme Crowell State Forest and Crane Wildlife Management Area support camping, fishing, hiking, and mountain biking. Camp Good News, a summer camp for children, is located on Snake Pond. Besides recreational usage, land is also used for agriculture. Most of the agricultural land is used for the cultivation of cranberries. The remaining land is used for the residential, commercial, and industrial sectors (CDM Federal, 1993).

2.1.4 Climate

The climate at MMR is classified as humid continental. The Atlantic Ocean moderates the temperature; therefore, Cape Cod undergoes warmer winters and cooler summers than inland areas in Massachusetts. February is usually the coldest month of the year with daily temperatures ranging from 23°F to 38°F. July is usually the warmest month of the year with daily temperatures ranging from 63°F to 78°F (CDM Federal, 1993).

Precipitation is fairly evenly distributed throughout the year, with the least rainfall occurring in June. The average annual rainfall is 46 inches (NCDC, 1990). The net annual recharge is estimated to be 21 inches (LeBlanc, 1982). Prevailing winds are from the northwest between the months of November and March with an average wind speed of 12 mph. Between the months of April and October, the prevailing winds are from the southwest with an average wind speed of 9 mph. Tropical and oceanic storms occasionally cause short periods of much higher wind speeds (CDM Federal, 1995).

2.1.5 Geology and Geography

Western Cape Cod is composed of glacial sediments deposited during the retreat of the Wisconsin glacier between 7,000 and 85,000 years ago. The western Cape Cod geology is dominated by three sedimentary units: Buzzards Bay moraine, Sandwich moraine, and Mashpee pitted plain. The Buzzards Bay moraine and Sandwich moraine are located along the western and northern edge of Cape Cod with the Mashpee pitted plain located to the south and east (see Figure 2-3). The Buzzards Bay and Sandwich moraines are composed of ablation glacial till, which is unsorted material ranging from clay to boulder-size rocks deposited at the leading edge of two lobes of the Wisconsin glacier. The Mashpee pitted plain is a glacial outwash plain composed of poorly sorted fine to coarse-grained sands. The Mashpee pitted plain is underlain by fine-grained glaciolacustrine sediments and base till (CDM Federal, 1993).

The sediment thickness ranges from 175 feet near Cape Cod Canal in the northwest to 325 feet at the thickest portion of the Buzzards Bay moraine. The Mashpee pitted plain outwash sediment varies in thickness from approximately 225 feet in the north to 80 feet near Nantucket Sound.

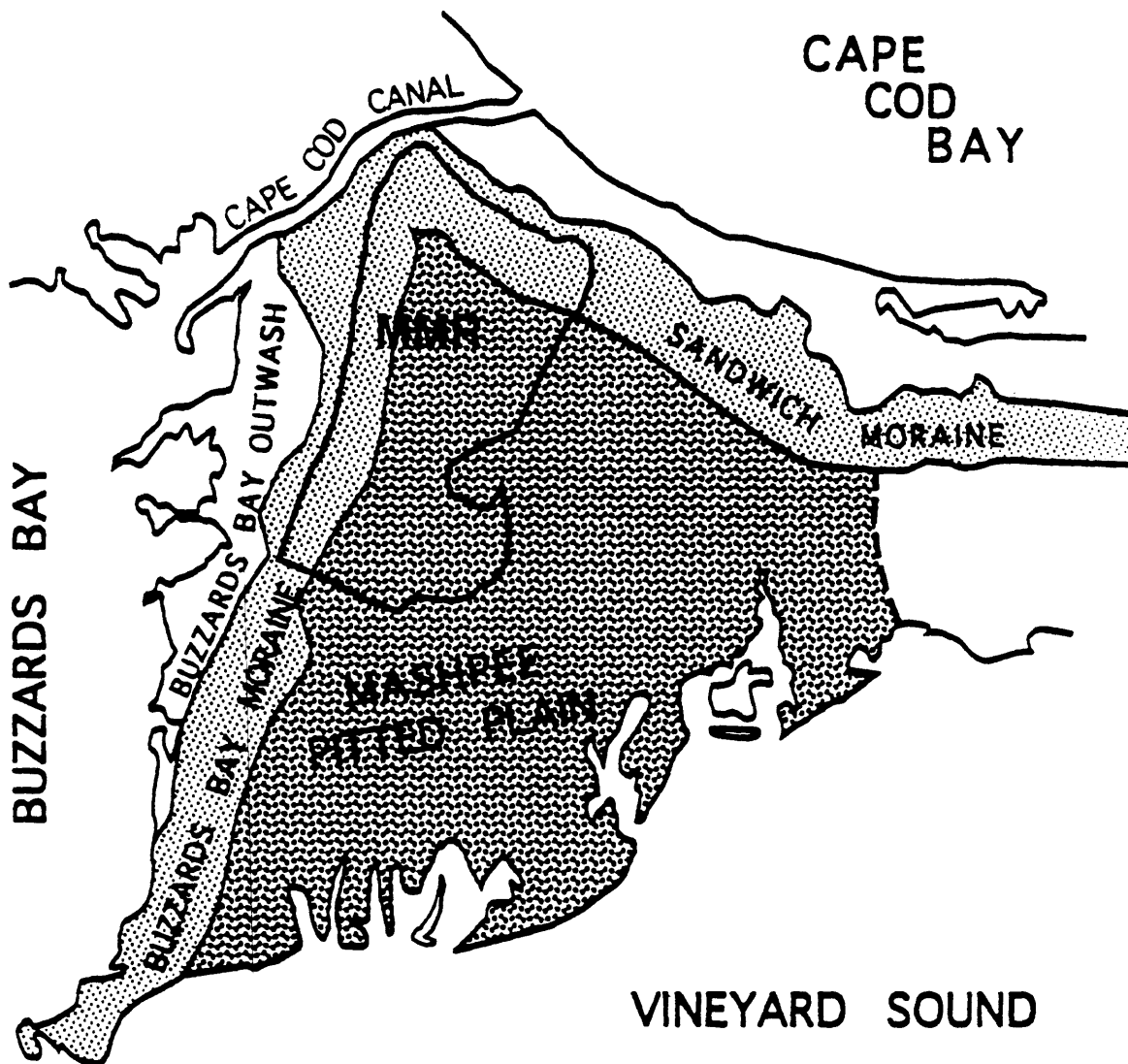


Figure 2-3

Upper Cape Cod Geologic Map
Massachusetts Military Reservation

ROW

Recirculating Well Technology
Masters of Engineering Thesis

Source: E.C. Jordan, 1989

The thickness of the glaciolacustrine sediment and base till underneath the Mashpee pitted plain increases as the Mashpee pitted plain sediment decreases. The granodiorite bedrock lies approximately 300 feet below ground surface and slopes to the south-east (CDM Federal, 1993).

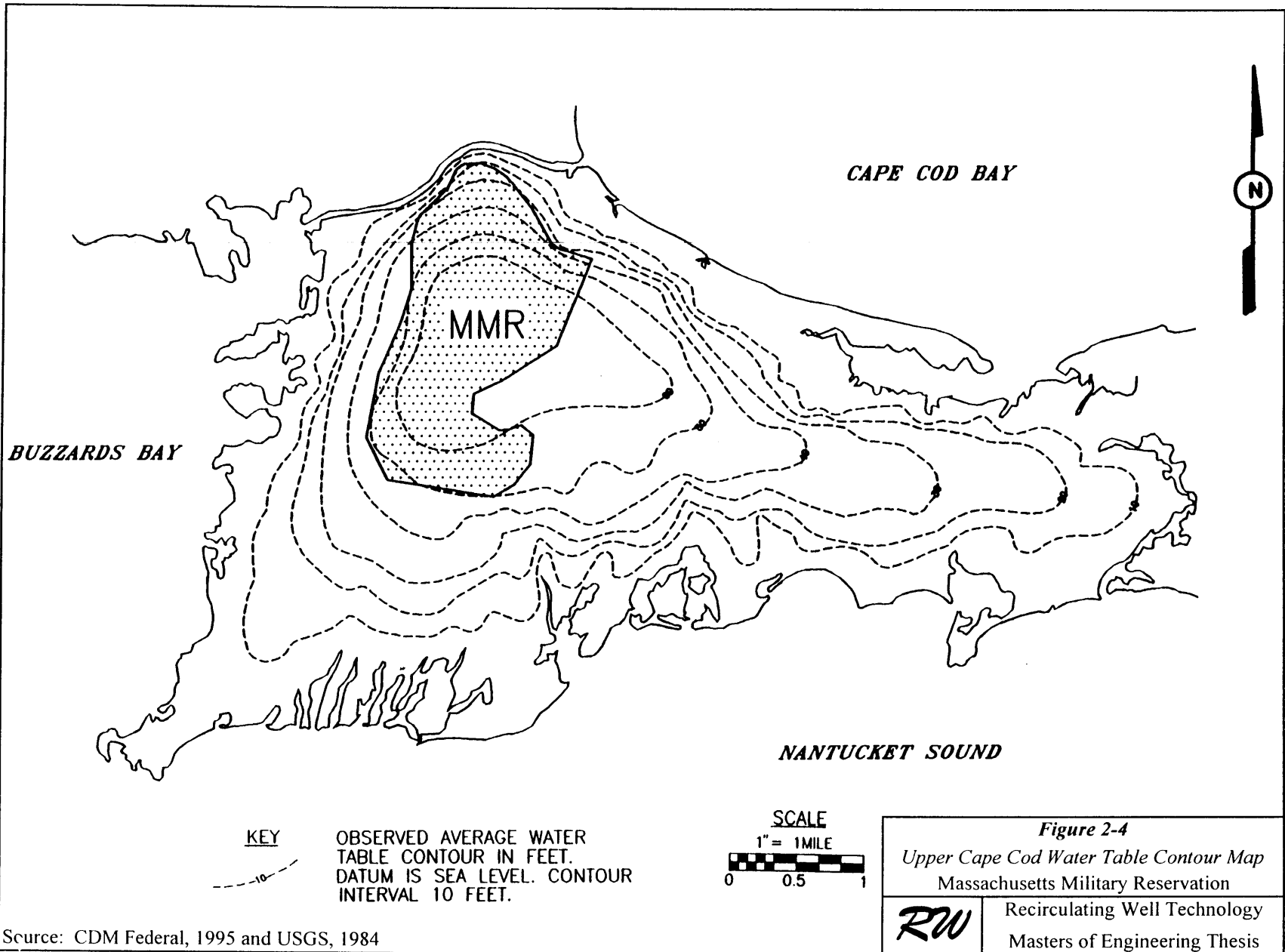
MMR is located on two types of geographic terrain. The Cantonment Area lies on a southward sloping outwash plain with elevation ranging from 100 to 140 feet above sea level. The area north and west of the Cantonment Area lies in the southern portion of the Wisconsin Age terminal moraines. The presence of irregular hills within this area causes the elevation to range from 100 to 250 feet above sea level, while kettle hole ponds and depressions are found over the entire site (CDM Federal, 1993).

2.1.6 Hydrogeology

The aquifer system in western Cape Cod is unconfined and is recharged by infiltration from precipitation. The high point of the water table occurs as a groundwater mound beneath the northern portion of MMR; therefore, groundwater flows radially outward (see Figure 2-4). The aquifer is bounded by the ocean on three sides, with groundwater discharging into Cape Cod Bay on the north, Buzzards Bay on the west, and Nantucket Sound on the south. Groundwater also discharges into the Bass River in Yarmouth, which forms the eastern lateral aquifer boundary (CDM Federal, 1995).

Surface water at the MMR includes streams and kettle hole ponds in the Mashpee pitted plain. A kettle hole pond is a pond created when buried glacial ice melts creating a local depression. Kettle ponds intercept the water table but cause only local impact on slope and direction of groundwater (CDM Federal, 1995).

The major geology of western Cape Cod is Mashpee pitted plain, which consists of coarse-grained sand and gravel outwash sediment underlain by finer-grained sediments. The hydraulic conductivity of the outwash sediment ranges up to 380 ft/day with a hydraulic gradient range of 0.0014 to 0.0018 ft/ft. The hydraulic conductivity of the underlying fine grained sediment is only 10 percent of the outwash; therefore, the bulk of regional groundwater is transmitted



through the upper outwash layer, where the horizontal flow velocities range from 1 to 3.4 ft/day (CDM Federal, 1995).

2.2 CS-10 Background and Site Description

This section describes the physical and environmental conditions of CS-10. Location and site history are also described in this section.

2.2.1 Location and Land Use

The CS-10 area of contamination is located adjacent to the northeastern boundary of MMR, immediately north of the MMR Sandwich gate on Greenway Road, geographically within the town of Sandwich, Massachusetts (see Figure 2-5). CS-10 occupies approximately 38 acres and is currently used for maintenance and storage of vehicles for the ARNG. Approximately 25 ARNG personnel currently work at CS-10 as part of the UTES operations (CDM Federal, 1993).

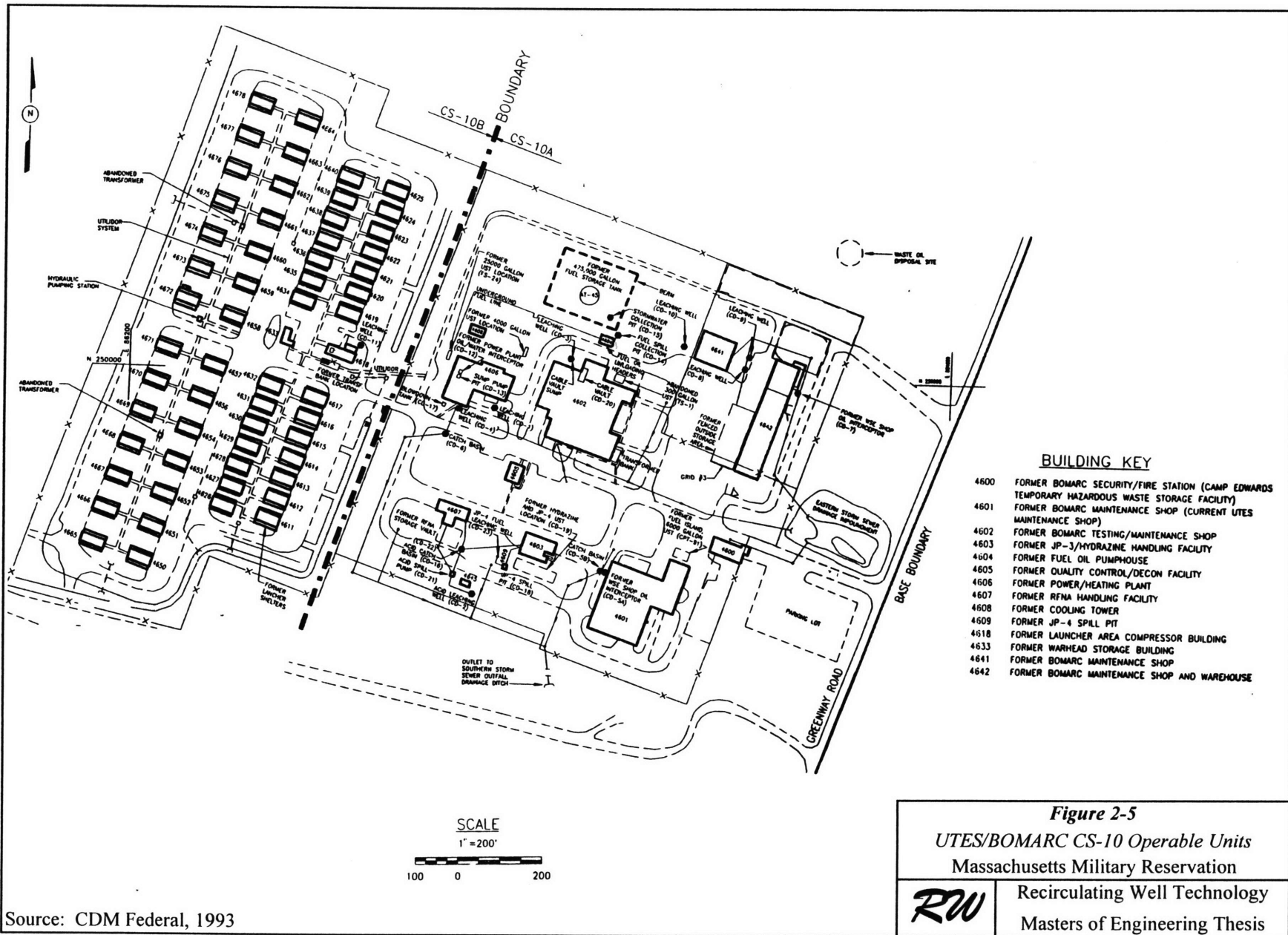
The nearest MMR housing is located approximately 19,000 ft southwest of the site. The nearest off-MMR housing area is located in the Town of Sandwich, with the closest home approximately 650 ft from the eastern fence line. Approximately 75 households are located within a half mile of the CS-10 site in the Town of Sandwich. The residences to the east of CS-10 are all served by private wells (CDM Federal, 1993).

2.2.2 History of Operation

Before 1956, the CS-10 location was occupied by a rifle range. In 1958, the Army Corps of Engineers began constructing the BOMARC missile facility for the USAF. The BOMARC facility was operated by the USAF from 1960 until it was decommissioned in 1973. In 1973, the facility was transferred from the USAF to the ARNG. In 1978, UTES began their activities at the site (CDM Federal, 1993).

2.2.2.1 BOMARC Activities

In December 1960, the 26th USAF Air Defense Missile Squadron began operating the BOMARC site at the MMR under Strategic Air Command control, with technical maintenance assistance



Source: CDM Federal, 1993

from Boeing Corporation. Between 1960 and 1973, the USAF maintained 56 BOMARC ground-to-air missile and launcher systems on site (CDM Federal, 1993).

Two models of BOMARC missiles were maintained at MMR. The BOMARC-A missile, a nuclear-warhead-capable missile, was powered by both a liquid-fuel rocket booster and a ramjet engine. The BOMARC-A missile was stationed at MMR beginning in 1960 and then phased out and replaced by BOMARC-B. The BOMARC-B was also a nuclear-warhead-capable missile which used a solid-fuel rocket booster. The BOMARC-B model was operational from 1962 to 1972. Because of the classified nature of the site activities, little public information exists regarding system operations and maintenance activities, but existing building design plans provide good indication of past actions. The BOMARC facility at MMR consisted of a power plant, a fire station, security and administrative buildings, missile maintenance building, fueling and defueling facility, fuel and oxidizer storage tanks, and 56 missile launcher shelters. The operations that generated the most hazardous waste at the BOMARC facility were missile guidance system maintenance, engine maintenance, and fueling and defueling operations (CDM Federal, 1993).

The maintenance of the guidance system would have required the use of halogenated solvents. Common solvents used by the military during this time period would most likely have been methylene chloride, 1,1,1-trichloroethane (TCA), trichloroethene (TCE), and tetrachloroethene (PCE). It is possible that the military switched to a freon-type solvent like chlorofluoromethane in the last few years of the BOMARC facility activities (CDM Federal, 1993).

The BOMARC-A missile ramjet engine used JP-4 jet fuel. JP-4 contains benzene, toluene, ethylbenzene, xylenes, naphthalene, 2-methylnaphthalene and other hydrocarbons. Waste JP-4 was generated as a result of refueling and maintenance and was disposed by using a leaching field (see CD-24 in Figure 2-5). The BOMARC-A missile also used liquid fuel to boost the missile to its cruising speed before the ramjet engine would take over and propel the missile to its target. In the BOMARC-A missile, the liquid fuel, Aerozine 50, reacted with a strong oxidizing agent, red-fuming nitric acid (RFNA), to produce the force needed to propel the rocket. Aerozine 50 consists of a 50:50 mixture of hydrazine and unsymmetrical dimethylhydrazine

(UDMH). Waste RFNA was disposed of in a neutralization pit containing crushed limestone (see Building 4645 in Figure 2-5). Waste hydrazine and UDMH were pumped into a waste fuel tank and released at a slow rate into a spill pit (see CD-18 in Figure 2-5) to allow complete auto-oxidation to occur (CDM Federal, 1993).

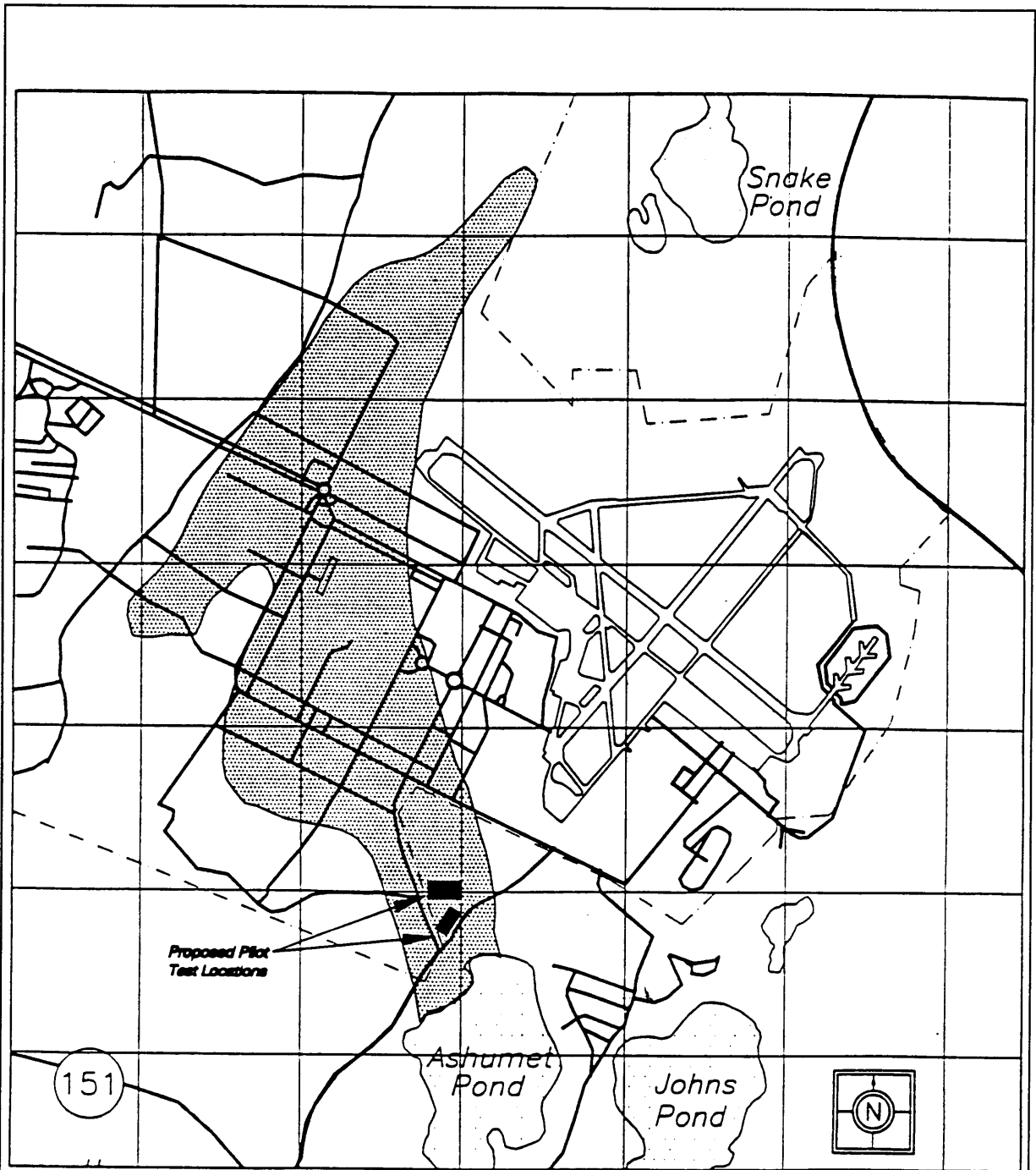
Other potential sources of site contamination at AOC CS-10 from BOMARC activities include vehicle fueling, vehicle maintenance, and power plant operation. Vehicle fueling was conducted at a fuel pump island, which was supplied by a 6,000 gallon underground storage tank (CPT-91 in Figure 2-5). Vehicle maintenance was conducted in the northern portion of Building 4642. The steam-heating and electrical power generation station was operated in Building 4606. No. 2 fuel oil was used to generate steam for the facility heating and electrical power. While these sites were potential sources of contamination, no documents exist to indicate the amount of waste produced or if any fuel spills occurred (CDM Federal, 1993).

2.2.2.2 UTES Activities

The UTES maintenance shop began operating at the BOMARC site in 1978. Currently, UTES is responsible for the maintenance of 300 to 350 armored and wheeled vehicles used for the ARNG training activities at MMR. The maintenance activities are conducted in Building 4601. Waste generated by UTES activities include and have included waste oil, halogenated solvents, petroleum distillate solvents, battery electrodes, paints, and paint removal solvents. From 1978 to 1985, UTES stored waste material in a 500 gallon trailer located near building 4601. From 1978 to 1983, the full 500 gallon trailer was towed to the Defense Property Disposal Office at MMR for disposal. From 1983 to 1985, the full 500 gallon trailer was towed to and emptied into a former BOMARC 10,000 gallon stainless steel RFNA tank located near Building 4607. In 1985, the 10,000 gallon tank were cleaned and removed from the site. Over the years the transfer of waste to the 500 gallon trailer caused the contamination of approximately 25 cubic feet of soil. After the decommissioning of the 500 gallon trailer in 1985, the contaminated soil was removed. Currently, UTES collects its waste into 55 gallon drums and stores them at the Camp Edwards Temporary Hazardous Waste Storage Facility (Building 4600) before they are shipped to an off-site disposal area (CDM Federal, 1993).

2.2.3 CS-10 Plume

As a result of intense land use and improper waste management, the activities at the UTES/BOMARC site have created a large amount of contaminated groundwater. The CS-10 plume originates near the eastern edge of the MMR property line under the UTES/BOMARC site (see Figure 2-6). The plume is approximately 12,500 feet long, up to 3,600 feet wide, up to 135 feet thick, and 140 feet below ground surface at the toe. Trichlorethene, Tetrachlorethene, cis-1,2-dichloroethene (c-1,2-DCE), benzene, lead, and manganese have all been detected in the CS-10 plume (CDM Federal, 1993).



- Primary Road
- Pond
- River/Stream
- MMR Boundary
- Solvent Groundwater Plume Greater Than MCL

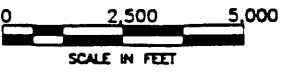


Figure 2-6
Extent of CS-10 Plume
 Massachusetts Military Reservation
 Recirculating Well Technology
 Masters of Engineering Thesis

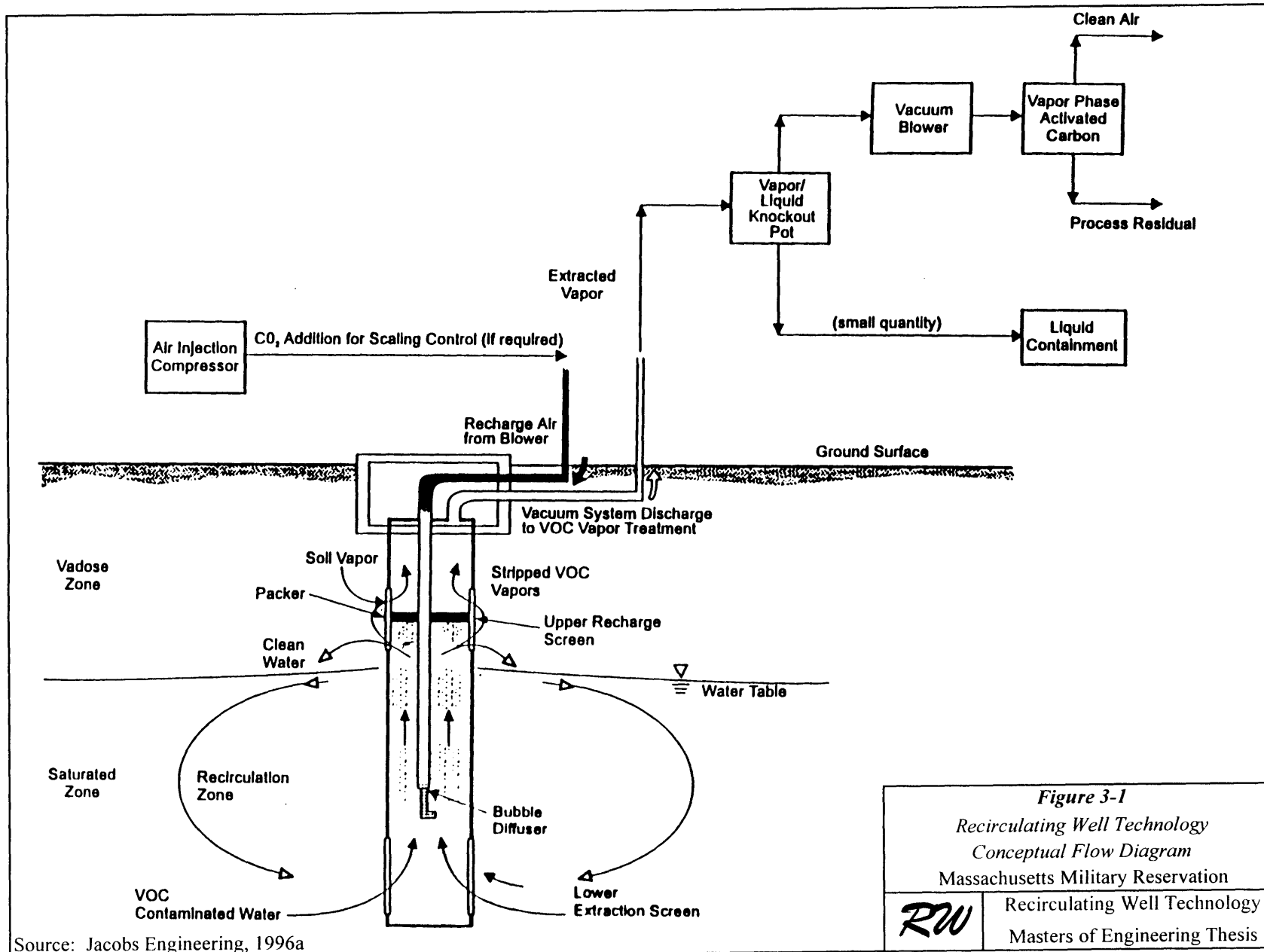
Source: Jacobs Engineering, 1996a

3. RECIRCULATING WELL TECHNOLOGY REVIEW

Recirculating well technology is a new method for in situ remediation of volatile organic compounds (VOCs). The treatment system primarily removes VOCs from groundwater by the physical process of air stripping. While the recirculating well at the MMR uses a modified design, the original recirculating well design relied on pressurized air to lift water through the well and promote the transfer of VOCs from the liquid phase to the vapor phase (see Figure 3-1). Groundwater entered the well through the screened opening and was lifted upward by the pressurized air. The diffused air bubbles stripped the VOCs from the groundwater. The stripped VOCs were collected and treated while the groundwater returned to the aquifer through a second screened opening. Additionally, the aeration of groundwater promoted in-situ aerobic biodegradation of VOCs (Jacobs Engineering, 1996a).

As a result of the contaminated groundwater entering the recirculating well at one screened interval and discharging out of the well at another screened interval, a circular flow cell develops in the aquifer. The circular cell causes a portion of the contaminated groundwater to be recirculated, which further reduces the contamination. The retreatment of groundwater is one reason why recirculating wells have an advantage over pump and treat systems. Another advantage of recirculating wells over pump and treat systems is that recirculating wells provide in situ treatment with minimal drawdown effects (Jacobs Engineering, 1996a).

The following sections discuss advantages and disadvantages of the technology along with the specific well designs currently used at the MMR.



Source: Jacobs Engineering, 1996a

3.1 Advantages and Disadvantages of Recirculating Wells

Recirculating wells have advantages and disadvantages over both pump and treat systems and air sparging systems. In order to understand the advantages associated with recirculating wells, one must understand the basic concepts behind treating VOCs with each system. As stated in the previous section, recirculating wells extract contaminated groundwater from one screened interval, treat the groundwater, and re-inject the treated groundwater at another screened interval in the same well. Pump and treat systems extract contaminated groundwater, treat the groundwater above the surface, and re-inject the treated groundwater at another location. Air sparging treats groundwater without the need to capture it. The succeeding sections discuss the advantages and disadvantages of recirculating wells, relative to pump and treat and air sparging.

3.1.1 Advantages over Pump and Treat Systems

Recirculating wells have numerous physical and cost advantages over pump and treat systems. First, recirculating wells strip VOCs without extracting large amounts of groundwater, thereby eliminating the environmental impact associated with drawdown. Water table drawdown can impact wetlands, water resources, saltwater intrusion, and foundation settlement. The second advantage of recirculating wells is the creation of a local groundwater circulation cell, in which groundwater travels both horizontally and vertically. The induced vertical flow is effective in flushing areas which are usually untreated because of horizontal heterogeneities. As a result, time and cost of remediation may be reduced. The third advantage over pump and treat systems is associated with enhanced biodegradation. After the VOCs are stripped, the groundwater returned to the aquifer is saturated with dissolved oxygen; therefore, the recirculating well creates an environment conducive to aerobic biodegradation. The enhanced biodegradation can also reduce the time and cost associated with remediation. The fourth advantage is that recirculating wells do not require that groundwater be extracted to the surface; consequently, recirculating wells reduce the cost associated with permitting and monitoring of groundwater extraction and reinjection. Finally, recirculating wells do not need separate reinjection wells; hence, the capital cost is reduced compared to a standard pump and treat system (Metcalf and Eddy, 1996a).

3.1.2 Advantages over Air Sparging

Recirculating wells also have numerous physical and cost advantages over air sparging systems. First, recirculating wells remove groundwater from the surrounding media; consequently, the air is able to contact the groundwater without the interference caused by the soil particles. The greatest limitation of an air sparging system is the phenomenon known as air channeling. When air travels through soil, it chooses the path of least resistance. Once the path is established, air will tend to travel through this channel. By stripping groundwater in the well vault, air channeling is eliminated; therefore, the air stripping efficiency of recirculating wells are more reliable than air sparging systems (Metcalf and Eddy, 1996a).

The second advantage is that recirculating wells extract groundwater; thus, they can be used to contain a contaminated plume, while air sparging systems cannot. The third advantage over air sparging systems is that recirculating wells cause the groundwater to travel horizontally and vertically. The horizontal component of the flow gradients is more effective in flushing areas farther from the well. As a result, time and cost of remediation may be reduced. The fourth advantage of recirculating wells is that they are cheaper to install compared to air sparging systems, because air sparging systems consists of two types of wells: an air injection well and a soil vapor extraction well. Since recirculating wells do not need a separate soil vapor extraction well, the capital cost is reduced compared to air sparging (Metcalf and Eddy, 1996a).

The final advantage of recirculating wells is that they can be installed in deep aquifers. Where as an air sparging system can be installed to remediate only the vadose zone or plumes near the phreatic surface of an aquifer, recirculating wells can be installed to remediate the vadose zone, as well as deep plumes in both phreatic and confined aquifers (Metcalf and Eddy, 1996a).

3.1.3 Disadvantages of Recirculating Wells

Only two companies in the world, IEG Technologies Corporation and EG&G Environmental, Inc., hold patents on the design of recirculating wells. Recirculating wells have been used in Germany to remove VOCs from the groundwater and vadose zone for ten years. The use of recirculating wells in the United States is still very limited (see Tables 3-1 and 3-2 for list of

installations). Because the data associated with the advantages of recirculating well on United States sites are scarce, the MMR is proceeding with caution and conducting a pilot test of both IEG's and EG&G's equipment.

Table 3-1: IEG Installation Summary (IEG, 1996)

Date	Location	Type of System	Geology	Contaminant	Horizontal Hydraulic Conductivity (cm/Sec)	Total Depth (Feet)
1992	Gas Station Troutman, NC	UVB 400 Single Pump	Saprolite Clayey Silt with Sand	Gasoline	1.0 x 10 ⁻⁴	41
1993	USAF Riverside, CA	UVB 400 Single Pump	Alluvial Fan Silty Sand	Chlorinated Hydrocarbons	7.5 x 10 ⁻³	81.7
1993	Confidential Charlotte, NC	UVB 400 3-Screens Single Pump	Saprolite Silty Sand with Clay	Chlorinated Hydrocarbons	1.8 x 10 ⁻³	133.5
1994	W.R. Grace Chester, SC	UVB 400 Single Pump	Saprolite Silty Clay with Clay	Gasoline	1.0 x 10 ⁻⁴	49
1995	U.S. Navy Gainesville, FL	UVB 400 Single Pump	Fine to Medium Sand	Creosote	1.0 x 10 ⁻³	25
1995	New York State Yonkers, NY	UVB 400 Single Pump	Fine to Med. Sand to Sandy Gravel	BTEX	8.8 x 10 ⁻³	30

Table 3-2: EG&G Installation Summary (Metcalf and Eddy, 1996a)

Location	Type of System	Geology	Contaminant	Horizontal Hydraulic Conductivity (cm/sec)	Total Depth (ft)
Edwards AFB California	NoVOC TM	Fine Sand, Silty Sand Clay Lenses	TCE 100 - 300 ppb	2.0×10^{-3}	50
Fairchild AFB Washington	NoVOC TM	Medium Sand with Silt	TPH 10,000 ppb	8.0×10^{-2}	14
Oceana NAS Virginia	NoVOC TM	fine Sand/Sandy Silt Silt	DCE 10,000 ppb	1.0×10^{-3}	20
Industrial Client Idaho	NoVOC TM	Sand with Silt and Clay Lenses	TCE 900 ppb	5.0×10^{-3}	220
USMC AS Arizona	NoVOC TM	Fine Sand	TCE 10 - 20 ppb	1.0×10^{-3}	92
Landfill Site Arizona	NoVOC TM	Medium Sand	100 ppb TCE 500 ppb PCE	2.0×10^{-2}	230

3.2 Design and Use at MMR

The following sections discuss the design of the specific recirculating wells installed for pilot-testing at the CS-10.

3.2.1 IEG Technologies Corporation

SPB Technology, Inc., a licensed representative of IEG Technologies Corporation, has installed two UVB (German acronym for vacuum-vaporized well) systems for the CS-10 groundwater contaminated plume at the MMR site. UVB technology provides in situ groundwater remediation by producing a vertical circulation cell that captures VOC-contaminated groundwater. The captured VOC-contaminated groundwater is then remediated by the combination of air stripping and bioremediation processes. Advertising literature provided by IEG further indicate that the UVB system can be enhanced to treat other contaminants by adding

systems such as biofilters, bioreactors, carbon adsorption containers, metal removal equipment, or nutrient addition. The UVB technology provides in situ remediation while maintaining an equilibrium flow in the aquifer, thereby eliminating the drawdown effect associated with traditional pump and treat systems (Jacobs Engineering, 1996a).

The UVB system installed at the MMR uses a specially adapted groundwater well that incorporates three screened casing sections, a groundwater stripping reactor located inside the well vault, an aboveground blower used to generate the negative pressure in the well, and a contaminant vapor collection system (see Figure 3-2). The aboveground blower is used to remove the contaminated air from the well vault, thereby creating a negative pressure within the vault. The negative pressure causes fresh air to enter the well vault through the fresh air pipe. It is this fresh air that is used to strip the VOCs from the groundwater. The fresh air pipe is connected to a stripping reactor which forms air bubbles as it jets through the pinhole plate of the stripping reactor and mixes with influent groundwater. There is a mass transfer of contaminants from the water phase to the air phase as bubbles expand and release the VOCs in the upper portion of the well vault, where they are transported by air flow to the carbon absorption treatment system (Jacobs Engineering, 1996a).

Because of the three-screen casing design, two types of circulation cells will be developed: a standard (clockwise) circulation cell on top of a reverse (counter-clockwise) circulation cell. The middle screen is installed in the vertical center of the plume. An intake pump is positioned in the center of the twenty-foot screen and packed off from the remaining well casing to create a reduced hydraulic head zone. The water is pumped to the UVB air stripping system located near the ground surface within the well vault, where VOCs are removed from the groundwater. After air stripping, the water is split into two streams and each stream is then pumped back down to either the upper or lower well screen. Because there are two areas of increased head and one area of reduced head, water flows horizontally and vertically into the center and creates the two circulation cells (Jacobs Engineering, 1996a).

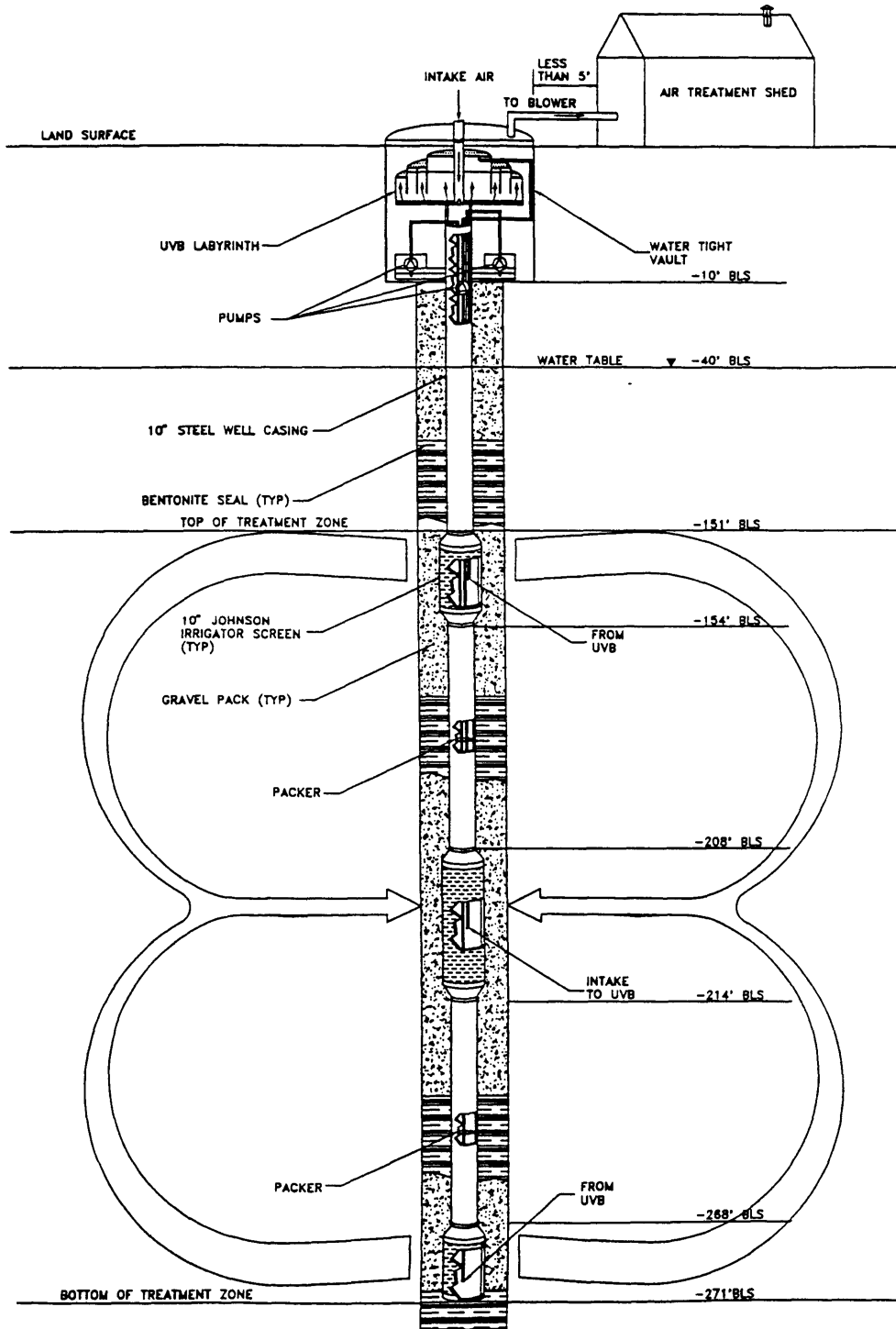


Figure 3-2
IEG Recirculating Well Technology
Conceptual Flow Diagram
 Massachusetts Military Reservation

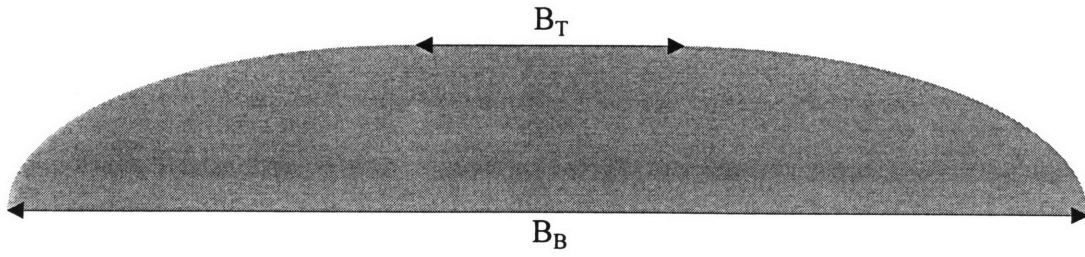
RW	Recirculating Well Technology Masters of Engineering Thesis
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Source: Jacobs Engineering, 1996a

IEG Technologies estimated the circulation cell dimensions using the well design and aquifer parameters. The capture zone bottom width B_B , and the top width B_T , are estimated for an upstream distance from the UVB of five times the height of the plume. The distance S is the stagnation point upstream and downstream of the UVB system or the maximum expansion of the sphere of influence of the UVB system (See Figure 3-3). The determination of the size of the capture, treatment, and release zones, the stagnation point, and time of particle travel were estimated and based upon models developed by Herrling et al. (1991). The calculations were performed using a proprietary software program. Table 3-3 lists the estimated dimensions for each of the two IEG Technologies Corporation UVB wells installed at MMR (Jacobs Engineering, 1996a).

