Analysis of Geologic Parameters on Recirculating Well Technology, Using 3-D Numerical Modeling: Massachusetts Military Reservation, Cape Cod

by

Tina L. Lin
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Submitted to the Department of Civil and Environmental Engineering
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ABSTRACT

Recirculating Well Technology is an in-situ groundwater and soil treatment system that remediates volatile organic compounds (VOCs) and petroleum hydrocarbons. By using a combination of physical and biological processes, recirculating wells can effectively strip VOCs from the groundwater while enhancing aerobic bioremediation as well. This study focused on the effect of geological conditions on Recirculating Well performance, using the Chemical Spill-10 (CS-10) groundwater contaminant plume located at the Massachusetts Military Reservation (MMR) as the base case.

According to past studies, anisotropy ratios seem to be the largest limiting hydrogeological parameter in recirculating well efficiency; therefore, a range of anisotropy ratios were considered in this study. By using the DYNSYSTEM software, developed by Camp Dresser & McKee, the hydraulics of the recirculating well technology as well as the hydrogeological and geological conditions of the CS-10 area were simulated. Currently, there are two recirculating well designs that are being considered for use at CS-10; therefore, two corresponding 3-D finite element groundwater flow models were developed: one to represent a design by IEG Technologies, Inc. and the other to simulate a design by EG&G Environmental. Once the base case models were established, hydraulic conductivity parameters were varied to represent different anisotropy ratios while various performance measures were evaluated. More specifically, various particle tracking investigations were conducted to determine general trends concerning the effects of anisotropy ratios on capture width, cross-sectional capture zone area, radius of influence, and percent recirculation.

The overall trends revealed a direct relationship between anisotropy ratios and corresponding capture widths, capture areas, and radius of influences, while an inverse relationship exists between anisotropy and percent recirculation. Consequently, Recirculating Well Technology can be more effective at some sites than others due to favorable hydrogeological conditions.

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INTRODUCTION

1.1 Problem Definition

The Massachusetts Military Reservation (MMR), located in Cape Cod, Massachusetts, was placed on the National Priorities List (NPL) in 1989 under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). CERCLA, created in 1980, provides guidelines for the remediation of hazardous constituents released from federal facilities. The Installation Restoration Program (IRP) at the MMR includes a number of remediation investigations and has initiated treatment of several of the groundwater plumes on site.

Although in January 1996 Operational Technologies (OpTech) prepared a 60 percent design of a pump and treat containment system for the MMR, residents of Cape Cod feared that the resulting drawdown of the groundwater table would cause ecological damage to the nearby Ashumet Pond (OpTech 1996b). As a result, an investigation began to re-evaluate the pump and treat option and to investigate other containment strategies.

The Technical Review and Evaluation Team (TRET) concurred with the residents and deemed pump and treat technology unacceptable for the MMR due to the potential ecological damage. As an alternative, TRET recommended the evaluation of recirculating well technology. Consequently, a pilot test was initiated at Chemical Spill Area-10 (CS-10) with the purpose of evaluating the potential use of this technology. TRET has acknowledged the advantages of recirculating wells as being capable of in-situ remediation by stripping volatile organic compounds (VOCs) from the groundwater without the need and expense of pumping the groundwater to the surface for treatment. Also, the environmental impact associated with drawdown is eliminated since recirculating wells operate without the need to withdrawal large amounts of groundwater.

1.2 Objectives and Methodology

Recirculating well technology is a new method of in-situ remediation of VOCs in groundwater. Although this technology shows much promise, as cited by TRET, it is still not clearly understood nor is it very predictable. Therefore, it is meaningful to evaluate the many factors that could affect the overall performance and feasibility of recirculating wells. This study focused on the effect that geological characteristics of a particular site have on this technology.

Given that the effectiveness of recirculating wells rests on the ability to create large circulation cells within the saturated zone of an aquifer, the anisotropy of a particular site can clearly enhance or limit this capability. Therefore, in order to better understand the relationship between anisotropy ratios and recirculating well performance, various computer simulations were conducted using the DYNSYSTEM groundwater flow software. More specifically, two finite element models were developed to portray the recirculating well designs of IEG Technologies and EG&G Environmental. Once accomplished, particle tracking simulations were executed at various anisotropy ratios to analyze performance criteria such as capture width, capture zone area, radius of influence, and percent recirculation.

In general, velocity vector profiles were generated by simulated heads in DYNFLOW and were used to determine capture widths. In order to conduct particle tracking simulations, efforts were shifted toward DYNTRACK applications. First, a "gate" of contaminant particles were seeded upstream of the recirculating well in order to track which of the particles were ultimately captured by the system. After determining the placement of these particles, the associated areas surrounding these particles were totaled to determine the cross-sectional capture zone area. Secondly, particles were seeded radially about the injection screened intervals of the wells to track the recirculating path of the captured particles. These particle tracks were not only used to estimate the radius of influence that a well could achieve, but they were also utilized to determine the percent of particles that were actually recirculated. From these simulations, performance trends were established to display the effects that anisotropy has on recirculating well technology.

2. BACKGROUND AND SITE DESCRIPTION

This chapter includes background information and site descriptions of the MMR and CS-10 specifically. Before investigating recirculating well technology for use at the MMR, it is essential to have an understanding of the location, history, and physical and environmental conditions of the area of concern.

2.1 MMR Background and Site Description

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

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):

1. ***Maneuver Range and Impact Area*** - 14,000-acre site occupying the northern 70 percent of the MMR. This area is used for training and maneuvers.

2. ***Cantonment Area*** - 5,000-acre area located in the southern portion of the MMR. This area includes administration, operation, maintenance, housing, and support facilities for the base.

3. ***Airfield*** - 4,000-acre area located along the southeastern edge of the MMR. This area contains runways and support facilities for aircraft.

4. ***Massachusetts National Cemetery*** - 750-acre area located along the western edge of the MMR. This area contains the Veterans Administration (VA) cemetery and support facilities.

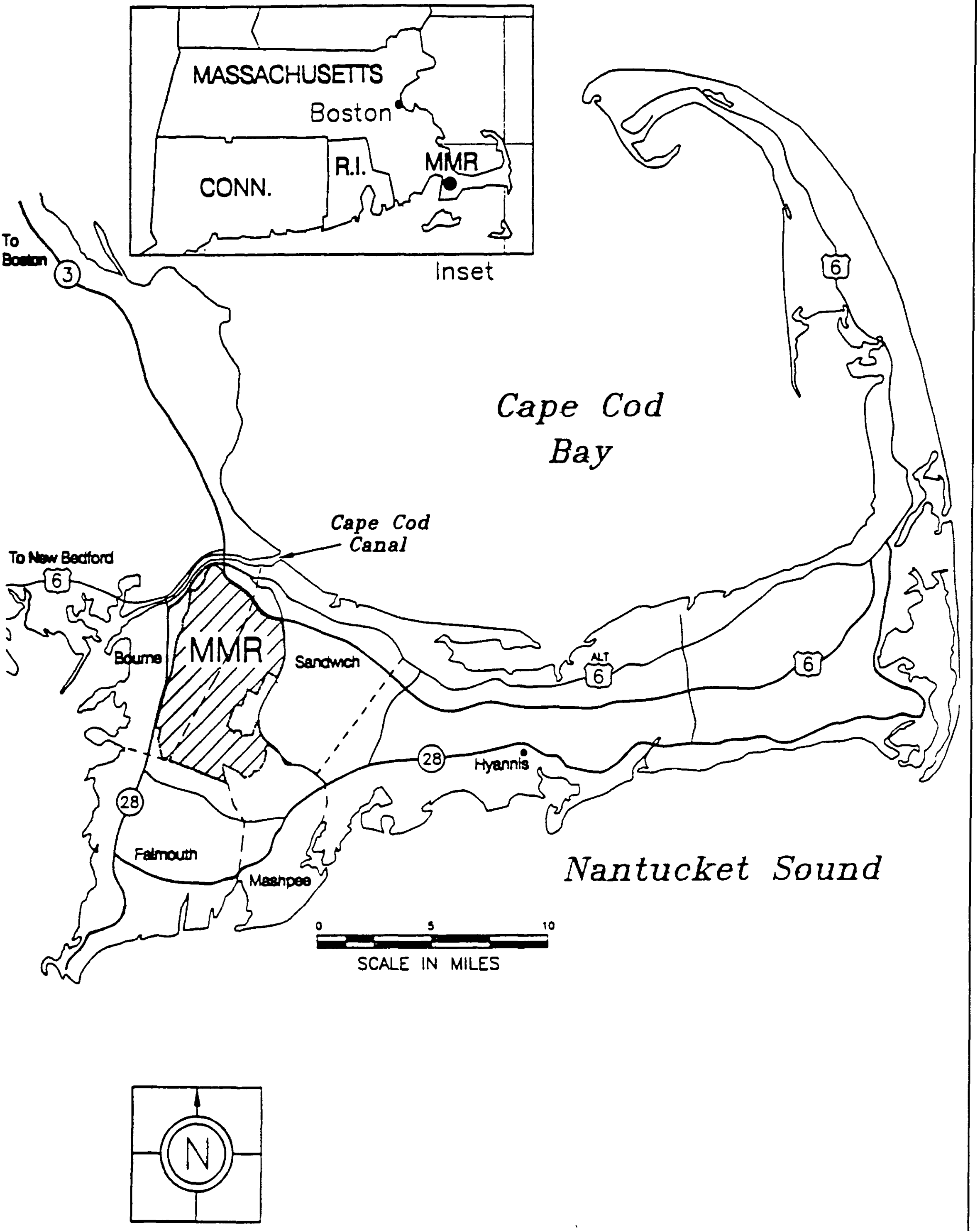


Figure 2-1
Site Location Map

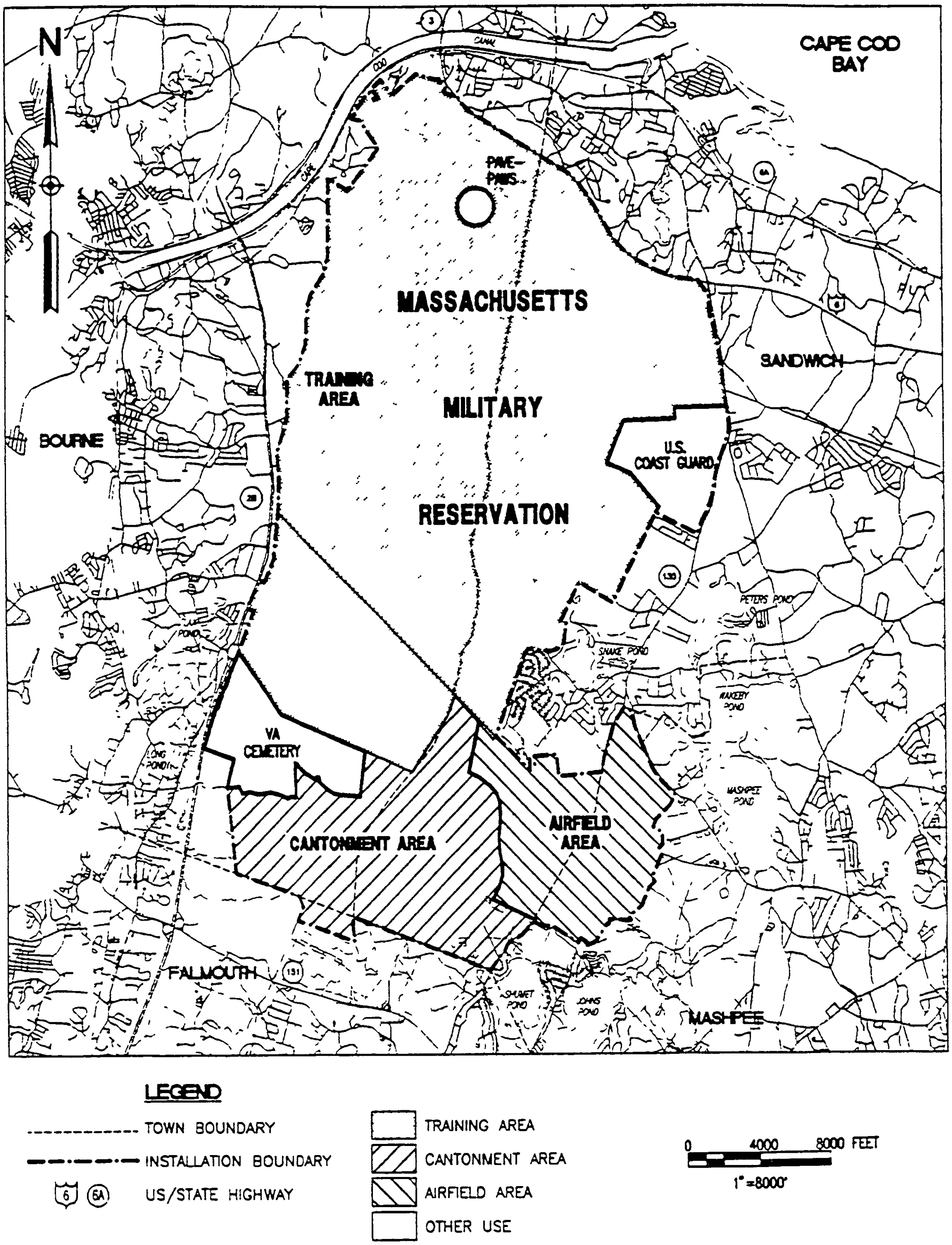


Figure 2-2

MMR Site Map

2.1.2 History of Operation

Although military activity at the MMR began in 1911, most of the military operations 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 the MMR has varied over its history. The most intensive 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. Also, the USAF maintained an intensive airborne surveillance operation from 1955 to 1970 (CDM Federal, 1993).

Currently, the ARNG and U.S. Army Reserve are conducting a variety of training activities at the MMR. The USCG air station at the 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 the MMR include a variety of recreational activities ranging from golfing to 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, the land surrounding MMR is also used for agricultural purposes. Most of the agricultural land is used for the cultivation of cranberries. The remaining land is used for the residential, commercial and industrial sector (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 (CDM Federal, 1993). Also, precipitation is fairly evenly distributed throughout the year, with an average annual rainfall of 46 inches (NCDC, 1990).

2.1.5 Geology and Geography

Western Cape Cod is composed of glacial sediments deposited during the retreat of the Wisconsinan glacier 7,000 and 85,000 years ago. The geology is dominated by three sedimentary units: Buzzards Bay moraine, Sandwich moraine, and Mashpee pitted plain. The Buzzards Bay and Sandwich moraines are located along the north and western edge of Cape Cod, with the Mashpee pitted plain located to the south-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 Wisconsinan glacier. The Mashpee pitted plain is a glacial outwash plain composed of poorly sorted fine to coarse-grained sands. This plain is underlain by fine-grained glaciolacustrine sediments and base till (CDM Federal, 1993).

The MMR is located on two types of geographic terrain. The Cantonment Area lies on a southward sloping outwash plain with elevations 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 Wisconsinan 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).

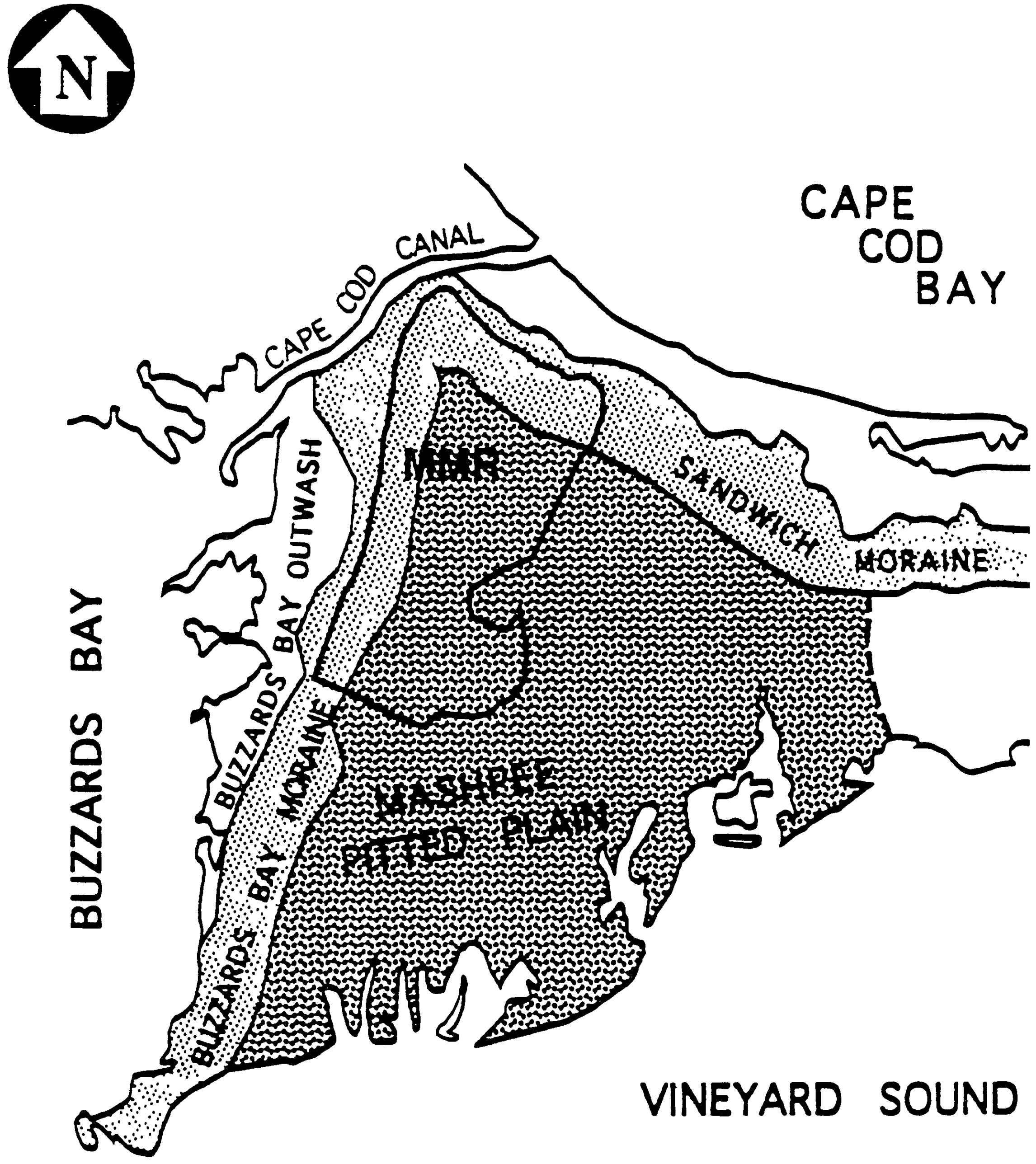


Figure 2-3

Upper Cape Cod Geologic Map

2.1.6 Hydrogeology

The aquifer system in western Cape Cod is unconfined and recharged by infiltration from precipitation. The high point of the water table occurs as a groundwater mound beneath the northern portion of MMR with groundwater flowing radially outward from the mound peak (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 created when buried glacial ice melts and thus creates a local depression. Kettle ponds intersect the water table but cause only local impact on the slope and direction of groundwater flow (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 measures up to 380 ft/day with a hydraulic gradient range of 0.0014 to 0.0018 ft/ft (E.C. Jordan, 1989) and a net annual recharge of 21 inches (LeBlanc, 1982). The hydraulic conductivity of the underlying fine grained sediment is only 10 percent of the outwash; therefore, the bulk of the 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).

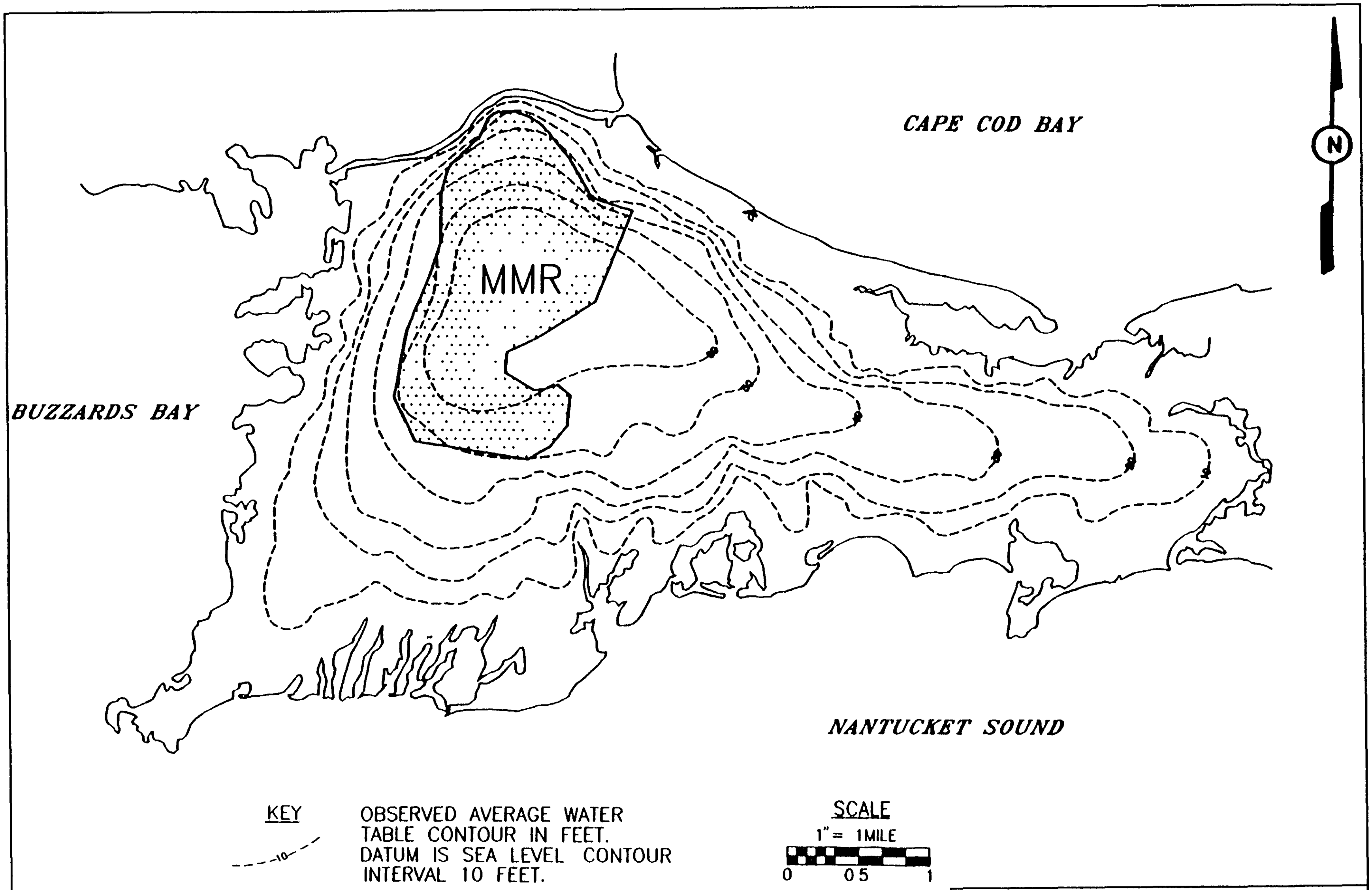


Figure 2-4
Upper Cape Cod Water Table Contour Map

2.2 CS-10 Background and Site Description

This chapter describes the physical and environmental conditions of Chemical Spill-10. Location and site history are also detailed 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 (see Figure 2-5), within the town of Sandwich, Massachusetts. This plume 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 Unit Training Equipment Site (UTES) operations (CDM Federal, 1993).

The nearest MMR housing is located approximately 19,000 ft southwest of CS-10. The nearest housing area outside of the MMR boundary 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 Sandwich. The residences to the east of CS-10 are all served by private wells (CDM Federal, 1993). Residents with drinking water wells in the immediate path of the plume have been placed on public water supply, while other owners of private wells have the option to have their wells tested by the IRP for contamination.

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 Boeing Michigan Aerospace Research Center (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). The following passages briefly describe the activities that occurred under the two operational periods.

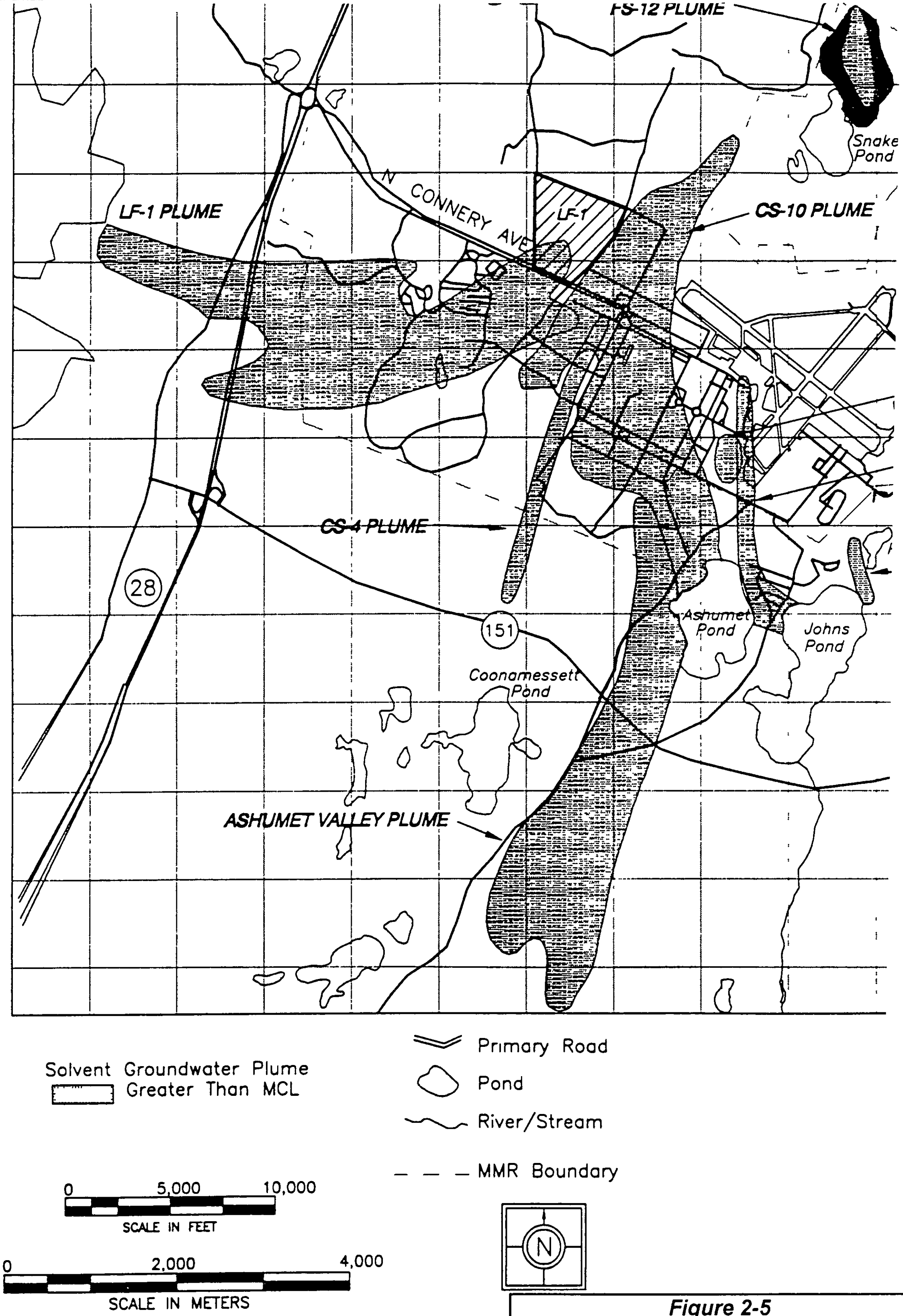


Figure 2-5

MMR Groundwater Plumes Map

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. 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 the MMR. The BOMARC-A missile, a nuclear-warhead-capable missile, was powered by both a liquid-fuel rocket booster and a ramjet engine. This 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 but 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 operations that seemed to generate 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, xylene, naphthalene, 2-methylnaphthalene and other hydrocarbons. JP-4 waste was generated as a result of refueling and maintenance and was disposed of by means of a leaching field. 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. This 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 in a neutralization pit containing crushed limestone. Waste hydrazine and UDMH were pumped into a waste fuel tank and released at a slow rate into a spill pit to allow complete auto-oxidation to occur (CDM Federal, 1993).

Other potential sources of site contamination at CS-10 from BOMARC activities include vehicle fueling, vehicle maintenance and power plant operation. While these activities are likely sources of contamination, no documents exist to indicate the amount of waste produced or if any fuel spills occurred (CDM Federal, 1993).

UTES Activities:

The UTES maintenance shop began operating at the BOMARC site in 1978. UTES is responsible for the maintenance of 300 to 350 armored and wheeled vehicles used for the ARNG training activities at MMR. Waste generated by UTES activities include waste oil, halogenated solvents, petroleum distillate solvents, battery electrodes, paints, and paint removal solvents. Over the years the stored waste has been transferred and transported many times and has consequently caused the contamination of approximately 25 cubic feet of soil. After the decommissioning of the main 500 gallon storage trailer in 1985, the contaminated soil was removed. Currently, UTES collects its waste in 55 gallon drums and stores them at the Camp Edwards Temporary Hazardous Waste Storage Facility before they are shipped to an off-site disposal area (CDM Federal, 1993).

2.2.3 Nature and Extent of the CS-10 Plume

The current understanding of the overall nature of the CS-10 groundwater plume is documented in the Remedial Investigation (RI) report for the UTES/BOMARC and BOMARC Area Fuel Spill AOC CS-10 Groundwater Operable Unit (CDM Federal, 1995). TCE, PCE, and 1,2-DCE were the primary chlorinated organic contaminants detected in the field work that was conducted in 1993. Other organic contaminants detected included 1,1-DCE, trans-1,2,-DCE, and trimethylbenzene. When the RI was conducted, total contaminant concentrations were detected, with TCE being the main contaminant having a maximum concentration of 3,200 ug/L. The maximum concentration of the next single contaminant was PCE at 500 ug/L.

The TCE "hot spot" was tracked downgradient of the well that measured 3,200 ug/L, but screened auger sampling did not detect TCE or any other chlorinated VOCs at those wells. Deep TCE contamination, however, was encountered during drilling at depths in excess of 105 feet below the water table (-55 feet mean sea level (MSL)). The extent of the deeper portions of the plume are still being defined through data gap field efforts.

The CS-10 plume is migrating primarily through the unconfined Mashpee Pitted Plain glacial outwash sand and gravel aquifer. The top of the plume is approximately at sea level and the base of the plume is at or within the underlying fine-grained glaciolacustrine sediments that form the base of the Mashpee Pitted Plain. Based upon TCE concentrations greater than 5 ug/L, the plume is currently estimated to be approximately 16,500 feet long, with a maximum width of 4,200 feet, and a thickness of about 120 feet (see Figure 2-6). The CS-10 plume includes an eastern lobe, whose leading edge has migrated underneath Ashumet Pond, and a western lobe that appears to be migrating in a south-southwesterly direction.

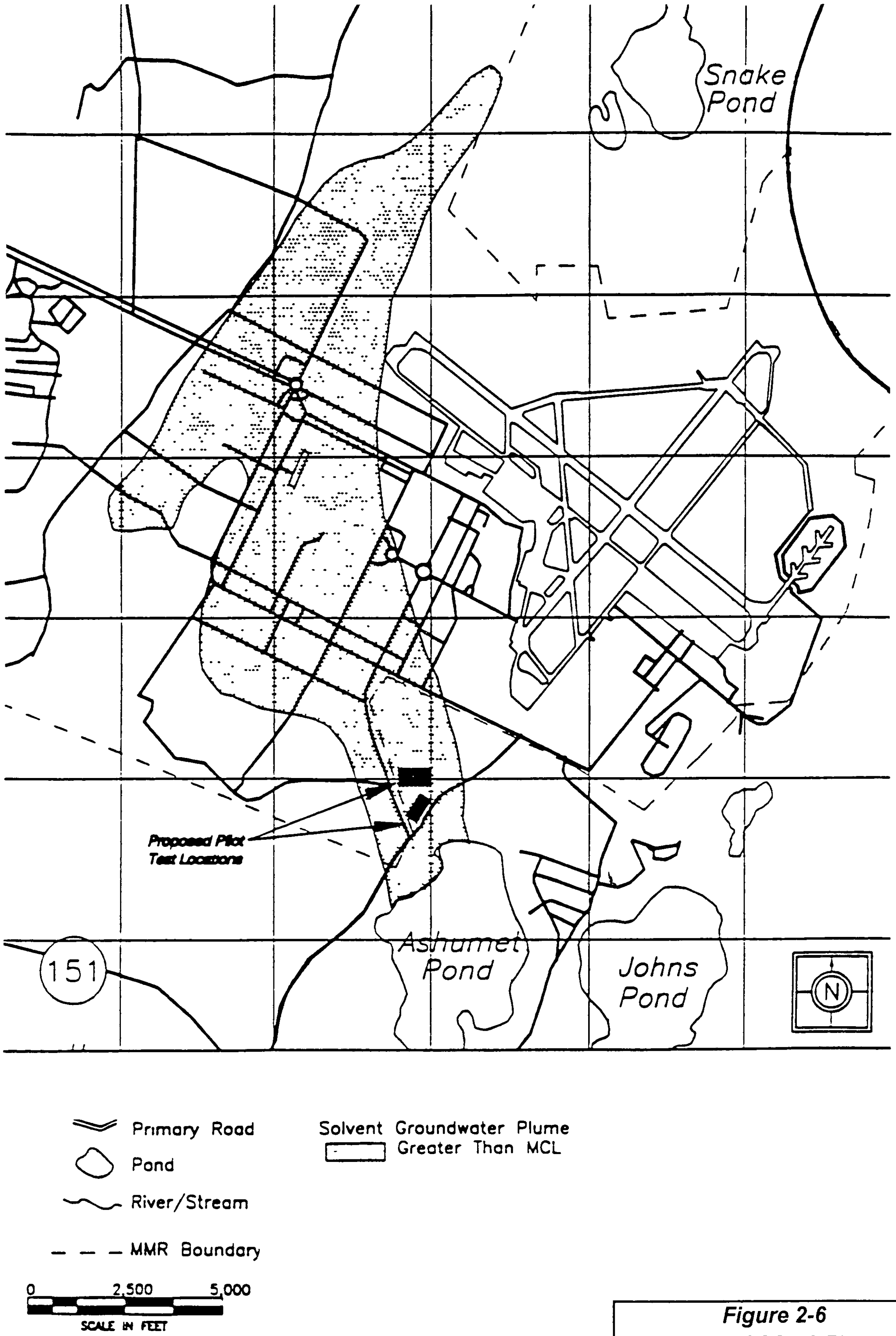


Figure 2-6

Extent of CS-10 Plume

3. RECIRCULATING WELL TECHNOLOGY

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. The basic recirculating well relies 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 enters the well through the extraction screened opening and is lifted upward by the pressurized air. The diffused air bubbles strip the VOCs from the groundwater. The vapor phase is then collected and treated aboveground while the groundwater is returned to the aquifer through the injection screened opening. In addition to air stripping, the aeration of groundwater stimulates aerobic biodegradation (Jacobs Engineering, 1996).

The following sections discuss the advantages of this technology, the history, and the specific designs of the two recirculating wells being considered for the MMR: IEG Technologies and EG&G Environmental.