Table 3-3: IEG Circulation Cell Dimensions

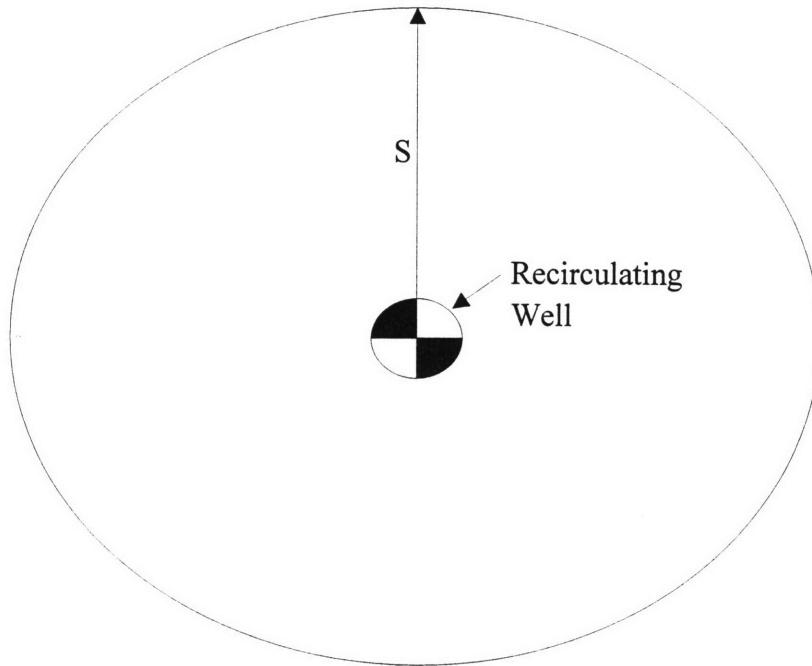
Internal Pumping Rate	20 m ³ /hr (88 gpm)
Internal Pumping Rate for Each Cell	10 m ³ /hr (44 gpm)
Downstream and Upstream Stagnation Point (S) from the UVB System for Each Cell	16.4 m (54 ft)
Top of the Capture Zone Width (B_T) for Each Cell	2.1 m (6.9 ft)
Bottom of the Capture Zone Width (B_B) for Each Cell	34.1 m (112 ft)
The Separation Distance Between UVB Perpendicular to the Groundwater Flow (D)	27.4 m (90 ft)
Natural Groundwater Entering Each Circulation Cell (Q_0)	8.04 m ³ /hr (35.4 gpm)



(a) Upstream Capture Zone

B_T = Top Width of Capture Zone

B_B = Bottom of Radius of Influence



(b) Plan View of Sphere of Influence

S = Stagnation Point

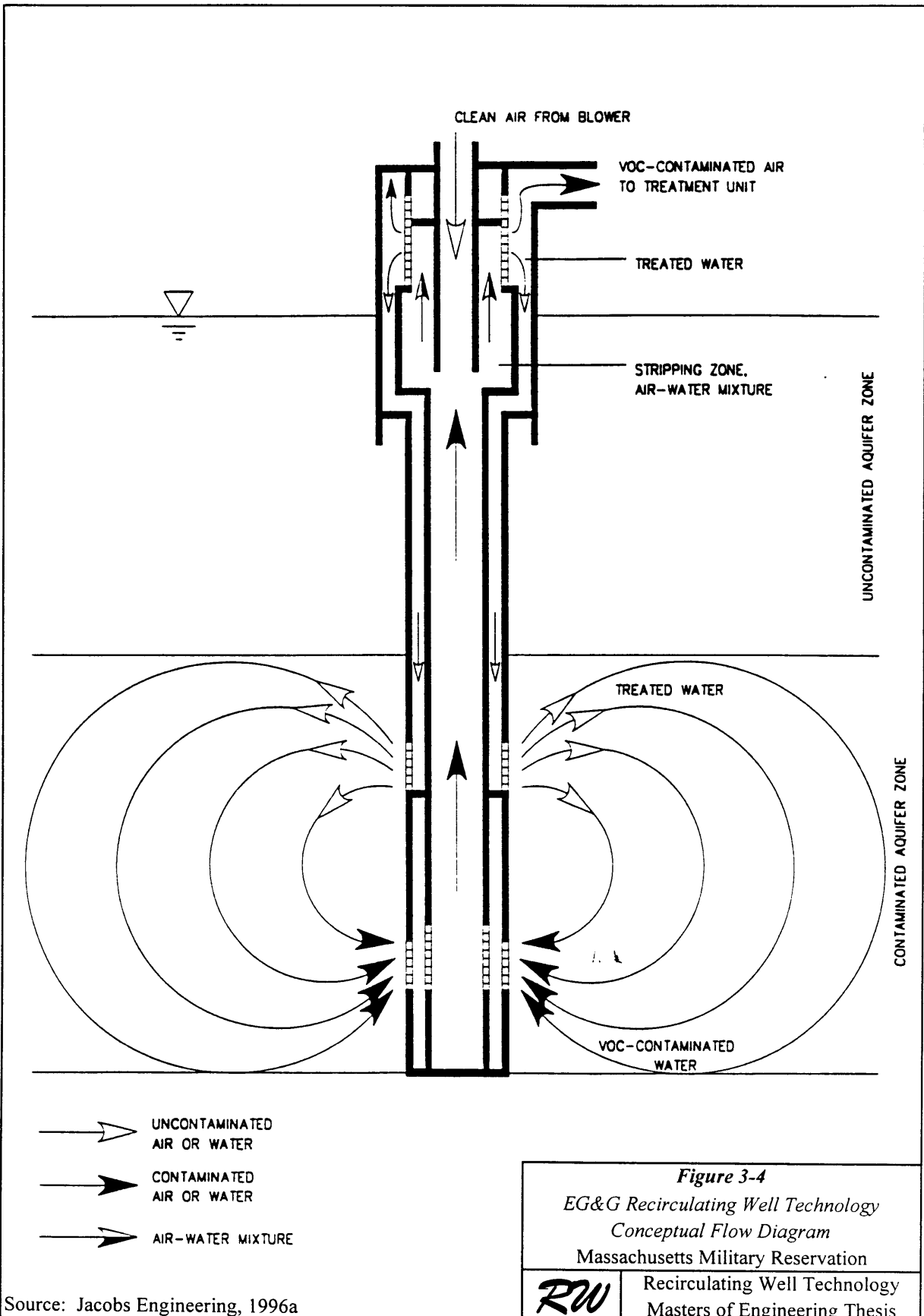
Figure 3-3	
<i>UVB Circulation Cell Dimension Notations</i> Massachusetts Military Reservation	
RW	Recirculating Well Technology Masters of Engineering Thesis

3.2.2 EG&G Environmental, Inc.

Metcalf and Eddy, a licensed representative of EG&G Environmental, Inc., has installed two NoVOCs™ systems for the CS-10 groundwater contaminated plume at the MMR site. NoVOCs™ technology provides in situ groundwater remediation by producing a vertical circulation cell that captures VOC-contaminated groundwater. The captured VOC-contaminated groundwater is then remediated by the combination of air stripping and bioremediation processes. The NoVOCs™ technology provides in situ remediation while maintaining an equilibrium flow in the aquifer, thereby eliminating the drawdown effect associated with traditional pump and treat systems (Jacobs Engineering, 1996a).

The NoVOCs™ system used at the MMR incorporates a dual casing design with two-screened intervals, a diffuser, an aboveground blower, and a contaminant vapor collection and treatment system (see Figure 3-4). The aboveground blower is used to remove the contaminated air from the recirculating well so the air can be treated by a carbon absorption system. The treated air is then injected back into the NoVOCs™ well. It is this treated air that is used to strip the VOCs from the groundwater. The treated air pipe is connected to a diffuser which forms air bubbles and mixes with influent groundwater. There is a mass transfer of contaminants from the water phase to the air phase as bubbles expand and release the VOCs in the upper portion of the NoVOCs™ well (Jacobs Engineering, 1996a).

The NoVOCs™ well uses a two-screened interval design with the upper screen located near the top of the plume and the lower screen located near the bottom of the plume. An intake pump is positioned in the center of the bottom screen to create a reduced hydraulic head zone. The water is pumped through the inner 6-inch casing, to the top of the NoVOCs™ well, where VOCs are removed from the groundwater. After air stripping, the treated groundwater spills out of the inner 6-inch casing into the outer 10-inch casing where it travels down to the upper screens and creates an increased hydraulic head zone. Owing to areas of increased and reduced head, water flows horizontally and vertically into the bottom screen and creates the circulation cells (Jacobs Engineering, 1996a).



- UNCONTAMINATED AIR OR WATER
- CONTAMINATED AIR OR WATER
- AIR-WATER MIXTURE

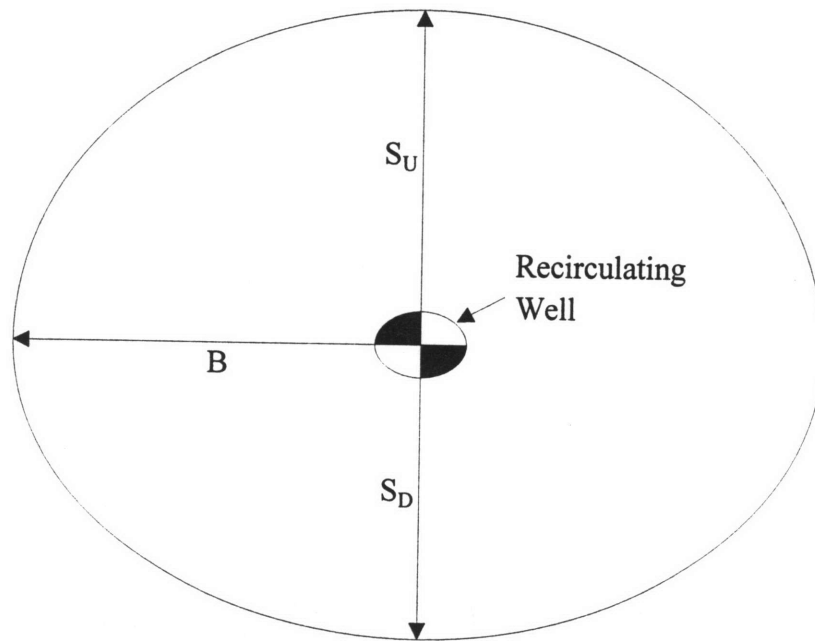
Figure 3-4
 EG&G Recirculating Well Technology
 Conceptual Flow Diagram
 Massachusetts Military Reservation
 RWU Recirculating Well Technology
 Masters of Engineering Thesis

Source: Jacobs Engineering, 1996a

The circulation cell dimensions were estimated by EGG&G based on the aquifer parameters. The distance B is defined as the radius of influence. Radius of influence is the maximum distance the recirculating well affects the groundwater flow. The distance S_U is the stagnation point upstream, and the distance S_D is the stagnation point downstream of the NoVOCs™ system (See Figure 3-5). The determination of the size of the radius of influence is based on dimensionless curves developed using the MODFLOW numerical groundwater flow model. Table 3-4 lists the estimated circulation cell dimensions for each of the EG&G Environmental NoVOCs™ systems installed at the MMR (Metcalf and Eddy, 1996a):

Table 3-4: EG&G Circulation Cell Dimensions

Internal Pumping Rate	45.5 m ³ /hr (200 gpm)
Upstream Stagnation Point (S_U)	45.7 m (150 ft)
Downstream Stagnation Point (S_D)	42.7 m (140 ft)
Radius of Influence	51.8 m (170 ft)
The Separation Distance Between NoVOCs™ Perpendicular to the Groundwater Flow (D)	30.5 m (100 ft)



S_U = Upstream Stagnation Point
 S_D = Downstream Stagnation Point
 B = Radius of Influence

Figure 3-5	
<i>NoVOCs™ Circulation Cell Dimension</i>	
<i>Notations</i>	
Massachusetts Military Reservation	
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4. METHOD OF DESIGNING RECIRCULATING WELLS

The design of recirculating wells is based on the air-to-water ratio required to strip VOCs from the groundwater. The first task in designing recirculating wells is to determine the maximum concentration of pollutants present at the site, because the air-to-water ratio is calculated to treat the maximum groundwater contamination. The air-to-water ratio is the amount of air that is required to volatilize the organic chemical from the aqueous phase to the gas phase (Jacobs Engineering, 1996a). The equilibrium partitioning of a contaminant between aqueous and vapor phase is quantified by the Henry's Law constant, which relates the aqueous phase concentration of a chemical to its partial pressure in the gas phase. The tendency for volatilization is determined by the ratio of the actual aqueous and vapor phase concentrations to the Henry's Law constant (Hemond and Fechner, 1994). The calculated air-to-water ratio is used to determine the internal groundwater pumping rate and air blower rate. Once the ratio is known, the groundwater pumping rate is maximized to produce the largest cost-effective upstream capture zone. This is accomplished by comparing the cost associated with an increase in the pumping rate and air blower rate to the decrease in the number of wells. Since the pumping rate controls the capture zone and number of wells, the following sections discuss two methods for determining the upstream capture zone of recirculating wells. The first is a general numerical modeling approach used by Herrling et al. (1991) to produce design curves. The second is a site specific numerical modeling approach used to produce design curves for MMR.

4.1 Herrling Approach

Recirculating wells' design characteristics for the size of the capture zone, the stagnation point, and time of particle travel have been calculated based upon numerical models developed by Herrling et al. (1991). They discuss the development of the circular flow system, sphere of influence, and capture zone associated with recirculating wells. The article also includes diagrams for dimensioning recirculating wells. The following is a summary of Herrling et al.'s results.

4.1.1 Sphere of Influence and Capture Zone

To estimate the sphere of influence and the capture zone for a recirculating well, Herrling et al. performed a numerical investigation. In order to calculate the complex three-dimensional flow field produced by recirculating wells, Herrling et al. made the following assumptions:

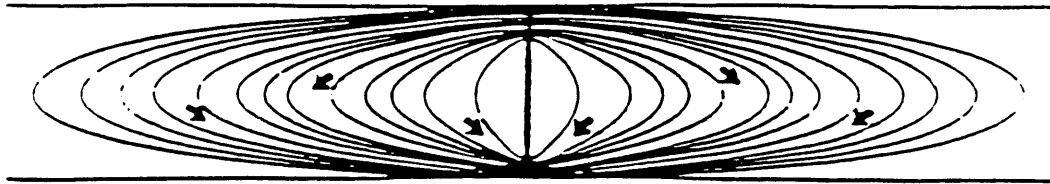
- Aquifer is of constant thickness.
- Aquifer is confined.
- Aquifer hydraulic conductivities are radially homogeneous. Although horizontal layers with different conductivities can be used, and hydraulic conductivities may be anisotropic, each layer may have only one vertical and one horizontal conductivity.
- Steady-state conditions.
- Advective transport only.

The three-dimensional flow field is obtained by superimposing a horizontal uniform flow field on the radially symmetric recirculating flow field. The radially symmetric flow field is computed about a vertical axis with a finite length line source (upper well screen) and finite length line sink (lower well screen). After each solution is computed on its own grid, the superposition of the different flow fields is achieved by interpolating and adding the different flow vectors at the various nodes of a simple rectangular grid.

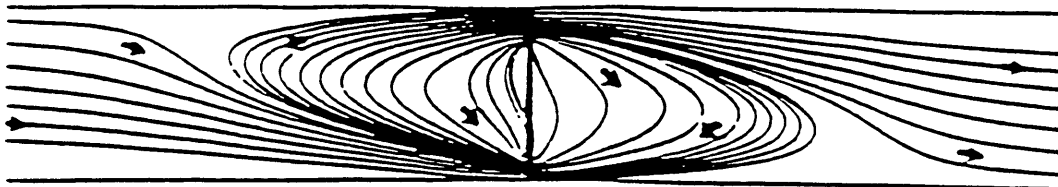
4.1.1.1 Recirculating Well Flow Field

A vertical longitudinal cross-section through the well in the direction of regional flow shows the complex flow field produced by a recirculating well (see Figure 4-1). The figure shows the resulting streamlines caused by three different uniform flow velocities (0.0 m/day, 0.3 m/day, and 1.0 m/day), while all other parameters remain constant.

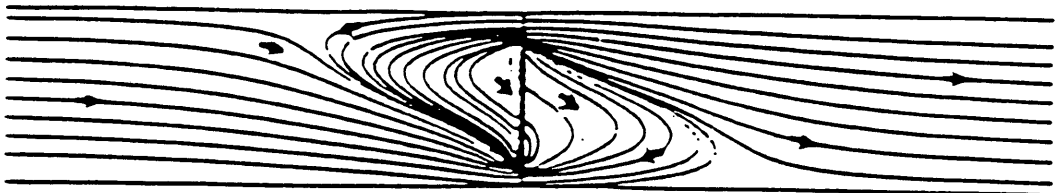
Figure 4-1 shows the groundwater flowing downward to the lower screened section as it flows from upgradient. The groundwater is then captured and transported upward inside the well casing and allowed to return to the aquifer via the upper screened section. The flow field can be plotted in such a simplistic way in this longitudinal section, otherwise the complex three-dimensional flow field has to be considered.



Darcy Velocity = 0.0 m/day



Darcy Velocity = 0.3 m/day



Darcy Velocity = 1.0 m/day

Figure 4-1
*Vertical Longitudinal Cross Section
of the Flow Field Produced
Massachusetts Military Reservation*

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Recirculating Well Technology
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Source: Herrling et al., 1991

For a simple, fully penetrating extraction well in a confined homogenous aquifer, a separating streamline can be defined where all the water within the line is captured by the well and all the water outside the line flows past the well. In contrast to a simple extraction well, where the flow can be considered horizontal, the flow around a recirculating flow must be regarded as three-dimensional. Therefore, the water flowing toward the recirculating well cannot be delineated by a simple separating streamline but by a curved separating stream surface instead. The curved stream surface must be calculated on the basis of the three-dimensional flow field and three-dimensional particle tracking method.

4.1.1.2 Diagrams for the Dimensioning of Recirculating Wells

Figure 4-2 introduces Herrling's notation for an upstream cross section through the capture zone normal to the natural groundwater flow direction for one or two recirculating wells. B_T and B_B are the upstream capture widths, H is the height of the aquifer, A is the capture area, and D is the maximum distance between two wells such that no contaminated groundwater passes without being treated. Figure 4-3 shows the numerical results represented in dimensionless form for the sizing of recirculating wells. The results of Figure 4-3 were calculated for an upstream distance of five times the height of the aquifer from the well and for a constant ratio of the intake screen length to aquifer thickness (a/H) of 0.25.

The widths B_T and B_B of the upstream capture zone, measured at the aquifer top and bottom, are shown in Figure 4-3a. The ratios of B_T/H and B_B/H are dependent on the ratios $Q/(H^2v)$, K_H/K_V , and a/H where Q is the groundwater extraction rate, v is the Darcy velocity, K_H and K_V are the horizontal and vertical hydraulic conductivities respectively. Figure 4-3a illustrates how sensitive the results are to the degree of anisotropy.

Figure 4-3b shows the results for the influx area of the upstream capture zone, while Figure 4-3d shows the maximum well distance (D) between two wells without allowing contaminated groundwater to pass. The ratios of A/H^2 and D/H is dependent on the same parameters as the widths B_B/H and B_T/H .

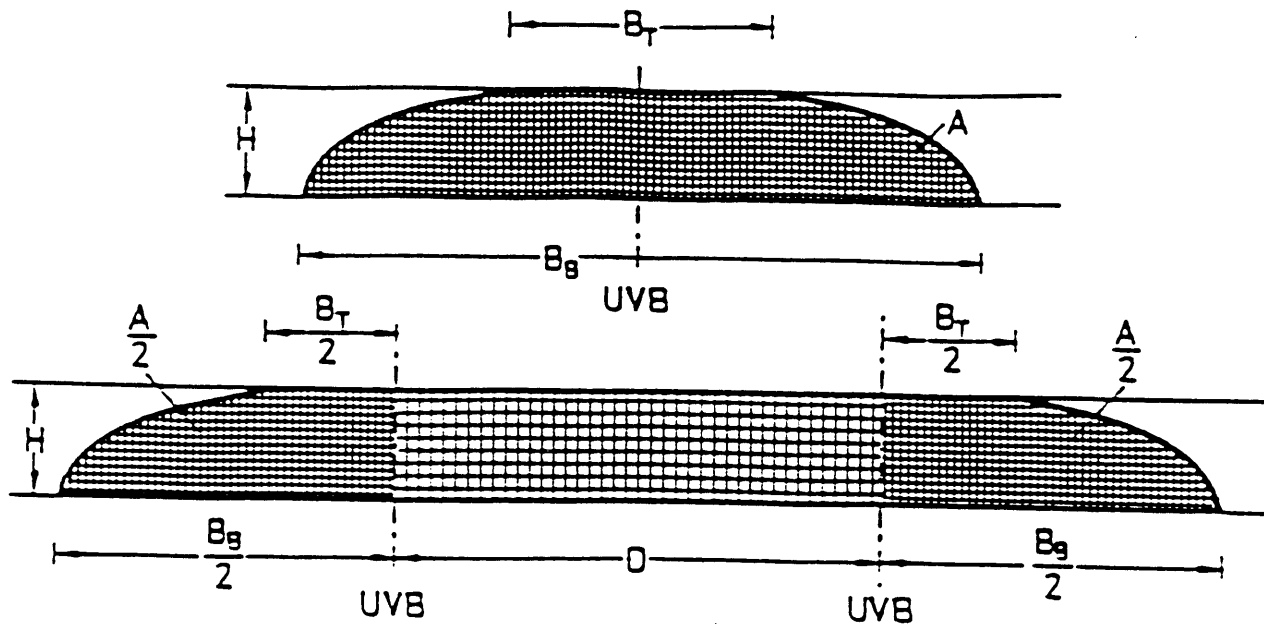
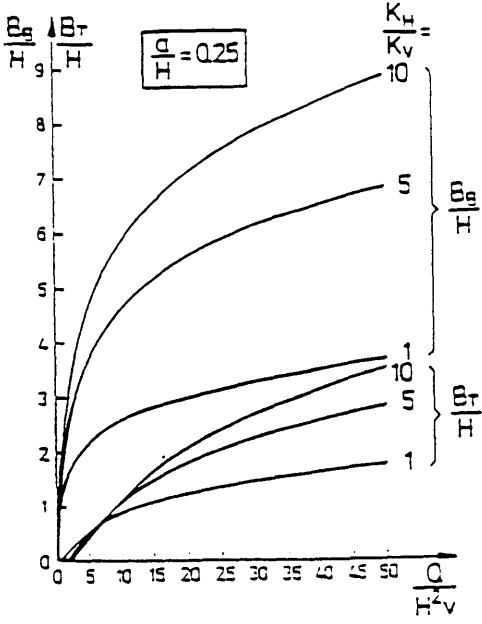


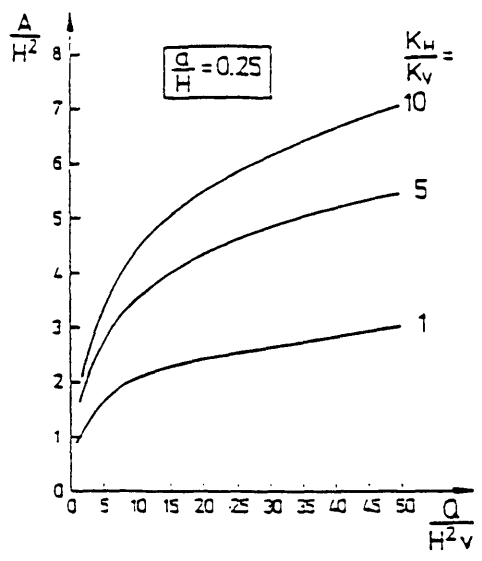
Figure 4-2
 Notation for the Upstream Capture Zone
 Massachusetts Military Reservation

<i>RW</i>	Recirculating Well Technology
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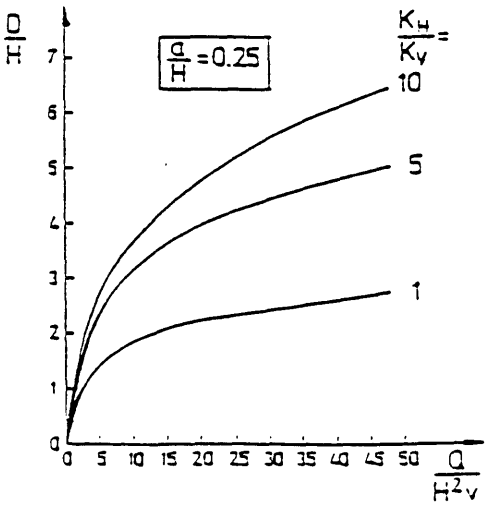
Source: Herrling et al., 1991



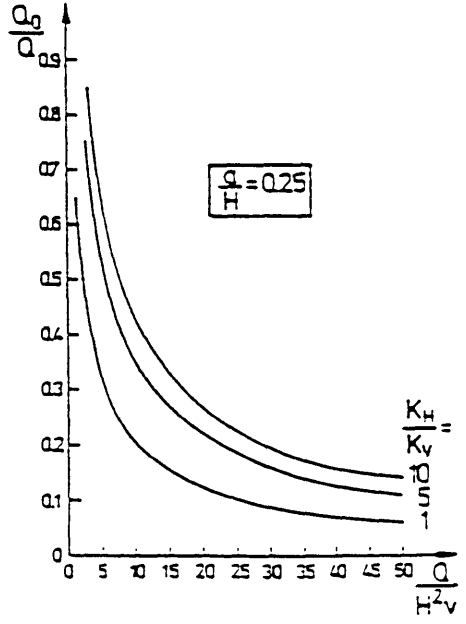
(a) Width B_T and B_B of the Upstream Capture Zone at the Aquifer Top and Bottom



(b) Influx Area A of the Upstream Capture Zone



(c) Maximum Well Distance D at which the Contaminated Groundwater cannot Pass Between the Wells without being Treated



(d) Upstream Discharge Q_0 in the Capture Zone, which is Diluted with the Circulating Water to the Total Well Discharge Q

Figure 4-3
Herrling Charts
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Source: Herrling et al., 1991

When contaminated groundwater flows into a recirculating well, it is diluted with water that has already been treated by the well. Thus, the contaminant concentration of the water within the recirculating well will be lower than in the upstream plume. Figure 4-3d illustrates the ratio of untreated groundwater flowing into the well (Q_0) to the total flow into the well portion Q . The ratio Q_0/Q is again dependent on the same parameters as the widths of the upstream capture zone. Figure 4-3d can be used to estimate the expected concentration in the water within the well casing for the dimensioning of a UVB installation.

In Figure 4-4 the upstream distance (S) of the stagnation point at the aquifer top from the well axis is described. The stagnation point is maximum expansion of the circulation cell parallel to groundwater flow. The ratio of S/H is also dependent on the parameters $Q/(H^2v)$, K_H/K_V , and a/H . The location of the stagnation point is highly sensitive to the anisotropy of the aquifer. The knowledge of the distance (S) from the stagnation point can be used to determine the positions of measuring equipment.

In the direction of groundwater flow, the circulation cell has a maximum expansion of S to the upstream and downstream sides. Normal to the groundwater flow, the maximum radius of the sphere of circulation is approximated by $(B_B + B_T)/4$, and in the case of several wells in one line by $D/2$.

The charts in Figures 4-3 and 4-4 can be used to size a recirculating well or a field of recirculating wells when the parameters K_H/K_V and Q/H^2v can be estimated. For an irregular well field, a layered aquifer, or in special critical cases, the charts in figure 4-3 and 4-4 cannot be used but a numerical calculation must be performed in order to determine the sphere of influence and upstream capture zone.

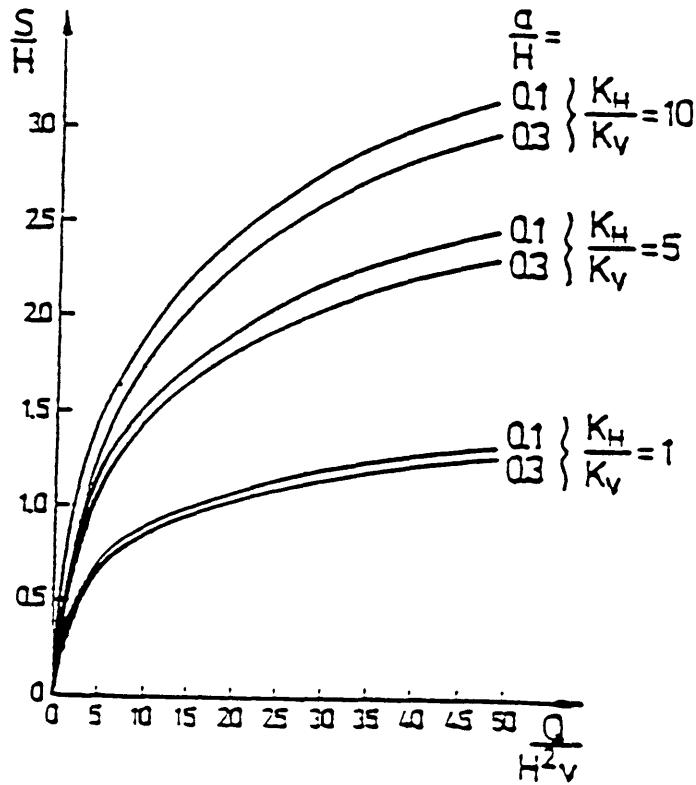


Figure 4-4
Herrling Charts for Stagnation Point
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Source: Herrling et al., 1991

4.1.2 Shortfalls of the Herrling Approach

Herrling's recirculating well design curves can be used as a first approximation of the upstream capture for recirculating wells with screens fixed at the top and bottom of the aquifer (Herrling et al., 1991). However, both well designs tested at the MMR differ substantially from the Herrling's Model. Although EG&G Environmental, Inc. recirculating wells consists of two screened intervals, the screens are placed at the top and bottom of the plume rather than at the top and bottom of the aquifer. Furthermore, IEG Technologies Corporation recirculating wells consists of three screened intervals which are placed at the top, middle, and bottom of the plume. The number of screens and location of screens will hydraulically affect the upstream capture zone, thereby affecting plume-wide remediation scheme. Also, the height of the water table above the screened intervals may hydraulically affect the upstream capture zone. Because the difference between the recirculating wells installed at MMR and the recirculating well used by Herrling, a site specific numerical model was developed.

4.2 Numerical Model Approach

Because Herrling's recirculating well design curves are not based on the exact recirculating wells installed at the MMR, a numerical model was developed to produce site specific design curves. The design curves will be a useful tool when designing recirculating wells for other areas on the MMR, because they were developed using the specific hydrogeology characteristics of the MMR, as well as the specific design of the wells that were used at the site. To develop recirculating well design graphs similar to design Herrling charts in Section 4.1 for the MMR, a particle tracking investigation was conducted using the DYNSTEM groundwater flow and transport software package. The following sections highlight the computer software package used and steps taken in performing the particle tracking investigation. The particle tracking investigation determined the upstream capture zone, the effect of the water table elevation on the upstream capture zone, and the percentage of recirculated groundwater for both IEG Technologies Corporation and EG&G Environmental, Inc. recirculating wells for various pumping rates.

4.2.1 DYNSTEM™ Description

In order to develop the design curves, the DYNSTEM™ was employed because of its versatility and powerful computation ability. The DYNSTEM™ computer program, developed by Camp Dresser and McKee (CDM), simulates three-dimensional groundwater flow and advective-dispersive contaminant transport. The DYNSTEM™ comprises of three components:

- DYNFLOW
- DYNTRACK
- DYNPLOT

The DYNFLOW component is a FORTAN-based program that simulates three-dimensional groundwater flow using the Galerkin finite element formulation. The DYNTRACK component of the DYNSTEM simulates three-dimensional advective-dispersive contaminant mass transport. DYNTRACK uses the same three-dimensional finite element grid, aquifer properties, stratigraphy, and flow field used in and generated by the DYNFLOW model. DYNTRACK can perform simple, single-particle tracking of conservative contaminants or complex three-dimensional transport including first-order decay, absorption, and dispersion. The DYNPLOT component is the graphical pre- and post-processor which supports DYNFLOW and DYNTRACK. In the pre-processing phase, DYNPLOT is used to build the finite element grid which is essential to both the flow and transport models. In the post-processing phase, DYNPLOT is used to display plan and cross-sectional results of both the flow and transport simulations (CDM Inc., 1995).

4.2.2 Model Development and Procedure

The first step in the development of a groundwater flow model was the creation of a finite element grid using DYNPLOT (see Figure 4-5). The dimensions of the finite element grid were chosen by multiplying the projected upstream capture zone given by the recirculating well vendors by a factor of 5 to insure that the recirculating well did not interfere with the boundary. A grid 800-foot wide and 1200-foot long was chosen. First, a 100-foot diameter grid with 222 nodes and 425 elements was built radially around the recirculating well node. The 100-foot

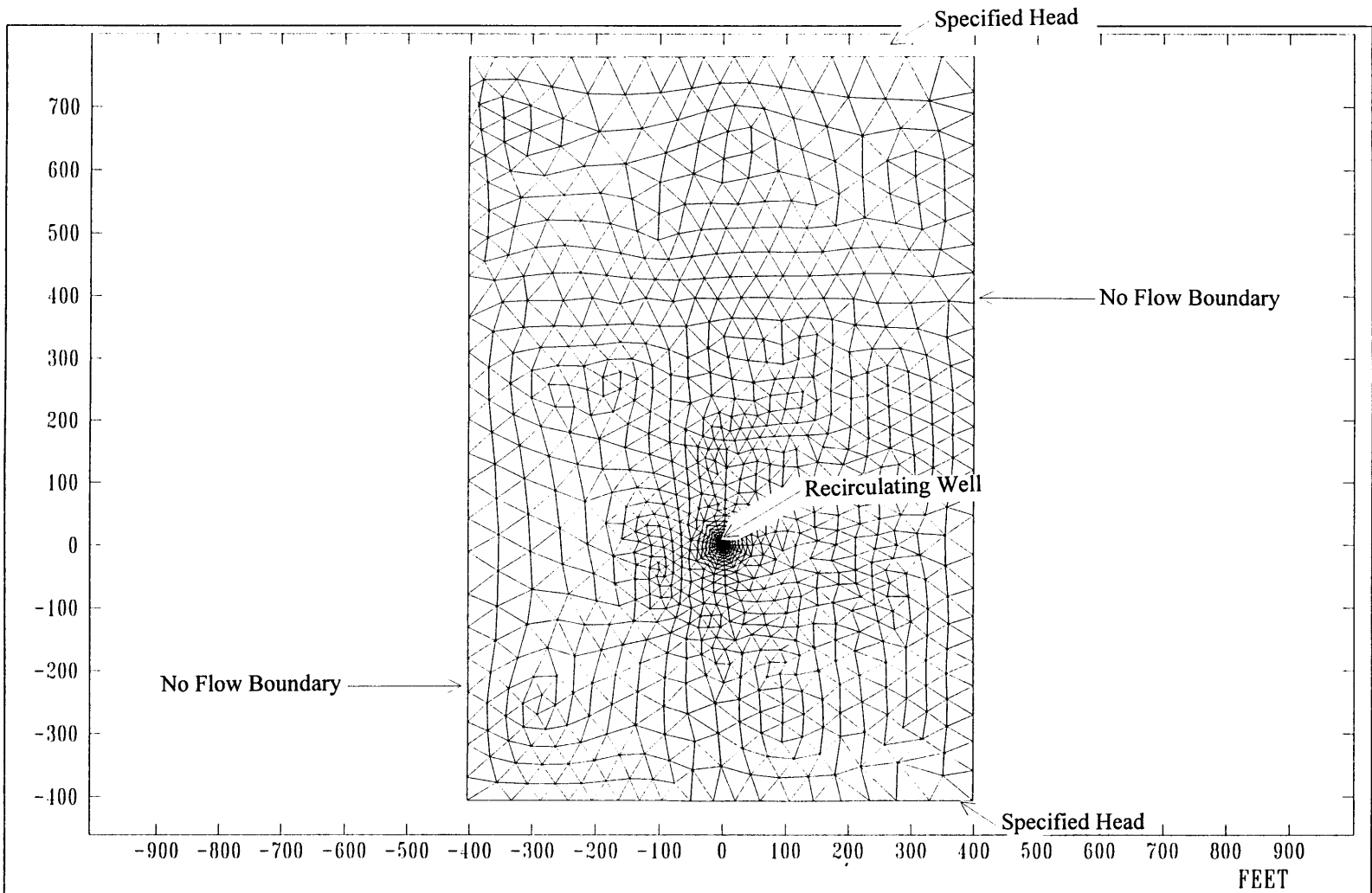


Figure 4-5
Finite Element Grid
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diameter grid was then expanded to fill the 800-foot by 1200-foot grid for a total of 1031 nodes and 1985 elements. Radial grid generation allowed the horizontal discretization of the nodes to be very dense near the well and slowly decrease in density until reaching the boundaries. High resolution in areas of interest allows more numerical calculations for change in head, thereby increasing the accuracy and precision of groundwater flow and contaminant transport. Once the flow field was established, the head contours were viewed to insure the recirculating well under operating circumstances did not interfere with the boundary conditions. Head contours were also viewed to insure the node resolution near the recirculating well was adequate to represent the rapidly changing head.

The next step in the development of the groundwater flow model was the creation of the necessary DYNFLOW input file. The DYNFLOW file defines the soil stratification, soil properties, water table elevations, recirculating well pumping rate information, and boundary conditions. For this investigation, the soil column was divided into 18 layers or 19 levels with horizontal hydraulic conductivities (K_x and K_y) set to 297.2 ft/day, vertical hydraulic conductivity (K_z) set to 59.5 ft/day, specific storativity (S_s) set to 0.00001, and specific yield (S_y) set to 0.07. The water table elevation was fixed to 36.1 ft above sea level (asl) at the upstream boundary and 34.4 ft asl at the downstream boundary, thereby producing a regional gradient of 0.0014 ft/ft. The 0.0014 ft/ft hydraulic gradient was given by CDM Federal (1993) and Masterson (1996). At the location of the recirculating well, positive and negative fluxes were assigned to the appropriate nodes to simulate the extraction and reinjection of groundwater by the recirculating well.

Once the DYNFLOW file was prepared, three different transport simulations were created. The first simulation investigated the upstream capture zone. The second simulation investigated the effect of the water elevation on the capture zone. The third simulation investigated the percentage of extracted groundwater that was previously treated by the recirculating well.

4.2.2.1 Capture Zone Simulation

For the capture zone simulation, a DYNTRACK file and property file were created. The DYNTRACK file defined the particles' starting positions, the time steps, and the total duration for the particle track simulation. In the DYNTRACK file, particles were seeded at a distance of five times the plume height upgradient of the recirculating well.

In conjunction with the DYNTRACK file, a property file was created that assigns values for the interrelationship between the particles and the aquifer in order to accurately simulate the mass transport of contamination. These interrelationship characteristics include the dispersion coefficient, effective porosity, and retardation factor. This file set the dispersion coefficient to zero, effective porosity to 0.35, and retardation factor of one. The value 0.35 for effective porosity was chosen because it is a typical value for a glacial outwash sand (Daniel, 1993). Dispersion and retardation were ignored during a hydraulic capture zone investigation, because their effect is insignificant compared to the advection transport process associated with the groundwater velocity caused by the recirculating well.

Once the files were written, DYNTRACK was run to obtain the steady state transport solution for the recirculating well. DYNPLOT, the graphical processor, was used to view the resulting capture zone as defined by the particle tracks.

4.2.2.2 Effect of the Water Elevation Simulation

For the second simulation, the DYNFLOW file was altered to demonstrate the effect of the water table elevation would have on the capture zone. First, the water table elevation was increased by 40 ft. while maintaining the hydraulic gradient at 0.0014 ft/ft. Using the same DYNTRACK and property files from the capture zone simulation, the steady state transport solution was obtained.

Second, the water table elevation was decreased by 35 ft. while maintaining the hydraulic gradient at 0.0014 ft/ft. Using the same DYNTRACK and property files from the capture zone simulation, the steady state transport solution was obtained.

4.2.2.3 Recirculating Particle Simulation

For the third simulation, a new DYNTRACK file was created to investigate the percent of recirculated particles. The DYNTRACK file defined the particles' starting positions, the time steps, and total duration for the particle track simulation. In this DYNTRACK file, particles were seeded 2 ft. radially around the recirculating well injection screens.

Similar to the capture zone simulation, a property file was used to assign values for the interrelationship between particles and aquifer in order to accurately simulate the mass transport of contamination. The values of dispersion coefficient, effective porosity, and retardation factor remained unchanged. See the above section for more detail.

Once the files were written, DYNTRACK was run to obtain the steady state transport solution for the recirculating well. Upon the completion of the simulation, DYNTRACK created an output file. By viewing the output file, the number of particles that were removed from the system by the recirculating well was determined. DYNPLOT, the graphical processor, was used to view the resulting sphere of influence as defined by the particles tracks.

4.2.3 Flow and Transport Simulation for IEG Technologies Corporation Well

The following table lists the inputs used in the numerical simulation of IEG’s recirculating well and Figure 4-6 illustrates the vertical discretization used for the model.

Table 4-1: IEG Technologies Corporation Model Input

Flow Model Input (see Appendix A1)	
Design Pumping Rate	88 gpm
Grid	800 x 1200
Layers	18
Levels	19
Horizontal Hydraulic Conductivity	297.2 ft/day
Vertical Hydraulic Conductivity	59.5 ft/day
Specific Storitivity (Ss)	0.00001
Specific Yield (Sy)	0.07
Hydraulic Gradient	0.0014
Property File Input (see Appendix A2)	
Dispersion Coefficient	0
Effective Porosity	0.35
Retardation Factor	1
Capture Zone Simulation (see Appendix A3)	
Number of Particles	420
Time Step	0.11 day (2.6 hr)
Duration	1200 days
Recirculated Particle Simulation (see Appendix A4)	
Number of Particles	216
Time Step	0.042 days (1 hr)
Duration	200 days

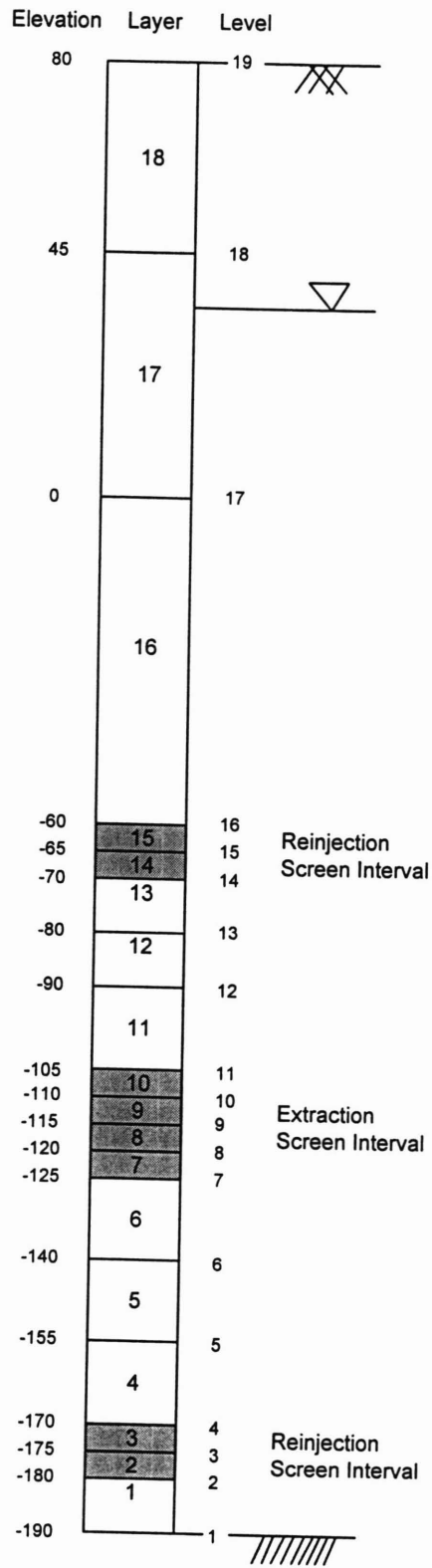


Figure 4-6
 IEG Technologies Corporation Model
 Vertical Discretization
 Massachusetts Military Reservation

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4.2.4 Flow and Transport Simulation for EG&G Environmental, Inc. Well

The following table lists the inputs used in the numerical simulation of EG&G's recirculating well and Figure 4-7 illustrates the vertical discretization used for the model.

Table 4-2: EG&G Environmental, Inc. Model Input

Flow Model Input (see Appendix B1)	
Design Pumping Rate	200 gpm
Grid	800 x 1200
Layers	18
Levels	19
Horizontal Hydraulic Conductivity	297.2 ft/day
Vertical Hydraulic Conductivity	59.5 ft/day
Specific Storitivity (Ss)	0.00001
Specific Yield (Sy)	0.07
Hydraulic Gradient	0.0014
Property File Input (see Appendix B2)	
Dispersion Coefficient	0
Effective Porosity	0.35
Retardation Factor	1
Capture Zone Simulation (see Appendix B3)	
Number of Particles	574
Time Step	0.08 day (1.92 hr)
Duration	1200 days
Recirculated Particle Simulation (see Appendix B4)	
Number of Particles	144
Time Step	0.042 days (1 hr)
Duration	200 days

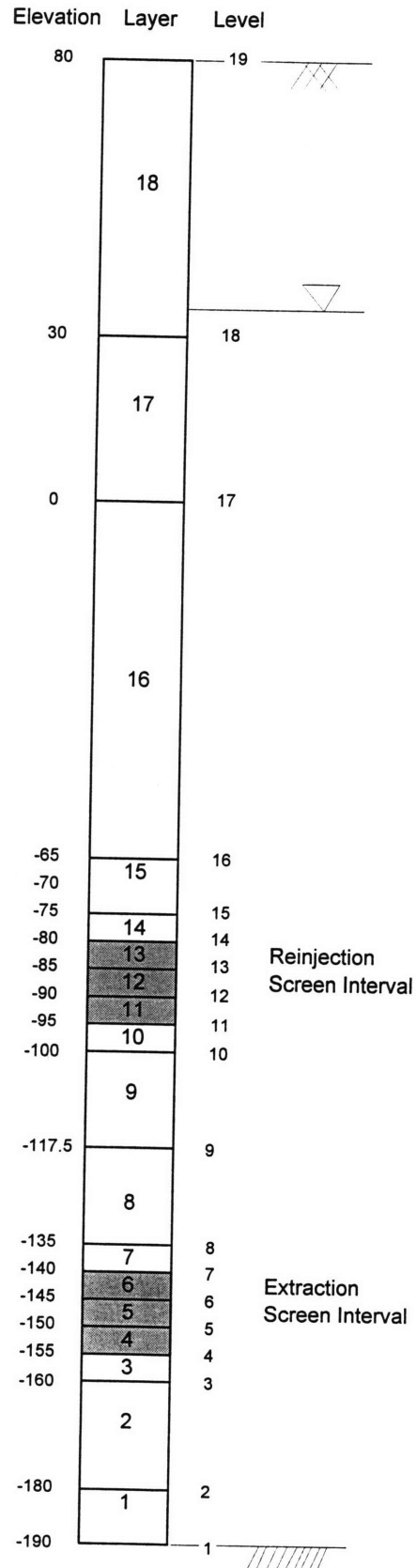


Figure 4-7
 EG&G Technologies Corporation
 Model Vertical Discretization
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4.2.5 Discussion of Simulations

As illustrated in Table 4-2 and Table 4-3, the only differences between the IEG model and the EG&G model are the:

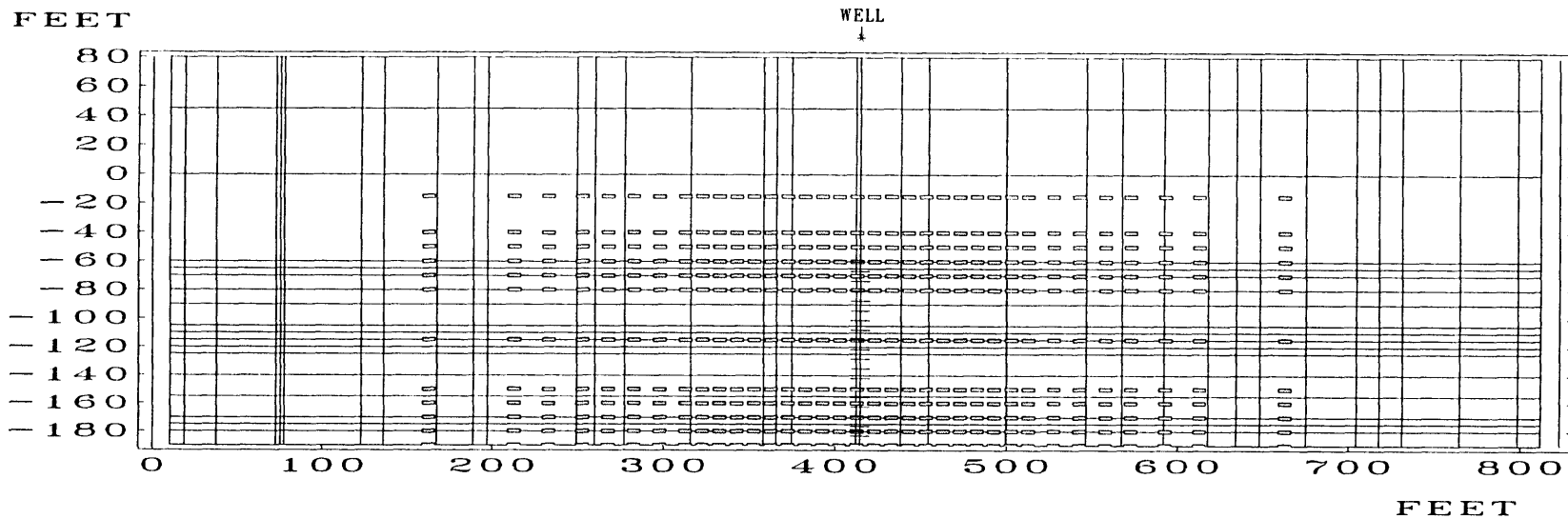
- Number of particles used in the capture zone simulation.
- Time steps used in the capture zone simulation.
- Number of particles used in the recirculated particle simulation.

More particles were used in the capture zone simulation for EG&G's model than IEG's model, because the hydraulics associated with EG&G recirculating well caused a larger capture width than IEG recirculating well. This was discovered during the simulation of EG&G's capture zone; therefore, particles were added to increase the vertical particle wall width by 100 feet to insure the capture zone could be viewed accurately (see Figure 4-8 and 4-9 for IEG and EG&G particle starting positions vertical particle wall).

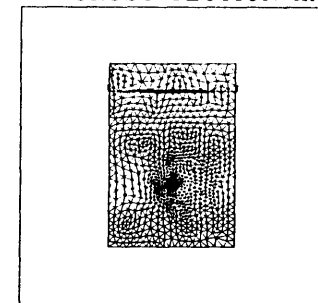
A smaller time step was used in the capture zone simulation for EG&G's system in order to produce a more accurate transport model. DYNTRACK calculates the new location of a particle based on a velocity vector and time step. If a velocity vector is extremely high and the time step is large, a particle could bypass the recirculating well. The hydraulics associated with EG&G's recirculating well produced higher velocities; therefore, a smaller time step was needed to decrease the time between calculation of particle positions (see Figures 4-10 and 4-11 for IEG and EG&G capture zone).

The number of particles used in the recirculating particle simulations for IEG and EG&G were different because the physical setup of the recirculating well. The same number of particles were placed in each model layer, but the number of layers in which the particles were placed changed according to the recirculating well system. For IEG, particles were placed in each of the six reinjection layers (see Figure 4-6). For EG&G, particles were placed in each of the four reinjection layers (see Figure 4-7).

By following the procedure described in Section 4.2.2 and using the input values described in Section 4.2.3 and Section 4.2.4, the upstream capture zone, the effect of the water table elevation,

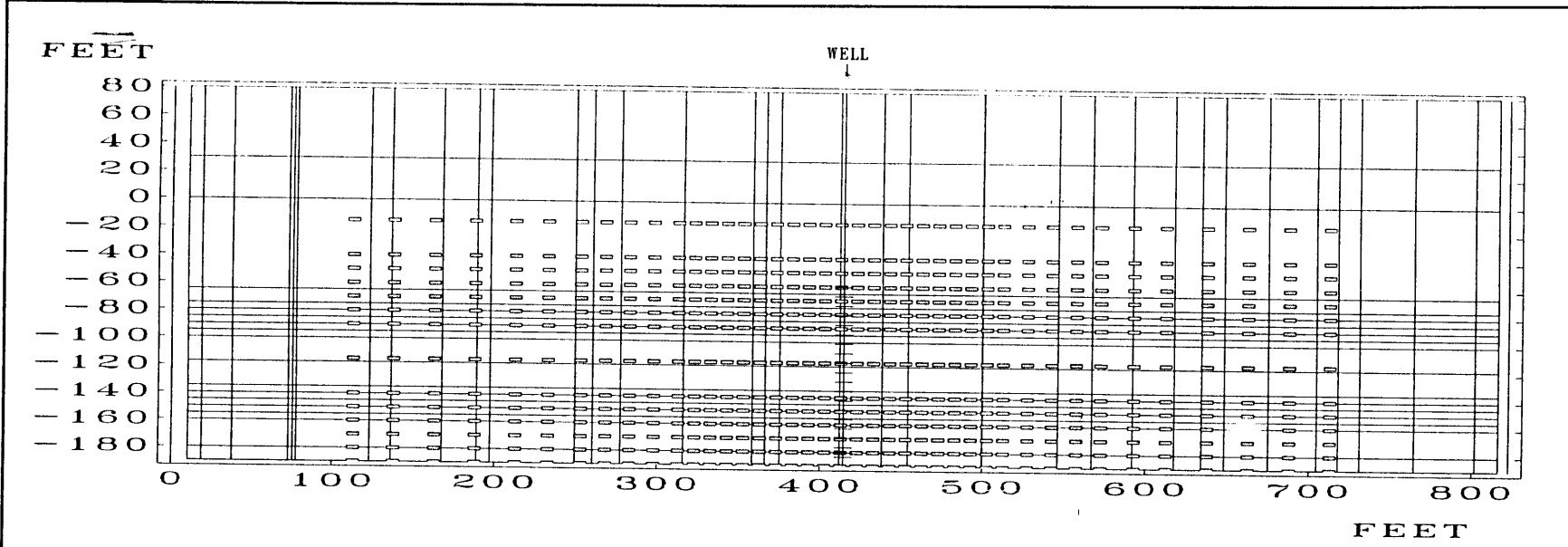


CROSS SECTION AA



· RECIRCULATING WELL
 WITHIN 600.0 FT
 — GROUND SURFACE
 - - - TOP OF SCREEN
 — BOTTOM OF SCREEN

Figure 4-8
 IEG's Model Particle Starting Position
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• RECIRCULATING WELL
 WITHIN 600.0 FT
 — GROUND SURFACE
 — TOP OF SCREEN
 — BOTTOM OF SCREEN

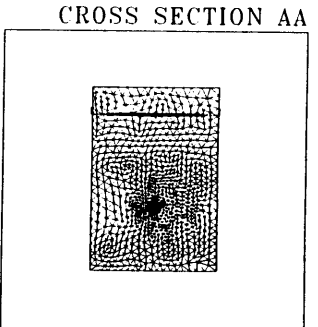
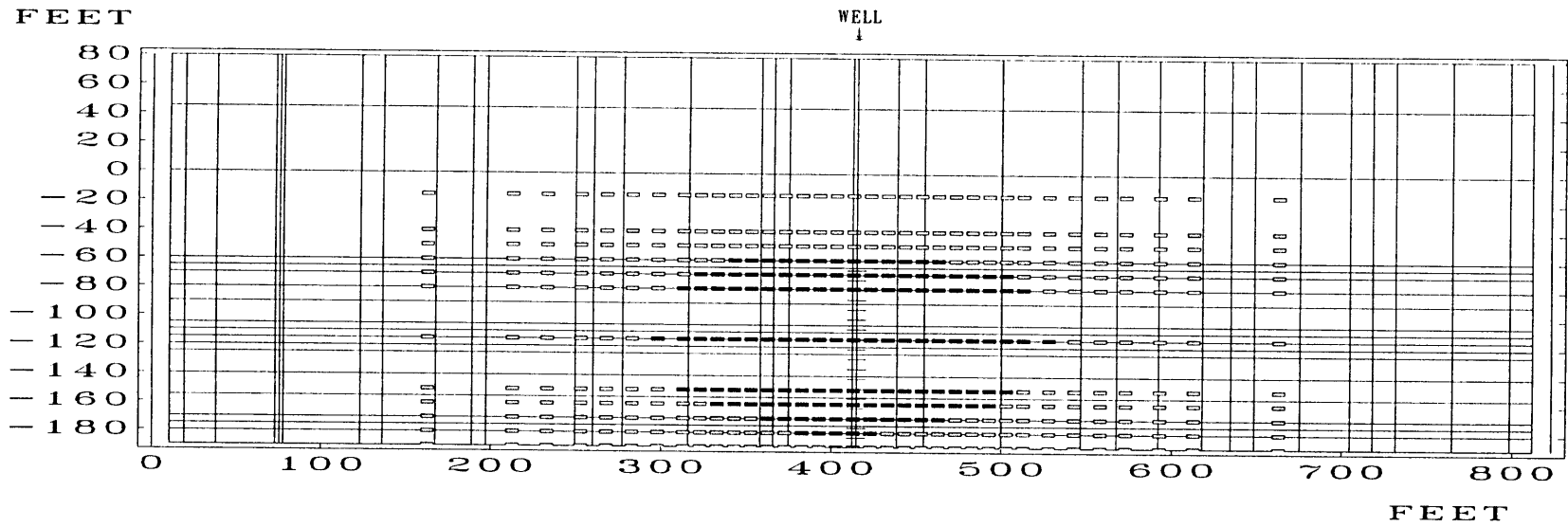


Figure 4-9
 EG&G's Model Particle Starting Position
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■ Captured
 □ Not Captured

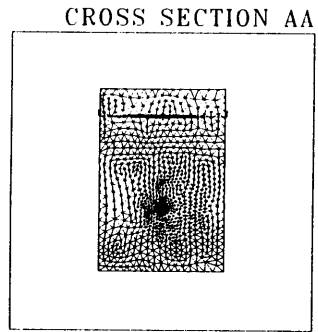
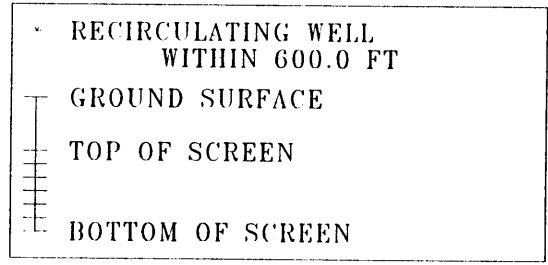
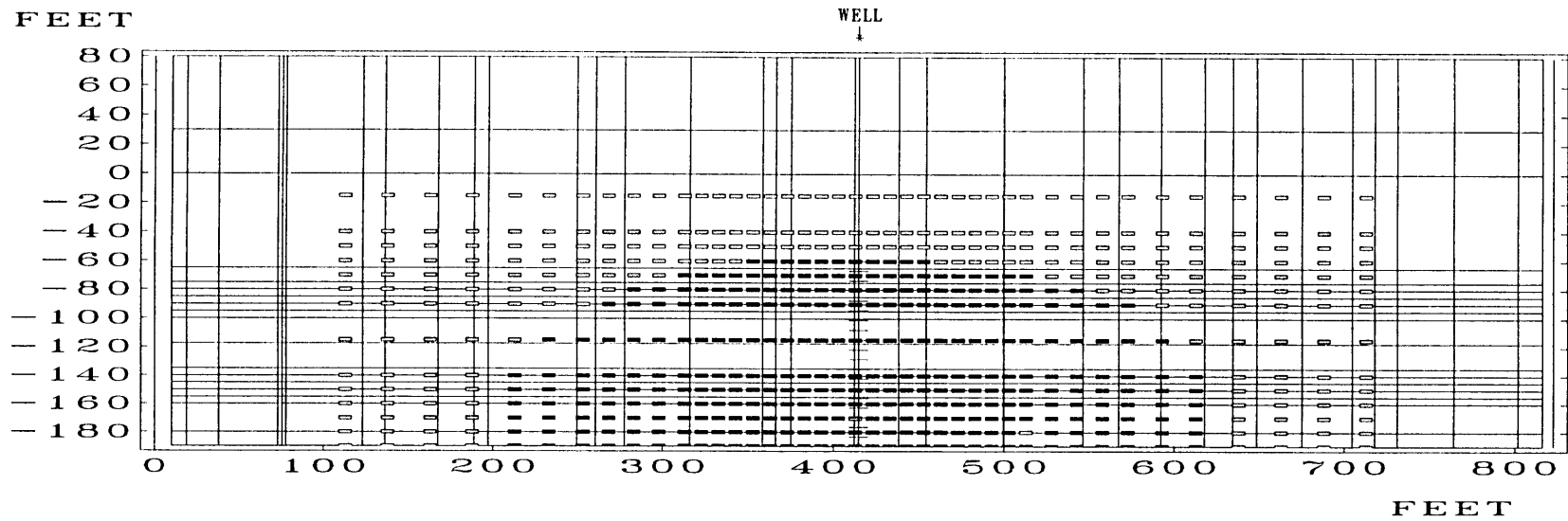
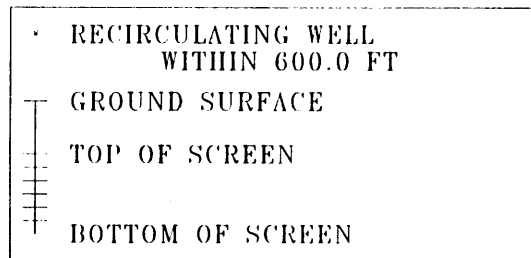


Figure 4-10
 IEG's Upstream Capture Zone
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■ Captured
 □ Not Captured



CROSS SECTION AA

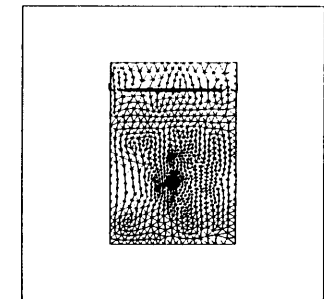


Figure 4-11
 EG&G's Upstream Capture Zone
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and the percentage of recirculated groundwater flow for both recirculating wells can be viewed. Chapter 5 presents the results obtained from the simulations using the design pumping rate, and illustrates the effect of pumping rate on the upstream capture zone and the percentage of recirculated groundwater flow.

5. RESULTS AND DISCUSSION

The following sections present the results obtained from the particle tracking investigation and discusses the results and their implications for design of a plume-wide treatment system.

5.1 Comparison Between Model Results and Herrling Charts

5.1.1 IEG Technologies Corporation

Using the numerical model described in Section 4.2, the resulting upstream top width (B_T) was 139 ft, the resulting upstream middle width (B_M) was 257 ft, and the amount of recirculated groundwater was 36 percent at the design pumping rate of 88 gpm.

Using the design curves of Herrling et al. (1991) (see Figure 4-3) to predict the capture width and percent of recirculated groundwater, the Darcian velocity was needed. With a horizontal hydraulic conductivity equal to 297.2 ft/day and a hydraulic gradient equal to 0.0014, the Darcian velocity is equal to 0.416 ft/day. With the pumping rate equal to 44 gpm, plume thickness equal to 60 ft, and the Darcian velocity equal to 0.416 ft/day, $Q/(H^2v)$ equals 5.6. One half the pumping rate and plume thickness are used because IEG Recirculating Well is equal to two recirculating wells stacked one on top of another. Therefore, one circulation cell is determined with half the pumping rate (44 gpm) and half the aquifer thickness (60 ft.). With $Q/(H^2v)$ equal to 5.6 and the anisotropy ratio (K_H/K_V) equal to 5, the corresponding values (read from Figure 4-3a) for the top width (B_T) and bottom width (B_B) are 36 ft and 222 ft, respectively, for each cell, while the percentage of recirculated groundwater equaled 42 percent.

Table 5-1: Summary of Results for IEG Technologies Corporation

	Predicted By Herrling's Charts	Predicted By Numerical Model
Pumping Rate	88 gpm * (44 gpm each cell)	88 gpm
Width at Top	36 ft.	139
Width at Bottom (or Middle)	222 ft.	257 ft.
Percent Recirculated	42%	36%

* IEG Recirculating Well is equal to two Recirculating Well stacked one on top of another; therefore, one circulation cell is determined with half the aquifer thickness (60 ft.) and half the pumping rate (44 gpm).

5.1.2 EG&G Environmental, Inc.

Using the numerical model described in Section 4.2, the resulting upstream top width (B_T) was 210 ft, the resulting upstream bottom width (B_B) was 402 ft, and the percent recirculated groundwater equaled 41 percent at the design pumping rate of 200 gpm.

Using Herrling's charts (see Figure 4-3) to predict the capture width and percent of recirculated groundwater, the Darcian velocity was needed. With a horizontal hydraulic conductivity equal to 297.2 ft/day and a hydraulic gradient equal to 0.0014, the Darcian velocity is equal to 0.416 ft/day. With the pumping equal to 200 gpm, plume thickness equal to 120 ft, and the Darcian velocity equal to 0.416 ft/day, $Q/(H^2v)$ is equal to 6.4. With $Q/(H^2v)$ equal to 6.4 and the anisotropic ratio (K_H/K_V) equal to 5, the corresponding values (read from Figure 4-3a) for the top width (B_T) and bottom width (B_B) are 108 ft and 468 ft, respectively, while the percentage of recirculated groundwater equaled 45 percent.

Table 5-2: Summary of Predicted for EG&G Environmental, Inc.

	Predicted By Herrling's Charts	Predicted By Numerical Model
Pumping Rate	200 gpm	200 gpm
Width at Top	108 ft.	210 ft.
Width at Bottom (or Middle)	468 ft.	415 ft.
Percent Recirculated	45%	41%

5.1.3 Discussion of Comparison

Table 5-1 and 5-2 report the values for the upstream capture width and the percentage of recirculated groundwater as predicted by both the DYNSTEM groundwater model and Herrling charts (1991). The predicted values based on the site-specific numerical model are slightly different than the predicted values provided by the Herrling charts. The first reason for the discrepancy is the number and spacing of the screens. Despite this difference, a consistent method was used to calculate the value for both the capture zone and the percentage of flow recirculated (see Section 5.1). The second reason for the discrepancy is based on the ratio of one screen length (a) to the plume height (H). In Figure 4-3, the ratio of a/H used in Herrling charts is shown as 0.25, while the ratio for IEG's recirculating well is 0.167 (10ft/60ft), and the ratio for EG&G's recirculating well is 0.125 (15ft/120ft). The a/H ratio controls the percent of recirculated water and the upstream capture zone. If the plume height (H) is constant, a larger a/H ratio means that a recirculating well has a larger line sink (a) and a larger line source (a). With a larger line sink (a) and line source (a) and a constant plume height (H), the distance between the screens is shortened, thereby causing greater recirculation between them. Because the extracted groundwater now includes more previously treated groundwater, the relative amount of untreated groundwater decreases reducing the capture area. The third reason for the discrepancy is due to the inability to accurately read the values from Herrling's charts (1991).

Because of the fundamental differences in the two methods of predicating upstream capture width and percentage of recirculated groundwater, site specific design graphs were developed for the MMR. First, CS-10 design graphs were produced that could aid engineers in the designing of a treatment system for the remediation of the CS-10 plume. Then, dimensionless design graphs were produced to assist in the design of recirculating well treatment systems for other plumes on MMR, or potentially at other sites.

5.2 Effect of Water Table Elevation Simulation

Table 5-3 is the resulting upstream capture width observed for IEG Technologies Corporation recirculating wells with a pumping rate of 88 gpm and different water table elevations (see Appendix A5 for DYNPLOT graphical outputs).

Table 5-3: IEG Capture Zone with different Water Table Elevations

Water Table Elevation (ft asl)	B _T (ft)	B _M (ft)	B _B (ft)
0	139	257	49
35	139	257	49
75	139	257	49

Table 5-4 is the resulting upstream capture width observed for EG&G Environmental, Inc. recirculating wells with a pumping rate of 200 gpm and different water table elevations (see Appendix B5 for DYNPLOT graphical outputs).

Table 5-4: EG&G Capture Zone with different Water Table Elevations

Water Table Elevation (ft asl)	B _T (ft)	B _M (ft)	B _B (ft)
0	210	415	402
35	210	415	402
75	210	415	402

The reported values in Tables 5-3 and 5-4 illustrate that the elevation of the water table did not effect the upstream capture zone. In general, the water table boundary does not affect the upstream capture zone because it lies above the re-injection screen and does not deflect the

stream lines produced by the recirculated well. Therefore, it is not necessary to produce different design curves for different water table elevation.

5.3 Design Curves

In order to develop design curves that relate the upstream capture curve to pumping rates, numerous DYNSTEM simulations were conducted for different pumping rates (see Section 4.2.2 for description of method). The following are the results obtained for IEG Technologies Corporation and EG&G Environmental, Inc.

5.3.1 Capture Zone Simulation

5.3.1.1 IEG Technologies Corporation

With the aid of DYNPLOT, the following results were obtained for different pumping rates (see Appendix A6 for the complete set of DYNPLOT graphical outputs).

Table 5-5: IEG Upstream Capture Width vs. Pumping Rate

Pumping Rate (gpm)	B _T (ft)	B _M (ft)	B _B (ft)
0	0	0	0
25	17	126	0
50	86	186	10
75	123	235	26
88	139	257	49
100	152	269	60
125	176	285	76
150	197	299	94
175	211	312	107
200	226	326	121
250	256	352	148
300	283	369	176

Note: B_T is the Upstream Capture Width at the Top of the Plume

B_M is the Upstream Capture Width at the Middle of the Extraction Screen

B_B is the Upstream Capture Width at the Bottom of the Plume

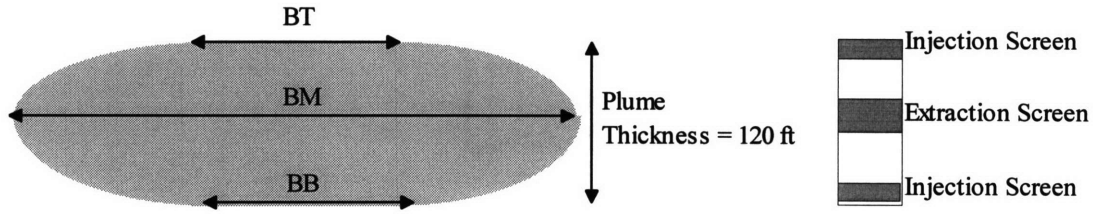


Figure 5-1: IEG Technologies Corporation Recirculating Well Schematic

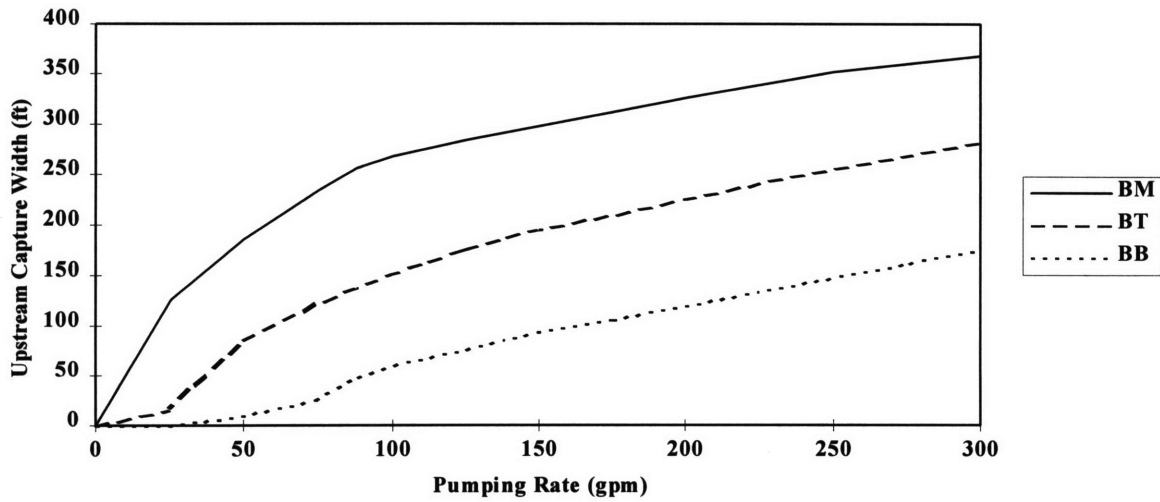


Figure 5-2: IEG Upstream Capture Width vs. Pumping Rate

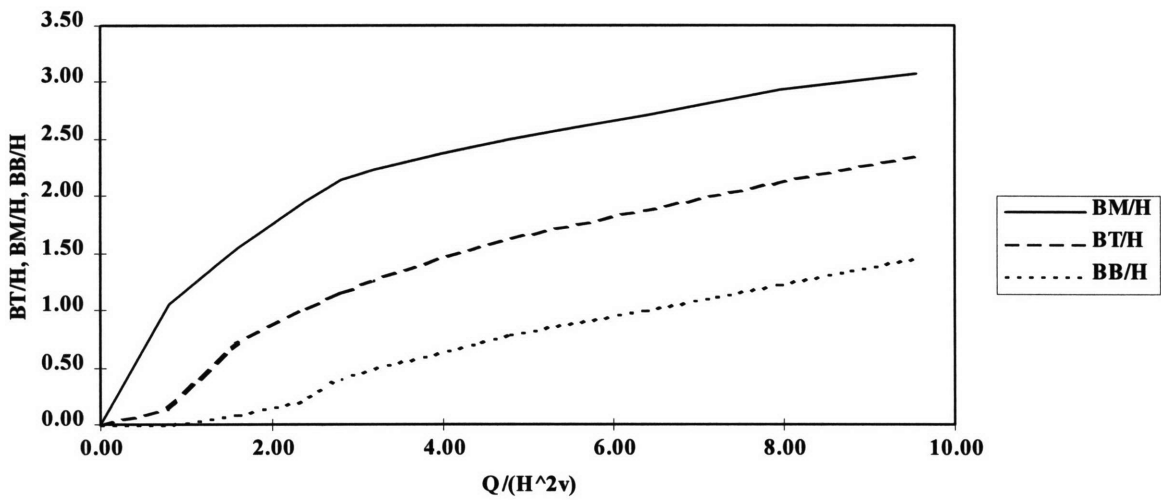


Figure 5-3: IEG Dimensionless Upstream Capture Width vs. Pumping Rate

5.3.1.2 EG&G Environmental, Inc.

With the aid of DYNPLOT, the resulting upstream capture curves were obtained for different pumping rates (see Appendix B6 for the complete set of DYNPLOT graphical outputs).

Table 5-6: EG&G Upstream Capture Width vs. Pumping Rate

Pumping Rate (gpm)	B_T^* (ft)	B_M^* (ft)	B_B^* (ft)
0	0	0	0
25	0	144	47
50	0	215	157
75	66	276	221
100	98	310	275
125	130	338	315
150	155	364	345
175	182	391	375
200	210	415	402
250	265	455	445
300	310	485	480

Note: B_T is the Upstream Capture Width at the Top of the Plume

B_M is the Upstream Capture Width at the Middle of the Extraction Screen

B_B is the Upstream Capture Width at the Bottom of the Plume

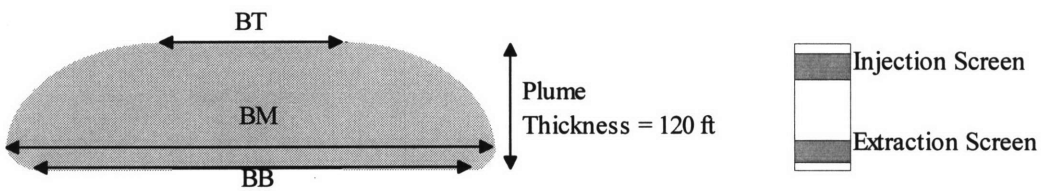


Figure 5-4: EG&G Environmental, Inc. Recirculating Well Schematic

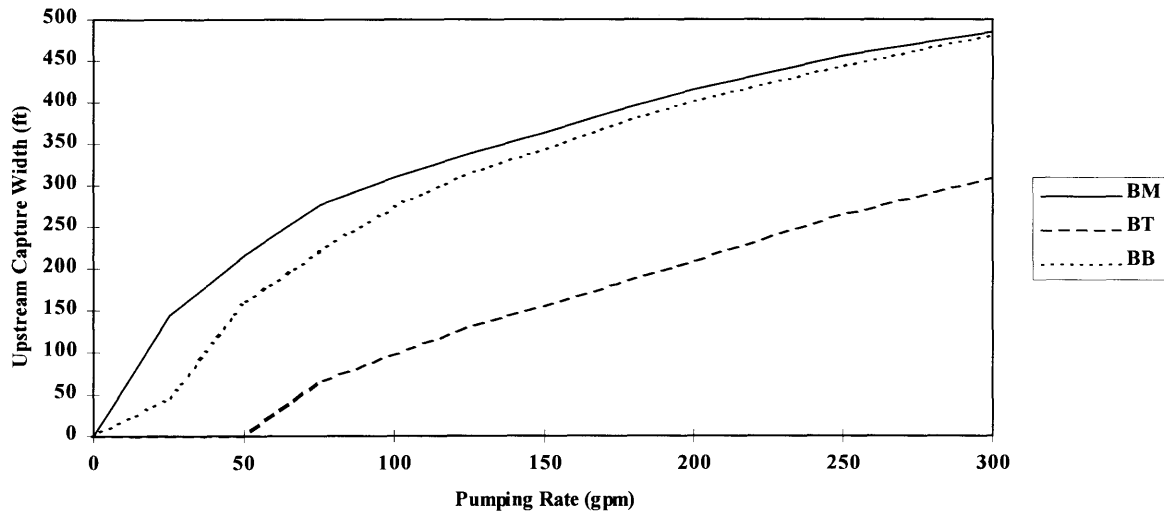


Figure 5-5: EG&G Upstream Capture Width vs. Pumping Rate

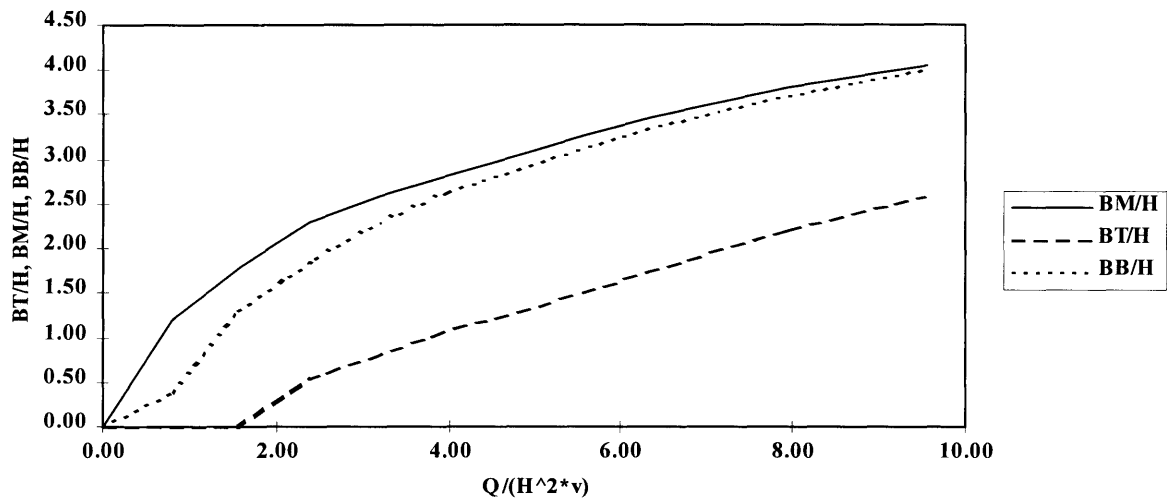


Figure 5-6: EG&G Dimensionless Upstream Capture Width vs. Pumping Rate

5.3.2 Recirculated Particle Simulation

In order to develop design curves that relate the percentage of retreated particles to pumping rates, numerous DYNSTEM simulations were conducted for different pumping rates. The following are the results obtained for IEG Technologies Corporation and EG&G Environmental, Inc.

5.3.2.1 IEG Technologies Corporation

Once the DYNTRACK simulation was complete, DYNTRACK created an output file. By viewing the output file, the number of particles that were removed from the system by the recirculating well was determined. Then DYNPLOT, the graphical processor, was used to view the resulting capture zone due to the extraction of groundwater by the recirculating well (see Appendix A7 for the complete set of DYNPLOT graphical outputs):

Table 5-7: IEG Percent of Recycled Flow vs. Pumping Rate

Pumping Rate (gpm)	Total Number of Particles Seeded	Number of Particles Captured	Percent of Recycled Flow (Q_r/Q)*
0	216	0	0%
25	216	1	0%
50	216	23	11%
75	216	62	29%
88	216	77	36%
100	216	89	41%
125	216	105	49%
150	216	119	55%
175	216	128	59%
200	216	133	62%
250	216	139	64%
300	216	144	67%

Note: Q_r is the Recycled Flow (gpm)

Q is the Pumping Rate (gpm)

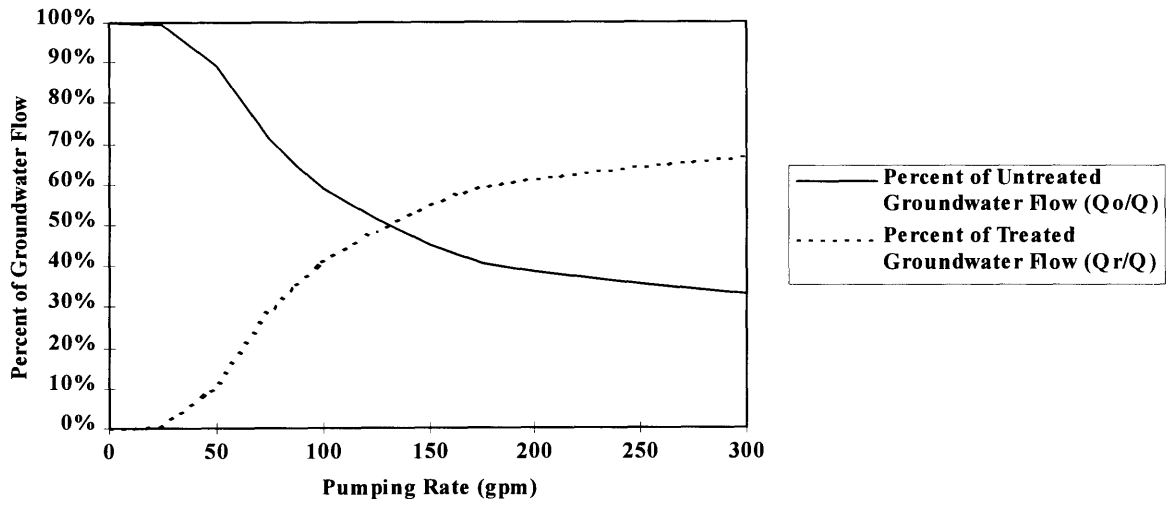


Figure 5-7: IEG Percent of Groundwater Flow vs. Pumping Rate

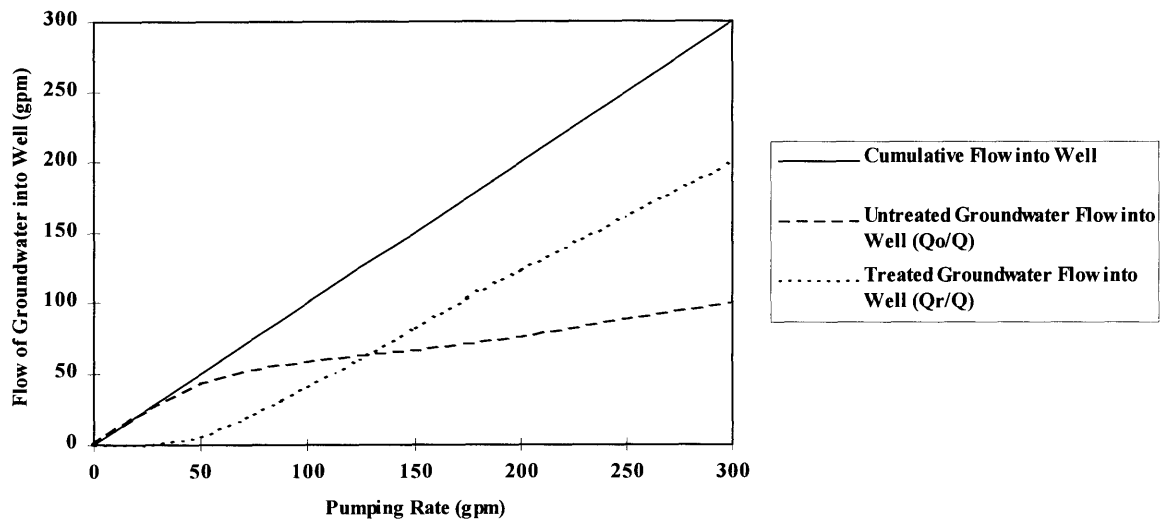


Figure 5-8: IEG Flow of Groundwater into Well vs. Pumping Rate

5.3.2.2 EG&G Environmental, Inc.

Once the DYNTRACK simulation was complete, DYNTRACK created an output file. By viewing the output file, the number of particles that were removed from the system by the recirculating well was determined. Then DYNPLOT, the graphical processor, was then used to view the resulting capture zone due to the extraction of groundwater by the recirculating well (see Appendix B7 for the complete set of DYNPLOT graphical outputs).