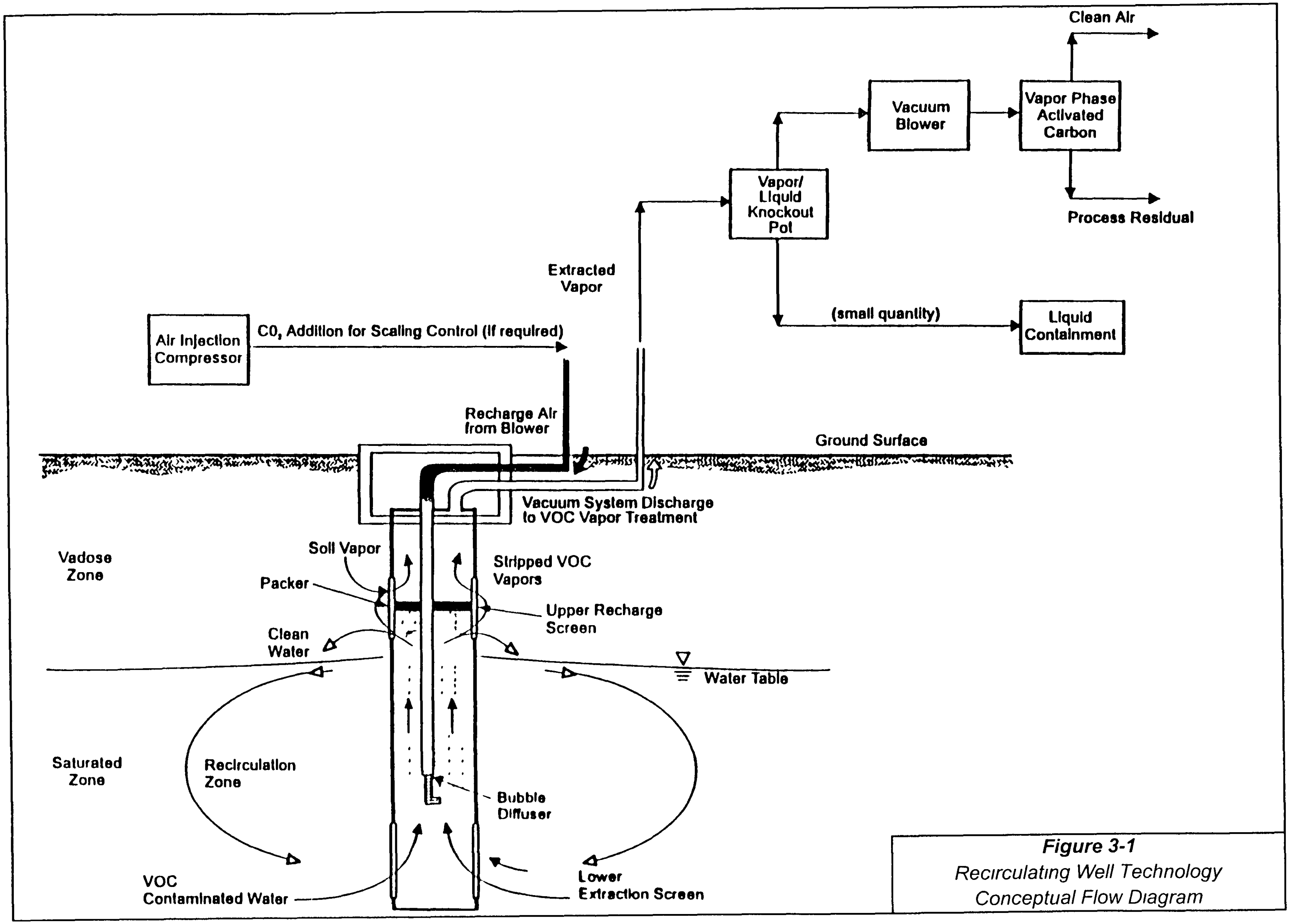


Figure 3-1

Recirculating Well Technology Conceptual Flow Diagram

3.1 Advantages of Recirculating Wells

Recirculating wells have many advantages over the traditional pump and treat systems and air sparging systems. The advantage derives from the means in which VOCs are treated. As stated in the previous section, the recirculating well technology is an in-situ method of treating VOCs whereby contaminated groundwater is extracted from one screened interval, treated within the well, and re-injected at another screened interval in the same well. However, unlike recirculating well technology, pump and treat systems extract contaminated groundwater, bring the groundwater to the surface, treat it, then re-inject the treated groundwater at another location at the site. In addition, air sparging is dissimilar in that it treats contaminants without physically capturing any groundwater. The following sections detail more specifically the advantages of recirculating wells.

3.1.1 Advantage over Pump and Treat Systems

Recirculating wells have numerous physical and cost advantages over pump and treat systems. First of all, since recirculating wells strip VOCs without extracting large amounts of groundwater, the environmental impact associated with drawdown is eliminated. This is quite favorable since water table drawdown can impact wetlands, water resources, saltwater intrusion and foundation settlement. Secondly, creating local groundwater recirculation is another key advantage of recirculating wells. The induced vertical flow effectively flushes out larger areas since it can overcome horizontal heterogeneities. As a result, time and cost of remediation may be reduced. In addition, biodegradation is enhanced because the groundwater that is recirculated in the aquifer is saturated with dissolved oxygen. Consequently, biodegradation can reduce the time and cost associated with remediation. Also, recirculating well technology does not require groundwater to be pumped to the surface; therefore, the cost associated with permitting and monitoring of groundwater extraction and reinjection is reduced. Finally, because recirculating wells extract and inject within the same well, the capital cost is greatly reduced compared to a standard pump and treat system that requires separate extraction and injection wells (Metcalf and Eddy, 1996).

3.1.2 Advantage over Air Sparging

Recirculating wells have many physical and cost advantages over air sparging systems as well. Because recirculating wells remove groundwater from the surrounding media, 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 know 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 though this channel. By removing groundwater from the soil media, air channeling is reduced; therefore, recirculating wells are more reliable than air sparging systems (Metcalf and Eddy, 1996).

Another advantage of recirculating wells is its ability to induce groundwater to travel horizontally and vertically; therefore, contaminant plumes can be contained. Air sparging systems cannot accomplish this type of containment. Also, the horizontal component of the flow gradient is effective in flushing a greater horizontal extent than air sparging. As a result, time and cost of remediation may be reduced. In addition, recirculating wells are cheaper to install since extraction and injection are performed in one well, compared to a two-well air sparging system. Air sparging requires an air injection well and a soil vapor extraction well, thus resulting in a larger capital cost (Metcalf and Eddy, 1996).

Finally, recirculating wells can be installed in deep aquifers, whereas sir sparging systems cannot. Air sparging systems are limited to the vadose zone or to plumes near the phreatic surface of an aquifer. Recirculating wells, on the other hand, can be installed to remediate the vadose zone as well as deep plumes in both phreatic and confined aquifers (Metcalf and Eddy, 1996).

3.1.3 Lack of Case History

Currently, only two companies in the world, IEG Technologies Corporation and EG&G Environmental, hold patents on recirculating well designs. Recirculating wells have been used in Germany for ten years, whereas in the United States use is still very limited (see Tables 3-1 and 3-2 for list of installations and dates if available). Due to the lack of pilot test studies conducted in the U.S., MMR is proceeding with this technology with caution and thereby conducting a pilot test of both IEG and EG&G's equipment to allow the best design for CS-10 to emerge.

Table 3-1: IEG Installation Summary

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

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 x 10^{-3}	50
Fairchild AFB Washington	NoVOC^{TM}	Medium Sand with Silt	TPH 10,000 ppb	8 0 x 10^{-2}	14
Oceana NAS Virginia	NoVOC^{TM}	Find Sand/Sandy Silt, Silt	DCE 10,000 ppb	1 0 x 10^{-3}	20
Industrial Client Idaho	NoVOC^{TM}	Sand with Silt and Clay Lenses	TCE 900 ppb	5 0 x 10^{-3}	220
USMC AS Arizona	NoVOC^{TM}	Fine Sand	TCE 10 - 20 ppb	1 0 x 10^{-3}	92
Landfill Site Arizona	NoVOC^{TM}	Medium Sand	100 ppb TCE 500 ppb PCE	2 0 x 10^{-2}	230

3.1.4 Performance Limitations

Physical and chemical properties of contaminants, as well as site characteristics, may enhance or limit the performance of recirculating well technology.

Contaminant Properties:

Air stripping is the dominant process by which the recirculating well system removes organic contaminants from the groundwater. Therefore, it is important for the contaminants of concern to be sufficiently volatile so that they may partition into the air stream and be removed by the vacuum extraction to achieve successful remediation. Since BTEX compounds are relatively volatile, this technology works well for gasoline and other hydrocarbon contaminants. The recirculating well system also removes non-volatile contaminants that undergo biologically mediated transformations under aerobic conditions. Overall, the volatility and the biodegradation of the individual compounds must be considered as part of the recirculating well design to ensure that appropriate remediation is achieved (Jacobs Engineering, 1996).

Hydrogeologic Setting:

Successful operation of the recirculating well depends on the hydrogeologic conditions of the site. Site-specific properties, such as contaminated aquifer thickness, stratigraphic uniformity, hydraulic conductivities, and groundwater velocity, will influence the performance of the recirculating well.

The thickness of the contaminated plume will affect the size and placement of many of the design features. The recirculating well is designed to draw water from the base of the plume and discharge it at the surface of the plume. Circulation is most effective when the soil beneath the recirculating cell is relatively impermeable. Also, flow rates through the well must be sufficient to ensure that a portion of the discharged water from the upper screen recirculates back through the lower screen. In addition, the recirculating well system is designed to operate through relatively homogeneous aquifer layers. Therefore, the presence of stratigraphic heterogeneities between the upper and lower screened intervals may restrict the recirculation pattern.

3.2 Design and Use at MMR

The following sections describe IEG Technologies' recirculating well design features, then detail the aspects of EG&G Environmental's design.

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. The UVB system used at the MMR incorporates a specially adapted groundwater well that utilizes three screened casing sections, a groundwater stripping reactor, an aboveground blower, and a contaminant vapor collection system (see Figure 3-2). The centrifugal blower at the ground level provides negative pressure for the system and is used to remove the contaminated air from the well vault. The negative pressure causes atmospheric air to enter the well through the air pipe. The fresh air pipe is connected to a stripping reactor which forms air bubbles as it jets through the pin hole plate 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. The contaminated vapor is then transported by air flow to an aboveground carbon absorption treatment system (Jacobs Engineering, 1996).

Because of the three-screen casing design, two types of circulation cells are 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. A pump is positioned in the center of the six-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 falls 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 of the well and creates two circulation cells (Jacobs Engineering, 1996).

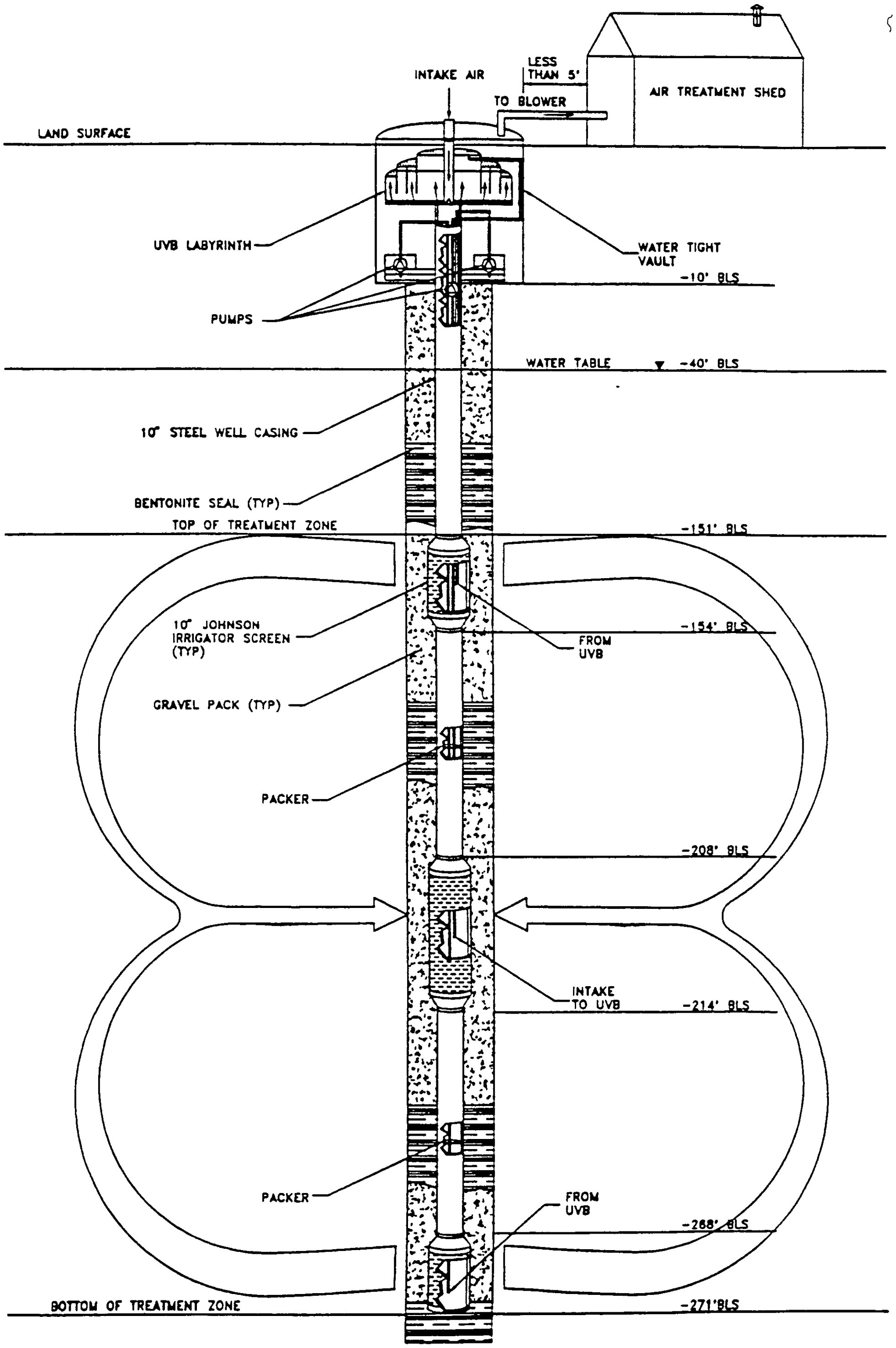


Figure 3-2

IEG Recirculating Well Technology
Conceptual Flow Diagram

IEG Technologies estimated the circulation cell dimensions using the well design and the aquifer parameters. The capture zone bottom width B_B, and top width B_T, are estimated at an upstream distance from the UVB system of five times the height of the plume. The distance, S, is the stagnation point upstream and downstream of the UVB system and is used as the maximum expansion of the sphere of influence of the UVB system. Models developed by Herrling are used to estimate the size of the capture, treatment, and release zones, the stagnation point, and time of particle travel (Herrling, 1991). The calculations for the CS-10 pilot study were performed using a proprietary software program. The estimated cell dimensions for the two IEG wells installed at MMR are shown in Table 3-3 (Jacobs Engineering, 1996).

Table 3-3: IEG Circulation Cell Dimensions

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_o)	8.04 m^3/hr (35.4 gpm)

3.2.2 EG&G Environmental

Metcalf and Eddy, a licensed representative of EG&G Environmental, has installed two EG&G NoVOCs™ systems for the CS-10 groundwater contaminated plume at the MMR site. 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 3-3). 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. Once the air is treated, it is then injected back into the NoVOCs™ system. 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, 1996).

Because of the two-screened-interval design, a clockwise circulation cell develops. The bottom screen is installed near the bottom of the plume. A pump is positioned in the center of the bottom screen to create a reduced hydraulic head zone. The water is then 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 falls out of the inner 6-inch casing into the outer 10-inch casing where it travels down to the upper screen. This significant hydraulic pressure forces the water horizontally into the aquifer through the upper screen, and owing to areas of increased and reduced head, water flows horizontally and vertically into the bottom screen and creates the circulation cell (Jacobs Engineering, 1996).

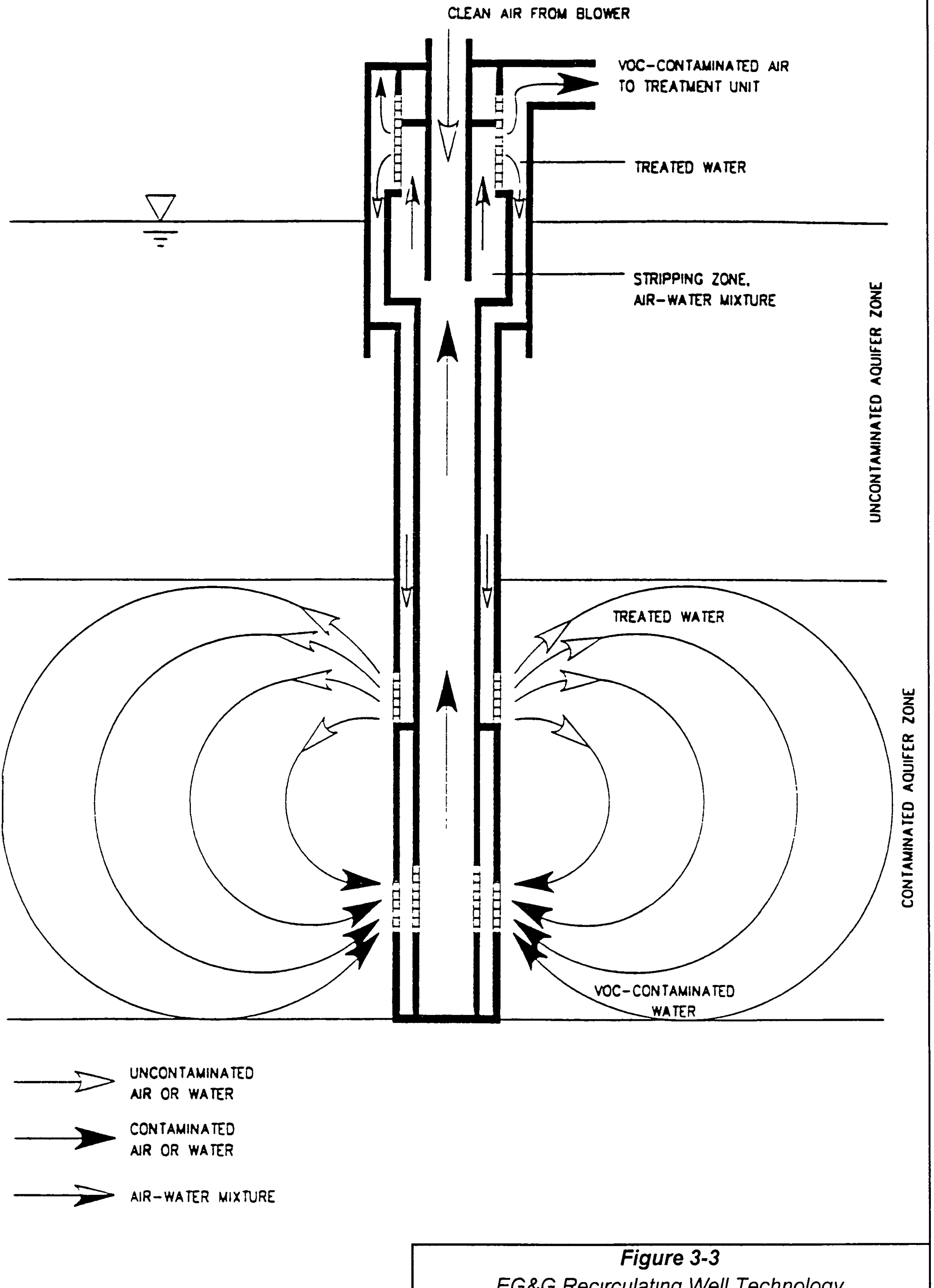


Figure 3-3

EG&G Recirculating Well Technology Conceptual Flow Diagram

EG&G Environmental calculated the circulation cell dimensions based on the aquifer parameters. The radius of influence is the maximum horizontal 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. The determination of the size of the radius of influence is based on dimensionless curves developed by MODFLOW, a numerical groundwater flow model. Table 3-4 shows the estimated circulation cell dimensions for each of the EG&G Environmental NoVOCs™ systems installed at the MMR (Jacobs Engineering, 1996).

Table 3-4: EG&G Circulation Cell Dimensions

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)

4. NUMERICAL MODELING APPROACH

4.1 Introduction

In order to predict the effectiveness of recirculating well technology at CS-10, groundwater flow modeling was performed. Computer modeling is an effective and cost-efficient means to anticipate the performance as well as determine the conditions in which this technology would most efficiently perform. Hydrogeological conditions can enhance or limit a recirculating well's capability; therefore, by coupling numerical models with particle tracking simulations, favorable hydrogeologic parameters can be determined for recirculating well use at a particular contaminated site.

The interaction of hydrogeologic conditions affecting the hydraulics of the recirculating well technology was investigated in this study. Since two recirculating well designs are being considered for use at CS-10, two corresponding 3-D finite element groundwater flow models were developed: one to represent IEG Technologies, Inc. and the other to simulate EG&G Environmental.

4.2 Description of Modeling System

Groundwater flow in the Chemical Spill-10 vicinity of the MMR was simulated using the three-dimensional, finite element DYNSYSTEM software. Camp, Dresser & McKee developed this dynamic groundwater flow simulation model as a tool for analyzing a variety of groundwater flow applications, such as coal strip mine dewatering projects, regional groundwater supply studies, pump test evaluations, vertical consolidation estimates, analyses of flow in fractured rock, and hazardous waste remediation studies (CDM Inc., 1994). For the case of CS-10, DYNSYSTEM was used to simulate the hydraulics of recirculating well technology to determine the effectiveness of contaminant particle capture and recirculation.

The DYNSYSTEM is composed of three sets of code, DYNFLOW, DYNPLOT, and DYNTRACK, as discussed in the following sections.

4.2.1 DYNFLOW

DYNFLOW is a computer program coded in the FORTRAN language that uses the Galerkin finite element formulation to simulate three-dimensional groundwater flow. Based on conventional flow equations in porous media, DYNFLOW can simulate equilibrium or transient responses of groundwater flow systems to various types of stresses. These stresses include induced infiltration from streams, artificial and natural recharge or discharge, pumping and evapotranspiration. This program uses linear finite elements and solves both linear (confined) and non-linear (unconfined) aquifer flow equations. DYNFLOW uses a trapezoidal time stepping scheme with both lumped and distributed storage term options. The program handles multi-level pumpage using one-dimensional elements, and can treat general anisotropy in terms of hydraulic conductivity (CDM Inc., 1994).

4.2.2 DYNPLOT

DYNPLOT serves as a graphic interface and geographic information system for the DYNSYSTEM groundwater models. It is a graphical pre- and post-processor that supports the groundwater flow and contaminant transport models DYNFLOW and DYNTRACK (CDM Inc., 1994). DYNPLOT creates displays in plan and cross-sectional views of various forms of data, such as measured field data, model input data, and results from previous simulations.

In building the numerical model for CS-10, DYNPLOT was first used to generate a grid by utilizing its automated grid generation and grid editing capabilities. Also, after each DYNFLOW and DYNTRACK simulation was conducted, DYNPLOT was used to graphically present the output of the run.

4.2.3 DYNTRACK

DYNTRACK is a companion mass transport program that simulates the spread of contaminants in the saturated zone using flow fields generated by DYNFLOW. DYNTRACK utilizes the same three-dimensional finite element grid representation of aquifer geometry, flow field, and stratigraphy used for the DYNFLOW model (CDM Inc., 1984). The particle tracking function is used in this model to follow the path of the conservative constituents. This enables DYNTRACK to determine an expected location of the contamination as well as an estimated time of travel.

5. GEOLOGICAL PARAMETER MODEL

5.1 CONCEPTUAL MODEL

Since the conceptual model dictates the shape that the DYNFLOW data and commands must follow, it is essential that it is clearly defined. The main motivation behind the grid design for the geologic parameter model was to simulate and predict the CS-10 pilot test results. However, the pilot test data were not available, so only initial head values were incorporated into the model, while more sophisticated model calibrations were unable to be conducted. Nevertheless, running the model with the pilot test configuration still provided significant understanding of recirculating well operations. More specifically, it generated general trends concerning capture widths, cross-sectional areas of capture zones, radius of influences, and recirculation efficiencies under various anisotropy ratio schemes.

The following parameters were specified in the conceptual model.

5.1.1 Geometric Boundaries

Horizontal limits of a grid must be set at points sufficiently far from the area of interest or at boundaries where the head or flux conditions are known. This is to ensure that the boundary conditions do not affect or limit the activity range within the region of interest. Currently at the CS-10 pilot test site, two different recirculating well technologies are being tested side by side (IEG and EG&G) with two wells of each design being tested. Since each vendor's proposal differs significantly from the other, the vertical discretization was modified for each design.

In order to simplify each model, a "half-space" grid was generated. In other words, only half the area of interest was specifically modeled taking advantage of the symmetry created by a two-well system (see Figure 5-1). The first horizontal limit was chosen at the no flow boundary that lies directly between the two wells. IEG and EG&G each installed their two wells approximately 90 feet apart; therefore, a lateral no-flow boundary of the model was set at 45 feet from the well. Next, since it is anticipated that the circulation cell radius, or radius of influence, of each

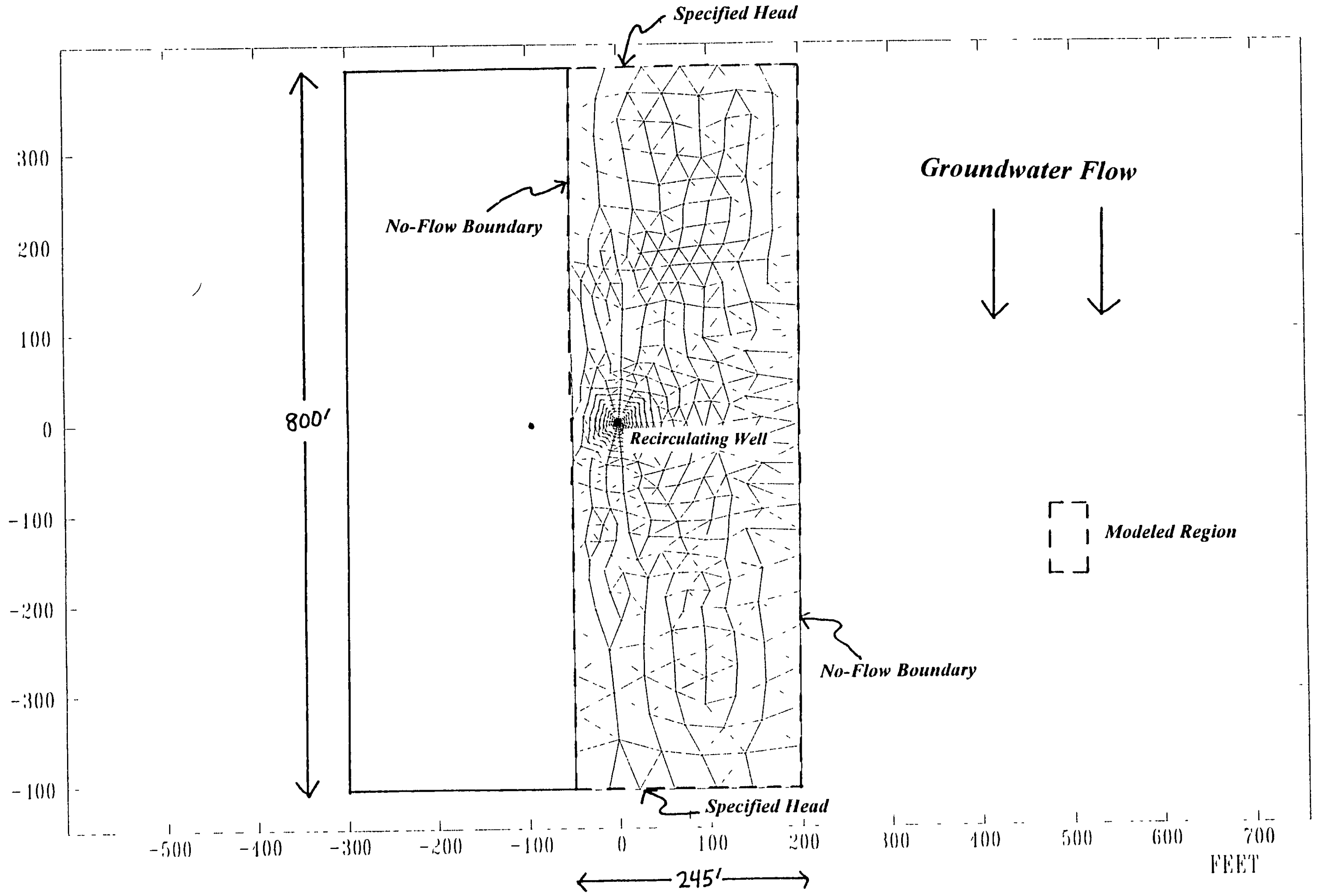


Figure 5-1
Half-Space Grid Configuration

operating well, subjected to the natural conditions of the site, will be between 50 and 100 feet, the opposite lateral limit was set at 200 feet from the well to allow sufficient room for the well activity. Finally, the horizontal boundaries upgradient and downgradient from the well were set 400 feet away from the recirculating well to allow for ample transitional space from uniform regional to local radial groundwater flow to occur in the modeled region.

Vertical limits of a grid depend both on the horizontal limits as well as on the site stratigraphy. The upper vertical limit was set at ground surface elevation, while the lower boundary was specified at the impervious bedrock (see Figure 5-2). The thickness of the modeled region is 270 vertical feet, which includes the 120 ft. thick contaminant CS-10 plume as well as the remaining sediments overlying it. Overall, the dimensions of the model are 800 feet long by 245 feet wide by 270 feet high, resulting in a total bulk volume of 53 million cubic feet.

5.1.2 Hydraulic Boundaries

The ground surface in the model is represented by a "rising" boundary condition. Setting a rising head condition at the surface stops the head from rising above this elevation and effectively allows surface discharge at that node (CDM Inc., 1994). Also, as noted in Figure 5-1, the boundaries parallel to the groundwater flow are designated as no flow, while the boundaries perpendicular to the regional flow are assigned fixed heads, which are based on the natural hydraulic gradient of the area.

5.1.3 Grid Generation and Discretization

The finite element grid for the numerical model consists of radially spaced nodes about the recirculating well. The grid spacing ranges from tens of feet at the boundaries of the model to fractions of feet near the well to allow for greater detail about the area of interest. In all models, areas of interest require more discretization to account for the rapidly changing conditions that occur at these areas, both in the horizontal and vertical directions. Figure 5-1 graphically displays the plan view of the grid created.

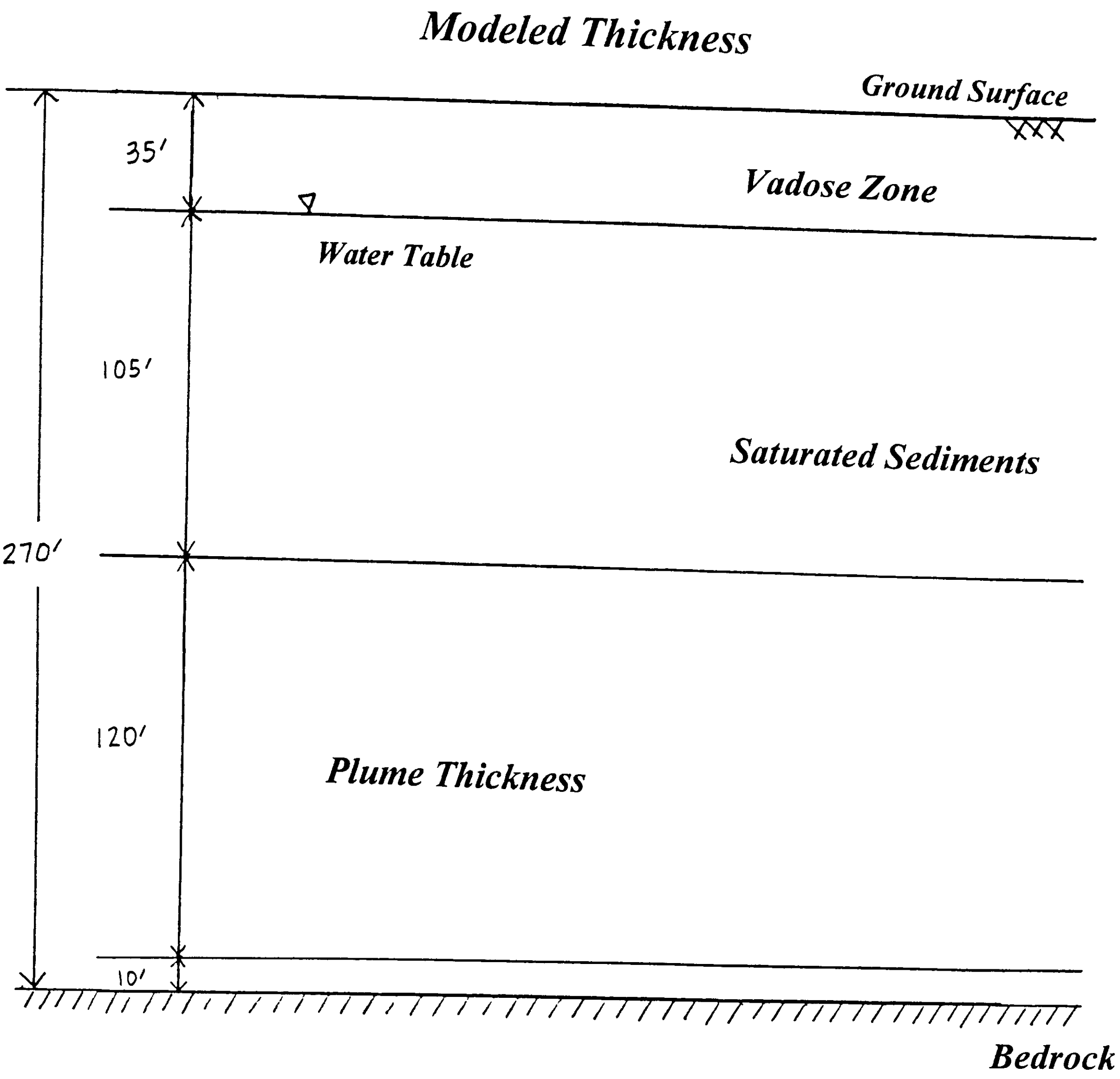


Figure 5-2
Vertical Extent of CS-10 Model

The model consists of 18 layers and 19 levels. The defined levels extend from bedrock to the ground surface. Again, more detail is desired in the areas of interest, which are the screened sections of the vertical well. Therefore, a range between 5 and 15 foot intervals was initially defined along the well, where screened sections were discretized into 5 foot intervals and areas between the screens up to 15 foot intervals. Not much activity was anticipated in the saturated area between the top of the well and the water table level, so much thicker layers were defined in that section of the vertical extent. However, once the DYNFLOW command files were executed, the head values were checked along the well node and the level elevations were adjusted in the areas of rapidly changing head. A cross-sectional view of the IEG and EG&G model grids displaying the discretization is shown in Figures 5-3 and 5-4, respectively.

The specific thickness distributions of the two recirculating well designs are detailed in Table 5-1. Note that levels start at bedrock up to the ground surface, and all elevations are relative to mean sea level.

Table 5-1: Thickness Distributions

IEG	Level	Elevation (ft)
	19	80
	18	45
	17	0
Injection	16	-60
Screened	15	-65
Interval	14	-70
	13	-80
	12	-90
	11	-105
Extraction	10	-110
Screened	9	-115
Interval	8	-120
	7	-125
	6	-140
	5	-155
Injection	4	-170
Screened	3	-175
Interval	2	-180
	1	-190

EG&G	Level	Elevation (ft)
	19	80
	18	30
	17	0
	16	-65
	15	-75
Injection	14	-80
Screened	13	-85
Interval	12	-90
	11	-95
	10	-100
	9	-117.5
	8	-135
Extraction	7	-140
Screened	6	-145
Interval	5	-150
	4	-155
	3	-160
	2	-180
	1	-190