Table 5-8: EG&G Percent of Recycled Flow vs. Pumping Rate

Pumping Rate (gpm)	Total Number of Particles Seeded	Number of Particles Captured	Percent of Recycled Flow (Q_r/Q)*
0	144	0	0%
25	144	1	1%
50	144	17	12%
75	144	34	24%
100	144	44	31%
125	144	49	34%
150	144	53	37%
175	144	56	39%
200	144	59	41%
250	144	64	44%
300	144	70	49%

Note: Q_r is the Recycled Flow (gpm)

Q is the Pumping Rate (gpm)

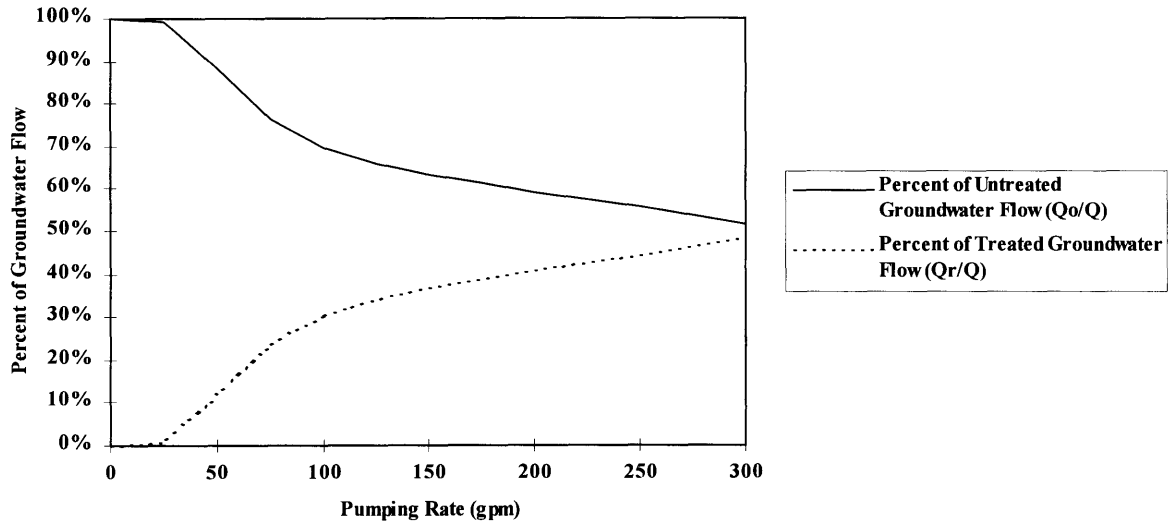


Figure 5-9: EG&G Percent of Groundwater Flow vs. Pumping Rate

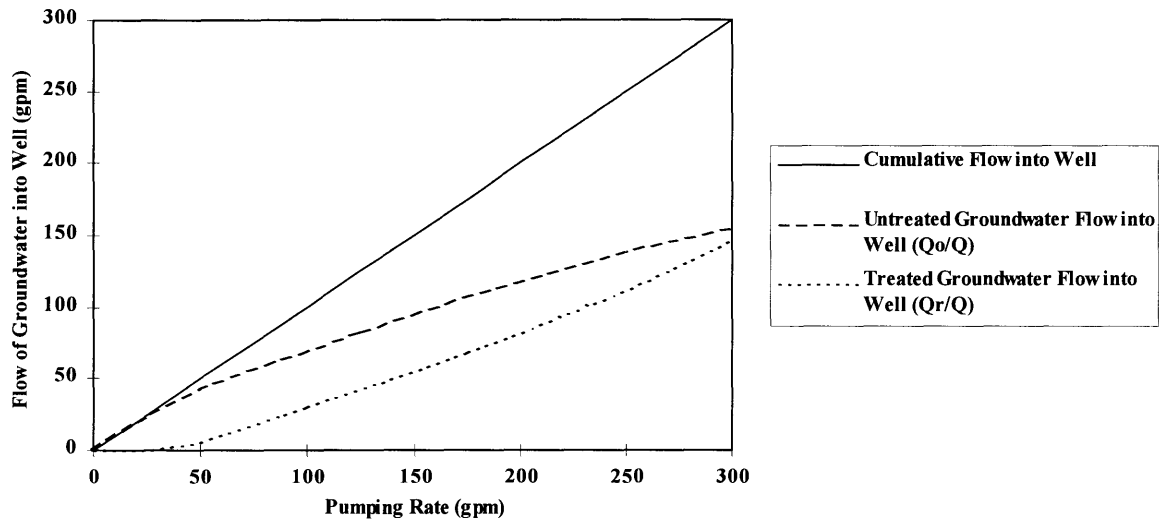


Figure 5-10: EG&G Flow of Groundwater into Well vs. Pumping Rate

5.3.3 Discussion of Results and Optimization

The primary reason for developing recirculating well design curves was to determine which recirculating well produces a larger upstream capture zone. Similar to the discussion in Section 5.1.2, the distance between a line sink and a line source controls the percent recirculated and the upstream capture zone. The distance between the line sink and line source for IEG's

recirculating well is 40 feet (see Figure 4-6). While, the distance between the line sink and line source for EG&G's recirculating well is 90 feet (see Figure 4-7). At a constant pumping rate, the recirculating well with the shorter distance between the screen intervals will have a larger percent of recirculation. Because IEG's recirculating well has a shorter distance between the screen intervals, it recirculates a greater percentage of re-injected groundwater than EG&G's recirculating well (see Figure 5-7 and Figure 5-9). At a constant pumping rate, the recirculating well that retreats a larger amount of re-injected groundwater extracts less untreated groundwater and thereby produces a smaller capture zone. As a result, IEG's recirculating well extracts less untreated groundwater (see Figure 5-8 and Figure 5-10) and produces a smaller capture zone (see Figure 5-2 and Figure 5-5) than EG&G's recirculating well.

The second reason for the development of recirculating well design curves is to aid the engineers at MMR in the design of a remediation system for CS-10. Figures 5-2 and 5-5 report the upstream capture zone as a function of the pumping rate. With this, a plume-wide remediation system for CS-10 can be established based on the recirculating well pumping rate and capture zone. The design curves were then converted into a dimensionless form (see Figure 5-3 and 5-6) to help design remediation systems for the other contaminant plumes on MMR.

These curves can also help to optimize a recirculating well remediation scheme to improve its cost-effectiveness. Figures 5-2 and 5-5 can be used to compare the cost associated with an increase in the pumping rate versus the benefit of an increase in capture zone. The pumping rate can then be optimized to provide a balance between the number of wells and the pumping rate. Figures 5-8 and 5-10 illustrate that the benefit associated with an increase in the pumping rate is not directly proportional to the increase in the upstream capture zone because the recirculating well increases the amount of retreated groundwater. Using the above design curves, a cost-effective recirculating well remediation scheme can be designed.

6. CONCLUSION

This thesis developed recirculating well design curves specifically for the MMR. These design curves related the recirculating well pumping rate to the resulting upstream capture zone. The graphs were based on results from numerical model simulations of both IEG Technologies Corporation and EG&G Environmental, Inc. recirculating well designs and the specific soil characteristics of the MMR.

First, the results indicate that the use of Herrling's charts in the design of a remediation strategy for the CS-10 plume will over estimate the recirculation rate and underestimate the capture area. The results then verify that a fluctuation in the water table elevation will not effect the upstream capture zone. Finally, the modeling results indicate that IEG's recirculating well retreats more groundwater while EG&G's recirculating well captures more of the untreated groundwater plume for any given pumping rate.

In conclusion, the site-specific design graphs and dimensionless design graphs will aid in the design of future recirculating well systems at the MMR, because engineers will be able to estimate the upstream capture zone based on the pumping rate.

7. FUTURE WORK

The logical approach at this point is to use the collected pilot test data and calibrate the design graphs presented in Section 5.3. This can be accomplished by recording head measurements in the field and comparing the observed head values to the predicted head values by the numerical model simulation. With the observed head values, the model can be calibrated to represent the actual observed head values by adjusting the model's hydraulic conductivity and the hydraulic gradient. With the calibrated model, new design graphs should be produced including design curves based on different a/H ratios. With the new graphs, engineers at MMR can be confident when using the graphs to predict the upstream capture zone and the amount of groundwater recirculated by the recirculating well for different pumping rates. The calibrated graphs can be a valuable tool during the design process, because engineers can determine the spacing between recirculating wells while capturing 100 percent of the plume.

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**APPENDIX A: MODEL INPUT AND COMMAND FILES FOR IEG
TECHNOLOGIES CORPORATION**

Appendix A.1 Command File for DYNFLOW

```
!create output file of session
OUTP DYN1.OUT
!read plan view finite element grid
GRID READ GRID.GRF FORM
!set number of levels
LEVEL 19
!set a rising head boundary condition for all nodes in level 19 (water table elev. to stop
!the head from rising above this level
RISI LEVEL 19
!set z-coordinates for each node/level
ELEV -190. LEVEL 1
ELEV -180. LEVEL 2
ELEV -175. LEVEL 3
ELEV -170. LEVEL 4
ELEV -155. LEVEL 5
ELEV -140. LEVEL 6
ELEV -125. LEVEL 7
ELEV -120. LEVEL 8
ELEV -115. LEVEL 9
ELEV -110. LEVEL 10
ELEV -105. LEVEL 11
ELEV -90. LEVEL 12
ELEV -80. LEVEL 13
ELEV -70. LEVEL 14
ELEV -65. LEVEL 15
ELEV -60. LEVEL 16
ELEV 0. LEVEL 17
ELEV 45. LEVEL 18
ELEV 80. LEVEL 19
!fix nodes upgradient and downgradient of well
FIX NODE 901 - 916 level all
FIX NODE 476 - 482 level all
FIX NODE 532 - 539 level all
FIX NODE 781 - 784 level all
!set initial head value for all nodes
INIT 35.
!fix head boundaries upgradient and downgradient of well (overall 0.0014 ft./ft. head drop)
INIT 34.4 NODE 476 - 482 level all
INIT 34.4 NODE 532 - 539 level all
INIT 34.4 NODE 781 - 784 level all
INIT 36.1 NODE 901 - 916 level all
!define materials from bottom of plume to water table elev. - here only 1 type, fine to
!coarse grained sand
ELEM 310 LAYER 1 - 18
!specify pumping rate of well
FLUX 2824. NODE 1 LEVEL 2
FLUX 2824. NODE 1 LEVEL 3
FLUX 2824. NODE 1 LEVEL 4
FLUX -3388. NODE 1 LEVEL 7
FLUX -3388. NODE 1 LEVEL 8
FLUX -3388. NODE 1 LEVEL 9
```

```
FLUX -3388. NODE 1 LEVEL 10
FLUX -3388. NODE 1 LEVEL 11
FLUX 2824. NODE 1 LEVEL 14
FLUX 2824. NODE 1 LEVEL 15
FLUX 2824. NODE 1 LEVEL 16
!define areas of 1-D elements/node (screened intervals)
ONED 120 NODE 1 1 LEVEL 2 3
ONED 120 NODE 1 1 LEVEL 3 4
ONED 120 NODE 1 1 LEVEL 7 8
ONED 120 NODE 1 1 LEVEL 8 9
ONED 120 NODE 1 1 LEVEL 9 10
ONED 120 NODE 1 1 LEVEL 10 11
ONED 120 NODE 1 1 LEVEL 14 15
ONED 120 NODE 1 1 LEVEL 15 16
!specify recharge rate (ft/d)
RECH .0044 ELEM ALL
!define following properties of 1-d elements: #, K, Ss, Sy
PROP
20, 10000000.,0.,1.
!define following properties of material: #, Kx (ft/d), Ky, Kz, Ss, Sy
PROP
10, 297.2, 297.2, 59.53, .00001, .07
iter 10
goti
!save to file
SAVE RC1.SAV
XOUT
XCFI
```

Appendix A.2 Command File for DYNTRACK Capture Zone Simulations

```
!COMMAND FILE FOR CROSS-SECTIONAL PARTICLE TRACKING
!restore the Dynflow file
REST RC1.SAV
!create an output file
OUTP SAVE XS1.OUT FORM
!read the transport property
DPRO READ PROP.DPR
!Turn off dispersion simulation
XDISP
!set radius of capture for well
RADI 10
!set weight of particle
WEIGH 1000
!set starting time (units: days)
TIME 0
!set time step (units: days)
DT 0.11
!seed particles
PART
-250,600,-15
PART
-200,600,-15
PART
-180,600,-15
PART
-160,600,-15
PART
-145,600,-15
PART
-130,600,-15
PART
-115,600,-15
PART
-100,600,-15
PART
-90,600,-15
PART
-80,600,-15
PART
-70,600,-15
PART
-60,600,-15
PART
-50,600,-15
PART
-40,600,-15
PART
-30,600,-15
PART
-20,600,-15
```

PART	PART	PART	PART
-10,600,-15	-115,600,-40	160,600,-40	40,600,-50
PART	PART	PART	PART
0,600,-15	-100,600,-40	180,600,-40	50,600,-50
PART	PART	PART	PART
10,600,-15	-90,600,-40	200,600,-40	60,600,-50
PART	PART	PART	PART
20,600,-15	-80,600,-40	250,600,-40	70,600,-50
PART	PART	PART	PART
30,600,-15	-70,600,-40	-250,600,-50	80,600,-50
PART	PART	PART	PART
40,600,-15	-60,600,-40	-200,600,-50	90,600,-50
PART	PART	PART	PART
50,600,-15	-50,600,-40	-180,600,-50	100,600,-50
PART	PART	PART	PART
60,600,-15	-40,600,-40	-160,600,-50	115,600,-50
PART	PART	PART	PART
70,600,-15	-30,600,-40	-145,600,-50	130,600,-50
PART	PART	PART	PART
80,600,-15	-20,600,-40	-130,600,-50	145,600,-50
PART	PART	PART	PART
90,600,-15	-10,600,-40	-115,600,-50	160,600,-50
PART	PART	PART	PART
100,600,-15	0,600,-40	-100,600,-50	180,600,-50
PART	PART	PART	PART
115,600,-15	10,600,-40	-90,600,-50	200,600,-50
PART	PART	PART	PART
130,600,-15	20,600,-40	-80,600,-50	250,600,-50
PART	PART	PART	PART
145,600,-15	30,600,-40	-70,600,-50	-250,600,-60
PART	PART	PART	PART
160,600,-15	40,600,-40	-60,600,-50	-200,600,-60
PART	PART	PART	PART
180,600,-15	50,600,-40	-50,600,-50	-180,600,-60
PART	PART	PART	PART
200,600,-15	60,600,-40	-40,600,-50	-160,600,-60
PART	PART	PART	PART
250,600,-15	70,600,-40	-30,600,-50	-145,600,-60
PART	PART	PART	PART
-250,600,-40	80,600,-40	-20,600,-50	-130,600,-60
PART	PART	PART	PART
-200,600,-40	90,600,-40	-10,600,-50	-115,600,-60
PART	PART	PART	PART
-180,600,-40	100,600,-40	0,600,-50	-100,600,-60
PART	PART	PART	PART
-160,600,-40	115,600,-40	10,600,-50	-90,600,-60
PART	PART	PART	PART
-145,600,-40	130,600,-40	20,600,-50	-80,600,-60
PART	PART	PART	PART
-130,600,-40	145,600,-40	30,600,-50	-70,600,-60

Note: The particle track command file must be entered in one column in order to successfully run the DYNTRACK particle simulation. The command file is presented here in four columns to save paper.

PART	PART	PART	PART
-60,600,-60	-200,600,-70	90,600,-70	-10,600,-80
PART	PART	PART	PART
-50,600,-60	-180,600,-70	100,600,-70	0,600,-80
PART	PART	PART	PART
-40,600,-60	-160,600,-70	115,600,-70	10,600,-80
PART	PART	PART	PART
-30,600,-60	-145,600,-70	130,600,-70	20,600,-80
PART	PART	PART	PART
-20,600,-60	-130,600,-70	145,600,-70	30,600,-80
PART	PART	PART	PART
-10,600,-60	-115,600,-70	160,600,-70	40,600,-80
PART	PART	PART	PART
0,600,-60	-100,600,-70	180,600,-70	50,600,-80
PART	PART	PART	PART
10,600,-60	-90,600,-70	200,600,-70	60,600,-80
PART	PART	PART	PART
20,600,-60	-80,600,-70	250,600,-70	70,600,-80
PART	PART	PART	PART
30,600,-60	-70,600,-70	-250,600,-80	80,600,-80
PART	PART	PART	PART
40,600,-60	-60,600,-70	-200,600,-80	90,600,-80
PART	PART	PART	PART
50,600,-60	-50,600,-70	-180,600,-80	100,600,-80
PART	PART	PART	PART
60,600,-60	-40,600,-70	-160,600,-80	115,600,-80
PART	PART	PART	PART
70,600,-60	-30,600,-70	-145,600,-80	130,600,-80
PART	PART	PART	PART
80,600,-60	-20,600,-70	-130,600,-80	145,600,-80
PART	PART	PART	PART
90,600,-60	-10,600,-70	-115,600,-80	160,600,-80
PART	PART	PART	PART
100,600,-60	0,600,-70	-100,600,-80	180,600,-80
PART	PART	PART	PART
115,600,-60	10,600,-70	-90,600,-80	200,600,-80
PART	PART	PART	PART
130,600,-60	20,600,-70	-80,600,-80	250,600,-80
PART	PART	PART	PART
145,600,-60	30,600,-70	-70,600,-80	-250,600,-115
PART	PART	PART	PART
160,600,-60	40,600,-70	-60,600,-80	-200,600,-115
PART	PART	PART	PART
180,600,-60	50,600,-70	-50,600,-80	-180,600,-115
PART	PART	PART	PART
200,600,-60	60,600,-70	-40,600,-80	-160,600,-115
PART	PART	PART	PART
250,600,-60	70,600,-70	-30,600,-80	-145,600,-115
PART	PART	PART	PART
-250,600,-70	80,600,-70	-20,600,-80	-130,600,-115

Note: The particle track command file must be entered in one column in order to successfully run the DYNTRACK particle simulation. The command file is presented here in four columns to save paper.

PART	PART	PART	PART
-115,600,-115	160,600,-115	40,600,-150	-60,600,-160
PART	PART	PART	PART
-100,600,-115	180,600,-115	50,600,-150	-50,600,-160
PART	PART	PART	PART
-90,600,-115	200,600,-115	60,600,-150	-40,600,-160
PART	PART	PART	PART
-80,600,-115	250,600,-115	70,600,-150	-30,600,-160
PART	PART	PART	PART
-70,600,-115	-250,600,-150	80,600,-150	-20,600,-160
PART	PART	PART	PART
-60,600,-115	-200,600,-150	90,600,-150	-10,600,-160
PART	PART	PART	PART
-50,600,-115	-180,600,-150	100,600,-150	0,600,-160
PART	PART	PART	PART
-40,600,-115	-160,600,-150	115,600,-150	10,600,-160
PART	PART	PART	PART
-30,600,-115	-145,600,-150	130,600,-150	20,600,-160
PART	PART	PART	PART
-20,600,-115	-130,600,-150	145,600,-150	30,600,-160
PART	PART	PART	PART
-10,600,-115	-115,600,-150	160,600,-150	40,600,-160
PART	PART	PART	PART
0,600,-115	-100,600,-150	180,600,-150	50,600,-160
PART	PART	PART	PART
10,600,-115	-90,600,-150	200,600,-150	60,600,-160
PART	PART	PART	PART
20,600,-115	-80,600,-150	250,600,-150	70,600,-160
PART	PART	PART	PART
30,600,-115	-70,600,-150	-250,600,-160	80,600,-160
PART	PART	PART	PART
40,600,-115	-60,600,-150	-200,600,-160	90,600,-160
PART	PART	PART	PART
50,600,-115	-50,600,-150	-180,600,-160	100,600,-160
PART	PART	PART	PART
60,600,-115	-40,600,-150	-160,600,-160	115,600,-160
PART	PART	PART	PART
70,600,-115	-30,600,-150	-145,600,-160	130,600,-160
PART	PART	PART	PART
80,600,-115	-20,600,-150	-130,600,-160	145,600,-160
PART	PART	PART	PART
90,600,-115	-10,600,-150	-115,600,-160	160,600,-160
PART	PART	PART	PART
100,600,-115	0,600,-150	-100,600,-160	180,600,-160
PART	PART	PART	PART
115,600,-115	10,600,-150	-90,600,-160	200,600,-160
PART	PART	PART	PART
130,600,-115	20,600,-150	-80,600,-160	250,600,-160
PART	PART	PART	PART
145,600,-115	30,600,-150	-70,600,-160	-250,600,-170

Note: The particle track command file must be entered in one column in order to successfully run the DYNTRACK particle simulation. The command file is presented here in four columns to save paper.

PART	PART	PART	PART
-200,600,-170	90,600,-170	-10,600,-180	-115,600,-190
PART	PART	PART	PART
-180,600,-170	100,600,-170	0,600,-180	-100,600,-190
PART	PART	PART	PART
-160,600,-170	115,600,-170	10,600,-180	-90,600,-190
PART	PART	PART	PART
-145,600,-170	130,600,-170	20,600,-180	-80,600,-190
PART	PART	PART	PART
-130,600,-170	145,600,-170	30,600,-180	-70,600,-190
PART	PART	PART	PART
-115,600,-170	160,600,-170	40,600,-180	-60,600,-190
PART	PART	PART	PART
-100,600,-170	180,600,-170	50,600,-180	-50,600,-190
PART	PART	PART	PART
-90,600,-170	200,600,-170	60,600,-180	-40,600,-190
PART	PART	PART	PART
-80,600,-170	250,600,-170	70,600,-180	-30,600,-190
PART	PART	PART	PART
-70,600,-170	-250,600,-180	80,600,-180	-20,600,-190
PART	PART	PART	PART
-60,600,-170	-200,600,-180	90,600,-180	-10,600,-190
PART	PART	PART	PART
-50,600,-170	-180,600,-180	100,600,-180	0,600,-190
PART	PART	PART	PART
-40,600,-170	-160,600,-180	115,600,-180	10,600,-190
PART	PART	PART	PART
-30,600,-170	-145,600,-180	130,600,-180	20,600,-190
PART	PART	PART	PART
-20,600,-170	-130,600,-180	145,600,-180	30,600,-190
PART	PART	PART	PART
-10,600,-170	-115,600,-180	160,600,-180	40,600,-190
PART	PART	PART	PART
0,600,-170	-100,600,-180	180,600,-180	50,600,-190
PART	PART	PART	PART
10,600,-170	-90,600,-180	200,600,-180	60,600,-190
PART	PART	PART	PART
20,600,-170	-80,600,-180	250,600,-180	70,600,-190
PART	PART	PART	PART
30,600,-170	-70,600,-180	-250,600,-190	80,600,-190
PART	PART	PART	PART
40,600,-170	-60,600,-180	-200,600,-190	90,600,-190
PART	PART	PART	PART
50,600,-170	-50,600,-180	-180,600,-190	100,600,-190
PART	PART	PART	PART
60,600,-170	-40,600,-180	-160,600,-190	115,600,-190
PART	PART	PART0	PART
70,600,-170	-30,600,-180	-145,600,-190	130,600,-190
PART	PART	PART	PART
80,600,-170	-20,600,-180	-130,600,-190	145,600,-190

Note: The particle track command file must be entered in one column in order to successfully run the DYNTRACK particle simulation. The command file is presented here in four columns to save paper.

```
PART
160,600,-190
PART
180,600,-190
PART
200,600,-190
PART
250,600,-190
!store particle track in file
RESU 40 SAVE XS1.RES
GOTI 100
GOTI 200
GOTI 300
GOTI 400
GOTI 500
GOTI 600
GOTI 700
GOTI 800
GOTI 900
GOTI 1000
GOTI 1100
GOTI 1200
PRIN
!finish
XRES
XOUT
END
```

Appendix A.3 Property File Used for DYNTRACK

```
!dyntrack property file
!prop. no., disp.(long.), disp.(trans.), disp. ratio (vert./horiz.), effect. porosity, retardation
10,0.,0.,0.,0.35,1.00
20,0.,0.,0.,1.00,1.00
```

Appendix A.4 Command File for DYNTRACK Retreatment Simulations

```
!COMMAND FILE FOR CIRCULAR PARTICLE TRACKING
!restore the Dynflow file
REST RC1.SAV
!create an output file
OUTP SAVE SPHERE1.OUT FORM
!read the transport property
DPRO READ PROP.DPR
!Turn off dispersion simulation
XDISP
!set radius of capture for well
RADI 10
!set weight of particle
WEIGH 1000
!set starting time (units: days)
TIME 0
!set time step (units: days)
DT 0.042
!seed particles
PART
0.0000,2.0000,-180
PART
0.3473,1.9696,-180
PART
0.6840,1.8794,-180
PART
1.0000,1.7321,-180
PART
1.2856,1.5321,-180
PART
1.5321,1.2856,-180
PART
1.7321,1.0000,-180
PART
1.8794,0.6840,-180
PART
1.9696,0.3473,-180
PART
2.0000,0.0000,-180
PART
1.9696,-0.3437,-180
PART
1.8794,-0.6840,-180
PART
1.7321,-1.0000,-180
PART
1.5321,-1.2856,-180
PART
1.2856,-1.5321,-180
PART
1.0000,-1.7321,-180
```

PART	PART	PART	PART
0.6840,-1.8794,-180	1.5321,1.2856,-175	-1.7321,1.0000,-175	-0.3473,-1.9696,-170
PART	PART	PART	PART
0.3473,-1.9696,-180	1.7321,1.0000,-175	-1.5321,1.2856,-175	-0.6840,-1.8794,-170
PART	PART	PART	PART
0.0000,-2.0000,-180	1.8794,0.6840,-175	-1.2856,1.5321,-175	-1.0000,-1.7321,-170
PART	PART	PART	PART
-0.3473,-1.9696,-180	1.9696,0.3473,-175	-1.0000,1.7321,-175	-1.2856,-1.5321,-170
PART	PART	PART	PART
-0.6840,-1.8794,-180	2.0000,0.0000,-175	-0.6840,1.8794,-175	-1.5321,-1.2856,-170
PART	PART	PART	PART
-1.0000,-1.7321,-180	1.9696,-0.3437,-175	-0.3473,1.9696,-175	-1.7321,-1.0000,-170
PART	PART	PART	PART
-1.2856,-1.5321,-180	1.8794,-0.6840,-175	0.0000,2.0000,-170	-1.8794,-0.6840,-170
PART	PART	PART	PART
-1.5321,-1.2856,-180	1.7321,-1.0000,-175	0.3473,1.9696,-170	-1.9696,-0.3473,-170
PART	PART	PART	PART
-1.7321,-1.0000,-180	1.5321,-1.2856,-175	0.6840,1.8794,-170	-2.0000,0.0000,-170
PART	PART	PART	PART
-1.8794,-0.6840,-180	1.2856,-1.5321,-175	1.0000,1.7321,-170	-1.9696,0.3473,-170
PART	PART	PART	PART
-1.9696,-0.3473,-180	1.0000,-1.7321,-175	1.2856,1.5321,-170	-1.8794,0.6840,-170
PART	PART	PART	PART
-2.0000,0.0000,-180	0.6840,-1.8794,-175	1.5321,1.2856,-170	-1.7321,1.0000,-170
PART	PART	PART	PART
-1.9696,0.3473,-180	0.3473,-1.9696,-175	1.7321,1.0000,-170	-1.5321,1.2856,-170
PART	PART	PART	PART
-1.8794,0.6840,-180	0.0000,-2.0000,-175	1.8794,0.6840,-170	-1.2856,1.5321,-170
PART	PART	PART	PART
-1.7321,1.0000,-180	-0.3473,-1.9696,-175	1.9696,0.3473,-170	-1.0000,1.7321,-170
PART	PART	PART	PART
-1.5321,1.2856,-180	-0.6840,-1.8794,-175	2.0000,0.0000,-170	-0.6840,1.8794,-170
PART	PART	PART	PART
-1.2856,1.5321,-180	-1.0000,-1.7321,-175	1.9696,-0.3437,-170	-0.3473,1.9696,-170
PART	PART	PART	PART
-1.0000,1.7321,-180	-1.2856,-1.5321,-175	1.8794,-0.6840,-170	0.0000,2.0000,-70
PART	PART	PART	PART
-0.6840,1.8794,-180	-1.5321,-1.2856,-175	1.7321,-1.0000,-170	0.3473,1.9696,-70
PART	PART	PART	PART
-0.3473,1.9696,-180	-1.7321,-1.0000,-175	1.5321,-1.2856,-170	0.6840,1.8794,-70
PART	PART	PART	PART
0.0000,2.0000,-175	-1.8794,-0.6840,-175	1.2856,-1.5321,-170	1.0000,1.7321,-70
PART	PART	PART	PART
0.3473,1.9696,-175	-1.9696,-0.3473,-175	1.0000,-1.7321,-170	1.2856,1.5321,-70
PART	PART	PART	PART
0.6840,1.8794,-175	-2.0000,0.0000,-175	0.6840,-1.8794,-170	1.5321,1.2856,-70
PART	PART	PART	PART
1.0000,1.7321,-175	-1.9696,0.3473,-175	0.3473,-1.9696,-170	1.7321,1.0000,-70
PART	PART	PART	PART
1.2856,1.5321,-175	-1.8794,0.6840,-175	0.0000,-2.0000,-170	1.8794,0.6840,-70

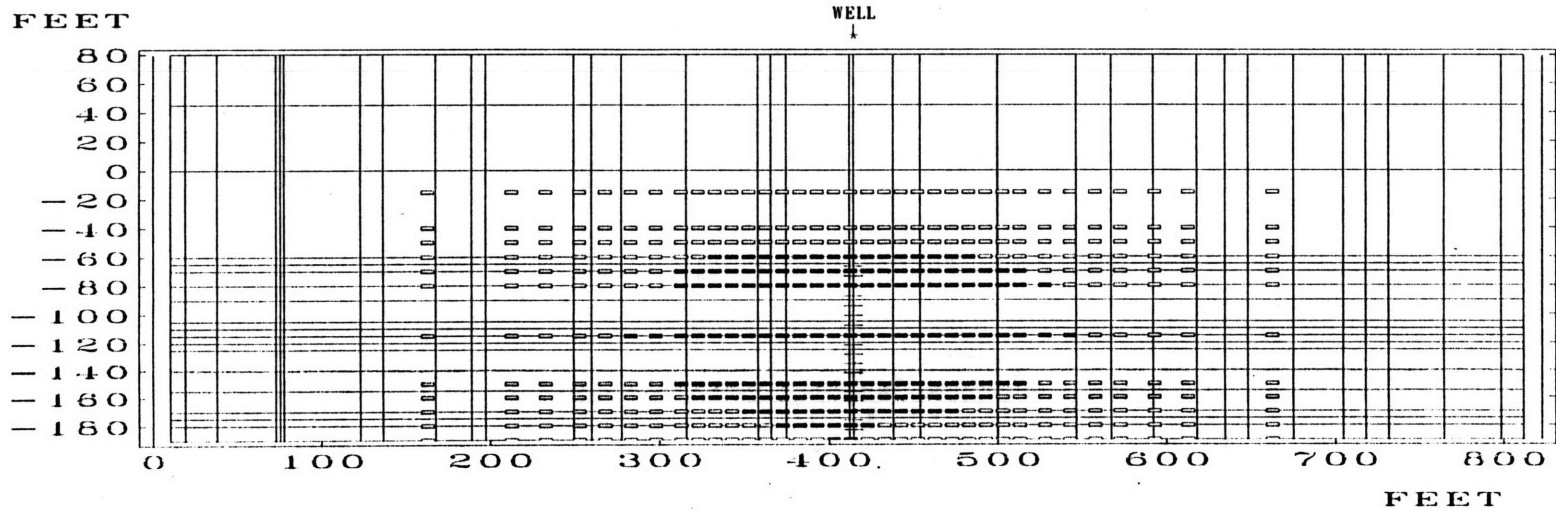
Note: The particle track command file must be entered in one column in order to successfully run the DYNTRACK particle simulation. The command file is presented here in four columns to save paper

PART	PART	PART	PART
1.9696,0.3473,-70	-1.0000,1.7321,-70	-1.2856,-1.5321,-65	1.8794,-0.6840,-60
PART	PART	PART	PART
2.0000,0.0000,-70	-0.6840,1.8794,-70	-1.5321,-1.2856,-65	1.7321,-1.0000,-60
PART	PART	PART	PART
1.9696,-0.3437,-70	-0.3473,1.9696,-70	-1.7321,-1.0000,-65	1.5321,-1.2856,-60
PART	PART	PART	PART
1.8794,-0.6840,-70	0.0000,2.0000,-65	-1.8794,-0.6840,-65	1.2856,-1.5321,-60
PART	PART	PART	PART
1.7321,-1.0000,-70	0.3473,1.9696,-65	-1.9696,-0.3473,-65	1.0000,-1.7321,-60
PART	PART	PART	PART
1.5321,-1.2856,-70	0.6840,1.8794,-65	-2.0000,0.0000,-65	0.6840,-1.8794,-60
PART	PART	PART	PART
1.2856,-1.5321,-70	1.0000,1.7321,-65	-1.9696,0.3473,-65	0.3473,-1.9696,-60
PART	PART	PART	PART
1.0000,-1.7321,-70	1.2856,1.5321,-65	-1.8794,0.6840,-65	0.0000,-2.0000,-60
PART	PART	PART	PART
0.6840,-1.8794,-70	1.5321,1.2856,-65	-1.7321,1.0000,-65	-0.3473,-1.9696,-60
PART	PART	PART	PART
0.3473,-1.9696,-70	1.7321,1.0000,-65	-1.5321,1.2856,-65	-0.6840,-1.8794,-60
PART	PART	PART	PART
0.0000,-2.0000,-70	1.8794,0.6840,-65	-1.2856,1.5321,-65	-1.0000,-1.7321,-60
PART	PART	PART	PART
-0.3473,-1.9696,-70	1.9696,0.3473,-65	-1.0000,1.7321,-65	-1.2856,-1.5321,-60
PART	PART	PART	PART
-0.6840,-1.8794,-70	2.0000,0.0000,-65	-0.6840,1.8794,-65	-1.5321,-1.2856,-60
PART	PART	PART	PART
-1.0000,-1.7321,-70	1.9696,-0.3437,-65	-0.3473,1.9696,-65	-1.7321,-1.0000,-60
PART	PART	PART	PART
-1.2856,-1.5321,-70	1.8794,-0.6840,-65	0.0000,2.0000,-60	-1.8794,-0.6840,-60
PART	PART	PART	PART
-1.5321,-1.2856,-70	1.7321,-1.0000,-65	0.3473,1.9696,-60	-1.9696,-0.3473,-60
PART	PART	PART	PART
-1.7321,-1.0000,-70	1.5321,-1.2856,-65	0.6840,1.8794,-60	-2.0000,0.0000,-60
PART	PART	PART	PART
-1.8794,-0.6840,-70	1.2856,-1.5321,-65	1.0000,1.7321,-60	-1.9696,0.3473,-60
PART	PART	PART	PART
-1.9696,-0.3473,-70	1.0000,-1.7321,-65	1.2856,1.5321,-60	-1.8794,0.6840,-60
PART	PART	PART	PART
-2.0000,0.0000,-70	0.6840,-1.8794,-65	1.5321,1.2856,-60	-1.7321,1.0000,-60
PART	PART	PART	PART
-1.9696,0.3473,-70	0.3473,-1.9696,-65	1.7321,1.0000,-60	-1.5321,1.2856,-60
PART	PART	PART	PART
-1.8794,0.6840,-70	0.0000,-2.0000,-65	1.8794,0.6840,-60	-1.2856,1.5321,-60
PART	PART	PART	PART
-1.7321,1.0000,-70	-0.3473,-1.9696,-65	1.9696,0.3473,-60	-1.0000,1.7321,-60
PART	PART	PART	PART
-1.5321,1.2856,-70	-0.6840,-1.8794,-65	2.0000,0.0000,-60	-0.6840,1.8794,-60
PART	PART	PART	PART
-1.2856,1.5321,-70	-1.0000,-1.7321,-65	1.9696,-0.3437,-60	-0.3473,1.9696,-60

Note: The particle track command file must be entered in one column in order to successfully run the DYNTRACK particle simulation. The command file is presented here in four columns to save paper

```
!store particle track in file
RESU 25 SAVE SPHERE1.RES
GOTI 25
GOTI 50
GOTI 75
GOTI 100
GOTI 125
GOTI 150
GOTI 175
GOTI 200
PRIN
!finish
XRES
XOUT
END
```

Appendix A.5 DYNPLOT Graphical Output of Capture Zone for Design Pumping Rate



* RECIRCULATING WELL
WITHIN 600.0 FT

— GROUND SURFACE

- - - TOP OF SCREEN

—| BOTTOM OF SCREEN

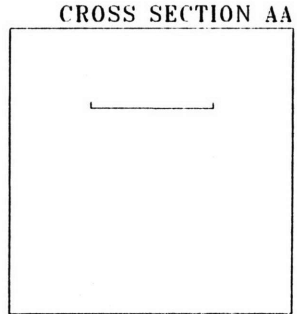
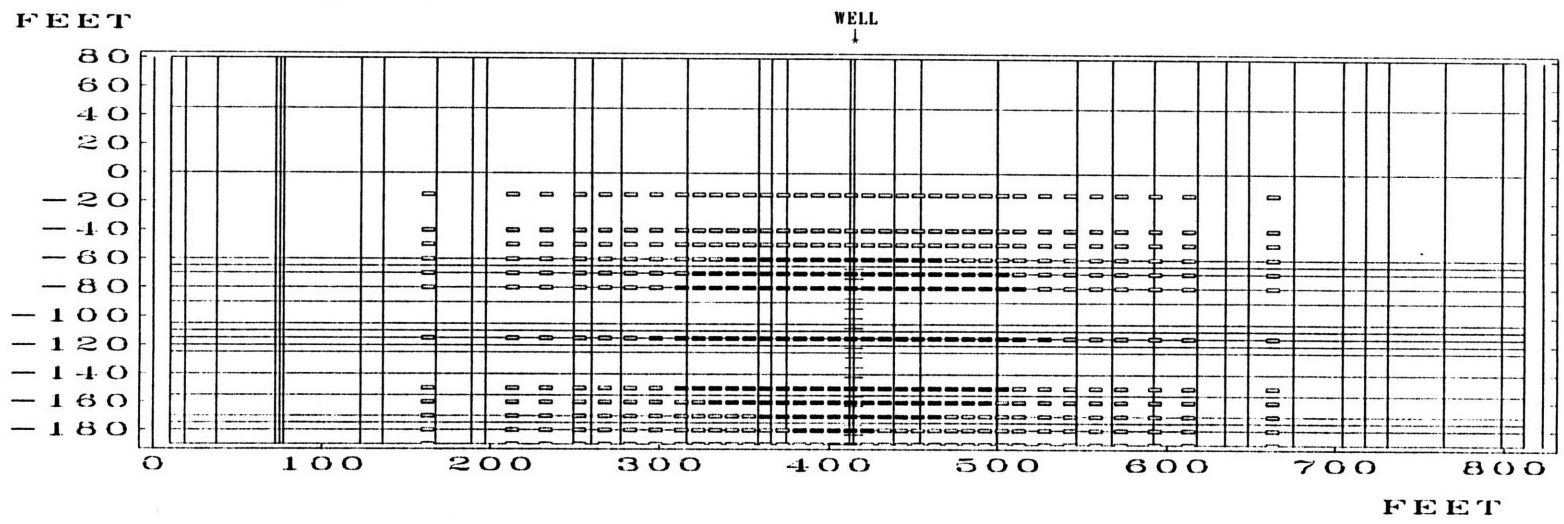


Figure A5-1: Water Table Simulation
Pumping Rate - 88 gpm
Water Table Elevation - 0 ft. asl
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* RECIRCULATING WELL
WITHIN 600.0 FT