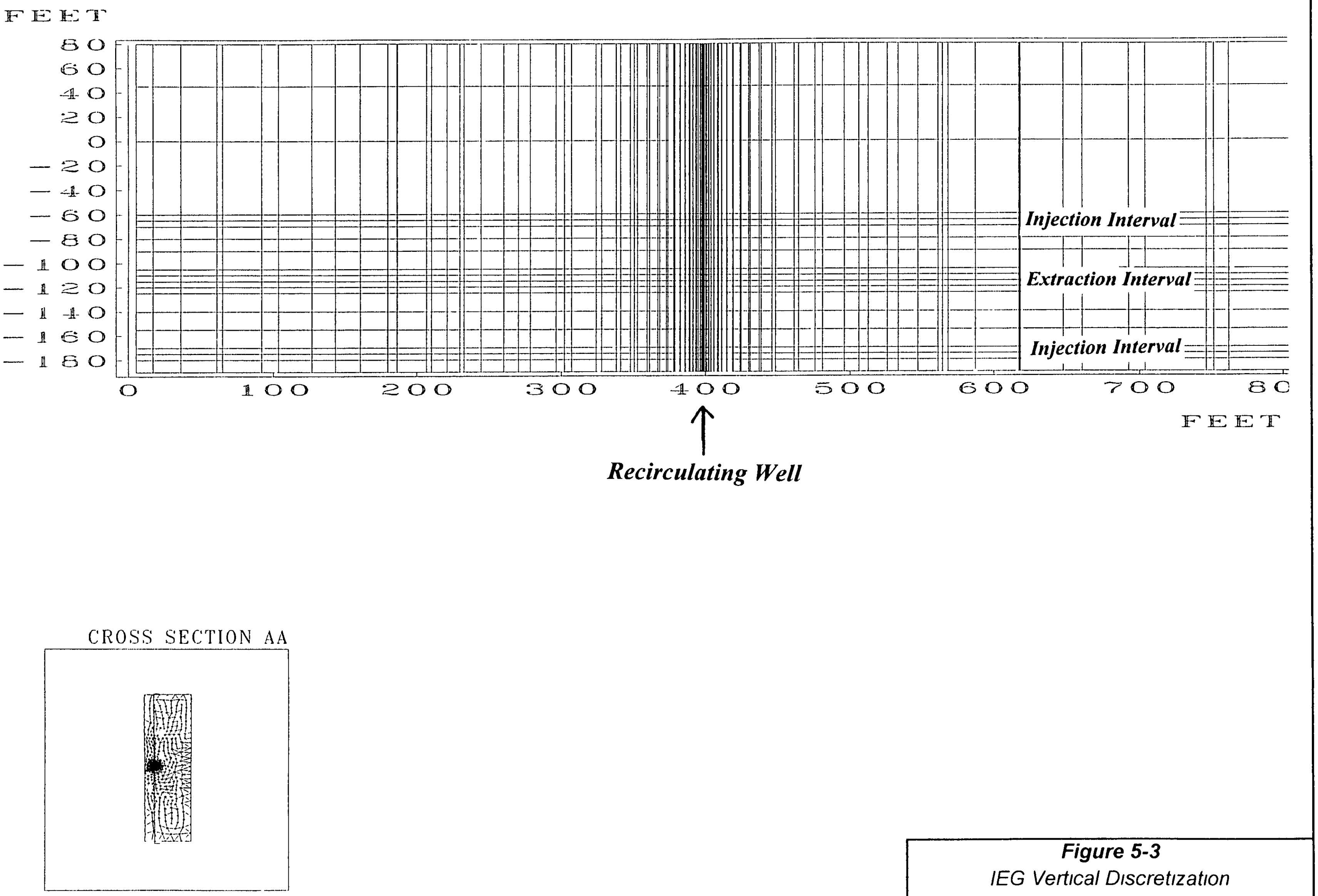


Figure 5-3
IEG Vertical Discretization

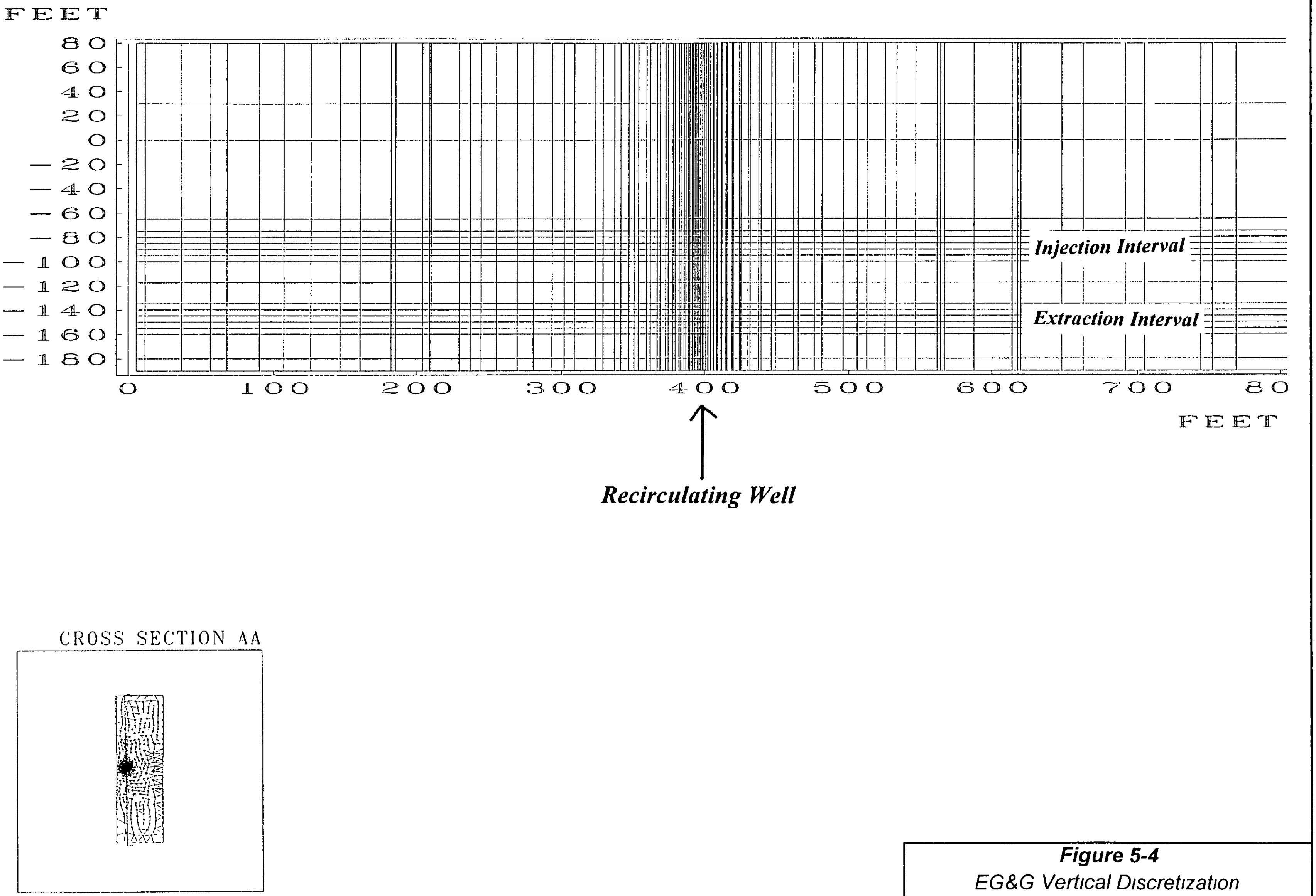


Figure 5-4

EG&G Vertical Discretization

5.2 Design Parameters

5.2.1 Pumping Rates

Each recirculating well design calls for different pumping rates with different numbers of screened intervals. For instance, IEG's well design develops two circulation cells operating at 44 gallons per minute (gpm) each. On the other hand, EG&G's design creates only one circulation cell and it is pumped at a maximum of 200 gpm. For either case, the nodes corresponding to the extraction and injection sections of the vertical circulation well were assigned negative and positive pumping values, respectively.

In addition, one-dimensional elements, with high conductivity values, were defined at the screened intervals of the wells so that significant head differences would not occur across these areas. As a result, a more accurate simulation of injection and extraction was achieved.

5.2.2 Screened Intervals

IEG's recirculating well design utilizes four, 10-ft. screened intervals, while the EG&G well only has two, 15-ft. screens. The number of circulation cells developed by each design impacts the radius of influence that each recirculating well can achieve (see Figures 3-2 and 3-3).

5.3 Aquifer Parameters

5.3.1 Aquifer Thickness

The unconfined aquifer underlying CS-10 is 270 feet in total thickness. The model extends throughout the thickness of the aquifer and therefore incorporates the entire interval that lies between bedrock and the ground surface (see Figure 5-2).

5.3.2 Hydraulic Conductivity

The hydraulic conductivities in the CS-10 area were defined as shown in Table 5-2.

Table 5-2: CS-10 Hydraulic Conductivities

3-D Elements	
Kx	297 ft/day
Ky	297 ft/day
Kz	59.5 ft/day

Note that for the screened areas of the wells, 1-D elements were defined with very large conductivities of 10 million ft/day. This conductivity value was set at this high level in order to eliminate significant head differences across each screen.

The anisotropy ratio between the horizontal and vertical directions is approximately 5:1 in this region, according to the CS-10 Final Report. As proven later, the anisotropy of a site strongly influences the effectiveness of recirculating well operations.

In addition, since the aquifer associated with CS-10 consists of a homogeneous distribution of fine to coarse grained sand, only this one type of material was defined in the model. Therefore, the hydraulic conductivity values above represent the entire extent of the modeled aquifer.

5.3.3 Hydraulic Gradient

Since the natural head drop of the CS-10 area is understood to be approximately 1 ft/day, or more specifically to have a hydraulic gradient of 0.0014 ft/ft, the overall head drop across the 800 ft.

extent of the grid is 1.13 feet. The boundaries upstream and downstream of the recirculating well were assigned fixed head values. Given that the initial head value assigned to all nodes in the model was 35 feet, the upgradient boundary was defined at a head value of 35.56 feet, while the boundary downgradient of the well was set at 34.33 feet.

5.3.4 Recharge

Hydraulic parameters such as recharge rates must be defined to specific nodes in a model. In the CS-10 vicinity, infiltration from the surface is evenly distributed over the area at approximately 1.6 feet per year. Therefore, in the model, recharge was set at a constant 0.0044 ft/yr for all elements.

5.3.5 Other Parameters

In addition to the above-mentioned conditions, it is necessary to define the following parameters in order to accurately represent the characteristics of the CS-10 region.

3-D Elements	
Porosity	0.35
Retardation	1.00

Dispersion values were not taken into consideration in this model since the modeled region is dominated by advective transport. The extent of the grid is small; therefore, dispersion simply cannot exert much influence on the recirculating well operation. Also, since only steady-state simulations were conducted, it was not necessary to define storage characteristics.

Appendix A1 and B1 contain sample DYNFLOW command files that were written to develop the IEG and EG&G Recirculating Well models, respectively. Note that all command files included in the Appendix are samples representing CS-10 simulations. Therefore, the anisotropy ratio of 5:1 was incorporated into each command file attached.

5.4 Contaminant Transport Model

5.4.1 CS-10 Plume Dimension and Location

The CS-10 plume is located at the eastern edge of the MMR property line. It 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.

5.4.2 Capture Width

Before conducting particle tracking simulations, velocity vector profiles were generated based on heads simulated in DYNFLOW. By isolating in plan view a layer where extraction occurs (layer 8 for IEG and layer 5 for EG&G) and by following the streamlines of these velocity vectors, an approximate capture width can be established for the existing two well operation.

Figures 5-5 and 5-6 represent the velocity vector profiles from which capture widths were approximated. By doubling the measured width on the "half-space" grid, a total capture width can be determined. The estimated capture widths for the two designs are:

IEG: 340 feet

EG&G: 350 feet

5.4.3 Capture Width at Various Anisotropy Ratios

Since anisotropy ratios directly and significantly affect a recirculating well's capture and recirculation of a given contaminant plume, a range of potential anisotropy ratios was simulated in the above-mentioned manner. The anisotropy ratios were changed by varying the vertical conductivities, since these conductivity values are the most difficult to measure in the field and therefore are the most uncertain. Figure 5-7 graphically represents the trend of capture width vs. anisotropy ratio of both the IEG and EG&G systems.

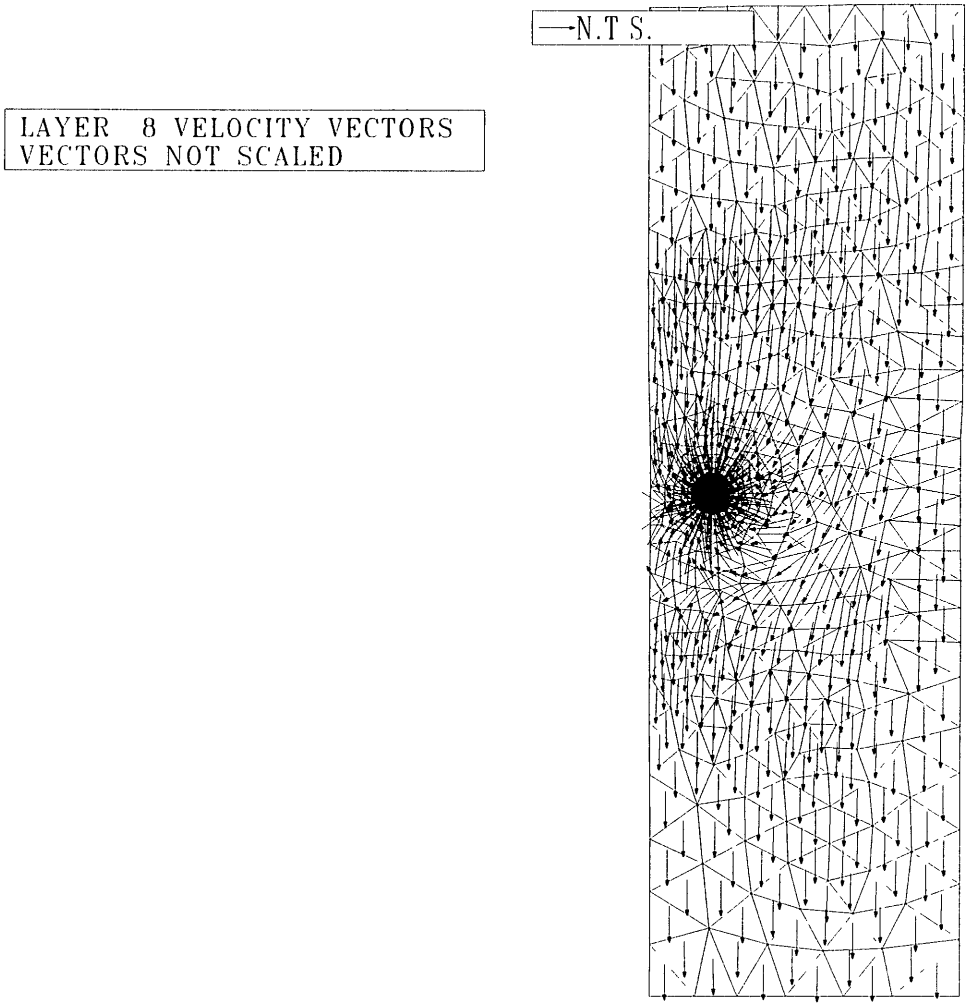


Figure 5-5

IEG Capture Width

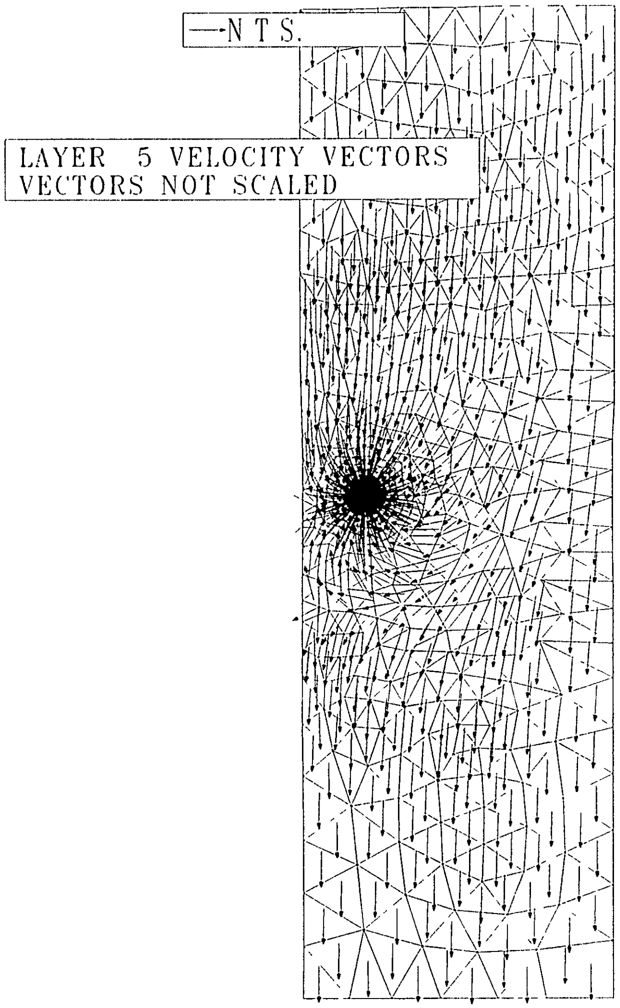


Figure 5-6

EG&G Capture Width

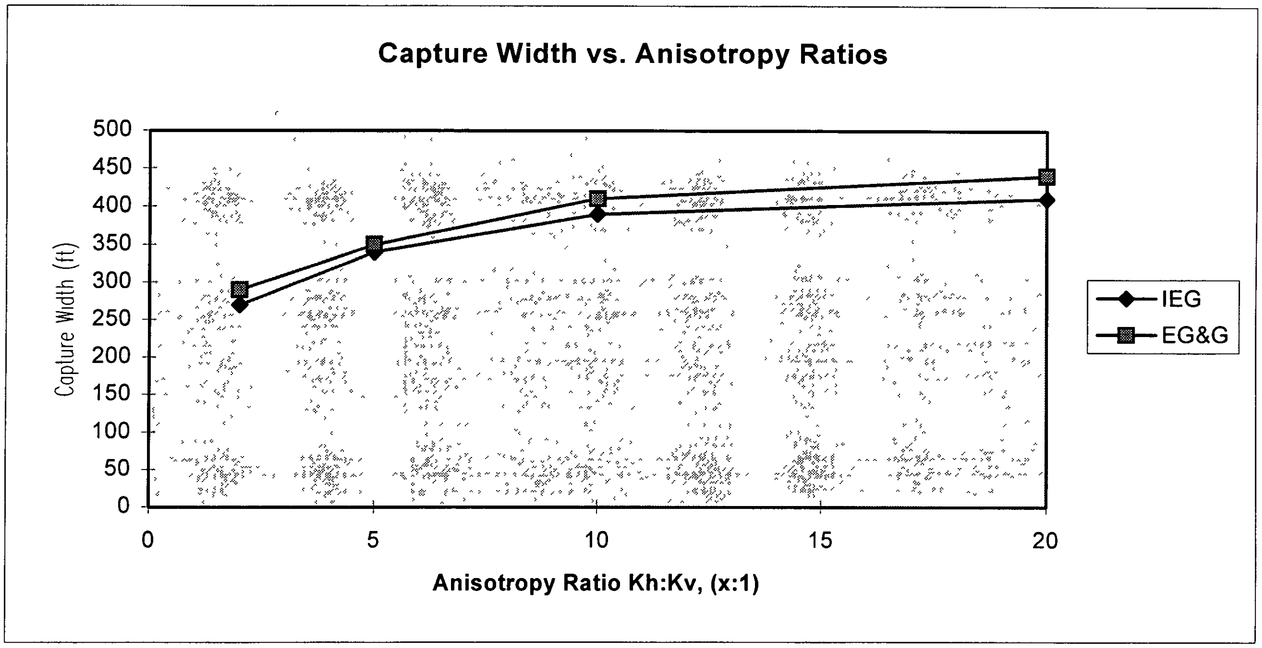


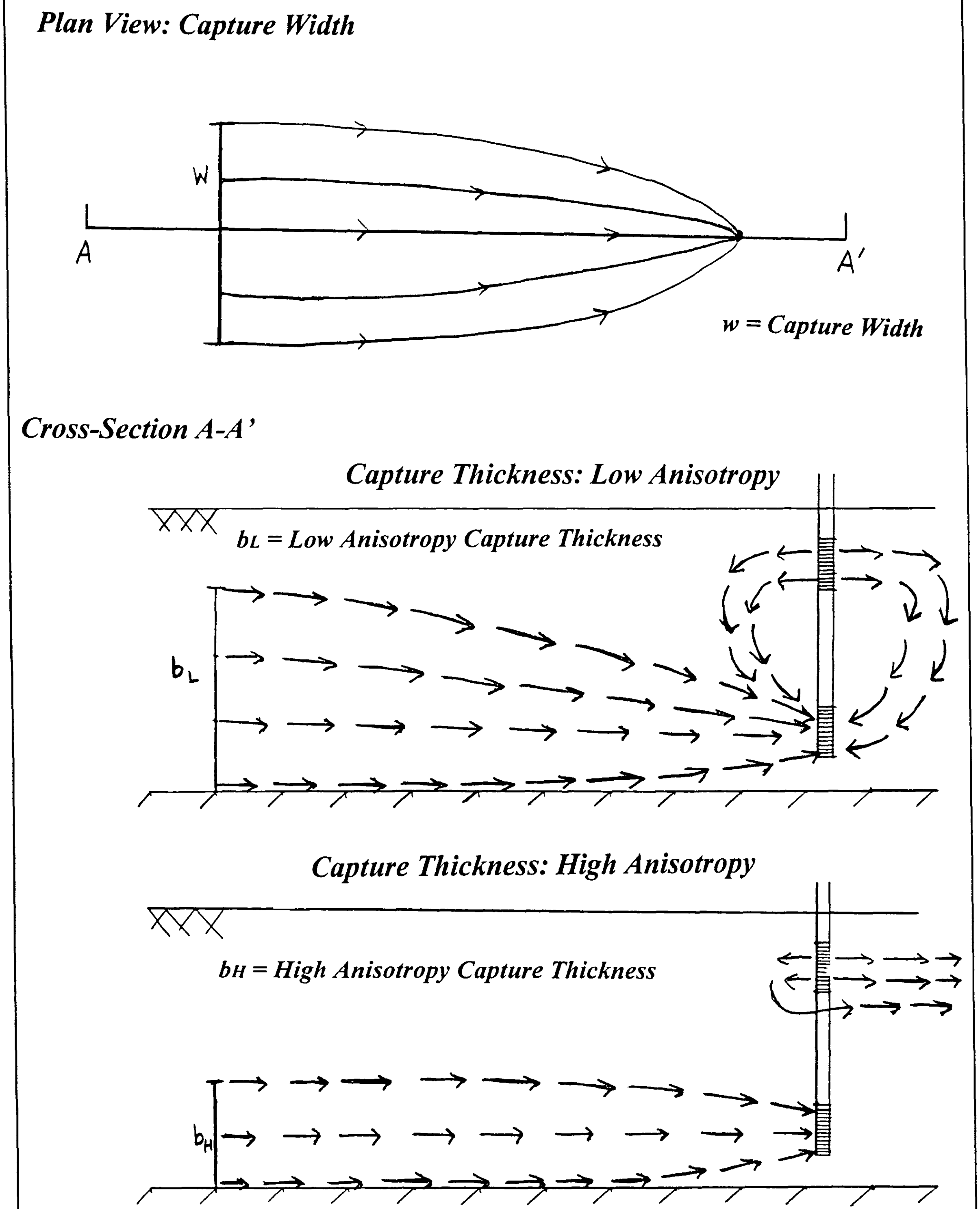
Figure 5-7: Capture Width vs. Anisotropy Ratio

It is clear from the above graph that with increasing anisotropy ratio, an increasing capture width can be achieved. The tendency for particles to travel laterally intensifies with increasing anisotropy ratio and thus results in a smaller capture thickness (see Figure 5-8). Given the relationship that well pumpage (Qw) equals the product of capture thickness (b), capture width (w), and specific discharge (q_a):

$Qw = b * w * q_a$ (Hemond and Fechner, 1994)

and given that Qw and q_a are fixed, it is clear that as b decreases (when anisotropies increase), w increases. However, the capture width levels off above an anisotropy ratio of about 10:1; therefore, anisotropy ratios above 10:1 are optimal for capture width.

Appendix A2 and B2 display the velocity vector profiles for the other anisotropy ratios considered in this study, for both the IEG and EG&G systems.



Plan View: Capture Width

Cross-Section A-A'

Capture Thickness: Low Anisotropy

Capture Thickness: High Anisotropy

Figure 5-8
Capture Width Theory

5.5 Particle Tracking Simulations

DYNTRACK has the capability to simulate the spread of contaminants in the saturated zone. By seeding a group of particles in strategic areas of the model, the particle tracking application will follow the path of conservative constituents. When seeding particles, each one must be specified at a particular coordinate and thus the exact location of each particle can be tracked. This provides a means to develop a 3-D description of the capture zone as well as an estimated time of travel. Since the desire was to determine the capture zone area, the radius of influence of each well, and each well's efficiency of recirculating the contaminated water, various particle seeding schemes were developed to address these issues. The idea behind wanting to recirculate the water several times is to have the contaminated water pass through the system more than once, since with each pass through the well more VOCs are stripped.

5.5.1 Cross-Sectional Area of Capture Zone

Of the captured width of the plume, only a portion of the contaminated particles are actually captured by the recirculating well. By seeding a "gate" of particles upstream of the well, DYNTRACK can simulate which of the seeded particles are actually pumped through the system. The particles were seeded at 10 ft. intervals from each other on all levels corresponding to the depths of the recirculating well. In addition, in order to determine whether or not particles above the well would be captured, two extra levels of particles were seeded 15 and 30 feet above the top of the plume. However, in all the IEG and EG&G simulations, these above-seeded particles were not captured by the system; thus, the extra levels of particles were removed from all the simulation results. Figures 5-9 and 5-10 are cross sections of the grid showing the relative spacing of the starting points of the seeded particles (open squares) as well as the starting points that were eventually pumped by the IEG and EG&G systems (shaded squares.)

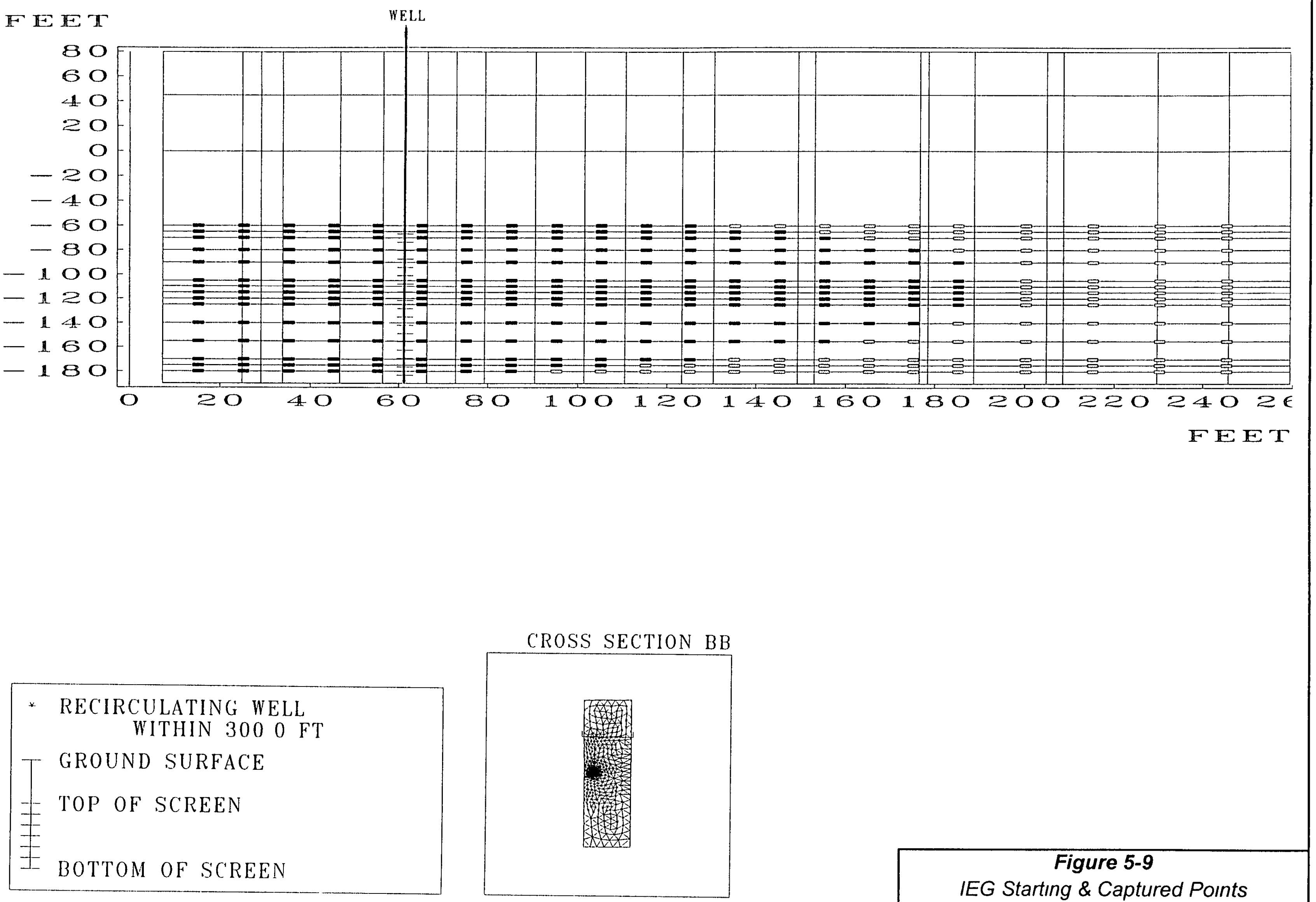


Figure 5-9

IEG Starting & Captured Points

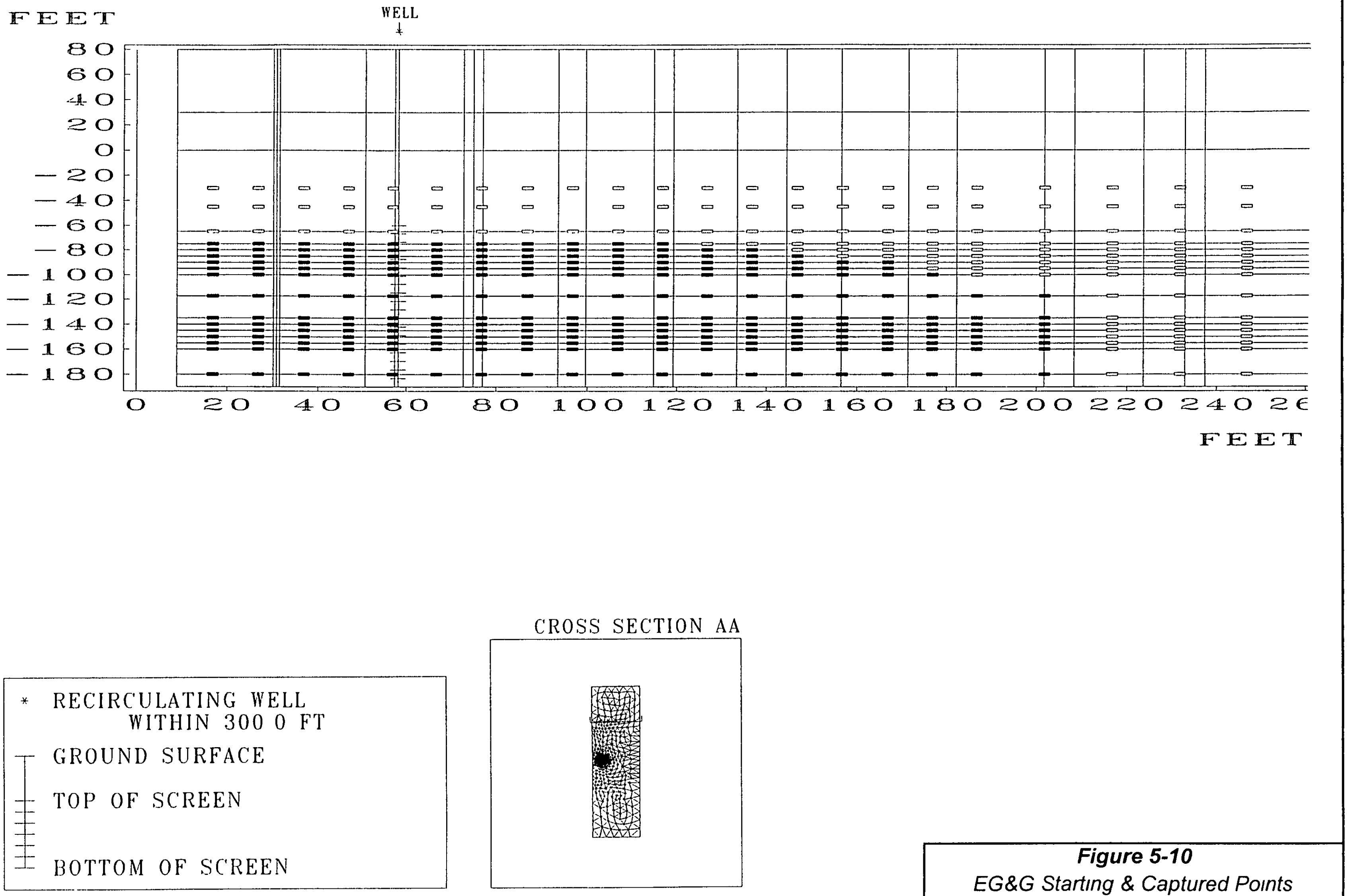


Figure 5-10

EG&G Starting & Captured Points

A total of 330 particles were ultimately specified 200 ft. upstream of the well. The "gate" of particles extends 245 ft. in length, which is the entire horizontal extent of the grid, and 120 ft. in height, which corresponds to the thickness of the plume as well as the height of the recirculating well. The total duration of the simulation was set at 60 days with 3-hour time steps. This specified duration time allowed for the particles to reach the well and move downgradient without leaving the extent of the grid.

In the process of executing the DYNTRACK command file, an output file is also created that tracks the locations of each particle at various time steps. Therefore, at the end of the simulation duration, the number of particles captured by the well can be accounted for and the corresponding cross-sectional areas surrounding the individual captured particles can be totaled. By doubling this cross-sectional area, a total capture zone area was established. In the IEG as well as the EG&G simulations, the total area captured amounted to approximately 35,000 square feet.

Appendix C contains the CS-10 property file that was used for all IEG and EG&G particle tracking simulations. Appendix A3 displays a sample DYNTRACK command file for the CS-10 capture area simulation using the IEG model, while Appendix B3 contains the file for the EG&G model.

5.5.2 Cross-Sectional Area of Capture Zone at Various Anisotropy Ratios

Anisotropy ratios affect the cross-sectional area of the capture zone of a plume, so using the same range of anisotropy ratios as before, capture area simulations were executed for each of the given ratios. Figure 5-11 graphically portrays the trend of cross-sectional areas of capture zones vs. anisotropy ratios of both IEG and EG&G systems.

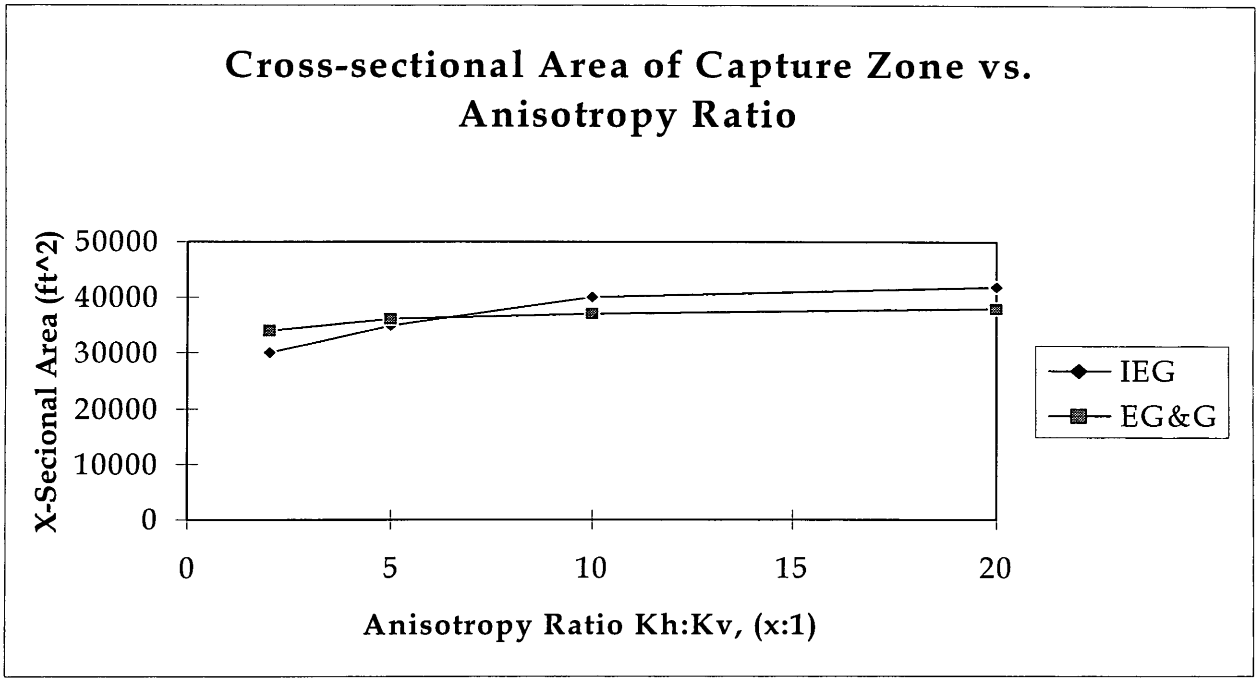
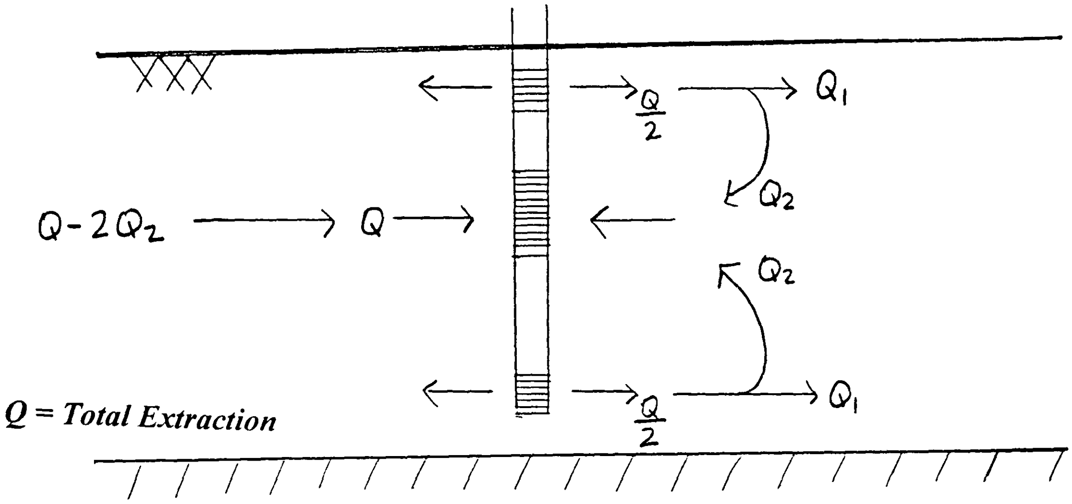


Figure 5-11: Cross-Sectional Area of Capture Zone vs. Anisotropy Ratio

Similar to the capture width results, the cross-sectional area of the capture zone increases with anisotropy ratios. Although it may seem that capture areas should remain approximately constant regardless of anisotropy ratios, this is not the case due to recirculating effects of the well. In other words, as anisotropy increases, recirculation becomes more difficult (since particles will tend to travel laterally), and thus the flow being pumped into the system is pumped out and away from the well (see Figure 5-12). Therefore, the flow going through the system is entirely untreated water, and as a result a large capture zone area is achieved. Conversely, only a fraction of flow is new when low anisotropies are encountered since recirculated water makes up a portion of the total water extracted. Since recirculation of water is desired to insure maximum VOC stripping, higher anisotropy ratios are not necessarily optimal even though they achieve a larger capture area. A balance between retreatment of water and capture area must be determined based on site and plume characteristics. Overall, concordant to capture widths, capture areas seem to level off above the ratio 10:1.