— GROUND SURFACE

— TOP OF SCREEN

— BOTTOM OF SCREEN

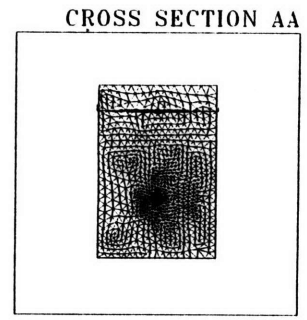
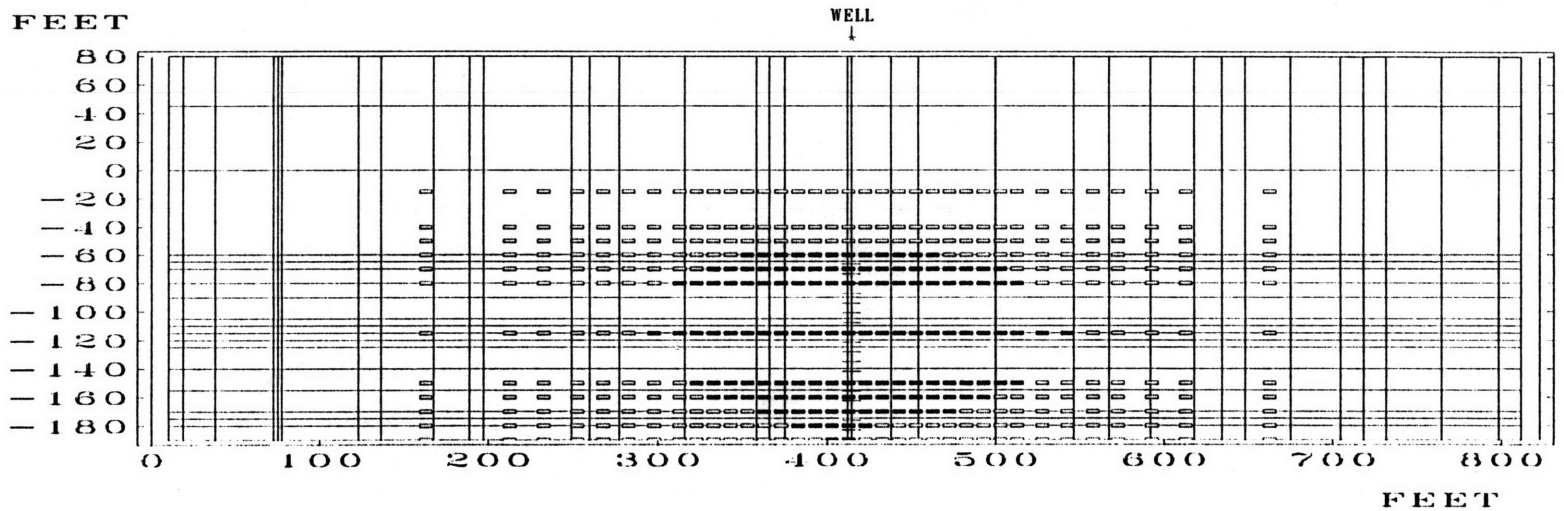


Figure A5-2: Water Table Simulation
Pumping Rate - 88 gpm
Water Table Elevation - 35 ft. asl
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* RECIRCULATING WELL
 WITHIN 600.0 FT
 GROUND SURFACE
 TOP OF SCREEN
 BOTTOM OF SCREEN

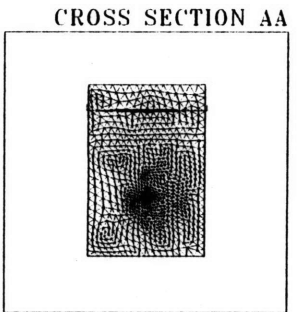
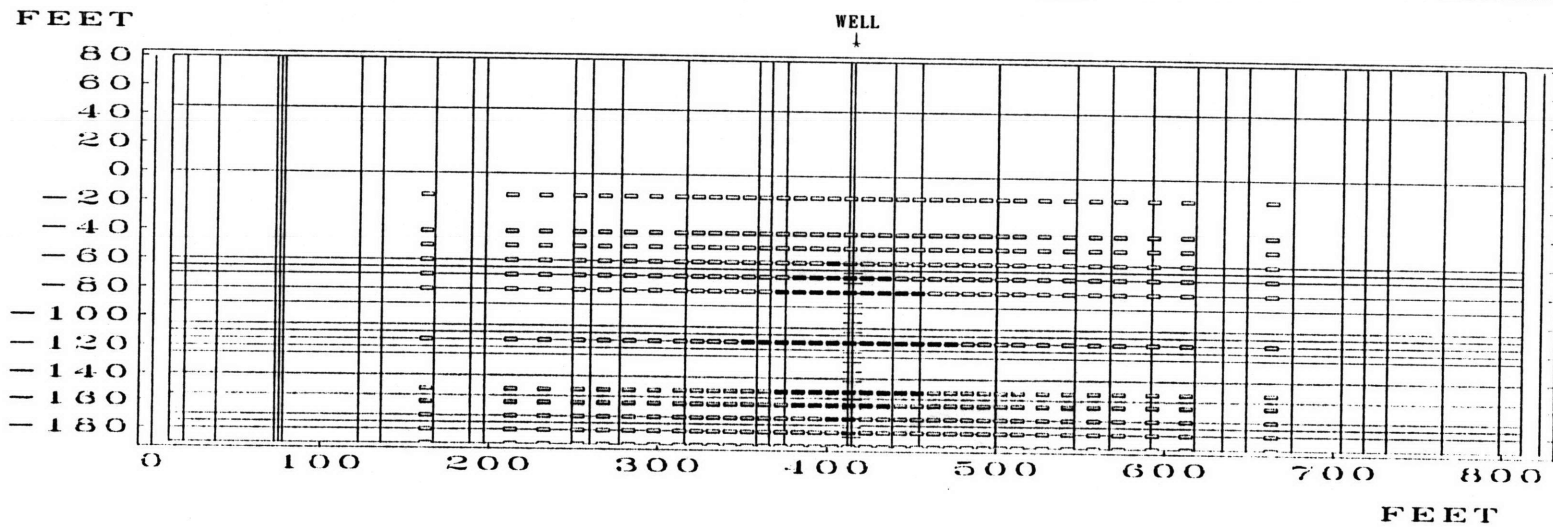


Figure A5-3: Water Table Simulation
 Pumping Rate - 88 gpm
 Water Table Elevation - 75 ft. asl
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Appendix A.6 DYNPLOT Graphical Output of Capture Zone for Different Pumping Rates



* RECIRCULATING WELL
WITHIN 600.0 FT

— GROUND SURFACE

— TOP OF SCREEN

— BOTTOM OF SCREEN

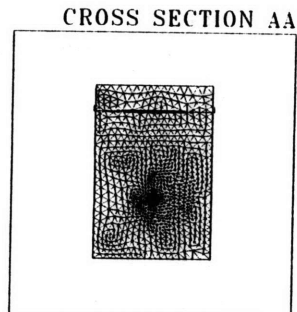
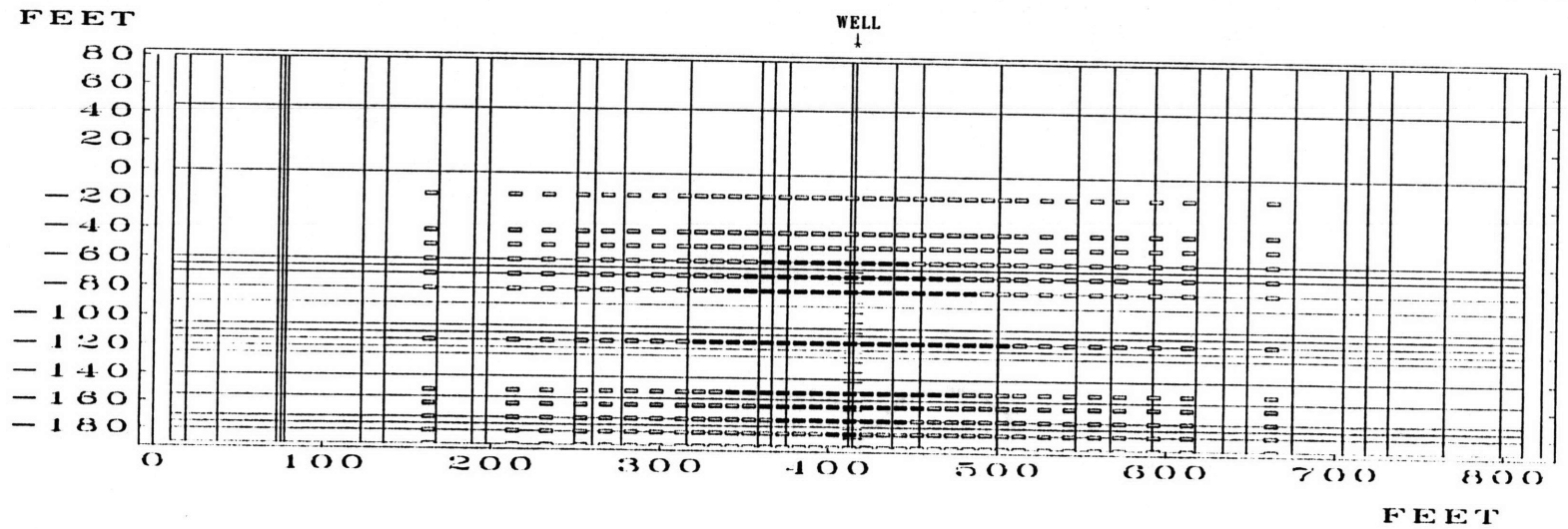
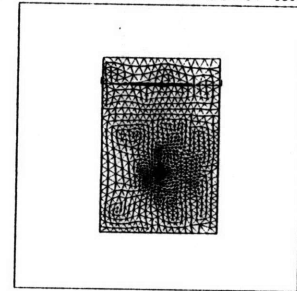


Figure A6-1: Capture Zone Simulation
Pumping Rate - 25 gpm
Water Table Elevation - 35 ft. asl
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CROSS SECTION AA



* RECIRCULATING WELL
WITHIN 600.0 FT

GROUND SURFACE

TOP OF SCREEN

BOTTOM OF SCREEN

Figure A6-2: Capture Zone Simulation
Pumping Rate - 50 gpm
Water Table Elevation - 35 ft. asl
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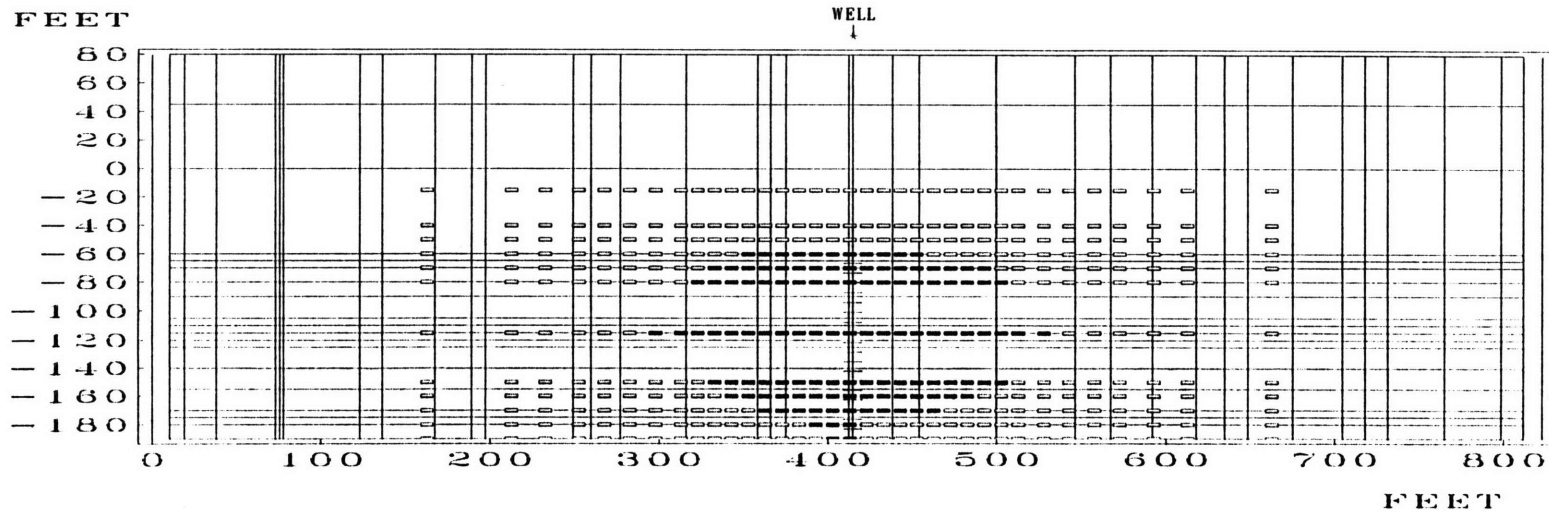


Figure A6-3: Capture Zone Simulation

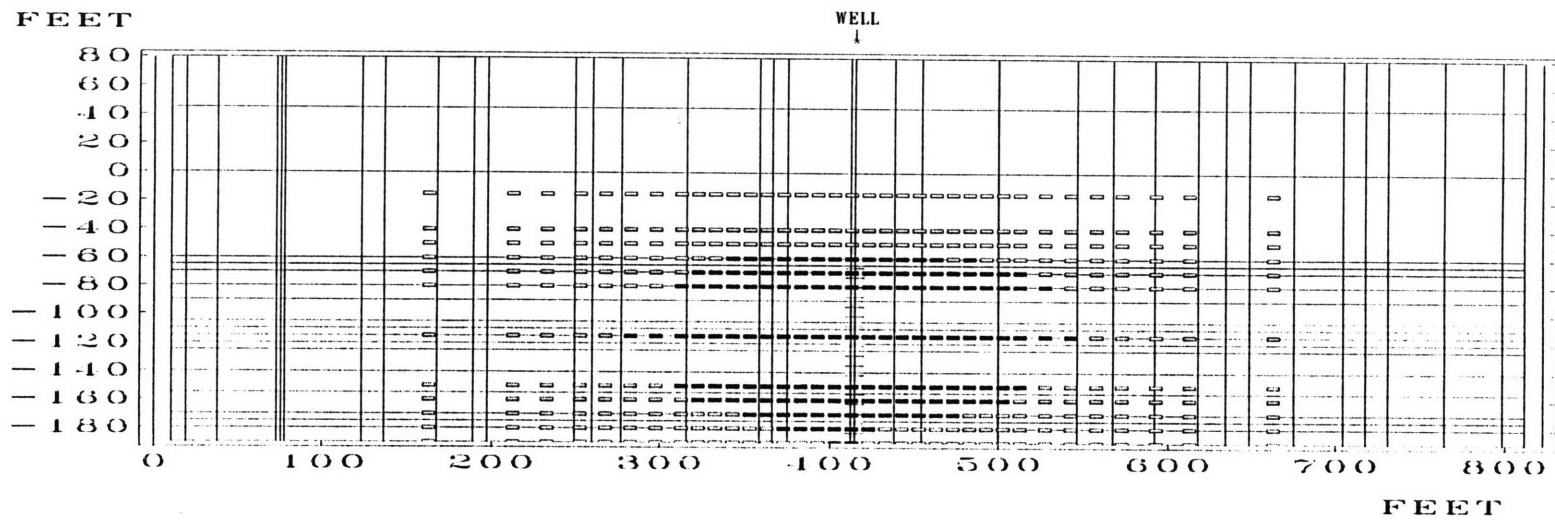
Pumping Rate - 75 gpm

Water Table Elevation - 35 ft. asl

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* RECIRCULATING WELL
WITHIN 600.0 FT

GROUND SURFACE

TOP OF SCREEN

BOTTOM OF SCREEN

CROSS SECTION AA

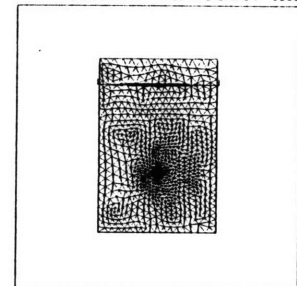
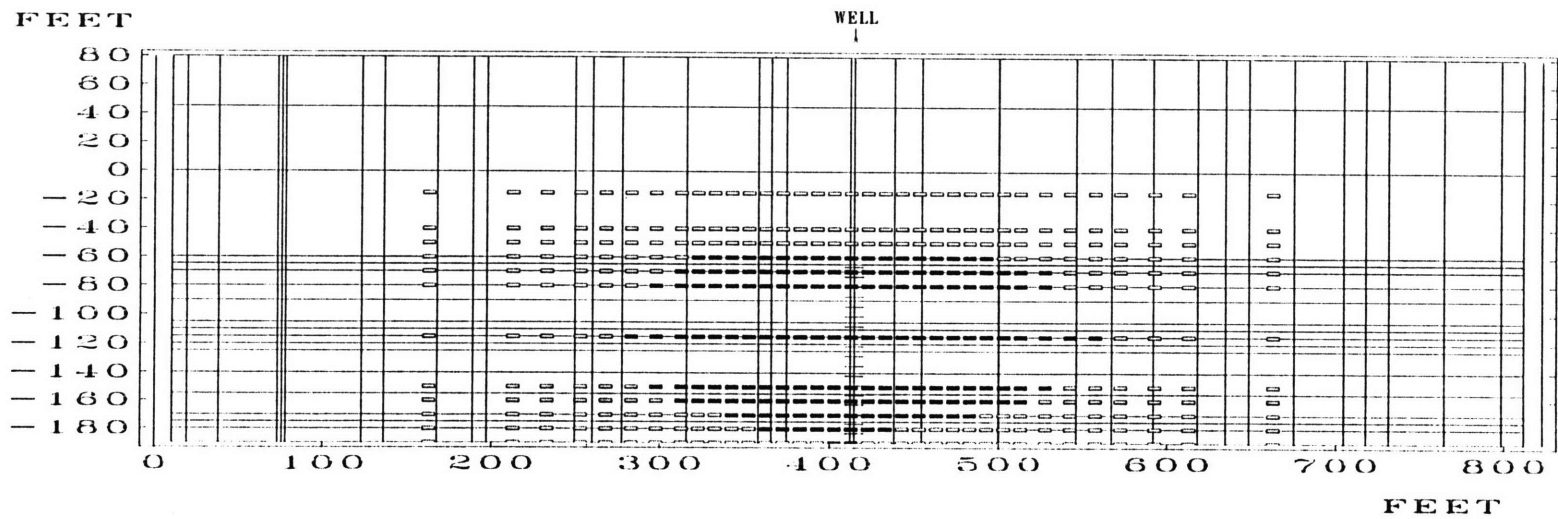


Figure A6-4: Capture Zone Simulation
Pumping Rate - 100 gpm
Water Table Elevation - 35 ft. asl
 Massachusetts Military Reservation

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* RECIRCULATING WELL
WITHIN 600.0 FT

— GROUND SURFACE

— TOP OF SCREEN

— BOTTOM OF SCREEN

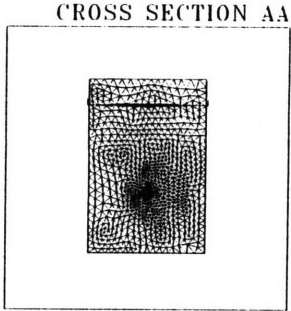
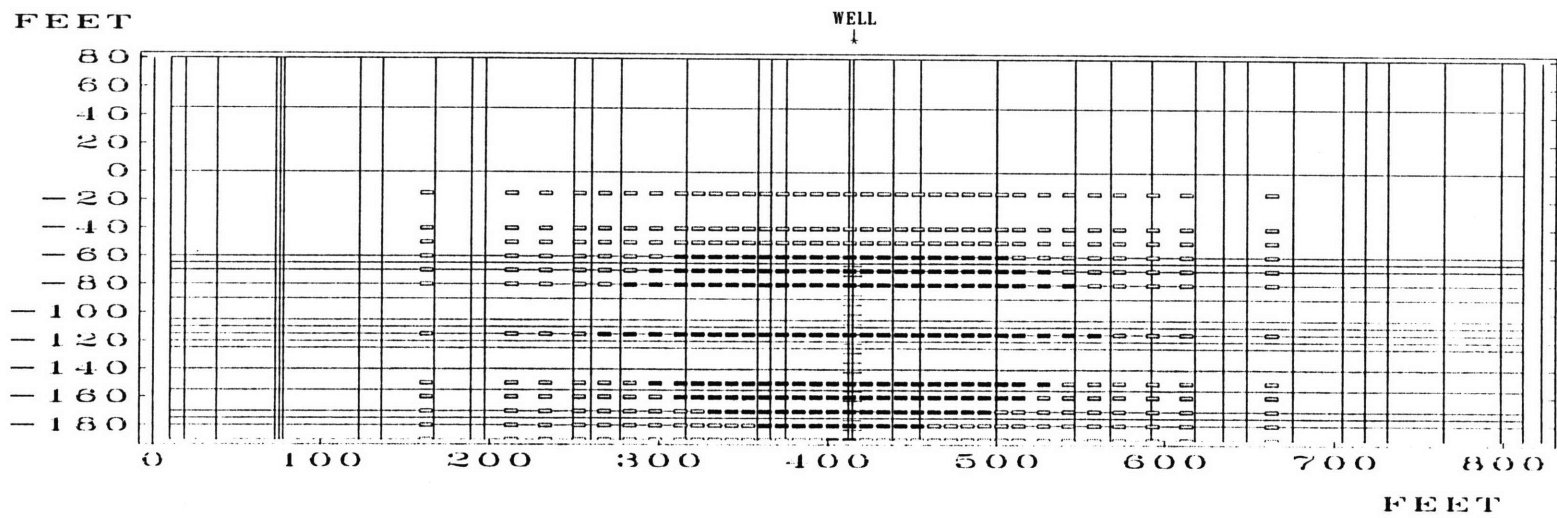


Figure A6-5: Capture Zone Simulation
Pumping Rate - 125 gpm
Water Table Elevation - 35 ft. asl
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* RECIRCULATING WELL
WITHIN 600.0 FT

— GROUND SURFACE

— TOP OF SCREEN

— BOTTOM OF SCREEN

CROSS SECTION AA

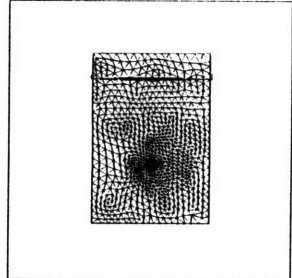
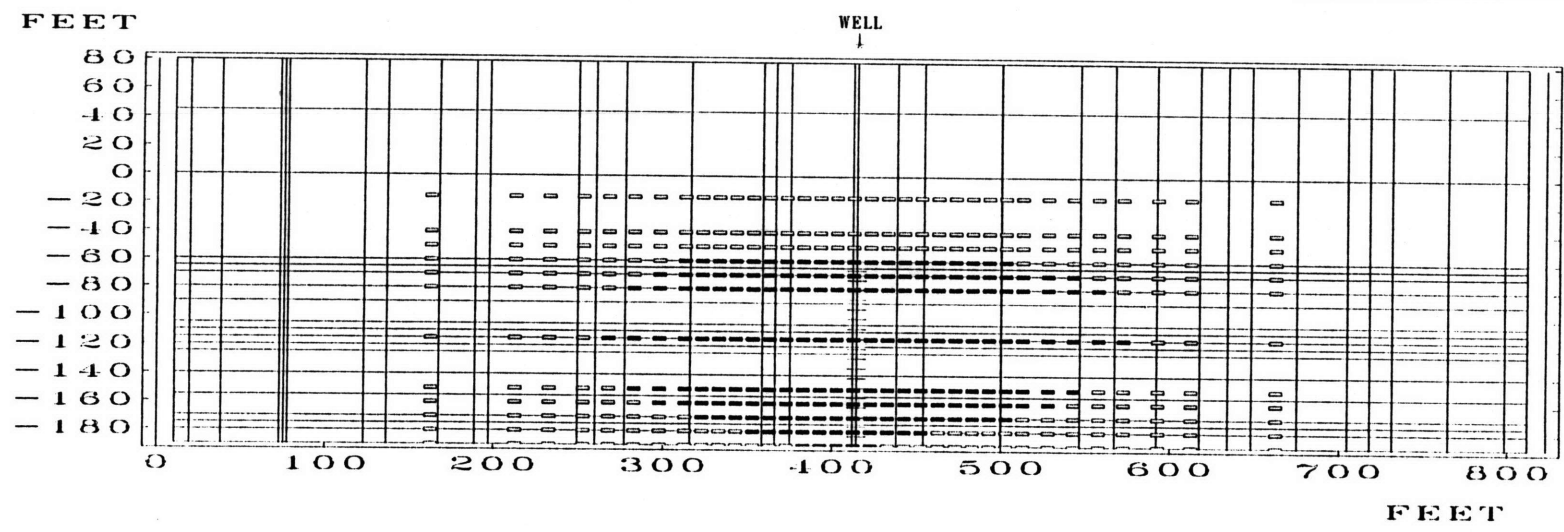


Figure A6-6: Capture Zone Simulation
Pumping Rate - 150 gpm
Water Table Elevation - 35 ft. asl
 Massachusetts Military Reservation

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* RECIRCULATING WELL
WITHIN 600.0 FT

— GROUND SURFACE

— TOP OF SCREEN

— BOTTOM OF SCREEN

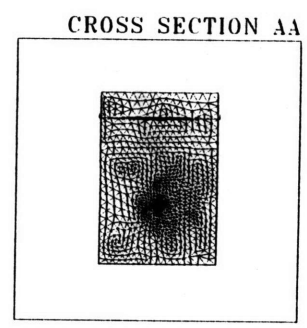
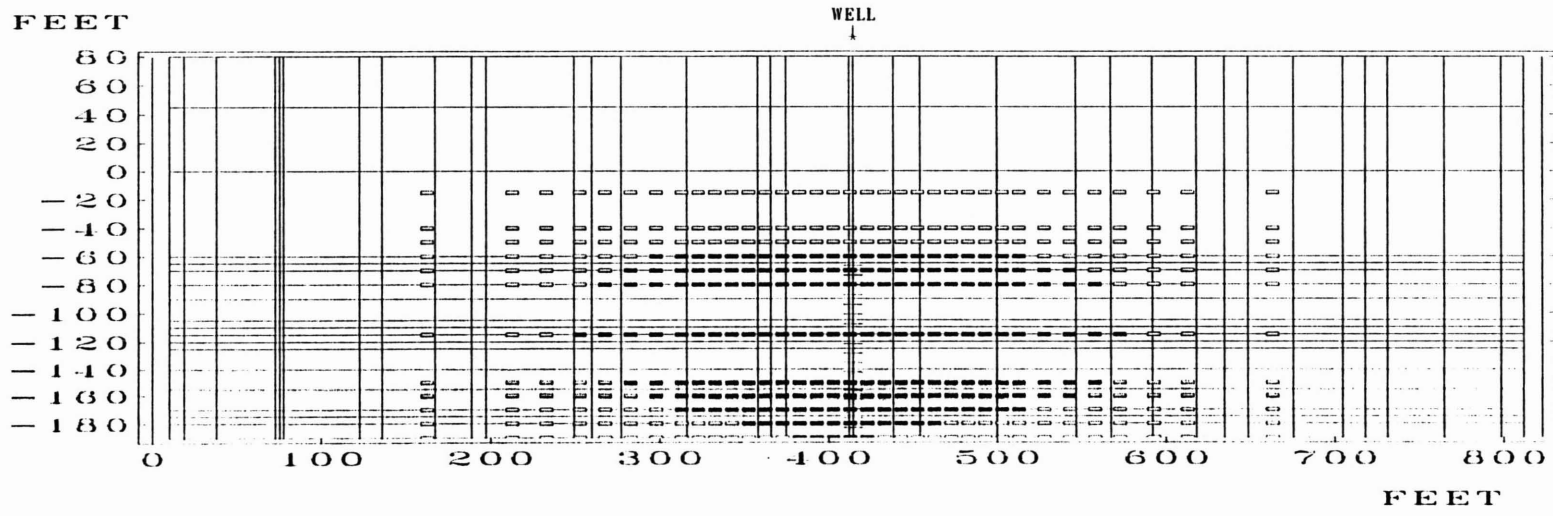
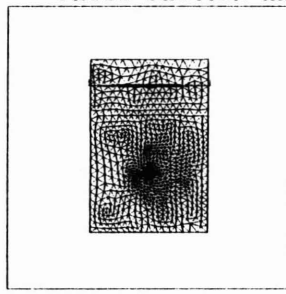


Figure A6-7: Capture Zone Simulation
Pumping Rate - 175 gpm
Water Table Elevation - 35 ft. asl
 Massachusetts Military Reservation

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CROSS SECTION AA

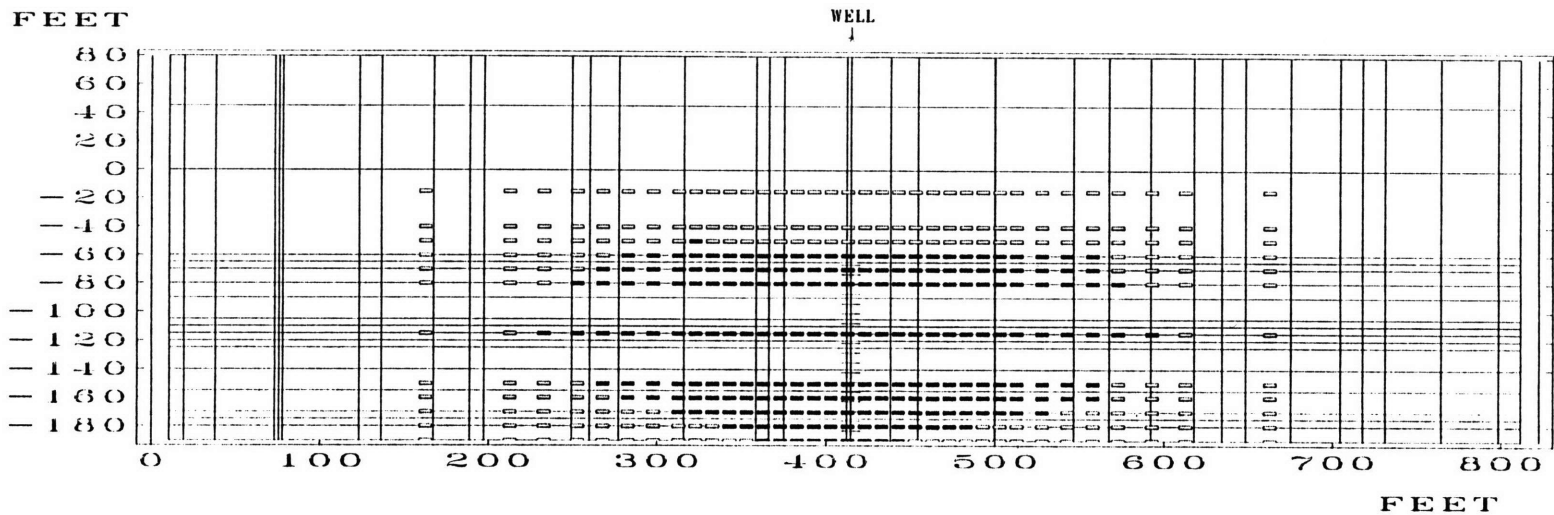


- * RECIRCULATING WELL WITHIN 600.0 FT
- GROUND SURFACE
- TOP OF SCREEN
- BOTTOM OF SCREEN

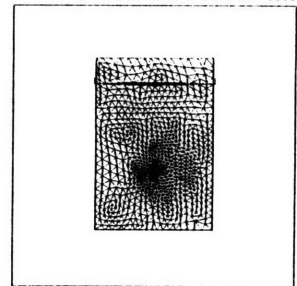
Figure A6-8: Capture Zone Simulation
Pumping Rate - 200 gpm
Water Table Elevation - 35 ft. asl
 Massachusetts Military Reservation

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CROSS SECTION AA



* RECIRCULATING WELL
WITHIN 600.0 FT

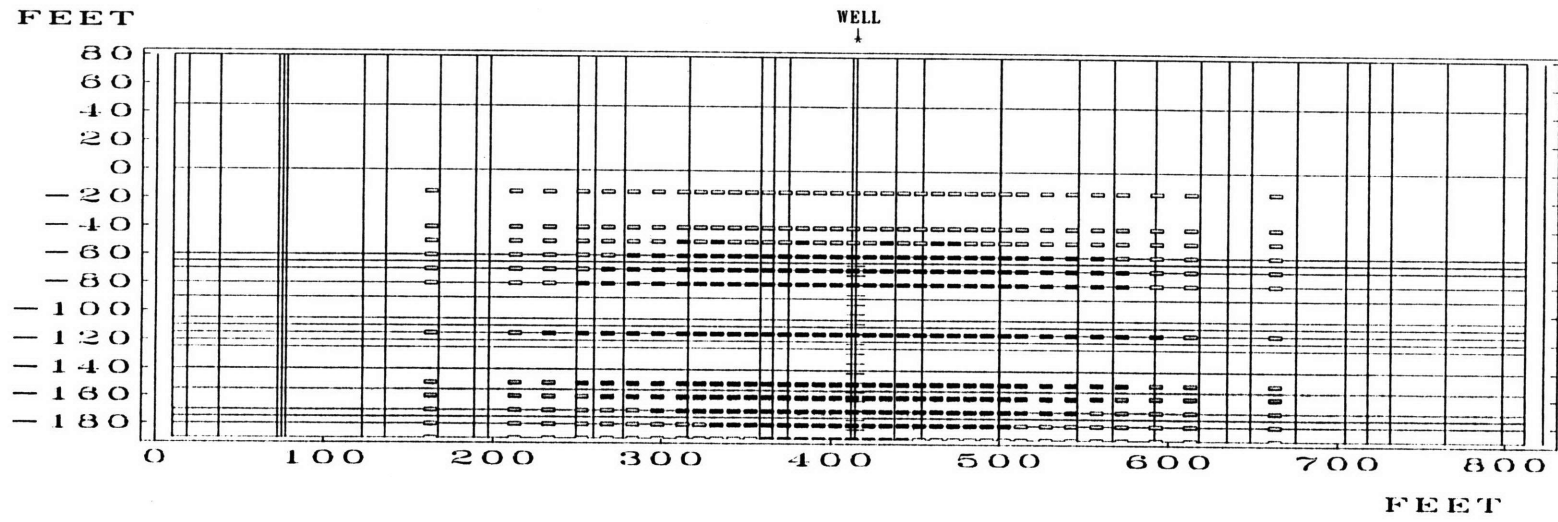
— GROUND SURFACE

- - - TOP OF SCREEN

—|— BOTTOM OF SCREEN

Figure A6-9: Capture Zone Simulation
Pumping Rate - 250 gpm
Water Table Elevation - 35 ft. asl
 Massachusetts Military Reservation

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* RECIRCULATING WELL
WITHIN 600.0 FT

— GROUND SURFACE

— TOP OF SCREEN

— BOTTOM OF SCREEN

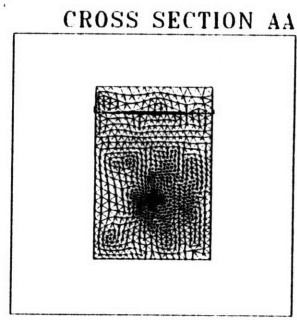
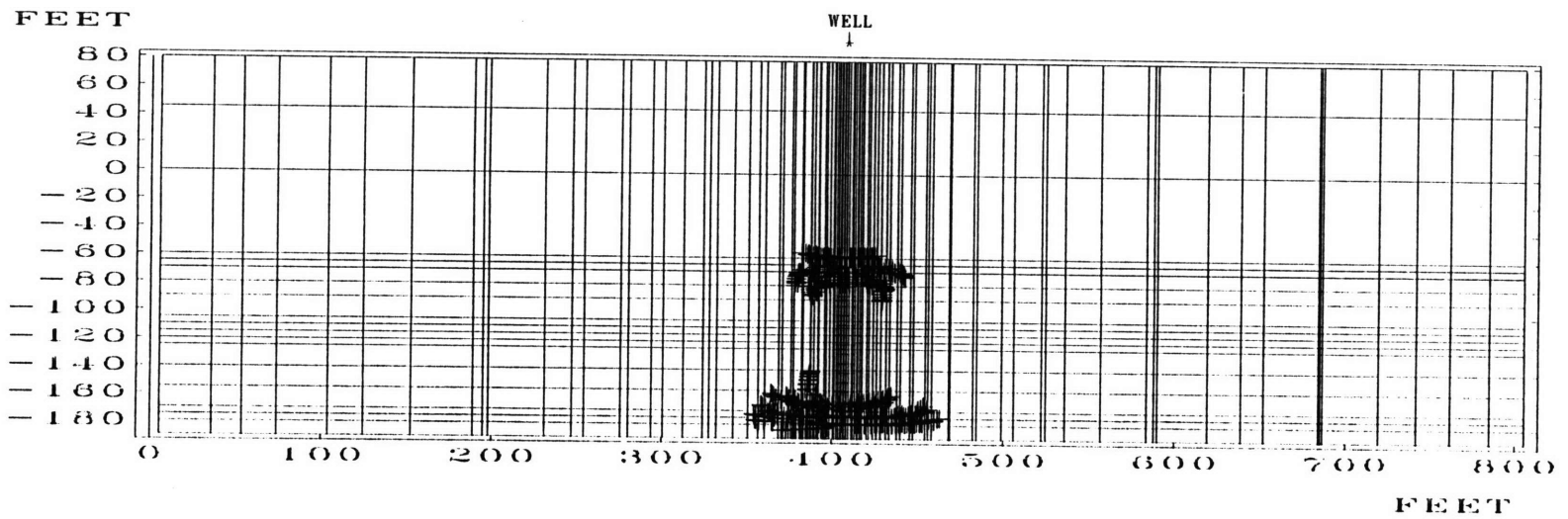


Figure A6-10: Capture Zone Simulation
Pumping Rate - 300 gpm
Water Table Elevation - 35 ft. asl
 Massachusetts Military Reservation

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Appendix A.7 DYNPLOT Graphical Output of Recirculating Zone for Different Pumping Rates



- RECIRCULATING WELL
 WITHIN 10.0 FT
 | GROUND SURFACE
 | TOP OF SCREEN
 | BOTTOM OF SCREEN

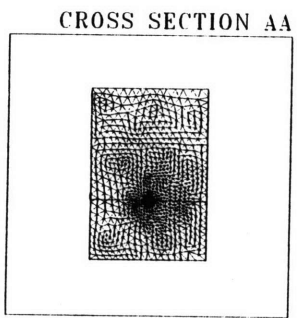
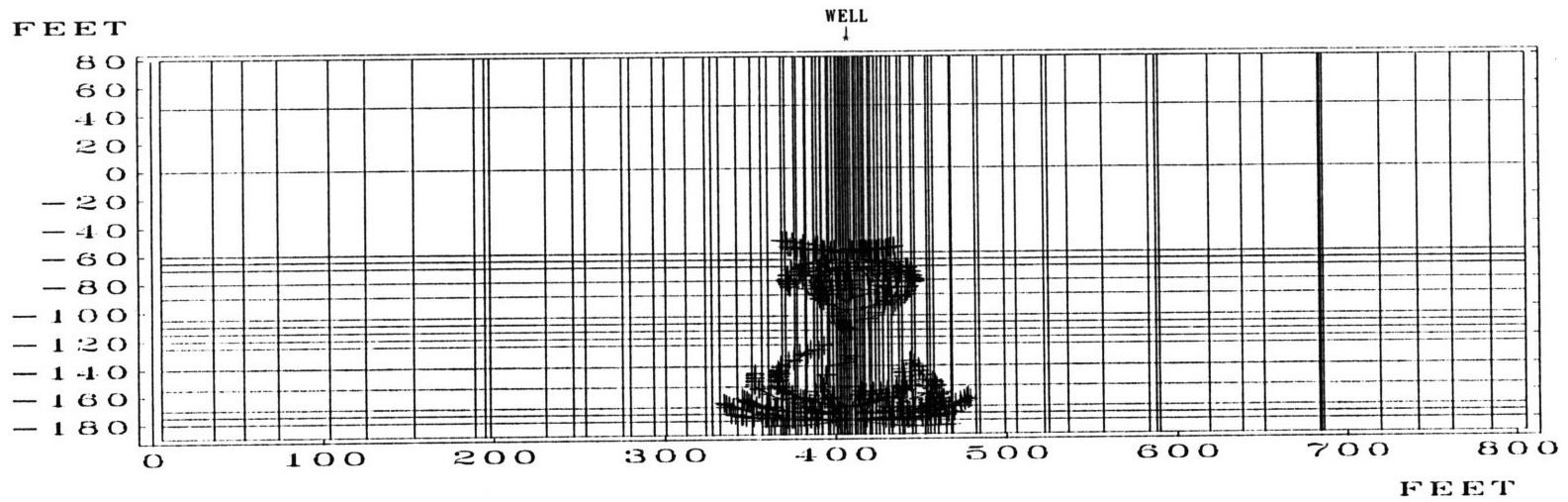


Figure A7-1: Recirculated Particle Simulation
 Pumping Rate - 25 gpm
 Water Table Elevation - 35 ft. asl
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* RECIRCULATING WELL
WITHIN 10.0 FT

GROUND SURFACE

TOP OF SCREEN

BOTTOM OF SCREEN

CROSS SECTION AA

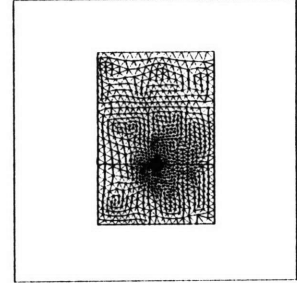
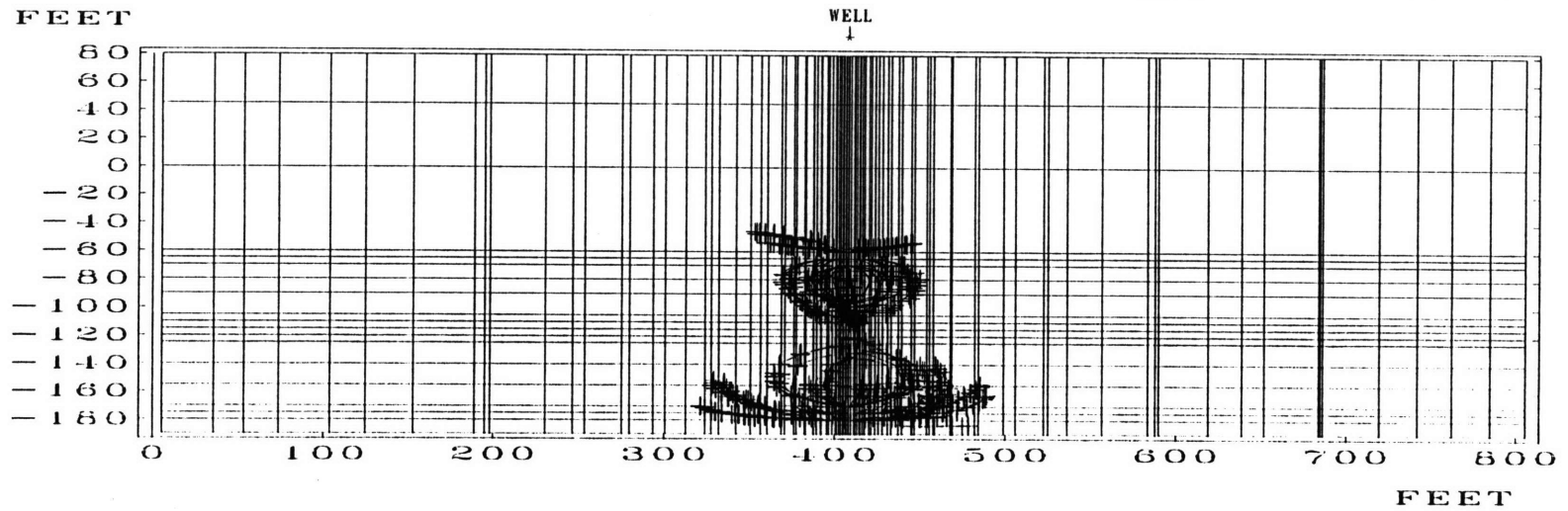


Figure A7-2: Recirculated Particle Simulation
Pumping Rate - 50 gpm
Water Table Elevation - 35 ft. asl
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* RECIRCULATING WELL
WITHIN 10.0 FT

— GROUND SURFACE
— TOP OF SCREEN
— BOTTOM OF SCREEN

CROSS SECTION AA

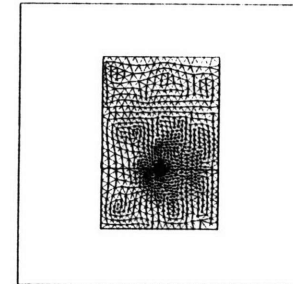
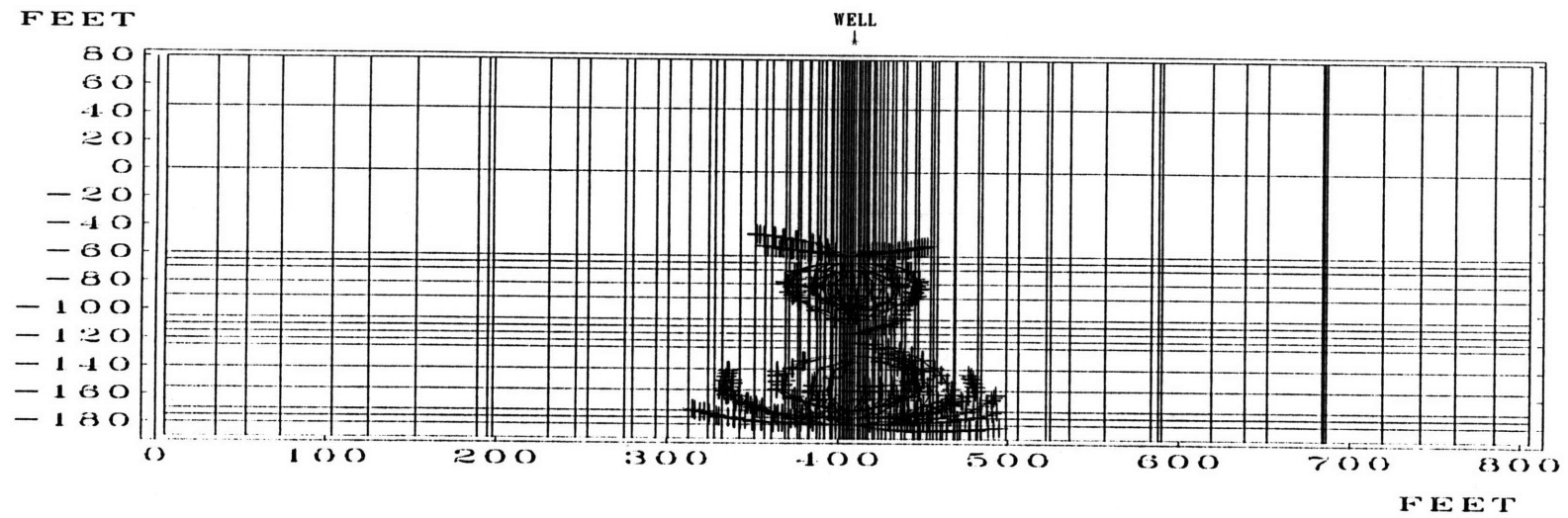


Figure A7-3: Recirculated Particle Simulation
Pumping Rate - 75 gpm
Water Table Elevation - 35 ft. asl
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CROSS SECTION AA

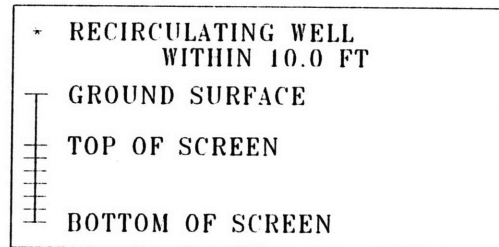
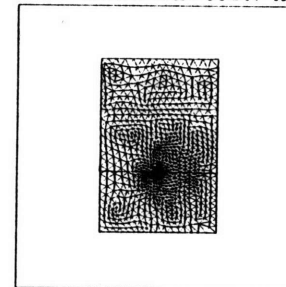


Figure A7-4: Recirculated Particle Simulation

Pumping Rate - 88 gpm

Water Table Elevation - 35 ft. asl

Massachusetts Military Reservation

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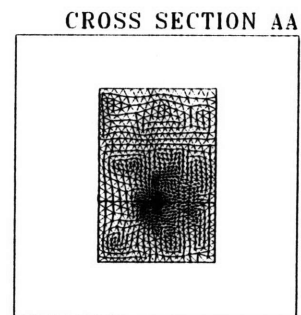
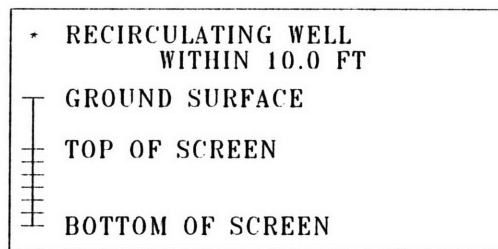
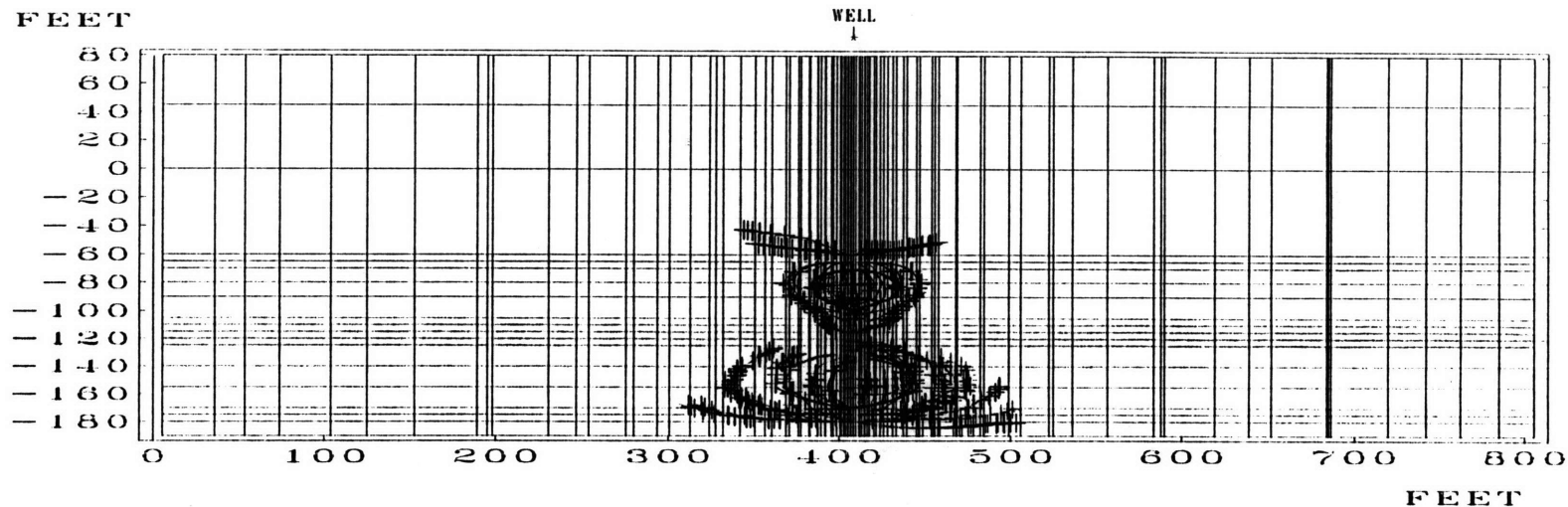


Figure A7-5: Recirculated Particle Simulation
Pumping Rate - 100 gpm
Water Table Elevation - 35 ft. asl
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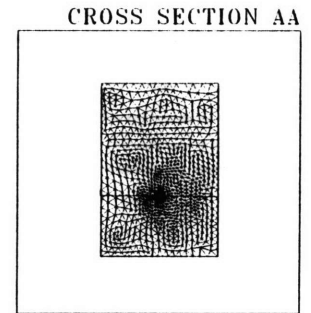
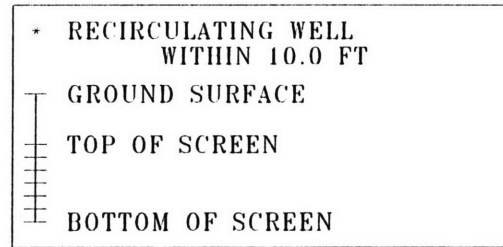
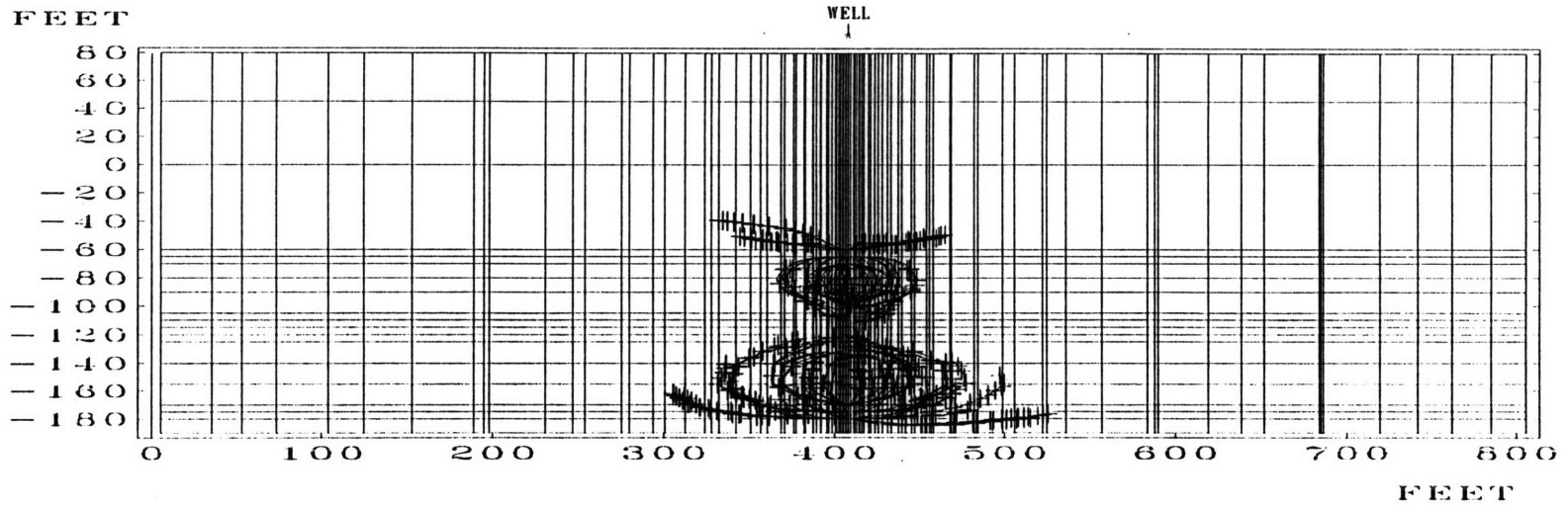


Figure A7-6: Recirculated Particle Simulation
Pumping Rate - 125 gpm
Water Table Elevation - 35 ft. asl
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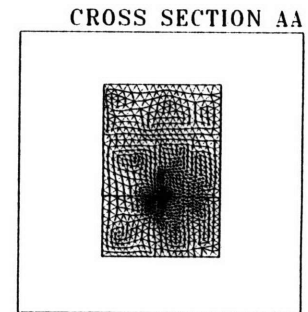
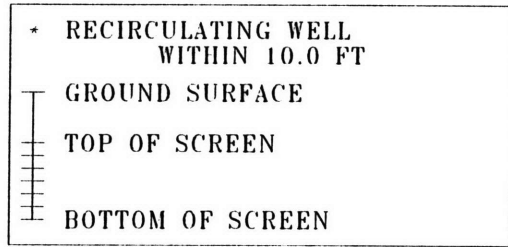
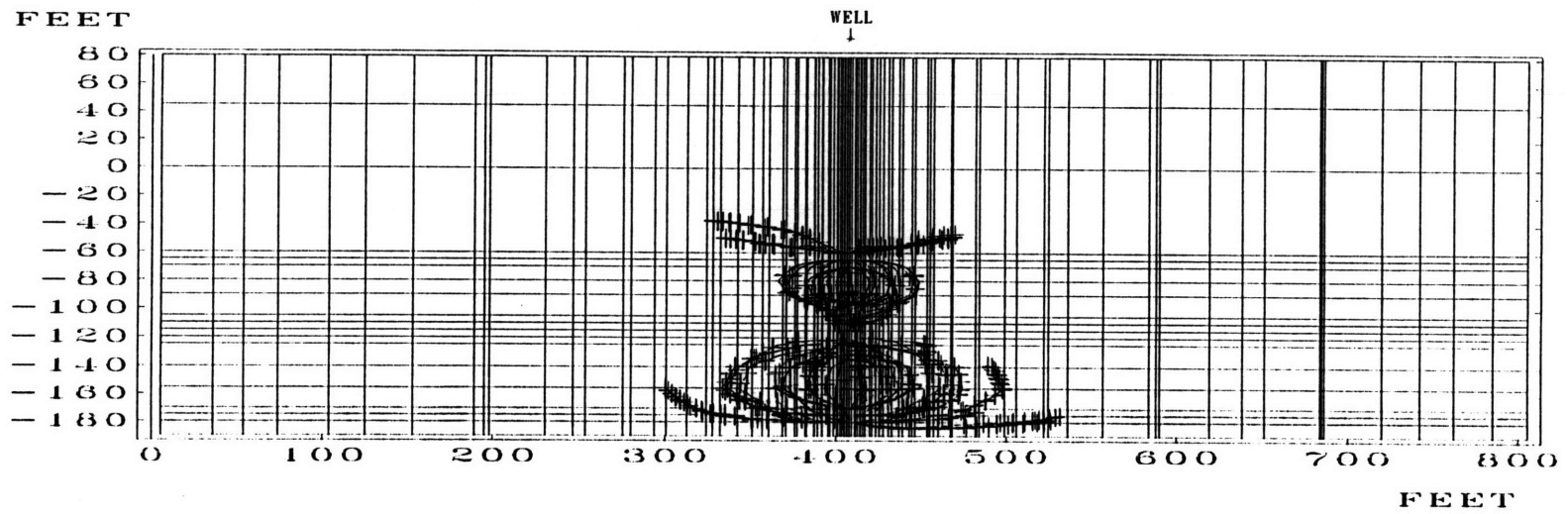
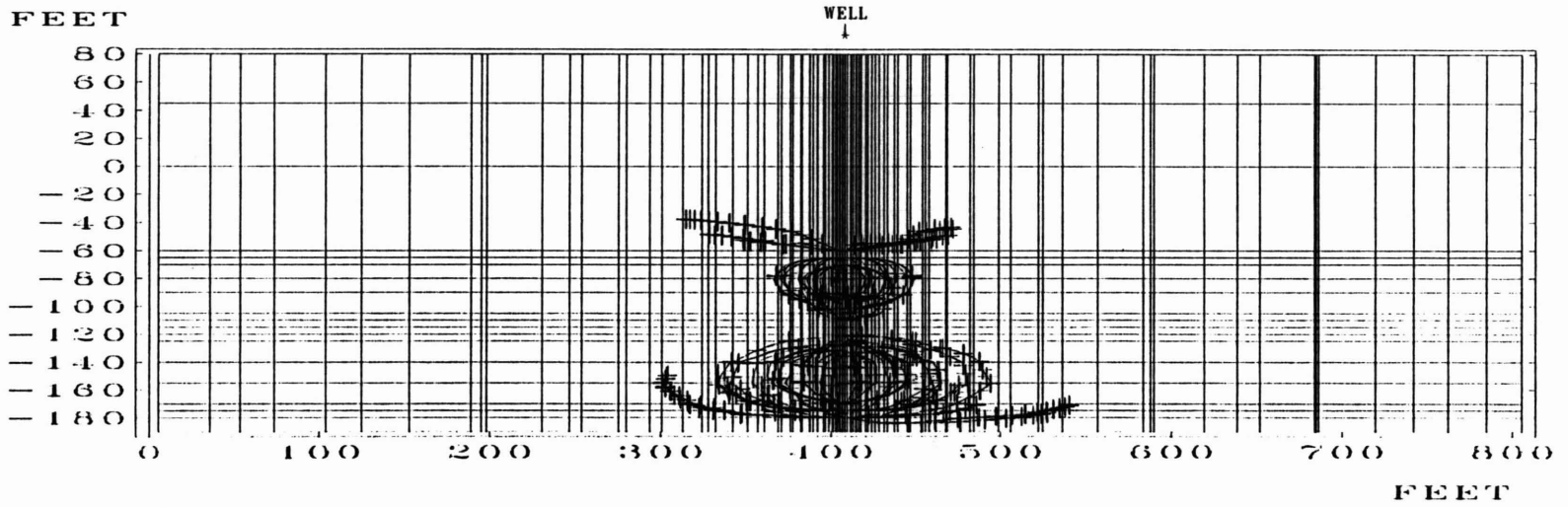


Figure A7-7: Recirculated Particle Simulation
Pumping Rate - 150 gpm
Water Table Elevation - 35 ft. asl
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* RECIRCULATING WELL
 WITHIN 10.0 FT
 — GROUND SURFACE
 — TOP OF SCREEN
 — BOTTOM OF SCREEN

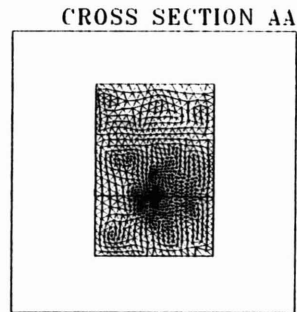


Figure A7-8: Recirculated Particle Simulation
 Pumping Rate - 175 gpm
 Water Table Elevation - 35 ft. asl
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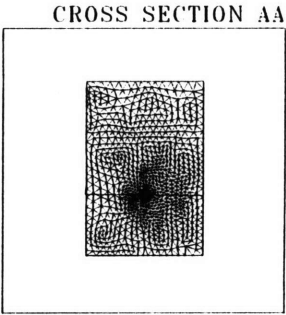
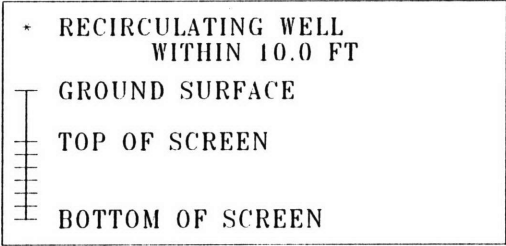
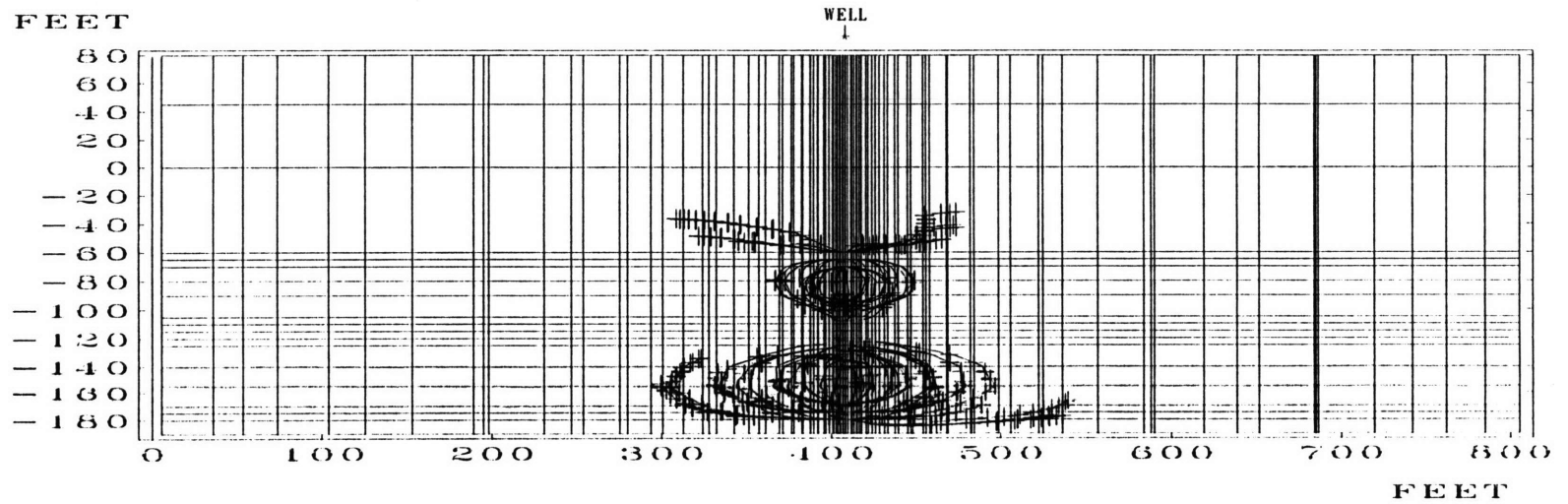


Figure A7-9: Recirculated Particle Simulation
Pumping Rate - 200 gpm
Water Table Elevation - 35 ft. asl
 Massachusetts Military Reservation

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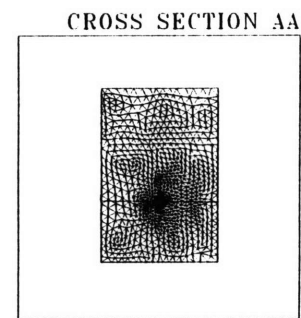
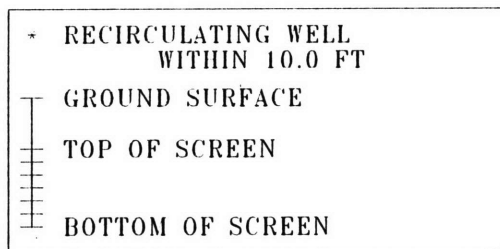
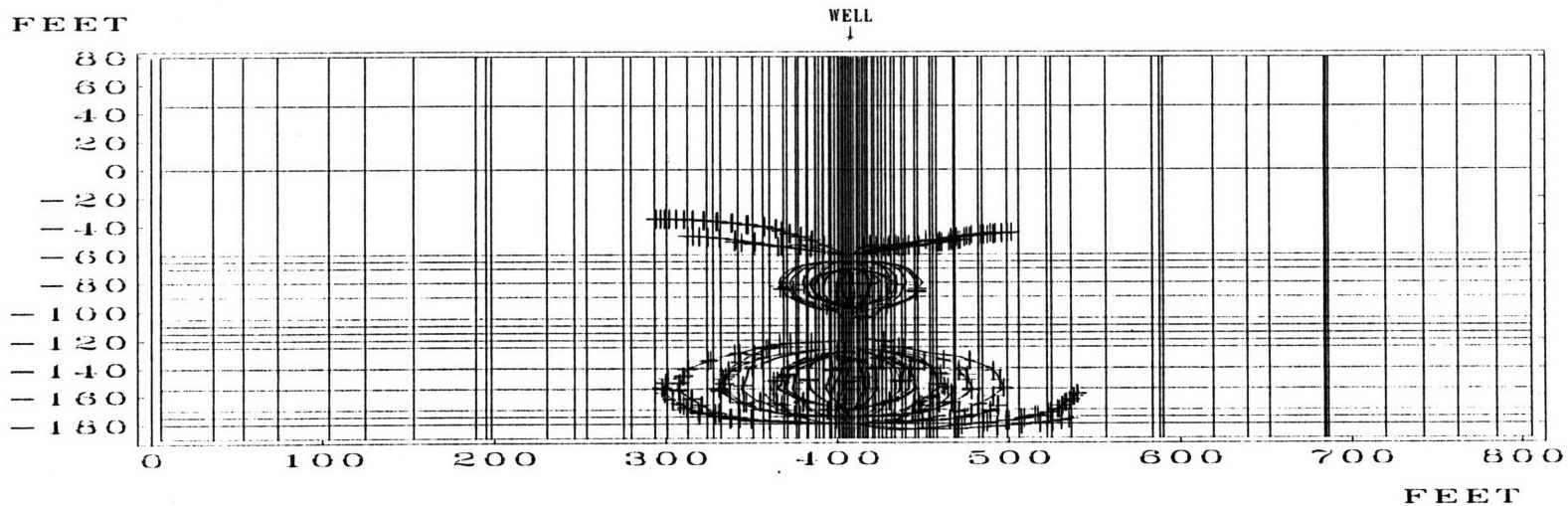
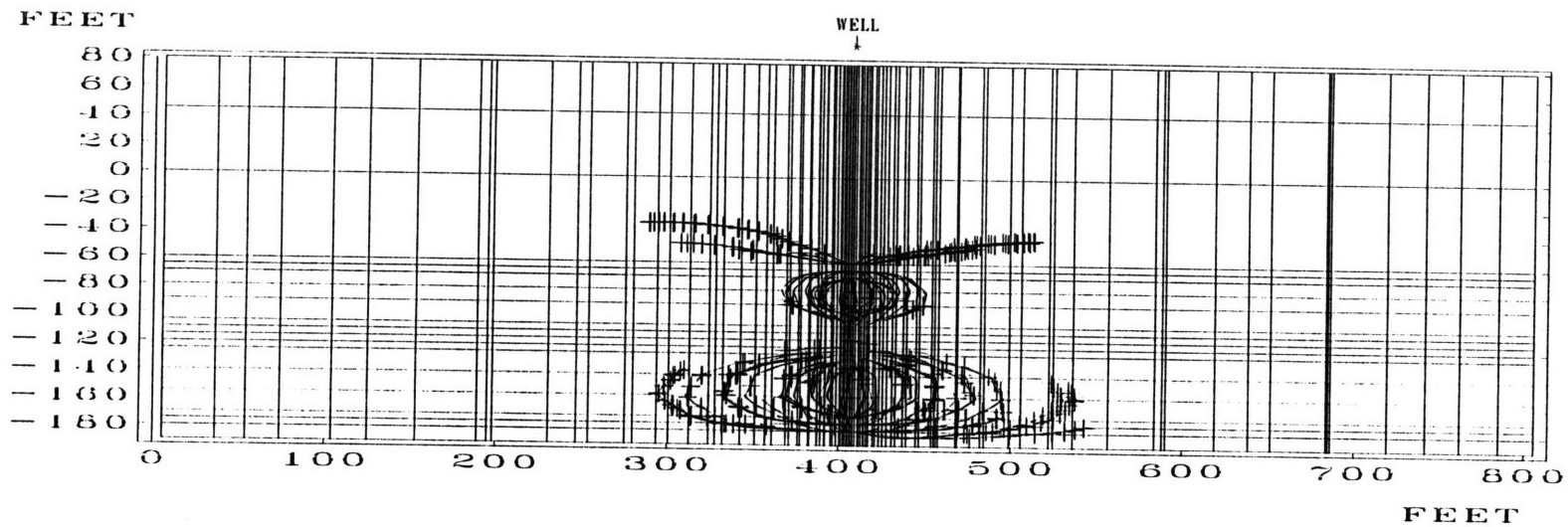


Figure A7-10: Recirculated Particle Simulation
Pumping Rate - 250 gpm
Water Table Elevation - 35 ft. asl
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* RECIRCULATING WELL
 WITHIN 10.0 FT
 | GROUND SURFACE
 | TOP OF SCREEN
 | BOTTOM OF SCREEN

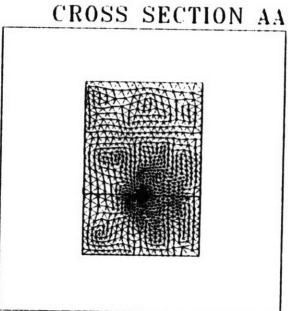


Figure A7-11: Recirculated Particle Simulation
 Pumping Rate - 300 gpm
 Water Table Elevation - 35 ft. asl
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APPENDIX B: MODEL INPUT AND COMMAND FILES FOR EG&G ENVIRONMENTAL, INC.

Appendix B.1 Command File for DYNFLOW

```
!create output file of session
OUTP DYN1.OUT
!read plan view finite element grid
GRID READ GRID.GRF FORM
!set number of levels
LEVEL 19
!set a rising head boundary condition for all nodes in level 19 (water table elev. to stop
!the head from rising above this level
RISI LEVEL 19
!set z-coordinates for each node/level
ELEV -190. LEVEL 1
ELEV -180. LEVEL 2
ELEV -160. LEVEL 3
ELEV -155. LEVEL 4
ELEV -150. LEVEL 5
ELEV -145. LEVEL 6
ELEV -140. LEVEL 7
ELEV -135 LEVEL 8
ELEV -117.5 LEVEL 9
ELEV -100. LEVEL 10
ELEV -95. LEVEL 11
ELEV -90. LEVEL 12
ELEV -85. LEVEL 13
ELEV -80. LEVEL 14
ELEV -75. LEVEL 15
ELEV -65. LEVEL 16
ELEV 0. LEVEL 17
ELEV 30. LEVEL 18
ELEV 80. LEVEL 19
!fix nodes upgradient and downgradient of well
FIX NODE 901 - 916 level all
FIX NODE 476 - 482 level all
FIX NODE 532 - 539 level all
FIX NODE 781 - 784 level all
!set initial head value for all nodes
INIT 35.
!fix head boundaries upgradient and downgradient of well (overall 0.0014 ft./ft. head drop)
INIT 34.4 NODE 476 - 482 level all
INIT 34.4 NODE 532 - 539 level all
INIT 34.4 NODE 781 - 784 level all
INIT 36.1 NODE 901 - 916 level all
!define materials from bottom of plume to water table elev. - here only 1 type, fine to
!coarse grained sand
ELEM 310 LAYER 1 - 18
!specify pumping rate of well
FLUX -9626. NODE 1 LEVEL 4
FLUX -9626. NODE 1 LEVEL 5
FLUX -9626. NODE 1 LEVEL 6
FLUX -9626. NODE 1 LEVEL 7
FLUX 9626. NODE 1 LEVEL 11
FLUX 9626. NODE 1 LEVEL 12
```

```
FLUX 9626. NODE 1 LEVEL 13
FLUX 9626. NODE 1 LEVEL 14
!define areas of 1-D elements/node (screened intervals)
ONED 120 NODE 1 1 LEVEL 4 5
ONED 120 NODE 1 1 LEVEL 5 6
ONED 120 NODE 1 1 LEVEL 6 7
ONED 120 NODE 1 1 LEVEL 11 12
ONED 120 NODE 1 1 LEVEL 12 13
ONED 120 NODE 1 1 LEVEL 13 14
!specify recharge rate (ft/d)
RECH .0044 ELEM ALL
!define following properties of 1-d elements: #, K, Ss, Sy
PROP
20, 10000000.,0.,1.
!define following properties of material: #, Kx (ft/d), Ky, Kz, Ss, Sy
PROP
10, 297.2, 297.2, 59.53, .00001, .07
iter 10
goti
!save to file
SAVE RC1.SAV
XOUT
XCFI
```

Appendix B.2 Command File for DYNTRACK Capture Zone Simulations

```
!COMMAND FILE FOR CROSS-SECTIONAL PARTICLE TRACKING
!restore the Dynflow file
REST RC1.SAV
!create an output file
OUTP SAVE XS1.OUT FORM
!read the transport property
DPRO READ PROP.DPR
!Turn off dispersion simulation
XDISP
!set radius of capture for well
RADI 20
!set weight of particle
WEIGH 1000
!set starting time (units: days)
TIME 0
!set time step (units: days)
DT 0.3
!seed particles
PART
-300,600,-15
PART
-275,600,-15
PART
-250,600,-15
PART
-225,600,-15
PART
-200,600,-15
PART
-180,600,-15
PART
-160,600,-15
PART
-145,600,-15
PART
-130,600,-15
PART
-115,600,-15
PART
-100,600,-15
PART
-90,600,-15
PART
-80,600,-15
PART
-70,600,-15
PART
-60,600,-15
PART
-50,600,-15
```

PART	PART	PART	PART
-40,600,-15	-300,600,-40	50,600,-40	-115,600,-50
PART	PART	PART	PART
-30,600,-15	-275,600,-40	60,600,-40	-100,600,-50
PART	PART	PART	PART
-20,600,-15	-250,600,-40	70,600,-40	-90,600,-50
PART	PART	PART	PART
-10,600,-15	-225,600,-40	80,600,-40	-80,600,-50
PART	PART	PART	PART
0,600,-15	-200,600,-40	90,600,-40	-70,600,-50
PART	PART	PART	PART
10,600,-15	-180,600,-40	100,600,-40	-60,600,-50
PART	PART	PART	PART
20,600,-15	-160,600,-40	115,600,-40	-50,600,-50
PART	PART	PART	PART
30,600,-15	-145,600,-40	130,600,-40	-40,600,-50
PART	PART	PART	PART
40,600,-15	-130,600,-40	145,600,-40	-30,600,-50
PART	PART	PART	PART
50,600,-15	-115,600,-40	160,600,-40	-20,600,-50
PART	PART	PART	PART
60,600,-15	-100,600,-40	180,600,-40	-10,600,-50
PART	PART	PART	PART
70,600,-15	-90,600,-40	200,600,-40	0,600,-50
PART	PART	PART	PART
80,600,-15	-80,600,-40	225,600,-40	10,600,-50
PART	PART	PART	PART
90,600,-15	-70,600,-40	250,600,-40	20,600,-50
PART	PART	PART	PART
100,600,-15	-60,600,-40	275,600,-40	30,600,-50
PART	PART	PART	PART
115,600,-15	-50,600,-40	300,600,-40	40,600,-50
PART	PART	PART	PART
130,600,-15	-40,600,-40	-300,600,-50	50,600,-50
PART	PART	PART	PART
145,600,-15	-30,600,-40	-275,600,-50	60,600,-50
PART	PART	PART	PART
160,600,-15	-20,600,-40	-250,600,-50	70,600,-50
PART	PART	PART	PART
180,600,-15	-10,600,-40	-225,600,-50	80,600,-50
PART	PART	PART	PART
200,600,-15	0,600,-40	-200,600,-50	90,600,-50
PART	PART	PART	PART
225,600,-15	10,600,-40	-180,600,-50	100,600,-50
PART	PART	PART	PART
250,600,-15	20,600,-40	-160,600,-50	115,600,-50
PART	PART	PART	PART
275,600,-15	30,600,-40	-145,600,-50	130,600,-50
PART	PART	PART	PART
300,600,-15	40,600,-40	-130,600,-50	145,600,-50

Note: The particle track command file must be entered in one column in order to successfully run the DYNTRACK particle simulation. The command file is presented here in four columns to save paper

PART	PART	PART	PART
160,600,-50	-20,600,-60	-250,600,-70	70,600,-70
PART	PART	PART	PART
180,600,-50	-10,600,-60	-225,600,-70	80,600,-70
PART	PART	PART	PART
200,600,-50	0,600,-60	-200,600,-70	90,600,-70
PART	PART	PART	PART
225,600,-50	10,600,-60	-180,600,-70	100,600,-70
PART	PART	PART	PART
250,600,-50	20,600,-60	-160,600,-70	115,600,-70
PART	PART	PART	PART
275,600,-50	30,600,-60	-145,600,-70	130,600,-70
PART	PART	PART	PART
300,600,-50	40,600,-60	-130,600,-70	145,600,-70
PART	PART	PART	PART
-300,600,-60	50,600,-60	-115,600,-70	160,600,-70
PART	PART	PART	PART
-275,600,-60	60,600,-60	-100,600,-70	180,600,-70
PART	PART	PART	PART
-250,600,-60	70,600,-60	-90,600,-70	200,600,-70
PART	PART	PART	PART
-225,600,-60	80,600,-60	-80,600,-70	225,600,-70
PART	PART	PART	PART
-200,600,-60	90,600,-60	-70,600,-70	250,600,-70
PART	PART	PART	PART
-180,600,-60	100,600,-60	-60,600,-70	275,600,-70
PART	PART	PART	PART
-160,600,-60	115,600,-60	-50,600,-70	300,600,-70
PART	PART	PART	PART
-145,600,-60	130,600,-60	-40,600,-70	-300,600,-80
PART	PART	PART	PART
-130,600,-60	145,600,-60	-30,600,-70	-275,600,-80
PART	PART	PART	PART
-115,600,-60	160,600,-60	-20,600,-70	-250,600,-80
PART	PART	PART	PART
-100,600,-60	180,600,-60	-10,600,-70	-225,600,-80
PART	PART	PART	PART
-90,600,-60	200,600,-60	0,600,-70	-200,600,-80
PART	PART	PART	PART
-80,600,-60	225,600,-60	10,600,-70	-180,600,-80
PART	PART	PART	PART
-70,600,-60	250,600,-60	20,600,-70	-160,600,-80
PART	PART	PART	PART
-60,600,-60	275,600,-60	30,600,-70	-145,600,-80
PART	PART	PART	PART
-50,600,-60	300,600,-60	40,600,-70	-130,600,-80
PART	PART	PART	PART
-40,600,-60	-300,600,-70	50,600,-70	-115,600,-80
PART	PART	PART	PART
-30,600,-60	-275,600,-70	60,600,-70	-100,600,-80

Note: The particle track command file must be entered in one column in order to successfully run the DYNTRACK particle simulation. The command file is presented here in four columns to save paper

PART	PART	PART	PART
-90,600,-80	200,600,-80	0,600,-90	-200,600,-115
PART	PART	PART	PART
-80,600,-80	225,600,-80	10,600,-90	-180,600,-115
PART	PART	PART	PART
-70,600,-80	250,600,-80	20,600,-90	-160,600,-115
PART	PART	PART	PART
-60,600,-80	275,600,-80	30,600,-90	-145,600,-115
PART	PART	PART	PART
-50,600,-80	300,600,-80	40,600,-90	-130,600,-115
PART	PART	PART	PART
-40,600,-80	-300,600,-90	50,600,-90	-115,600,-115
PART	PART	PART	PART
-30,600,-80	-275,600,-90	60,600,-90	-100,600,-115
PART	PART	PART	PART
-20,600,-80	-250,600,-90	70,600,-90	-90,600,-115
PART	PART	PART	PART
-10,600,-80	-225,600,-90	80,600,-90	-80,600,-115
PART	PART	PART	PART
0,600,-80	-200,600,-90	90,600,-90	-70,600,-115
PART	PART	PART	PART
10,600,-80	-180,600,-90	100,600,-90	-60,600,-115
PART	PART	PART	PART
20,600,-80	-160,600,-90	115,600,-90	-50,600,-115
PART	PART	PART	PART
30,600,-80	-145,600,-90	130,600,-90	-40,600,-115
PART	PART	PART	PART
40,600,-80	-130,600,-90	145,600,-90	-30,600,-115
PART	PART	PART	PART
50,600,-80	-115,600,-90	160,600,-90	-20,600,-115
PART	PART	PART	PART
60,600,-80	-100,600,-90	180,600,-90	-10,600,-115
PART	PART	PART	PART
70,600,-80	-90,600,-90	200,600,-90	0,600,-115
PART	PART	PART	PART
80,600,-80	-80,600,-90	225,600,-90	10,600,-115
PART	PART	PART	PART
90,600,-80	-70,600,-90	250,600,-90	20,600,-115
PART	PART	PART	PART
100,600,-80	-60,600,-90	275,600,-90	30,600,-115
PART	PART	PART	PART
115,600,-80	-50,600,-90	300,600,-90	40,600,-115
PART	PART	PART	PART
130,600,-80	-40,600,-90	-300,600,-115	50,600,-115
PART	PART	PART	PART
145,600,-80	-30,600,-90	-275,600,-115	60,600,-115
PART	PART	PART	PART
160,600,-80	-20,600,-90	-250,600,-115	70,600,-115
PART	PART	PART	PART
180,600,-80	-10,600,-90	-225,600,-115	80,600,-115

Note: The particle track command file must be entered in one column in order to successfully run the DYNTRACK particle simulation. The command file is presented here in four columns to save paper

PART	PART	PART	PART
90,600,-115	-70,600,-140	250,600,-140	20,600,-150
PART	PART	PART	PART
100,600,-115	-60,600,-140	275,600,-140	30,600,-150
PART	PART	PART	PART
115,600,-115	-50,600,-140	300,600,-140	40,600,-150
PART	PART	PART	PART
130,600,-115	-40,600,-140	-300,600,-150	50,600,-150
PART	PART	PART	PART
145,600,-115	-30,600,-140	-275,600,-150	60,600,-150
PART	PART	PART	PART
160,600,-115	-20,600,-140	-250,600,-150	70,600,-150
PART	PART	PART	PART
180,600,-115	-10,600,-140	-225,600,-150	80,600,-150
PART	PART	PART	PART
200,600,-115	0,600,-140	-200,600,-150	90,600,-150
PART	PART	PART	PART
225,600,-115	10,600,-140	-180,600,-150	100,600,-150
PART	PART	PART	PART
250,600,-115	20,600,-140	-160,600,-150	115,600,-150
PART	PART	PART	PART
275,600,-115	30,600,-140	-145,600,-150	130,600,-150
PART	PART	PART	PART
300,600,-115	40,600,-140	-130,600,-150	145,600,-150
PART	PART	PART	PART
-300,600,-140	50,600,-140	-115,600,-150	160,600,-150
PART	PART	PART	PART
-275,600,-140	60,600,-140	-100,600,-150	180,600,-150
PART	PART	PART	PART
-250,600,-140	70,600,-140	-90,600,-150	200,600,-150
PART	PART	PART	PART
-225,600,-140	80,600,-140	-80,600,-150	225,600,-150
PART	PART	PART	PART
-200,600,-140	90,600,-140	-70,600,-150	250,600,-150
PART	PART	PART	PART
-180,600,-140	100,600,-140	-60,600,-150	275,600,-150
PART	PART	PART	PART
-160,600,-140	115,600,-140	-50,600,-150	300,600,-150
PART	PART	PART	PART
-145,600,-140	130,600,-140	-40,600,-150	-300,600,-160
PART	PART	PART	PART
-130,600,-140	145,600,-140	-30,600,-150	-275,600,-160
PART	PART	PART	PART
-115,600,-140	160,600,-140	-20,600,-150	-250,600,-160
PART	PART	PART	PART
-100,600,-140	180,600,-140	-10,600,-150	-225,600,-160
PART	PART	PART	PART
-90,600,-140	200,600,-140	0,600,-150	-200,600,-160
PART	PART	PART	PART
-80,600,-140	225,600,-140	10,600,-150	-180,600,-160

Note: The particle track command file must be entered in one column in order to successfully run the DYNTRACK particle simulation. The command file is presented here in four columns to save paper