Appendix A4 and B4 contain graphs of particle starting and captured points for the remaining anisotropy ratios considered in this study, for both the IEG and EG&G systems.

IEG System: Low Anisotropy Ratio



IEG System: High Anisotropy Ratio

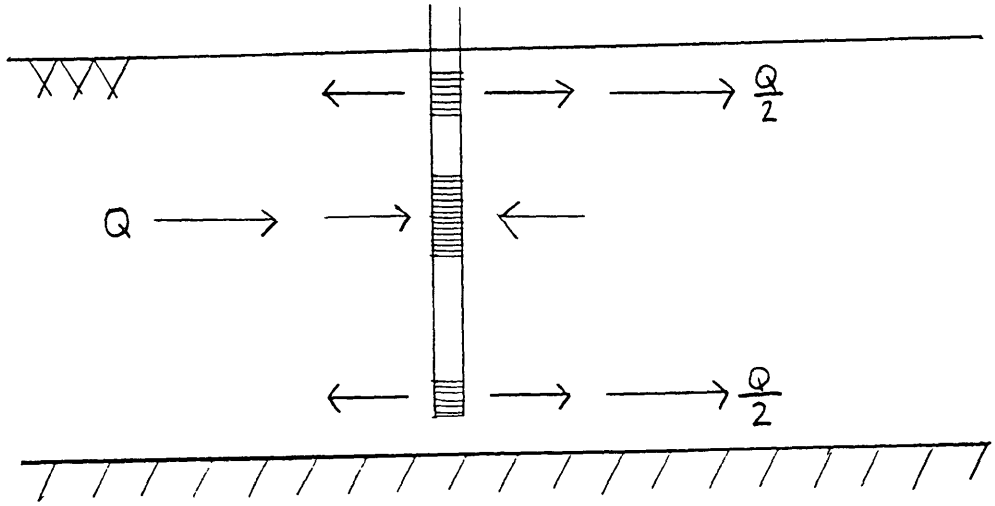


Figure 5-12

Capture Area Theory

5.5.3 Radius of Influence

Once contaminated water is captured by a recirculating well, a circulation cell develops whereby the extracted water is subjected to air stripping and then hydraulically forced back into the aquifer, only to be drawn back into the well again after circulating through a certain extent of the aquifer. This radius of influence, which is the furthest extent in the aquifer to which the recirculating well exerts an influence on the regional groundwater flow, is important when trying to determine the extent of recirculation as well as multiple well spacing.

To simulate recirculation effects, particles were seeded about the injection intervals of the wells. Therefore, the particles could be tracked going back into the extraction sections of the well or traveling downstream from the well. The tracks showing recirculation displayed the approximate radius of influence for each well and were measured.

Particles were spaced radially about the well at each level corresponding to the injection screens. These particles were seeded 2 feet away from the well and totaled 36 particles each screened level (see Figure 5-13). The total duration of the simulation was set at 175 days with one-hour time steps. This specified duration time allowed plenty of time for the particles to travel horizontally as far out into the aquifer as they were able and back again to the well.

Figures 5-14 and 5-15 display cross-sections of particle tracks under designed operating conditions for both IEG and EG&G systems. Looking at the IEG particle tracks, it is clear that the bottom circulation cell has a larger radius of influence than the top cell. This perhaps relates to the spacing of the screened intervals since there exists 35 ft. between the top two screens, while the bottom two screens are designed 45 ft. away from each other. Screened interval placement is an area in need of further research. In any case, the radius of influence for the top cell is approximately 40 feet, while the bottom cells reaches about 50 feet. As for the EG&G design, only one circulation cell is created, and the radius of influence is roughly 50 feet.

Appendix A5 and B5 contain sample DYNTRACK command files for CS-10 radius of influence and recirculation simulations for the IEG and EG&G systems, respectively.

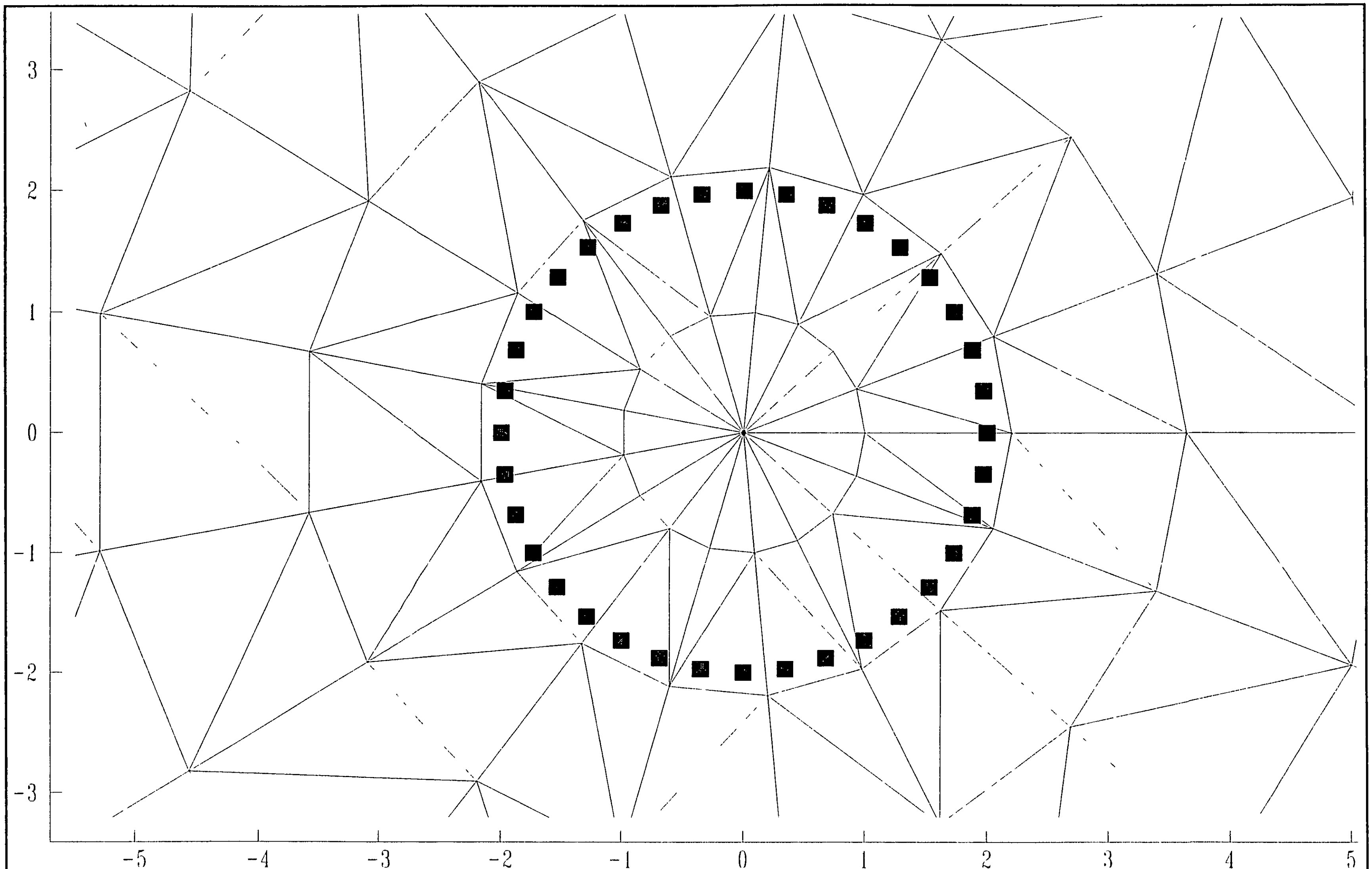


Figure 5-13
Plan View - Radial Placements of Particles

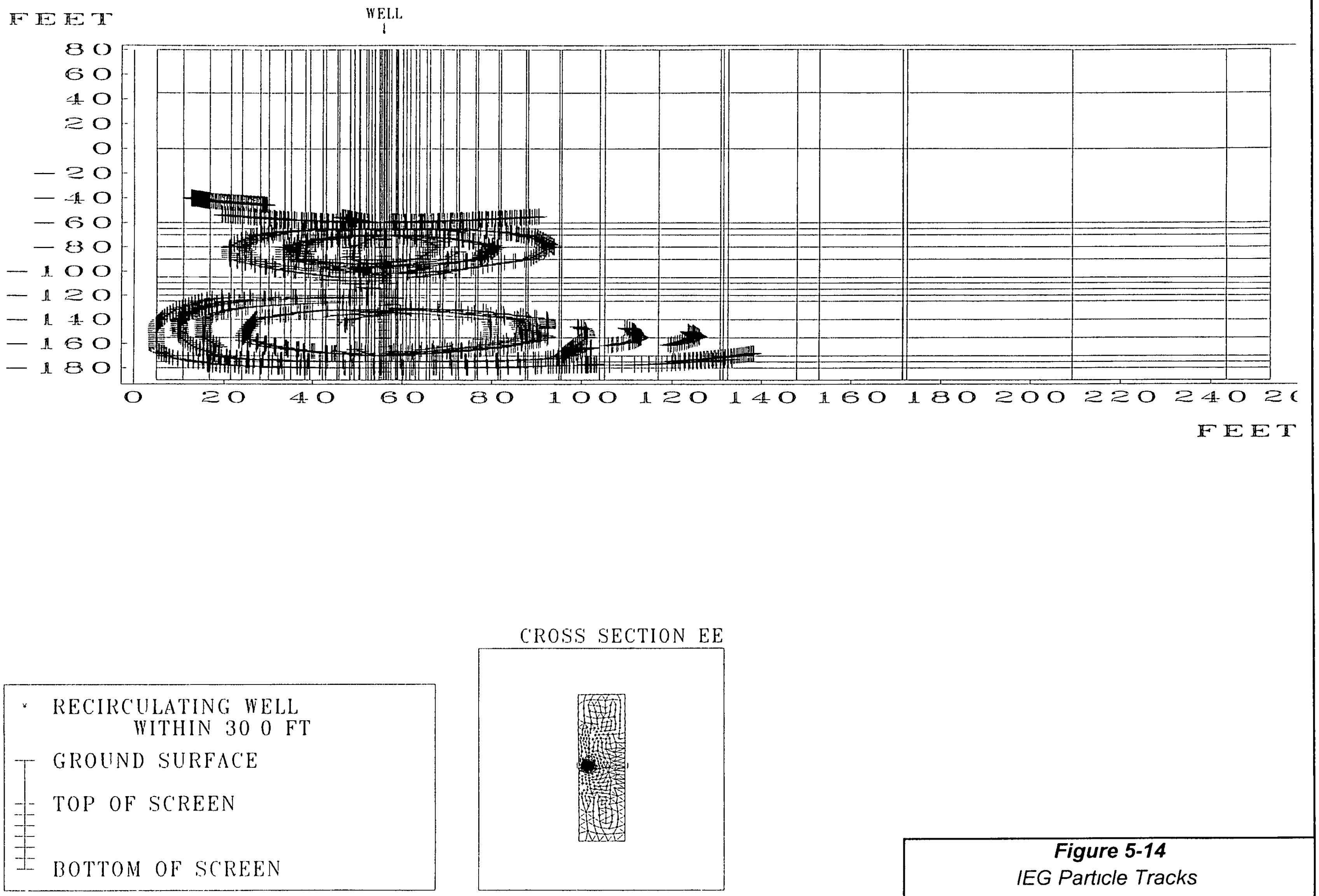


Figure 5-14

IEG Particle Tracks

Horizontal Cross-Section

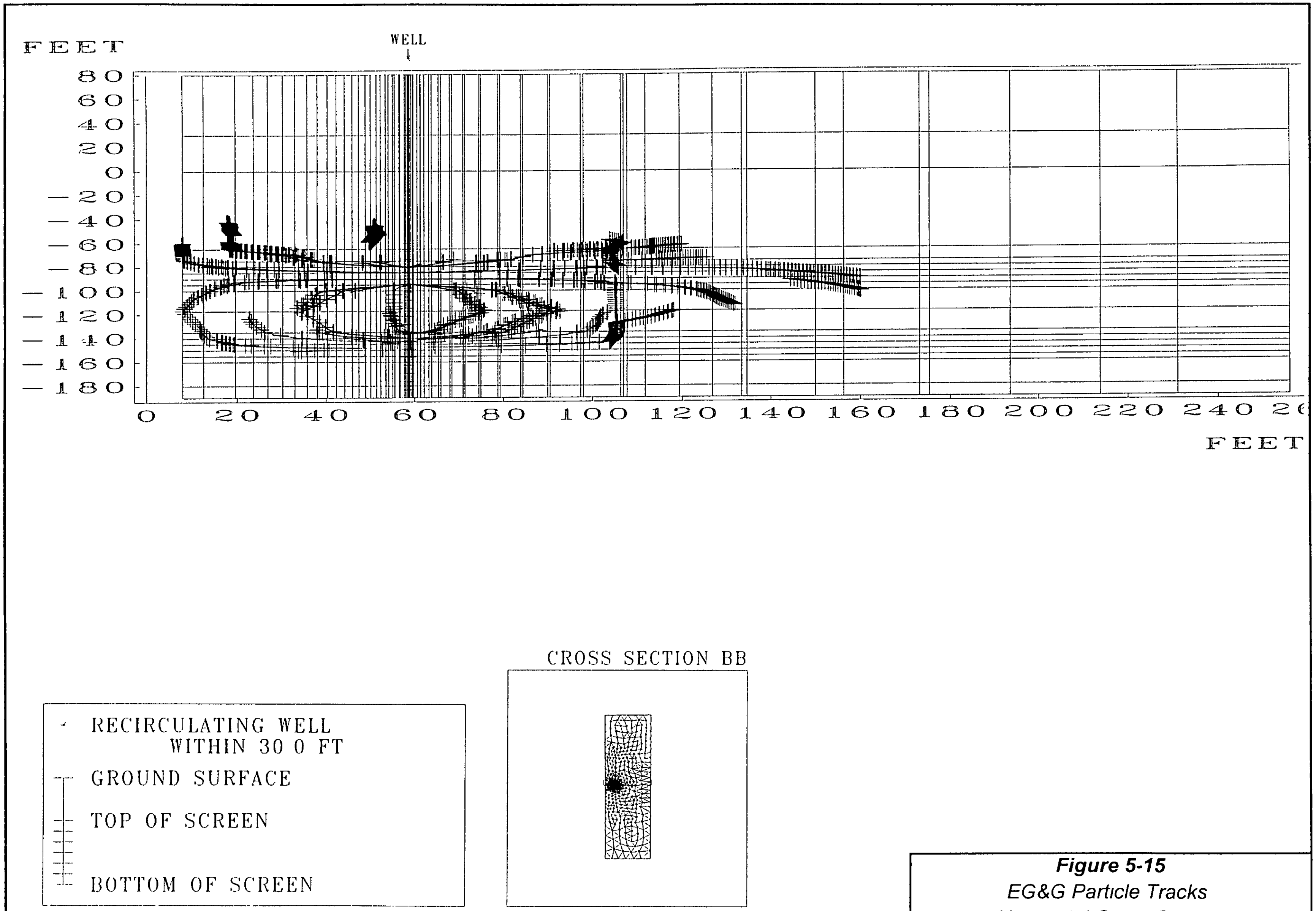


Figure 5-15

EG&G Particle Tracks

Horizontal Cross-Section

5.5.4 Radius of Influence at Various Anisotropy Ratios

Anisotropy ratios affect the radius of influence a recirculating well can achieve. Therefore, further recirculation simulations were executed using the same range of anisotropy ratios that was considered before. Figure 5-16 displays the overall trend regarding the radius of influence extent vs. anisotropy ratio of both IEG and EG&G systems.

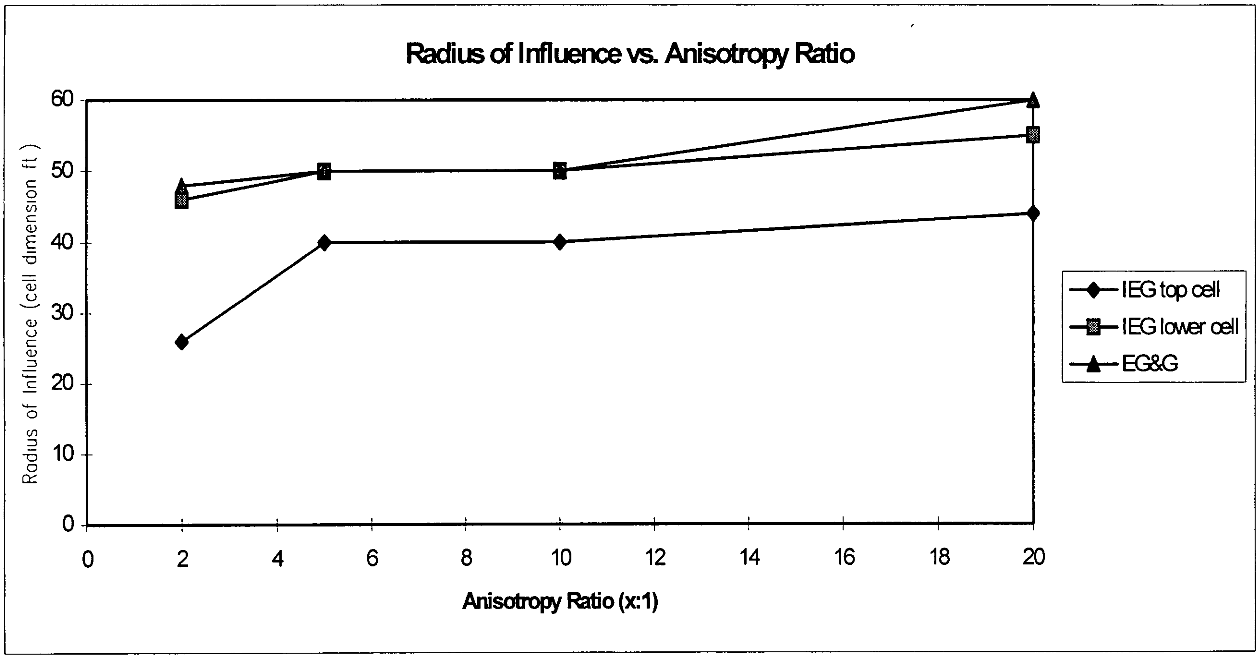


Figure 5-16: Radius of Influence vs. Anisotropy Ratio

Of all the previous tracking measurements, radius of influence was the most difficult to measure from the graphs. This difficulty rises from the inability of one cross-section to fully portray the track of a particle from injection to extraction. However, in general there seems to be an increase in radius of influence with anisotropy ratios. Note the similarity between the radius of influence of EG&G and IEG's lower cell. Due to the shorter distance between the screened intervals in IEG's top circulation cell, the radius of influence for this area is accordingly smaller.