PART	PART	PART	PART
-160,600,-160	115,600,-160	-50,600,-170	300,600,-170
PART	PART	PART	PART
-145,600,-160	130,600,-160	-40,600,-170	-300,600,-180
PART	PART	PART	PART
-130,600,-160	145,600,-160	-30,600,-170	-275,600,-180
PART	PART	PART	PART
-115,600,-160	160,600,-160	-20,600,-170	-250,600,-180
PART	PART	PART	PART
-100,600,-160	180,600,-160	-10,600,-170	-225,600,-180
PART	PART	PART	PART
-90,600,-160	200,600,-160	0,600,-170	-200,600,-180
PART	PART	PART	PART
-80,600,-160	225,600,-160	10,600,-170	-180,600,-180
PART	PART	PART	PART
-70,600,-160	250,600,-160	20,600,-170	-160,600,-180
PART	PART	PART	PART
-60,600,-160	275,600,-160	30,600,-170	-145,600,-180
PART	PART	PART	PART
-50,600,-160	300,600,-160	40,600,-170	-130,600,-180
PART	PART	PART	PART
-40,600,-160	-300,600,-170	50,600,-170	-115,600,-180
PART	PART	PART	PART
-30,600,-160	-275,600,-170	60,600,-170	-100,600,-180
PART	PART	PART	PART
-20,600,-160	-250,600,-170	70,600,-170	-90,600,-180
PART	PART	PART	PART
-10,600,-160	-225,600,-170	80,600,-170	-80,600,-180
PART	PART	PART	PART
0,600,-160	-200,600,-170	90,600,-170	-70,600,-180
PART	PART	PART	PART
10,600,-160	-180,600,-170	100,600,-170	-60,600,-180
PART	PART	PART	PART
20,600,-160	-160,600,-170	115,600,-170	-50,600,-180
PART	PART	PART	PART
30,600,-160	-145,600,-170	130,600,-170	-40,600,-180
PART	PART	PART	PART
40,600,-160	-130,600,-170	145,600,-170	-30,600,-180
PART	PART	PART	PART
50,600,-160	-115,600,-170	160,600,-170	-20,600,-180
PART	PART	PART	PART
60,600,-160	-100,600,-170	180,600,-170	-10,600,-180
PART	PART	PART	PART
70,600,-160	-90,600,-170	200,600,-170	0,600,-180
PART	PART	PART	PART
80,600,-160	-80,600,-170	225,600,-170	10,600,-180
PART	PART	PART	PART
90,600,-160	-70,600,-170	250,600,-170	20,600,-180
PART	PART	PART	PART
100,600,-160	-60,600,-170	275,600,-170	30,600,-180

Note: The particle track command file must be entered in one column in order to successfully run the DYNTRACK particle simulation. The command file is presented here in four columns to save paper

PART	PART0	PART	GOTI 1150
40,600,-180	-145,600,-190	115,600,-190	GOTI 1200
PART	PART	PART	PRIN
50,600,-180	-130,600,-190	130,600,-190	!finish
PART	PART	PART	XRES
60,600,-180	-115,600,-190	145,600,-190	XOUT
PART	PART	PART	END
70,600,-180	-100,600,-190	160,600,-190	
PART	PART	PART	
80,600,-180	-90,600,-190	180,600,-190	
PART	PART	PART	
90,600,-180	-80,600,-190	200,600,-190	
PART	PART	PART	
100,600,-180	-70,600,-190	225,600,-190	
PART	PART	PART	
115,600,-180	-60,600,-190	250,600,-190	
PART	PART	PART	
130,600,-180	-50,600,-190	275,600,-190	
PART	PART	PART	
145,600,-180	-40,600,-190	300,600,-190	
PART	PART	!store particle track in	
160,600,-180	-30,600,-190	file	
PART	PART	RESU 50 SAVE	
180,600,-180	-20,600,-190	XS1.RES	
PART	PART	GOTI 50	
200,600,-180	-10,600,-190	GOTI 100	
PART	PART	GOTI 150	
225,600,-180	0,600,-190	GOTI 200	
PART	PART	GOTI 250	
250,600,-180	10,600,-190	GOTI 300	
PART	PART	GOTI 350	
275,600,-180	20,600,-190	DT 0.08	
PART	PART	GOTI 400	
300,600,-180	30,600,-190	GOTI 450	
PART	PART	GOTI 500	
-300,600,-190	40,600,-190	GOTI 550	
PART	PART	GOTI 600	
-275,600,-190	50,600,-190	GOTI 650	
PART	PART	GOTI 700	
-250,600,-190	60,600,-190	GOTI 750	
PART	PART	GOTI 800	
-225,600,-190	70,600,-190	GOTI 850	
PART	PART	GOTI 900	
-200,600,-190	80,600,-190	GOTI 950	
PART	PART	DT 0.11	
-180,600,-190	90,600,-190	GOTI 1000	
PART	PART	GOTI 1050	
-160,600,-190	100,600,-190	GOTI 1100	

Note: The particle track command file must be entered in one column in order to successfully run the DYNTRACK particle simulation. The command file is presented here in four columns to save paper

Appendix B.3 Property File Used for DYNTRACK

```
!dyntrack property file
!prop. no., disp.(long.), disp.(trans.), disp. ratio (vert./horiz.), effect. porosity, retardation
10,0.,0.,0.,0.35,1.00
20,0.,0.,0.,1.00,1.00
```

Appendix B.4 Command File for DYNTRACK Retreatment Simulations

```
!COMMAND FILE FOR CIRCULAR PARTICLE TRACKING
!restore the Dynflow file
REST RC1.SAV
!create an output file
OUTP SAVE SPHERE1.OUT FORM
!read the transport property
DPRO READ PROP.DPR
!Turn off dispersion simulation
XDISP
!set radius of capture for well
RADI 10
!set weight of particle
WEIGH 1000
!set starting time (units: days)
TIME 0
!set time step (units: days)
DT 0.042
!seed particles
PART
0.0000,2.0000,-95
PART
0.3473,1.9696,-95
PART
0.6840,1.8794,-95
PART
1.0000,1.7321,-95
PART
1.2856,1.5321,-95
PART
1.5321,1.2856,-95
PART
1.7321,1.0000,-95
PART
1.8794,0.6840,-95
PART
1.9696,0.3473,-95
PART
2.0000,0.0000,-95
PART
1.9696,-0.3437,-95
PART
1.8794,-0.6840,-95
PART
1.7321,-1.0000,-95
PART
1.5321,-1.2856,-95
PART
1.2856,-1.5321,-95
PART
1.0000,-1.7321,-95
```

PART	PART	PART	PART
0.6840,-1.8794,-95	1.5321,1.2856,-90	-1.7321,1.0000,-90	-0.3473,-1.9696,-85
PART	PART	PART	PART
0.3473,-1.9696,-95	1.7321,1.0000,-90	-1.5321,1.2856,-90	-0.6840,-1.8794,-85
PART	PART	PART	PART
0.0000,-2.0000,-95	1.8794,0.6840,-90	-1.2856,1.5321,-90	-1.0000,-1.7321,-85
PART	PART	PART	PART
-0.3473,-1.9696,-95	1.9696,0.3473,-90	-1.0000,1.7321,-90	-1.2856,-1.5321,-85
PART	PART	PART	PART
-0.6840,-1.8794,-95	2.0000,0.0000,-90	-0.6840,1.8794,-90	-1.5321,-1.2856,-85
PART	PART	PART	PART
-1.0000,-1.7321,-95	1.9696,-0.3437,-90	-0.3473,1.9696,-90	-1.7321,-1.0000,-85
PART	PART	PART	PART
-1.2856,-1.5321,-95	1.8794,-0.6840,-90	0.0000,2.0000,-85	-1.8794,-0.6840,-85
PART	PART	PART	PART
-1.5321,-1.2856,-95	1.7321,-1.0000,-90	0.3473,1.9696,-85	-1.9696,-0.3473,-85
PART	PART	PART	PART
-1.7321,-1.0000,-95	1.5321,-1.2856,-90	0.6840,1.8794,-85	-2.0000,0.0000,-85
PART	PART	PART	PART
-1.8794,-0.6840,-95	1.2856,-1.5321,-90	1.0000,1.7321,-85	-1.9696,0.3473,-85
PART	PART	PART	PART
-1.9696,-0.3473,-95	1.0000,-1.7321,-90	1.2856,1.5321,-85	-1.8794,0.6840,-85
PART	PART	PART	PART
-2.0000,0.0000,-95	0.6840,-1.8794,-90	1.5321,1.2856,-85	-1.7321,1.0000,-85
PART	PART	PART	PART
-1.9696,0.3473,-95	0.3473,-1.9696,-90	1.7321,1.0000,-85	-1.5321,1.2856,-85
PART	PART	PART	PART
-1.8794,0.6840,-95	0.0000,-2.0000,-90	1.8794,0.6840,-85	-1.2856,1.5321,-85
PART	PART	PART	PART
-1.7321,1.0000,-95	-0.3473,-1.9696,-90	1.9696,0.3473,-85	-1.0000,1.7321,-85
PART	PART	PART	PART
-1.5321,1.2856,-95	-0.6840,-1.8794,-90	2.0000,0.0000,-85	-0.6840,1.8794,-85
PART	PART	PART	PART
-1.2856,1.5321,-95	-1.0000,-1.7321,-90	1.9696,-0.3437,-85	-0.3473,1.9696,-85
PART	PART	PART	PART
-1.0000,1.7321,-95	-1.2856,-1.5321,-90	1.8794,-0.6840,-85	0.0000,2.0000,-80
PART	PART	PART	PART
-0.6840,1.8794,-95	-1.5321,-1.2856,-90	1.7321,-1.0000,-85	0.3473,1.9696,-80
PART	PART	PART	PART
-0.3473,1.9696,-95	-1.7321,-1.0000,-90	1.5321,-1.2856,-85	0.6840,1.8794,-80
PART	PART	PART	PART
0.0000,2.0000,-90	-1.8794,-0.6840,-90	1.2856,-1.5321,-85	1.0000,1.7321,-80
PART	PART	PART	PART
0.3473,1.9696,-90	-1.9696,-0.3473,-90	1.0000,-1.7321,-85	1.2856,1.5321,-80
PART	PART	PART	PART
0.6840,1.8794,-90	-2.0000,0.0000,-90	0.6840,-1.8794,-85	1.5321,1.2856,-80
PART	PART	PART	PART
1.0000,1.7321,-90	-1.9696,0.3473,-90	0.3473,-1.9696,-85	1.7321,1.0000,-80
PART	PART	PART	PART
1.2856,1.5321,-90	-1.8794,0.6840,-90	0.0000,-2.0000,-85	1.8794,0.6840,-80

Note: The particle track command file must be entered in one column in order to successfully run the DYNTRACK particle simulation. The command file is presented here in four columns to save paper

PART	PART	PART	PART
1.9696,0.3473,-80	1.0000,-1.7321,-80	-1.2856,-1.5321,-80	-1.8794,0.6840,-80
PART	PART	PART	PART
2.0000,0.0000,-80	0.6840,-1.8794,-80	-1.5321,-1.2856,-80	-1.7321,1.0000,-80
PART	PART	PART	PART
1.9696,-0.3437,-80	0.3473,-1.9696,-80	-1.7321,-1.0000,-80	-1.5321,1.2856,-80
PART	PART	PART	PART
1.8794,-0.6840,-80	0.0000,-2.0000,-80	-1.8794,-0.6840,-80	-1.2856,1.5321,-80
PART	PART	PART	PART
1.7321,-1.0000,-80	-0.3473,-1.9696,-80	-1.9696,-0.3473,-80	-1.0000,1.7321,-80
PART	PART	PART	PART
1.5321,-1.2856,-80	-0.6840,-1.8794,-80	-2.0000,0.0000,-80	-0.6840,1.8794,-80
PART	PART	PART	PART
1.2856,-1.5321,-80	-1.0000,-1.7321,-80	-1.9696,0.3473,-80	-0.3473,1.9696,-80

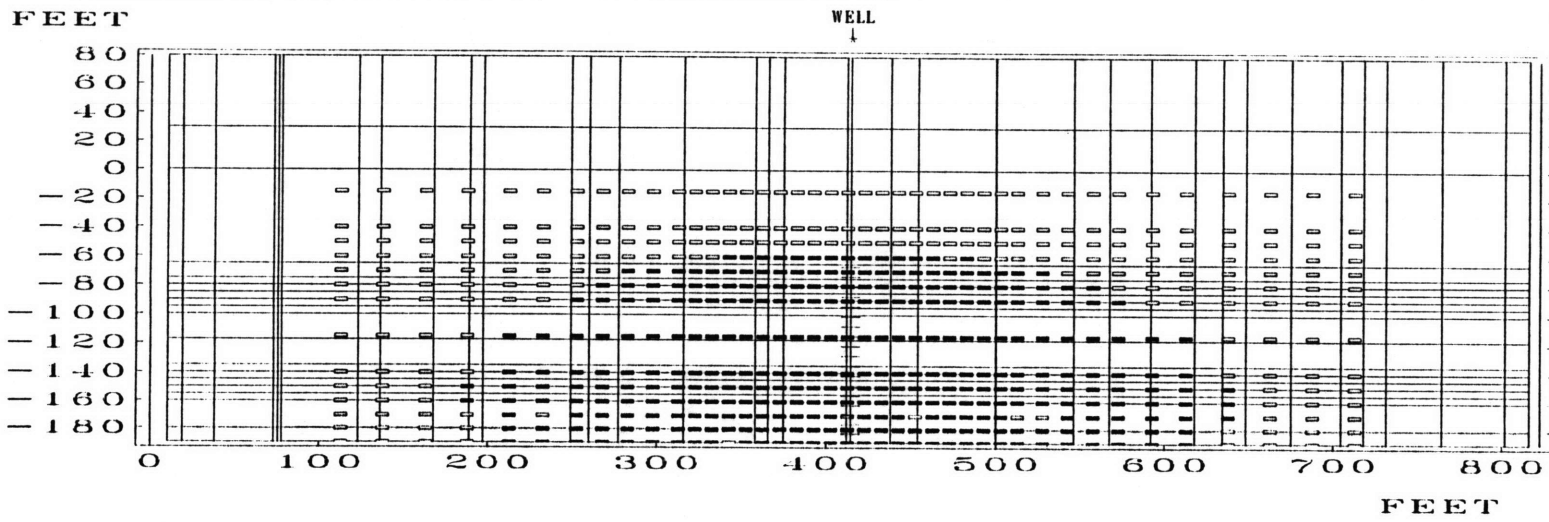
```

!store particle track in file
RESU 25 SAVE SPHERE1.RES
GOTI 25
GOTI 50
GOTI 75
GOTI 100
GOTI 125
GOTI 150
GOTI 175
GOTI 200
PRIN
!finish
XRES
XOUT
END

```

Note: The particle track command file must be entered in one column in order to successfully run the DYNTRACK particle simulation. The command file is presented here in four columns to save paper

Appendix B.5 DYNPLOT Graphical Output of Capture Zone for Design Pumping Rate



* RECIRCULATING WELL
WITHIN 600.0 FT

— GROUND SURFACE

— TOP OF SCREEN

— BOTTOM OF SCREEN

CROSS SECTION AA

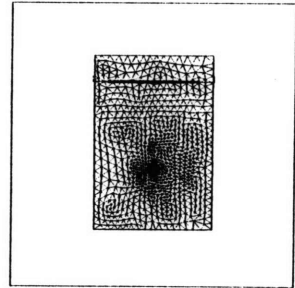
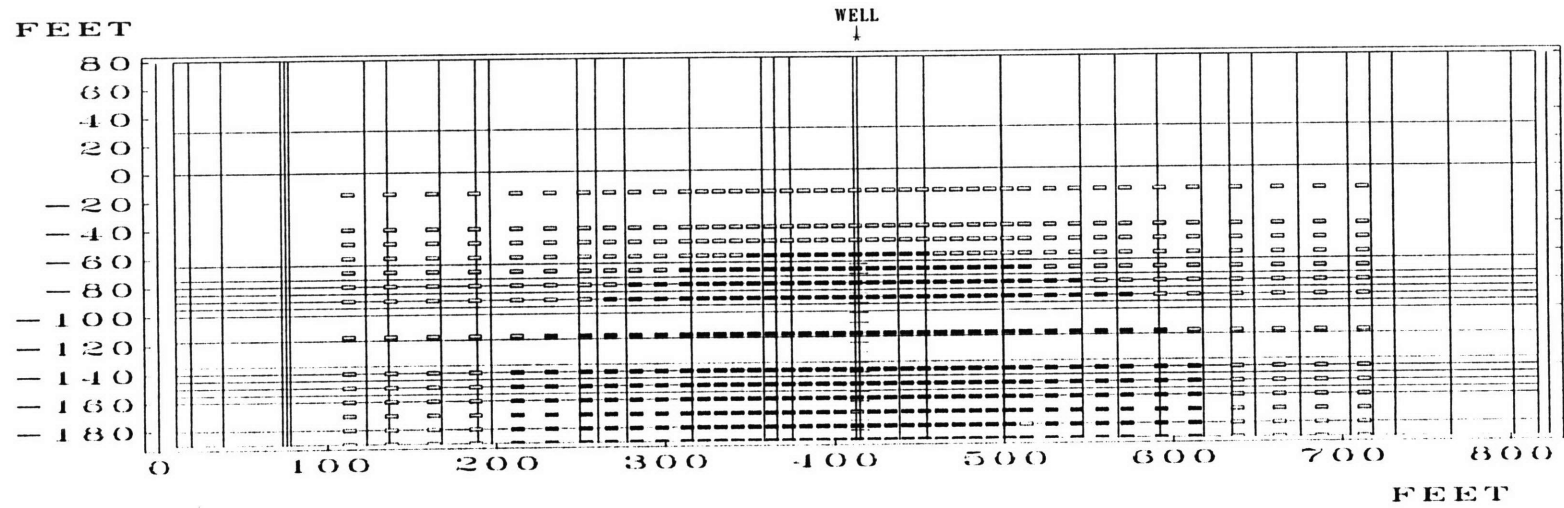


Figure B5-1: Water Table Simulation
Pumping Rate - 200 gpm
Water Table Elevation - 0 ft. asl
 Massachusetts Military Reservation

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* RECIRCULATING WELL
WITHIN 600.0 FT

— GROUND SURFACE

— TOP OF SCREEN

— BOTTOM OF SCREEN

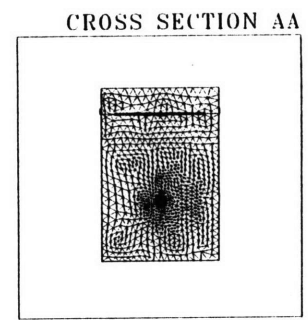
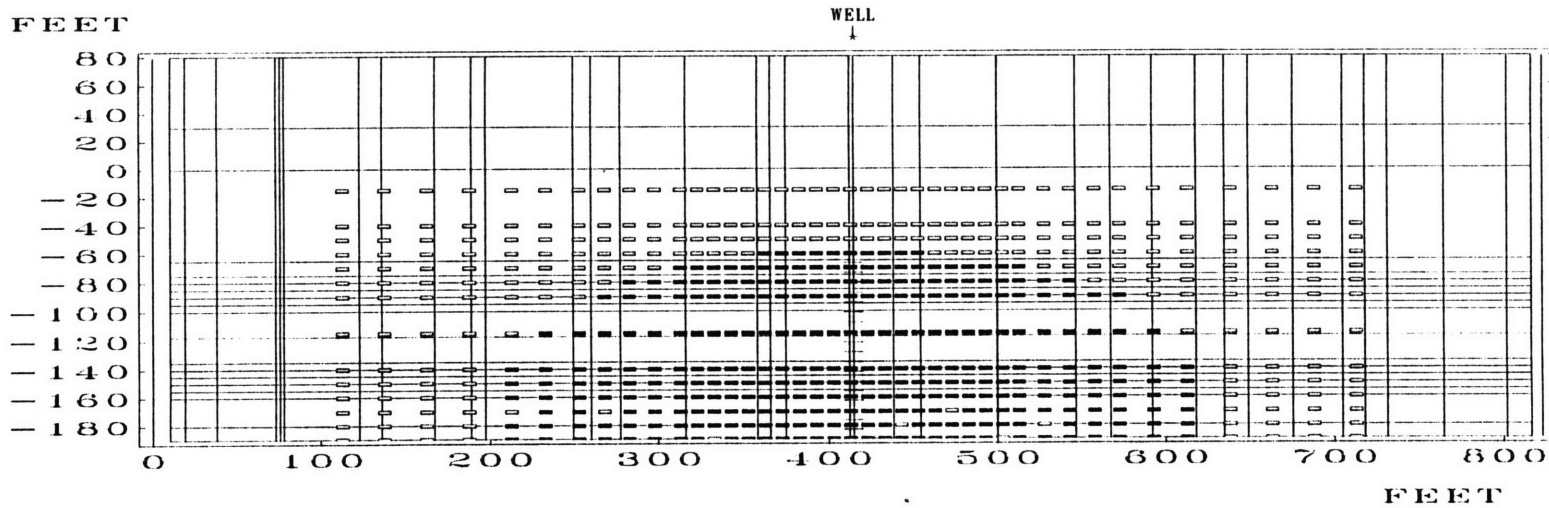


Figure B5-2: Water Table Simulation
Pumping Rate - 200 gpm
Water Table Elevation - 35 ft. asl
 Massachusetts Military Reservation

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* RECIRCULATING WELL
WITHIN 600.0 FT

— GROUND SURFACE

— TOP OF SCREEN

— BOTTOM OF SCREEN

CROSS SECTION AA

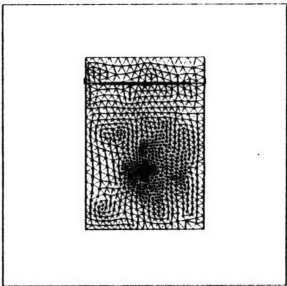
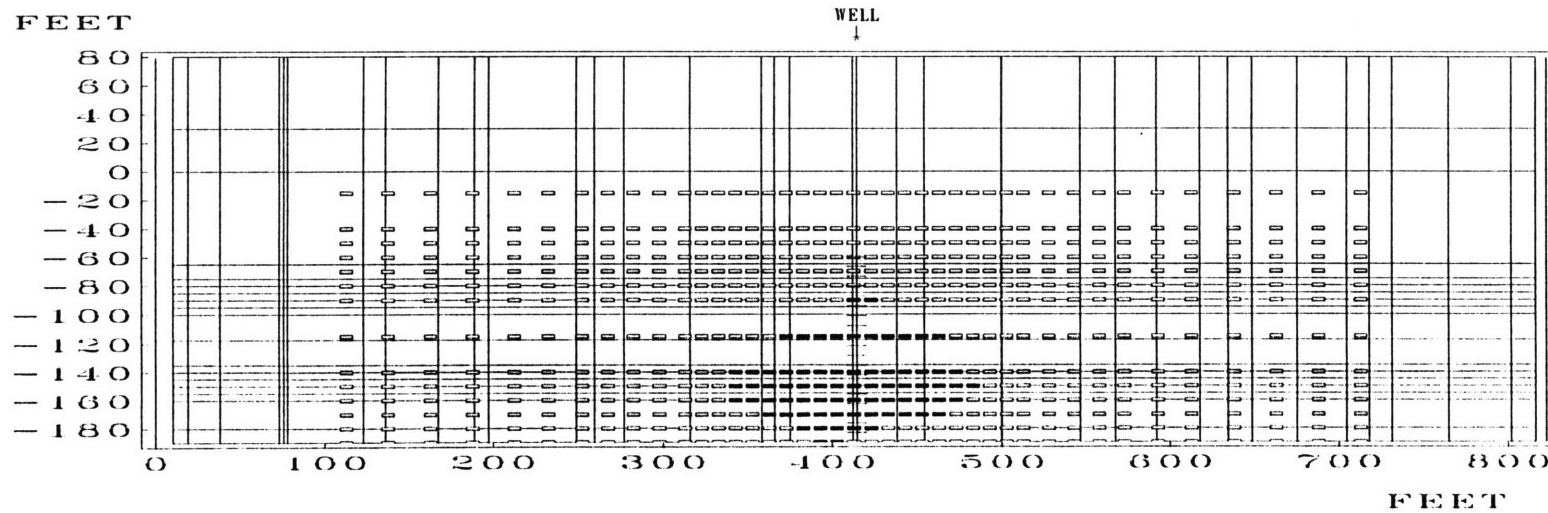


Figure B5-3: Water Table Simulation
Pumping Rate - 200 gpm
Water Table Elevation - 75 ft. asl
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Appendix B.6 DYNPLOT Graphical Output of Capture Zone for Different Pumping Rates



* RECIRCULATING WELL
WITHIN 600.0 FT

— GROUND SURFACE

--- TOP OF SCREEN

--- BOTTOM OF SCREEN

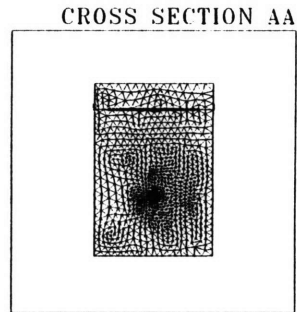
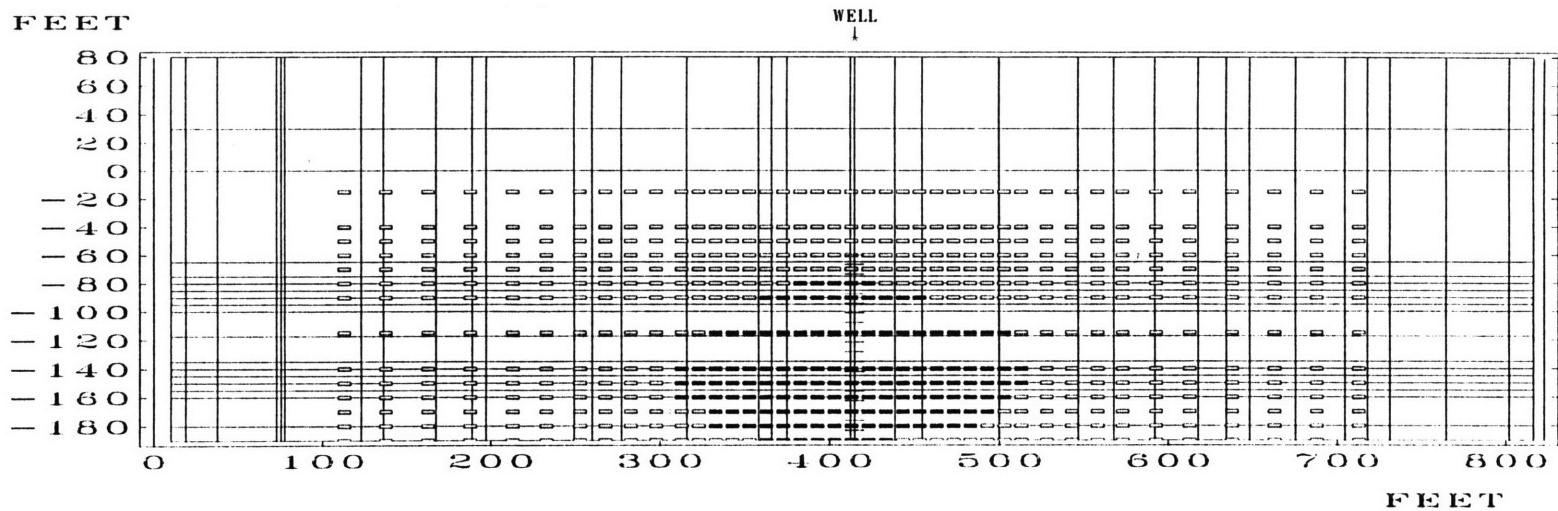


Figure B6-1: Capture Zone Simulation
Pumping Rate - 25 gpm
Water Table Elevation - 35 ft. asl
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* RECIRCULATING WELL
WITHIN 600.0 FT

— GROUND SURFACE

— TOP OF SCREEN

— BOTTOM OF SCREEN

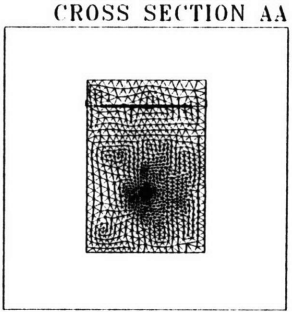
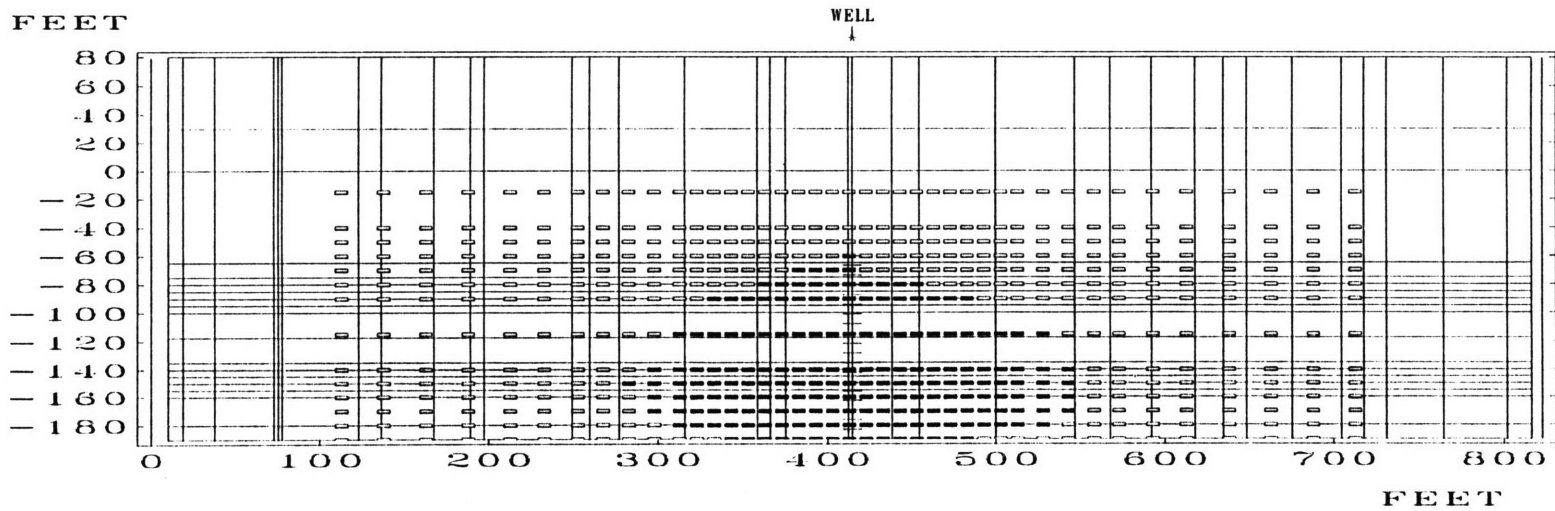


Figure B6-2: Capture Zone Simulation
Pumping Rate - 50 gpm
Water Table Elevation - 35 ft. asl
 Massachusetts Military Reservation

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* RECIRCULATING WELL
WITHIN 600.0 FT

— GROUND SURFACE

— TOP OF SCREEN

— BOTTOM OF SCREEN

CROSS SECTION AA

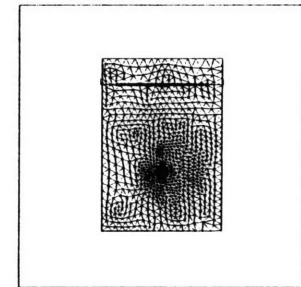


Figure B6-3: Capture Zone Simulation
Pumping Rate - 75 gpm
Water Table Elevation - 35 ft. asl
 Massachusetts Military Reservation

RW

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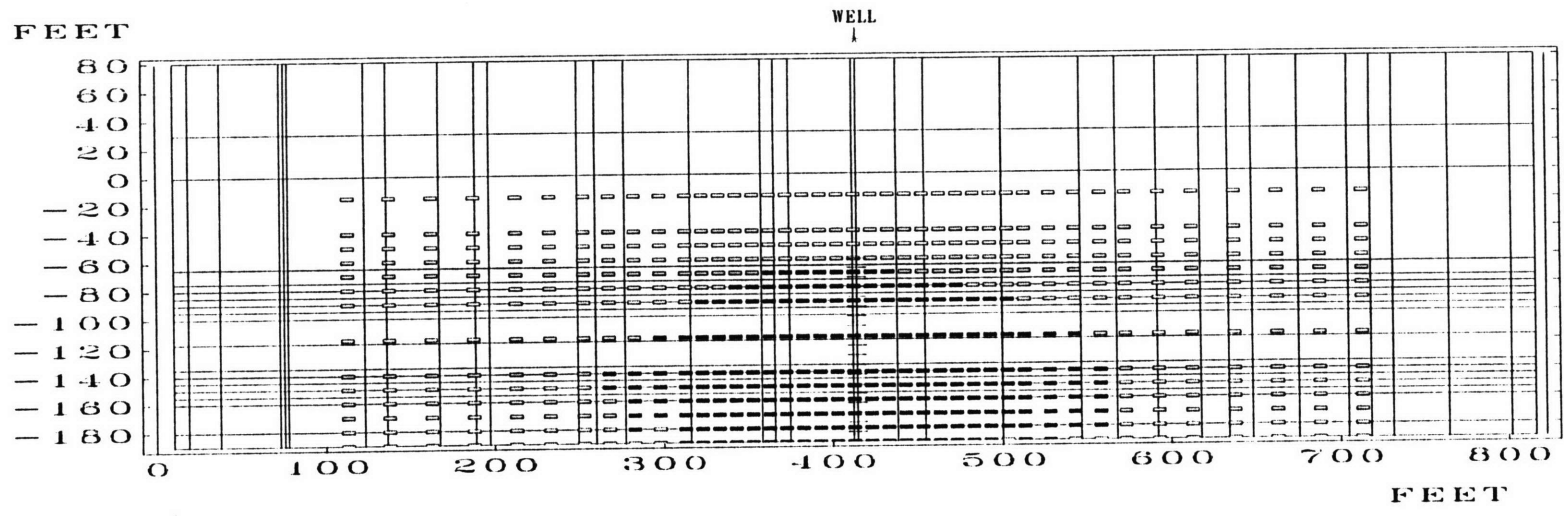
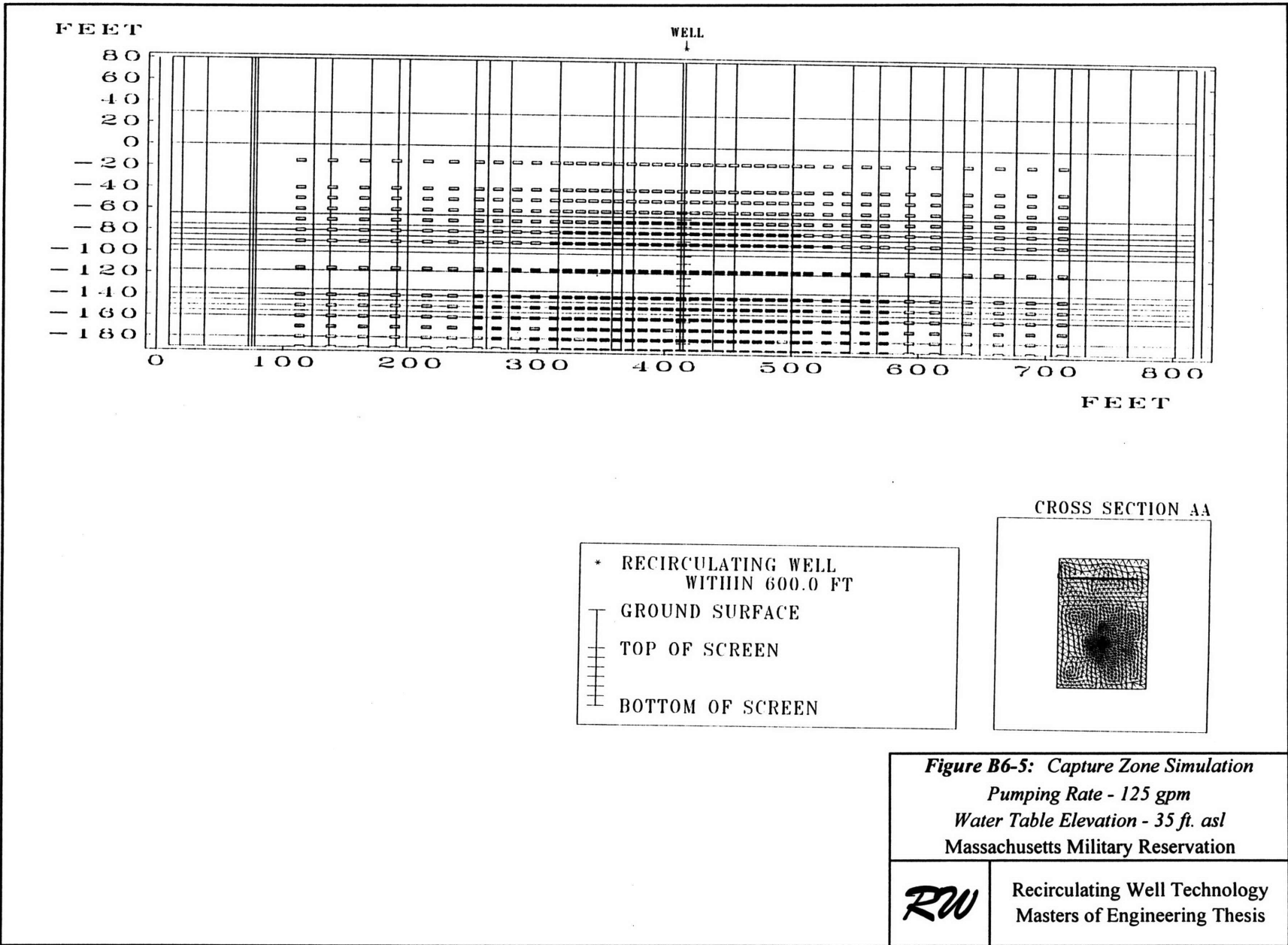
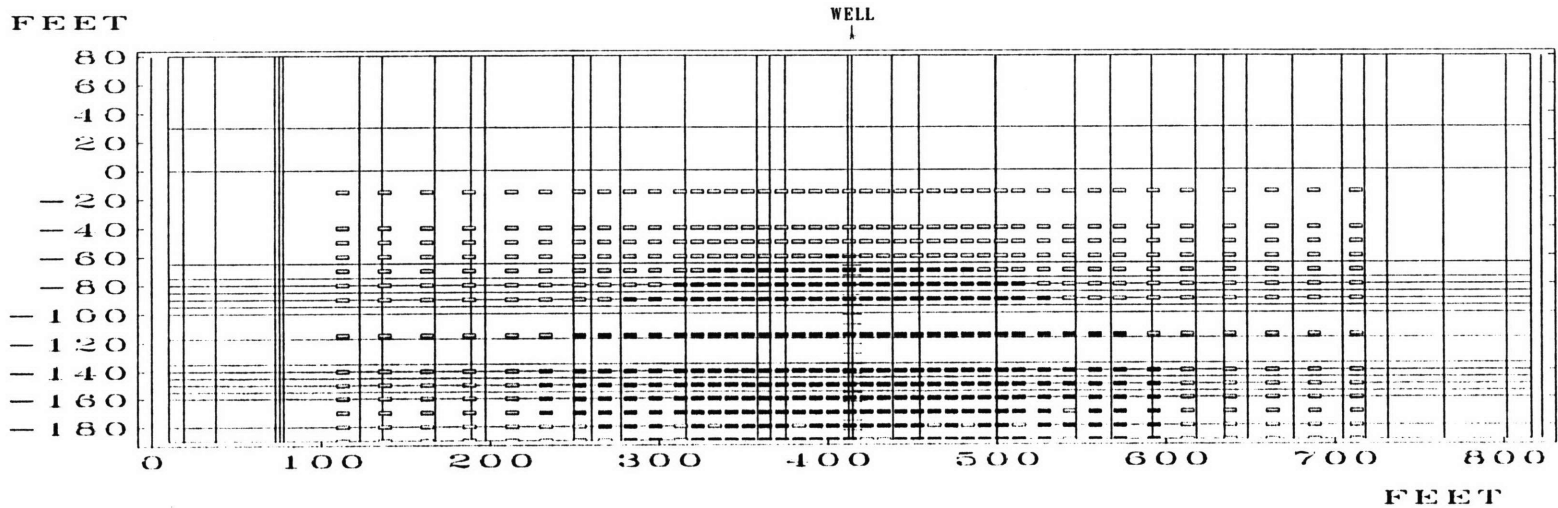


Figure B6-4: Capture Zone Simulation
Pumping Rate - 100 gpm
Water Table Elevation - 35 ft. asl
 Massachusetts Military Reservation

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* RECIRCULATING WELL
WITHIN 600.0 FT

— GROUND SURFACE

— TOP OF SCREEN

— BOTTOM OF SCREEN

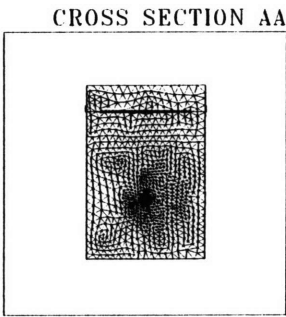
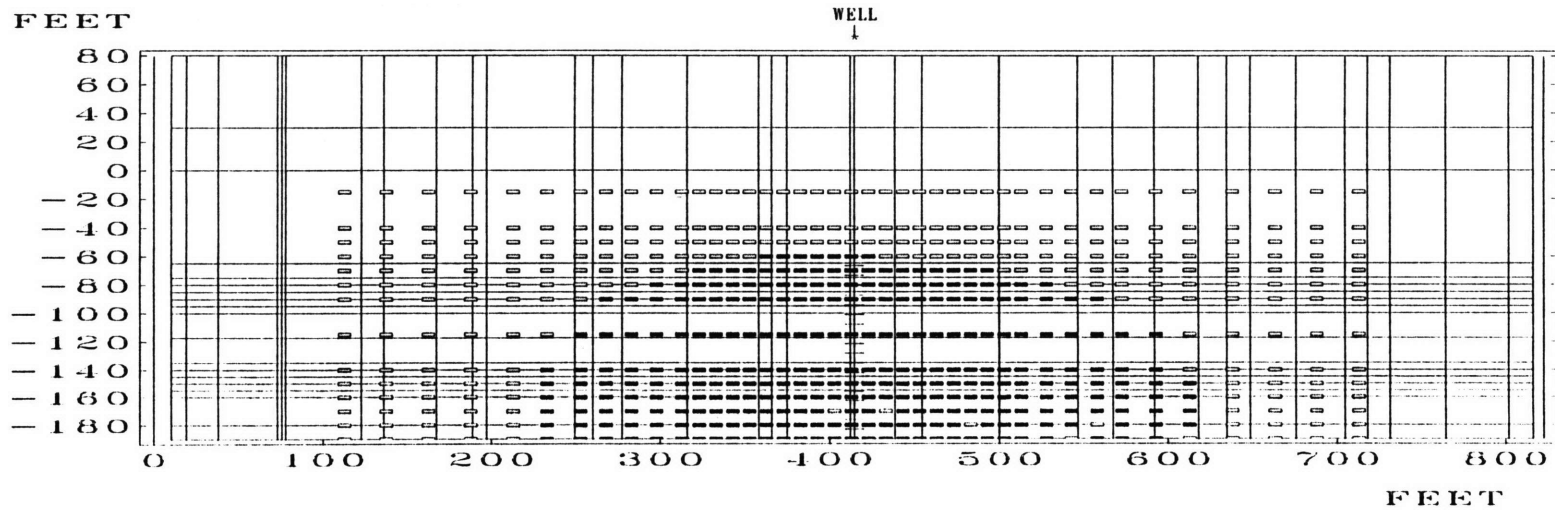
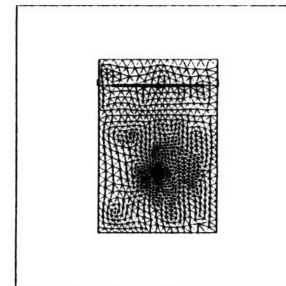


Figure B6-6: Capture Zone Simulation
Pumping Rate - 150 gpm
Water Table Elevation - 35 ft. asl
 Massachusetts Military Reservation

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CROSS SECTION AA



* RECIRCULATING WELL
WITHIN 600.0 FT

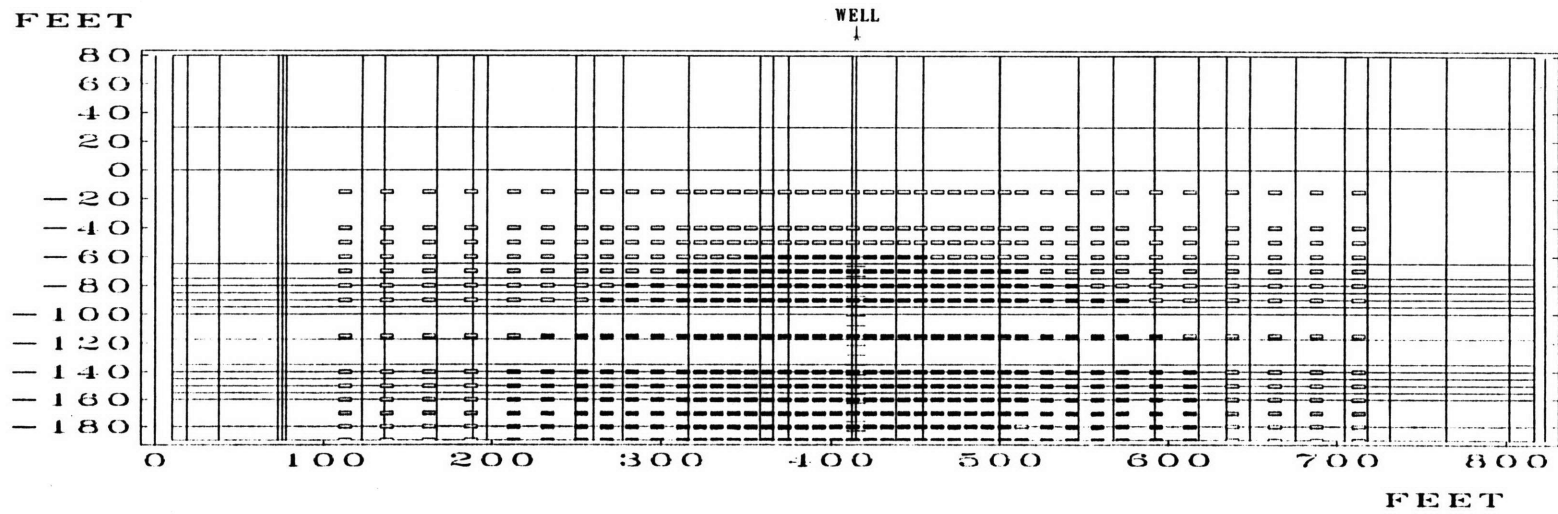
GROUND SURFACE

TOP OF SCREEN

BOTTOM OF SCREEN

Figure B6-7: Capture Zone Simulation
Pumping Rate - 175 gpm
Water Table Elevation - 35 ft. asl
 Massachusetts Military Reservation

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* RECIRCULATING WELL
WITHIN 600.0 FT

— GROUND SURFACE

— TOP OF SCREEN

— BOTTOM OF SCREEN

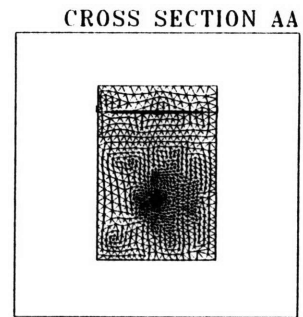
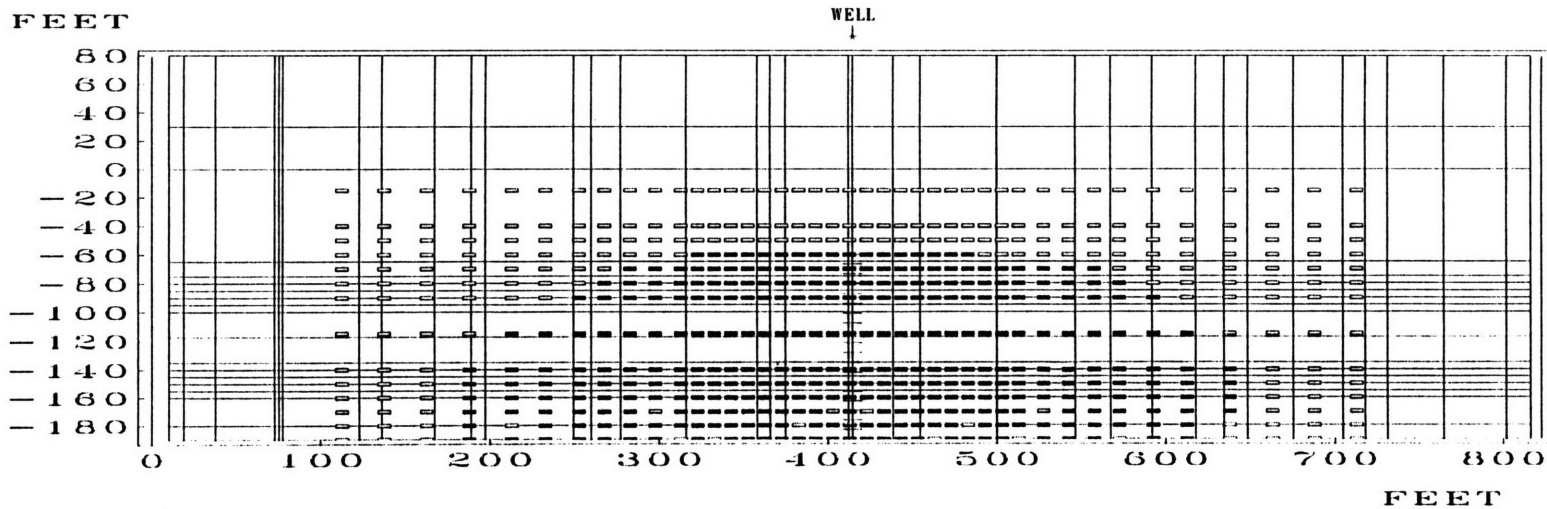
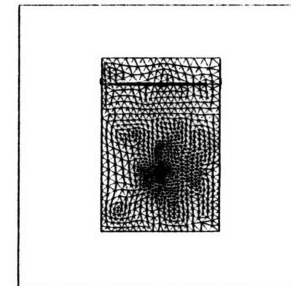


Figure B6-8: Capture Zone Simulation
Pumping Rate - 200 gpm
Water Table Elevation - 35 ft. asl
 Massachusetts Military Reservation

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CROSS SECTION AA



* RECIRCULATING WELL
WITHIN 600.0 FT

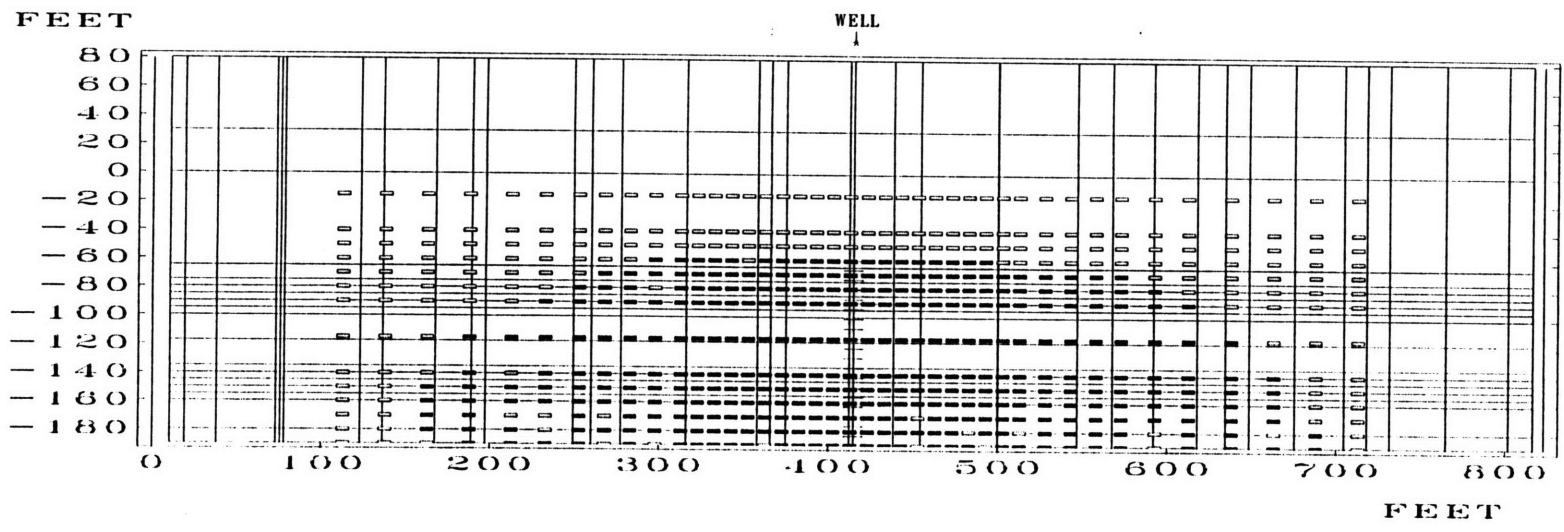
— GROUND SURFACE

— TOP OF SCREEN

— BOTTOM OF SCREEN

Figure B6-9: Capture Zone Simulation
Pumping Rate - 250 gpm
Water Table Elevation - 35 ft. asl
 Massachusetts Military Reservation

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* RECIRCULATING WELL
WITHIN 600.0 FT

GROUND SURFACE

TOP OF SCREEN

BOTTOM OF SCREEN

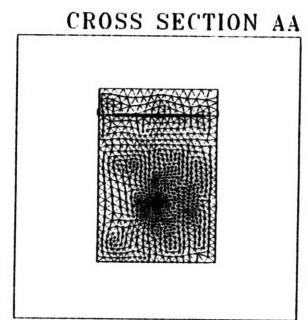
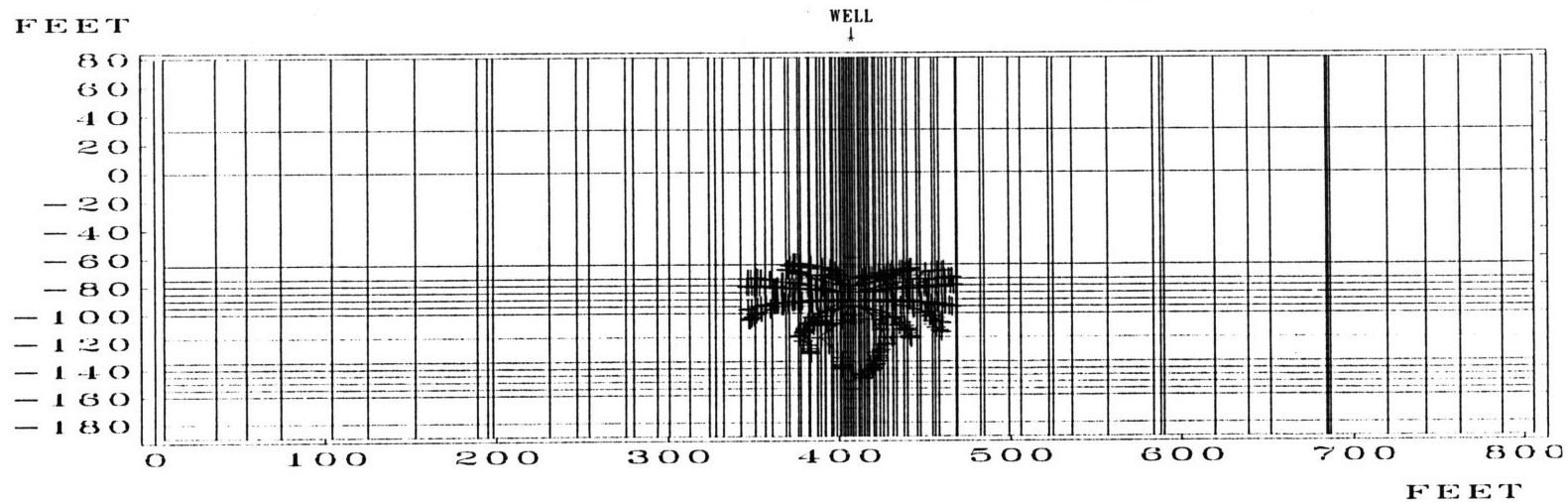


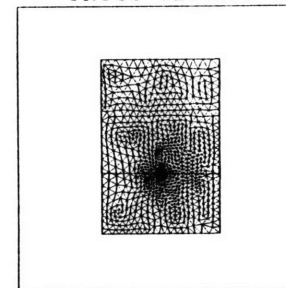
Figure B6-10: Capture Zone Simulation
Pumping Rate - 300 gpm
Water Table Elevation - 35 ft. asl
 Massachusetts Military Reservation

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Appendix B.7 DYNPLOT Graphical Output of Recirculating Zone for Different Pumping Rates



CROSS SECTION AA



- * RECIRCULATING WELL
WITHIN 10.0 FT
- GROUND SURFACE
- TOP OF SCREEN
- BOTTOM OF SCREEN

Figure B7-1: Recirculated Particle Simulation

Pumping Rate - 25 gpm

Water Table Elevation - 35 ft. asl

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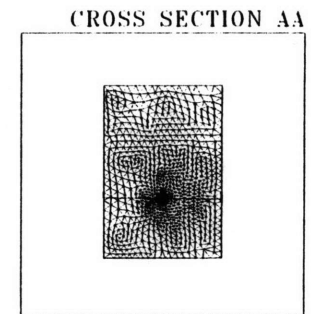
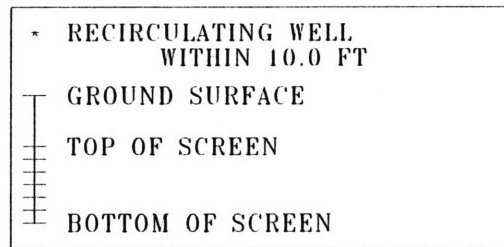
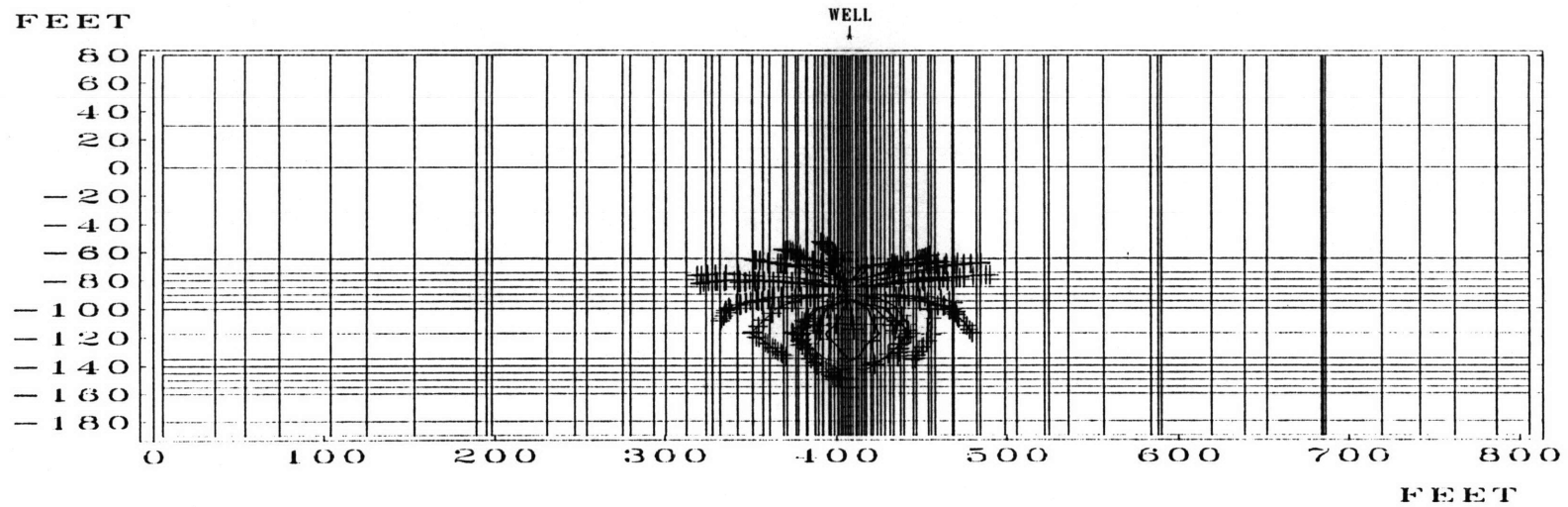
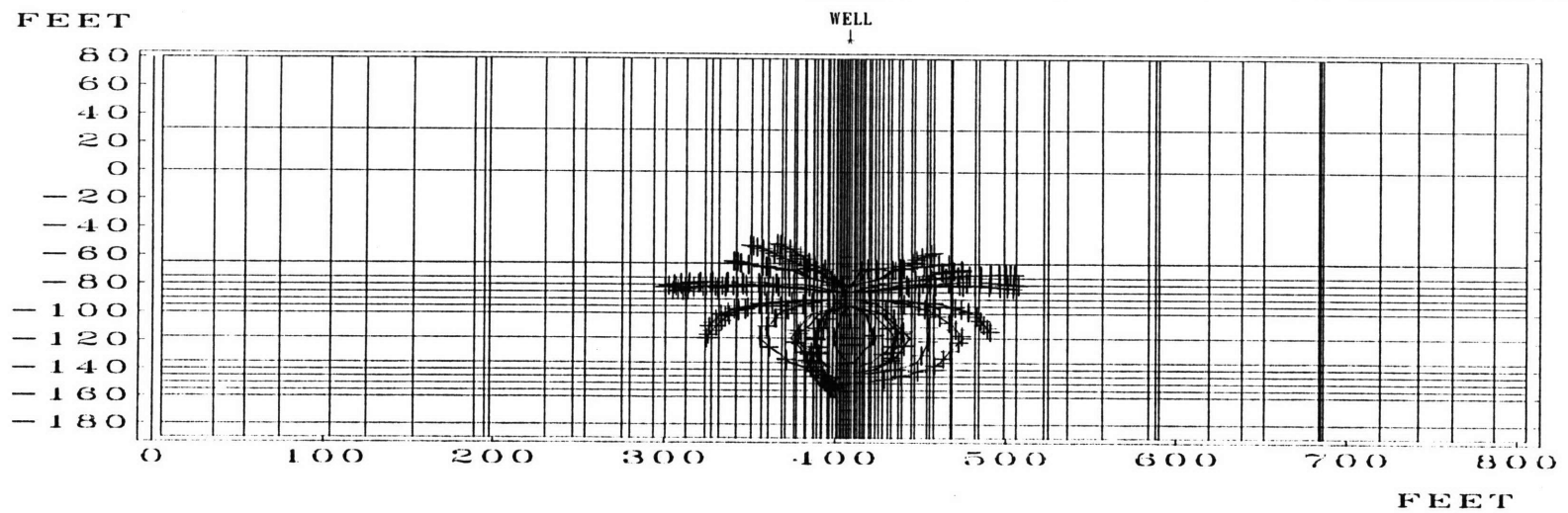


Figure B7-2: Recirculated Particle Simulation
Pumping Rate - 50 gpm
Water Table Elevation - 35 ft. asl
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* RECIRCULATING WELL
WITHIN 10.0 FT

— GROUND SURFACE

— TOP OF SCREEN

— BOTTOM OF SCREEN

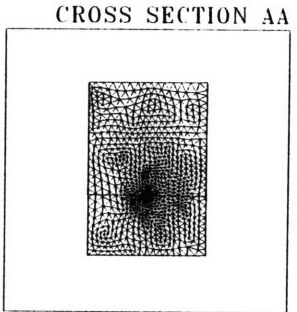


Figure B7-3: Recirculated Particle Simulation
Pumping Rate - 75 gpm
Water Table Elevation - 35 ft. asl
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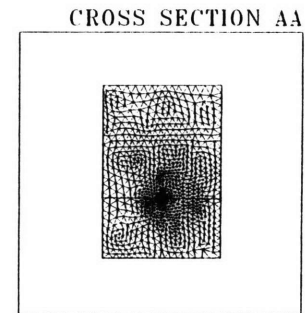
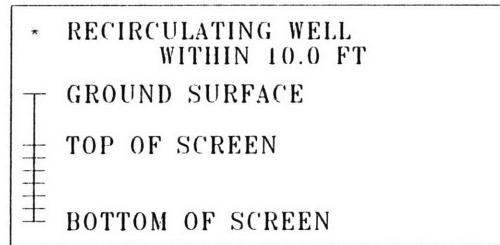
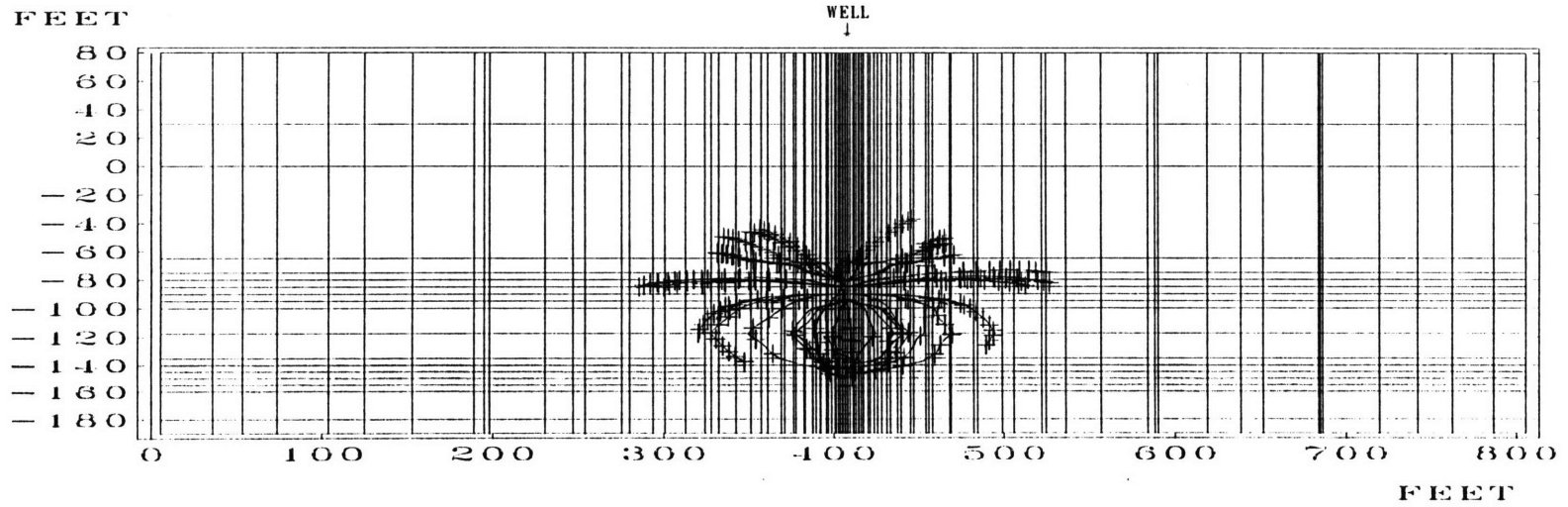


Figure B7-4: Recirculated Particle Simulation
Pumping Rate - 100 gpm
Water Table Elevation - 35 ft. asl
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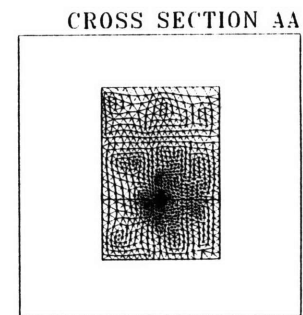
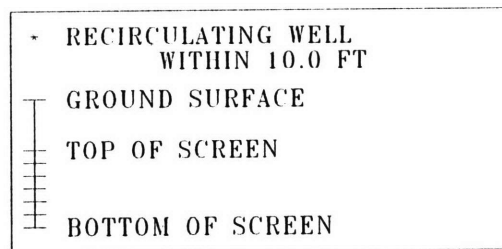
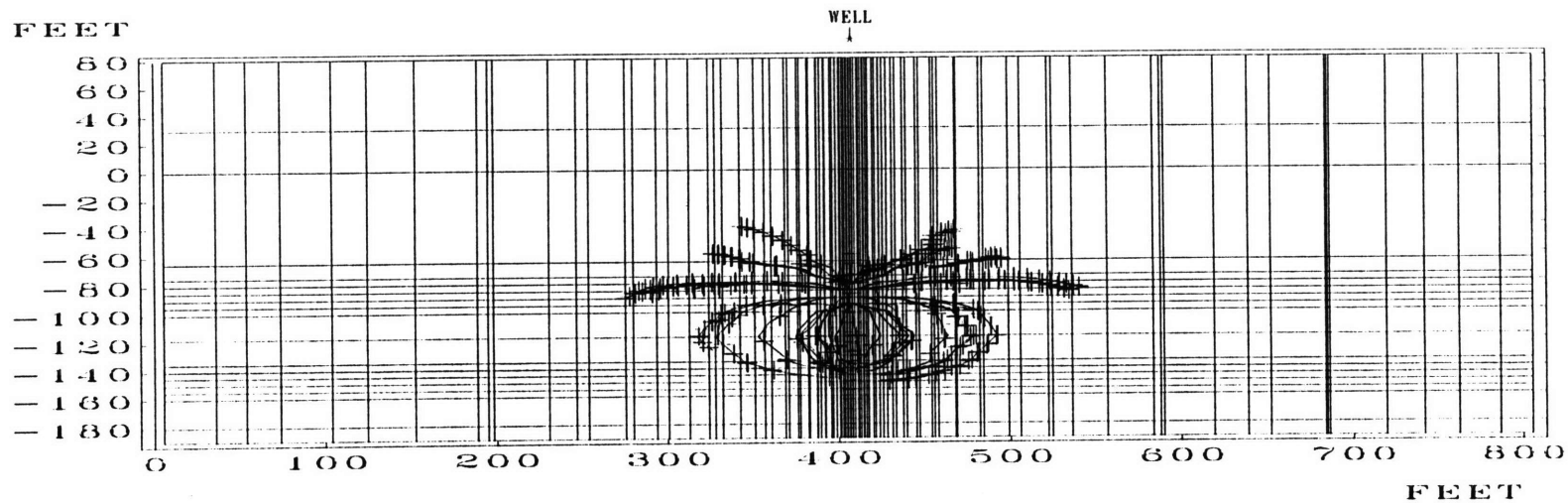


Figure B7-5: Recirculated Particle Simulation
Pumping Rate - 125 gpm
Water Table Elevation - 35 ft. asl
 Massachusetts Military Reservation

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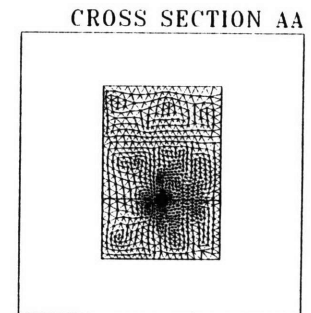
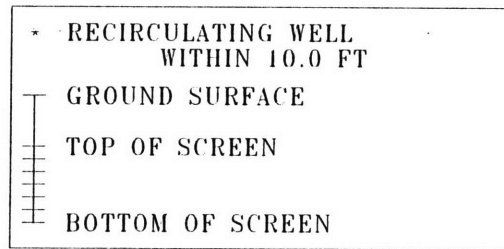
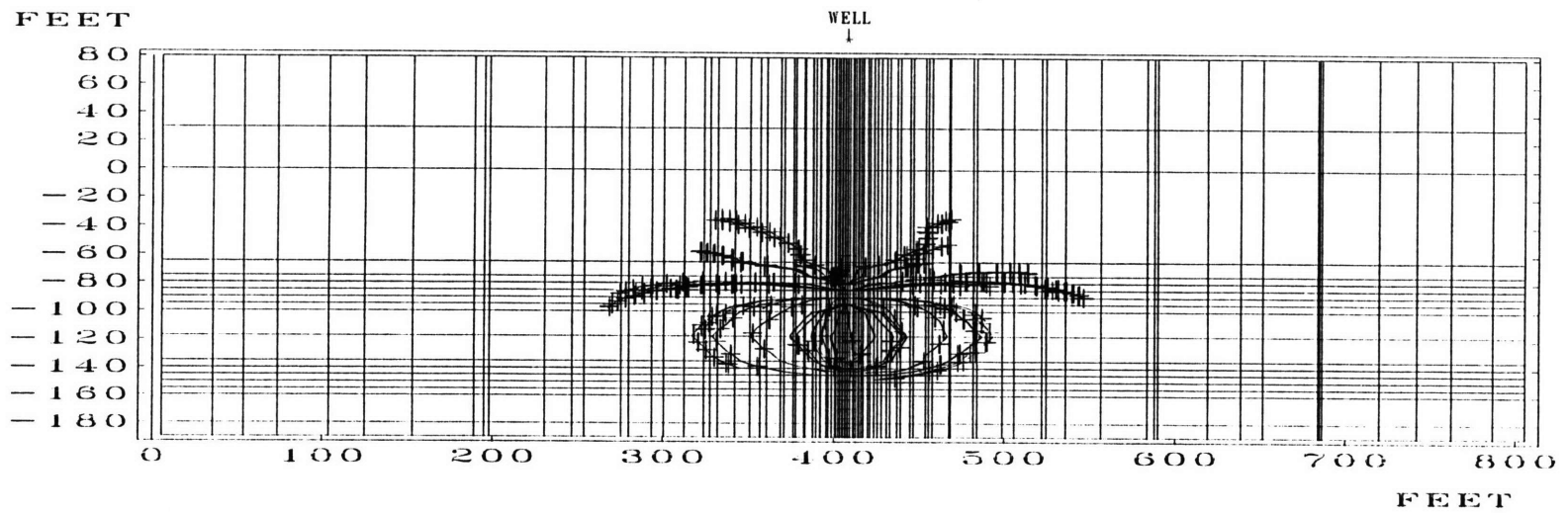
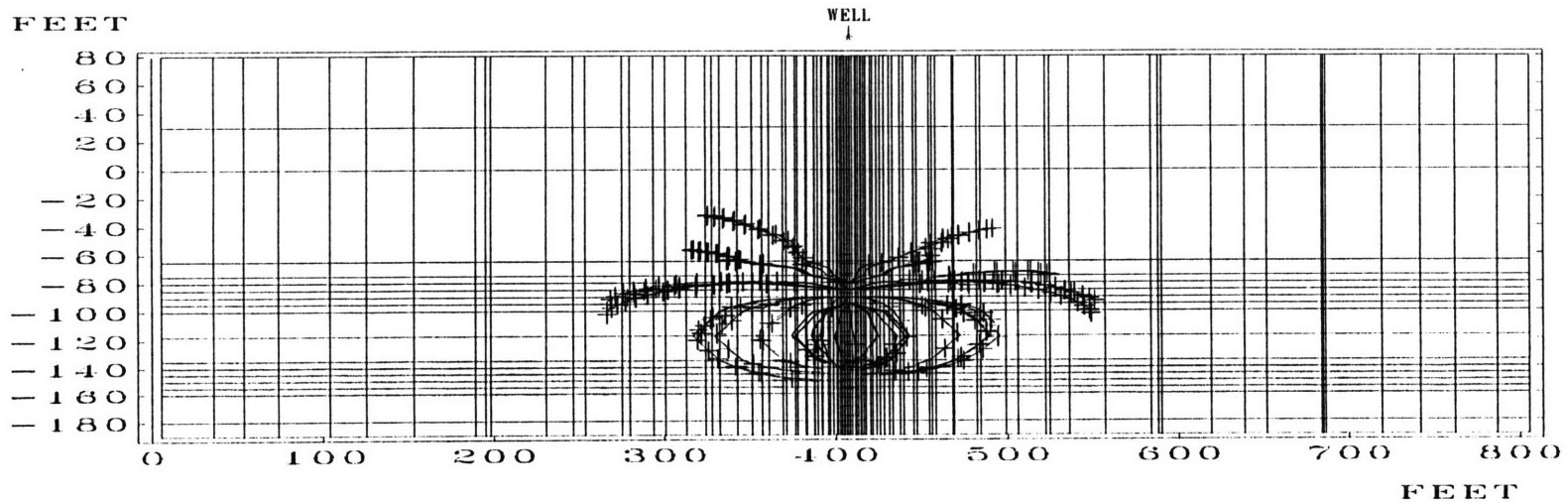


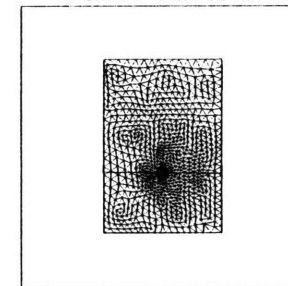
Figure B7-6: Recirculated Particle Simulation
Pumping Rate - 150 gpm
Water Table Elevation - 35 ft. asl
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CROSS SECTION AA



* RECIRCULATING WELL
WITHIN 10.0 FT

— GROUND SURFACE

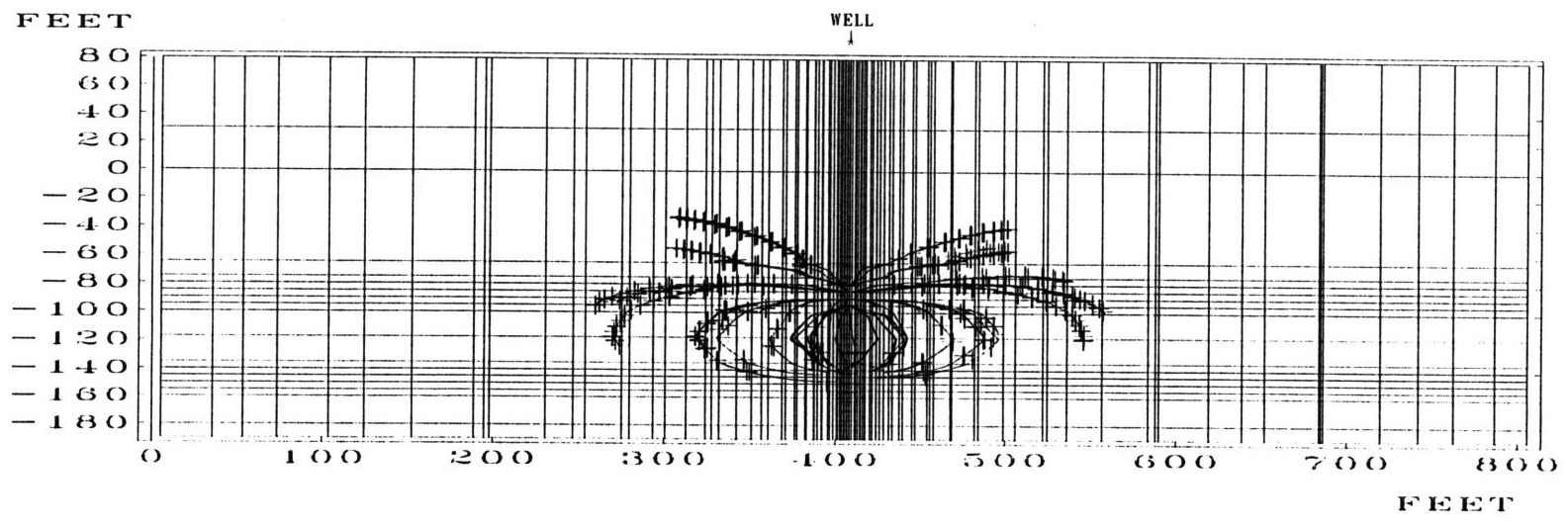
- - - TOP OF SCREEN

- - - BOTTOM OF SCREEN

Figure B7-7: Recirculated Particle Simulation
Pumping Rate - 175 gpm
Water Table Elevation - 35 ft. asl
 Massachusetts Military Reservation

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* RECIRCULATING WELL
WITHIN 10.0 FT

— GROUND SURFACE

— TOP OF SCREEN

— BOTTOM OF SCREEN

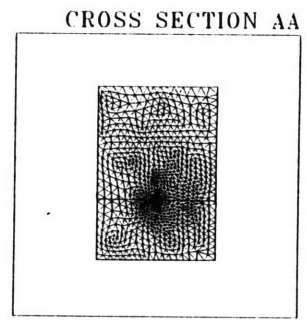
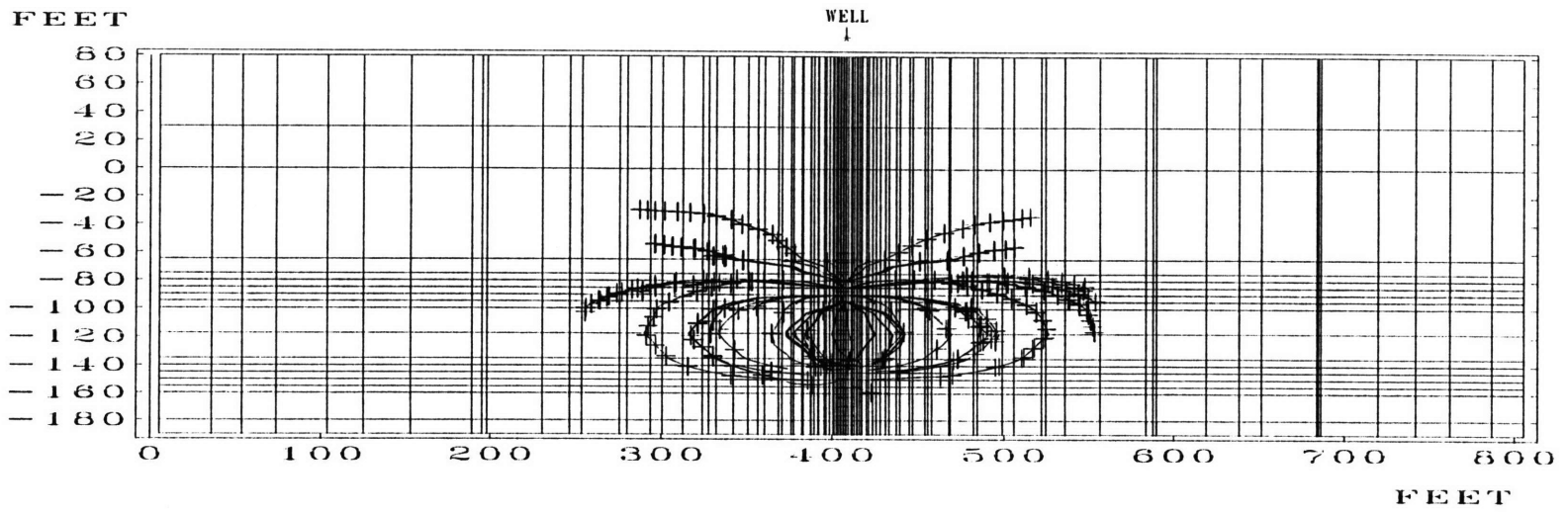


Figure B7-8: Recirculated Particle Simulation
Pumping Rate - 200 gpm
Water Table Elevation - 35 ft. asl
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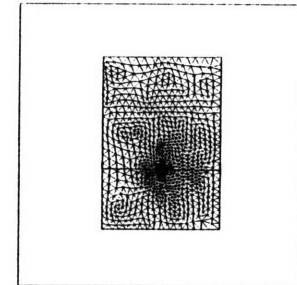


Figure B7-9: Recirculated Particle Simulation
Pumping Rate - 250 gpm
Water Table Elevation - 35 ft. asl
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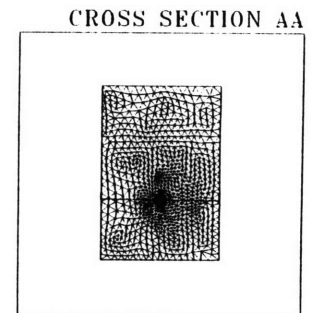
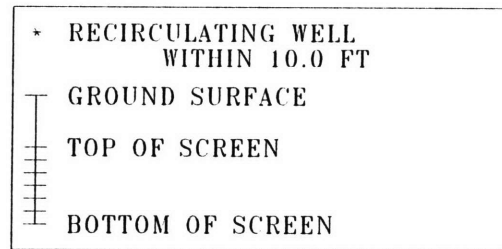
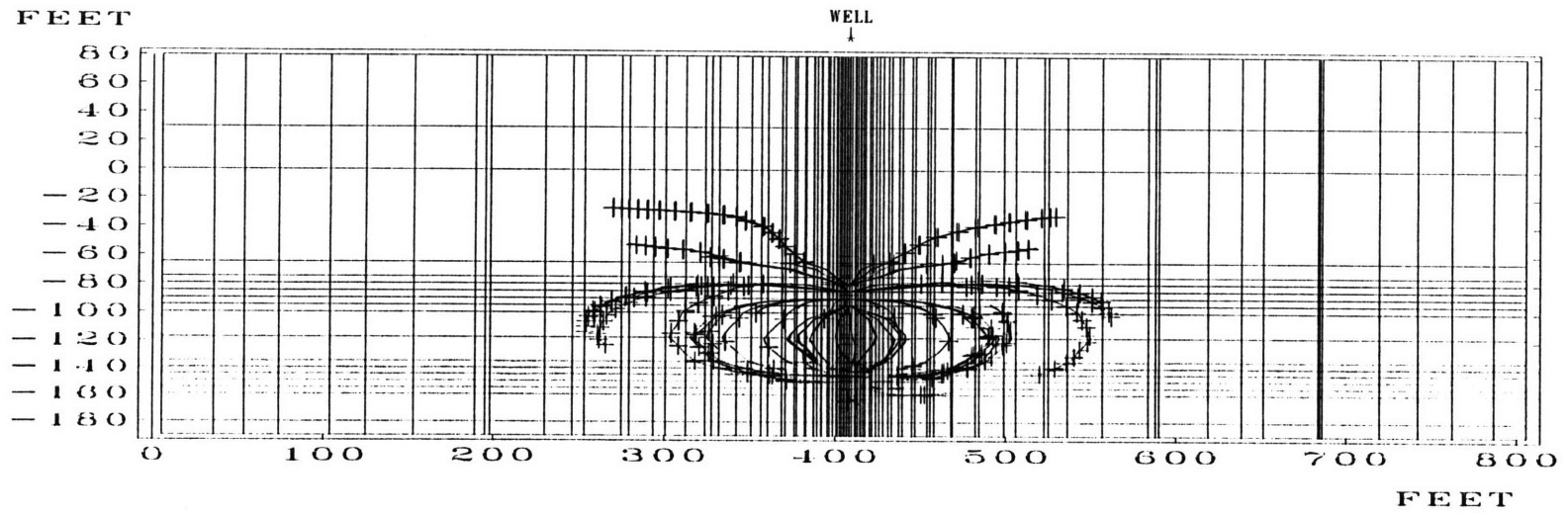


Figure B7-10: Recirculated Particle Simulation
 Pumping Rate - 300 gpm
 Water Table Elevation - 35 ft. asl
 Massachusetts Military Reservation

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