Appendix A6 and B6 contain graphs of particle tracks for the other anisotropy ratios considered in this study, for both the IEG and EG&G systems.

5.5.5 Percent Recirculation

Using the same simulation as above with radially placed particles about the vertical well, the percent of particle recirculation was calculated by utilizing the DYNTRACK output file. The number of particles that were recirculated were tracked and counted. Figures 5-18 and 5-19 display another cross-sectional view of IEG and EG&G particle tracks. It was determined that 106 out of the 216 particles that were initially seeded around the IEG well were recirculated, resulting in a 49% overall recirculation rate. As for EG&G, 58 out of the 144 seeded particles were recirculated, so a 40% recirculation rate was achieved. Again, 36 particles were seeded in each screened level; therefore, since IEG's design incorporates more screened intervals than EG&G's design, more particles were used for the IEG simulations.

5.5.6 Percent Recirculation at Various Anisotropy Ratios

Similar to other factors, anisotropy ratios affect the percent of recirculated contaminant particles. Therefore, using the same range of anisotropy ratios as before, percent recirculation simulations were executed for each of the given ratios. Figure 5-17 graphically portrays the trend of percent recirculation vs. anisotropy ratio of both IEG and EG&G systems.

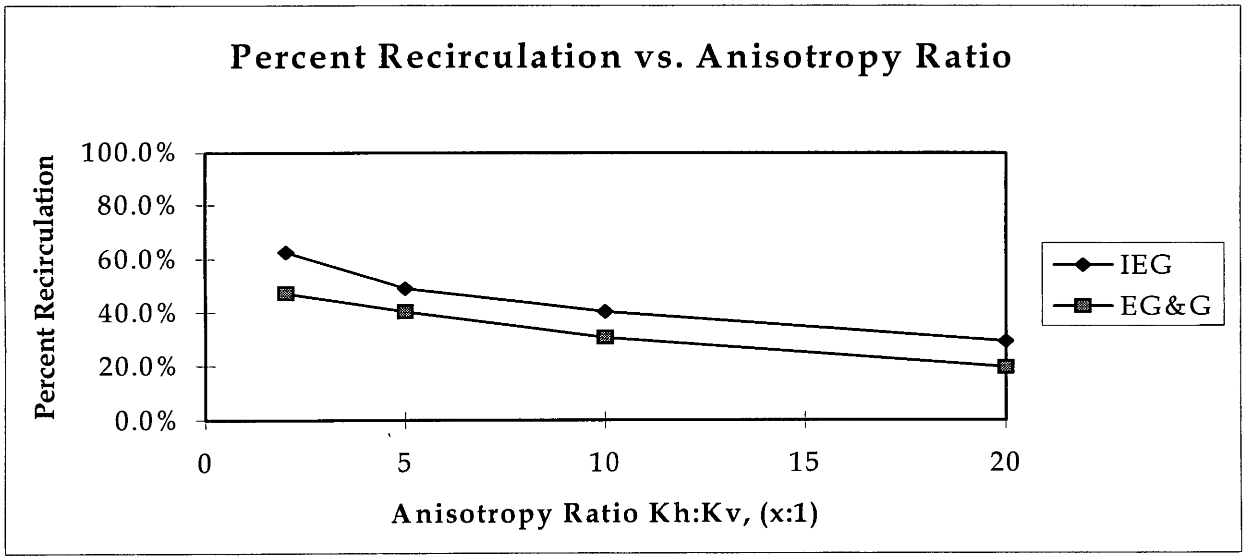


Figure 5-17: Percent Recirculation vs. Anisotropy Ratio

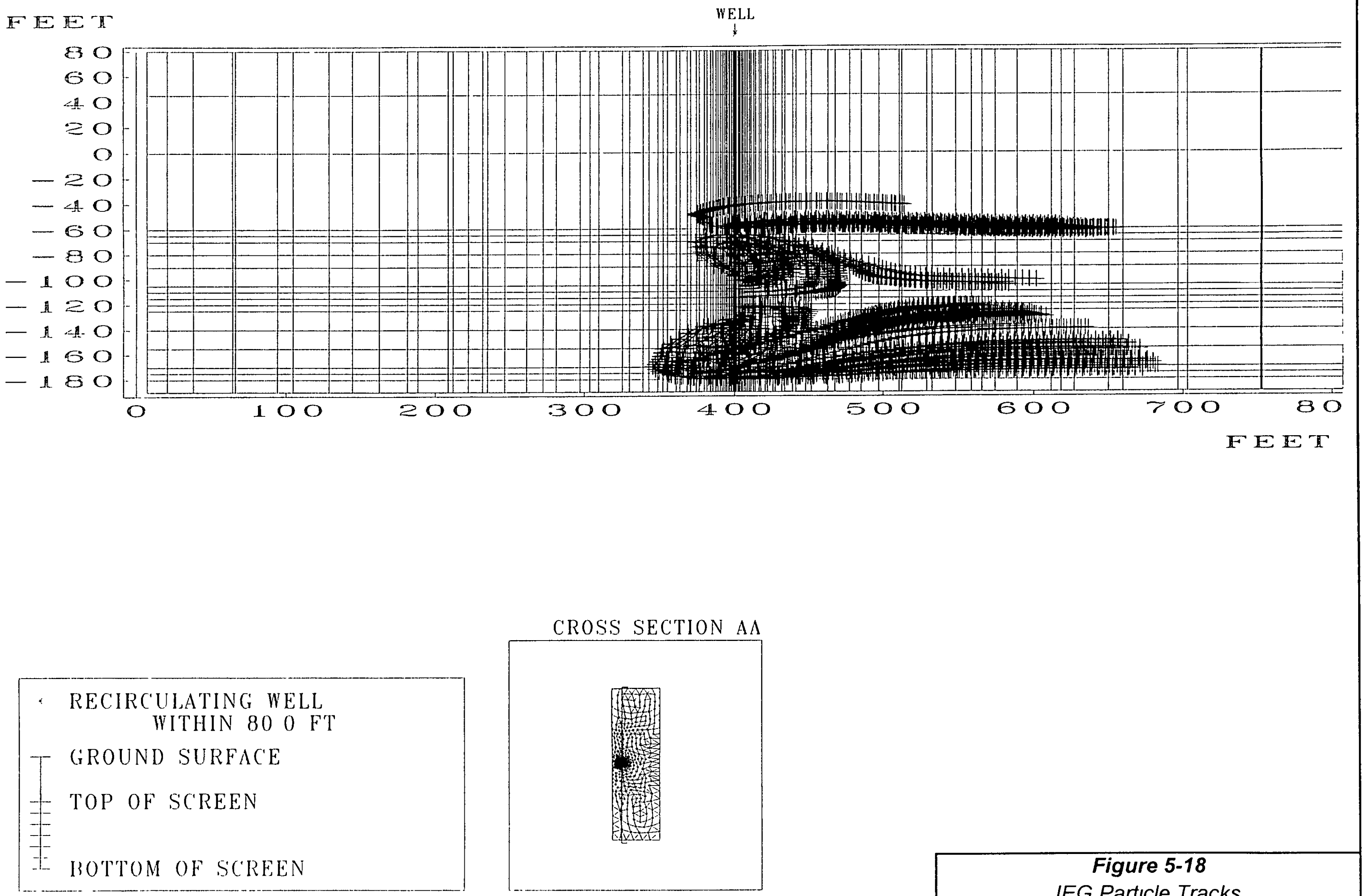


Figure 5-18

IEG Particle Tracks

Vertical Cross-Section

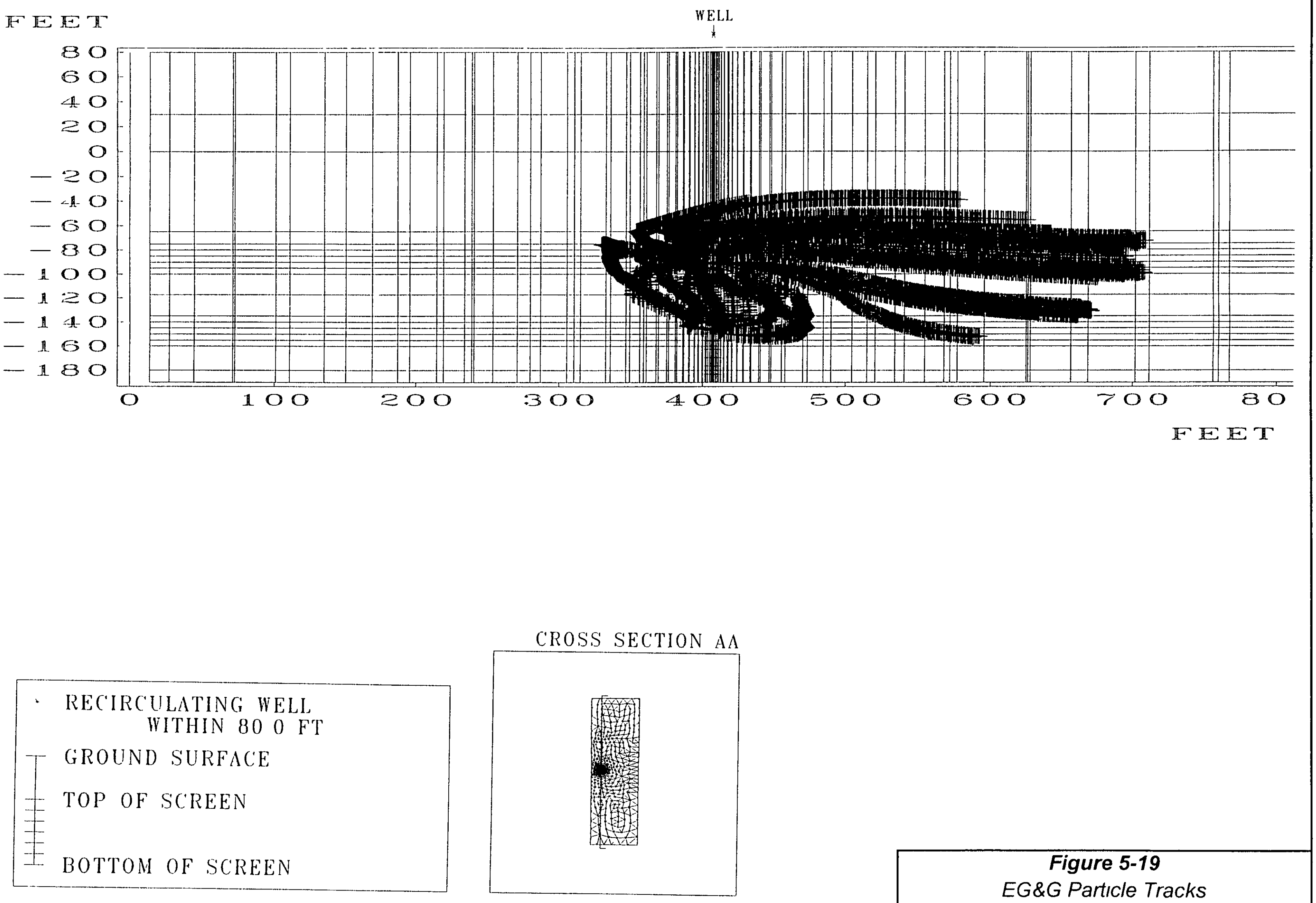


Figure 5-19

EG&G Particle Tracks

Vertical Cross-Section

Unlike the other parameters, percent recirculation of contaminated particles decreases with the increase in anisotropy ratio. This result was to be expected since with decreasing vertical conductivities, the ability for particles to recirculate back into the well also decreases.

Appendix A7 and B7 contain graphs of particle tracks for the remaining anisotropy ratios considered in this study, for both the IEG and EG&G systems.

5.6 Discussion

Given the CS-10 pilot test grid configuration, simulations were conducted to determine the effectiveness of recirculating well technology in various hydrogeological conditions. By testing a range of potential anisotropy ratios, favorable ratios were determined to provide the maximum capture width, capture zone area, radius of influence, and percent recirculation for the IEG and EG&G systems. The trends established with varying anisotropy ratios are useful when trying to predict the effectiveness of recirculating well technology use at a particular site given the extent of contamination and site geology. Overall, there exists a direct relationship between increasing anisotropy ratios and corresponding capture widths, capture areas, and radius of influences, while an inverse relationship exists with percent of recirculation.

6. CONCLUSION

A qualitative evaluation of recirculating well technology demonstrated many potential benefits of this technique. First of all, recirculating wells are capable of in-situ remediation by stripping VOCs from the groundwater without the need and expense of pumping the groundwater to the surface for treatment. This technology also prevents disturbance of the water table elevation and regional flow patterns, which can have adverse affects on ecological systems in the groundwater and nearby surface waters.

Although this technology has shown much promise, characteristics such as the geology of a particular site have proven to either enhance or limit recirculating well performance. This study focused on the effect that the hydrogeologic factor of anisotropy has on the hydraulics of this technology. The numerical models and particle tracking investigations conducted proved to be rather sensitive to anisotropy ratios. More specifically, the performance criteria of capture width, capture area, and radius of influence were shown to increase with anisotropy, whereas percent recirculation decreased with anisotropy.

Overall, future efforts to refine the recirculating well technology for the CS-10 site, given the results of the pilot tests, could improve recirculating well performance at MMR. Calibrating the models with the actual pilot test data would significantly increase the confidence and accuracy of the predicted results. Therefore, recommendations could be made to improve the overall system in a cost-effective manner.

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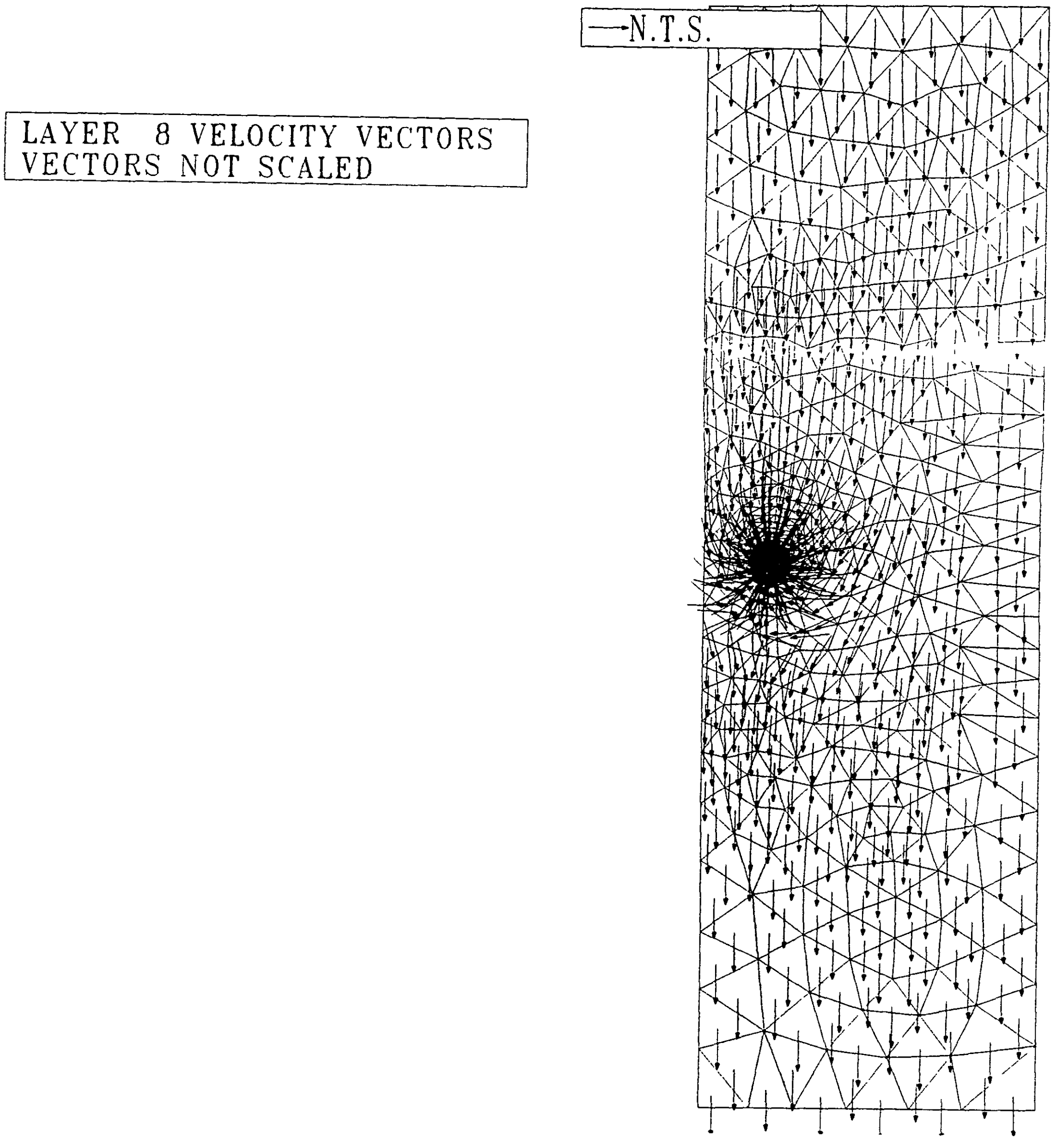
APPENDIX A1: SAMPLE DYNFLOW COMMAND FILE

```
!IEG (SBP) MODEL
'create output file of session
OUTP SBP.OUT
'read plan view finite element grid
GRID READ GRID5.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 (relative to mean sea 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 383 - 389 level all
FIX NODE 476 - 482 level all
'set initial head value for all nodes (water table elevation)
INIT 35.
'fix head boundaries upgradient and downgradient of well
'hydraulic gradient 0.0014 ft/ft (about 1 ft/day) - overall 1.12 ft. head drop
across 800 ft. grid extent)
INIT 34.44 NODE 476 - 482 level all
INIT 35.56 NODE 383 - 389 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 (total 88gpm, or 44gpm per cell)
!note: need to divide flux by number of levels
FLUX 2824. NODE 1 LEVEL 2 - 4
FLUX -3388. NODE 1 LEVEL 7 - 11
FLUX 2824. NODE 1 LEVEL 14 - 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
```

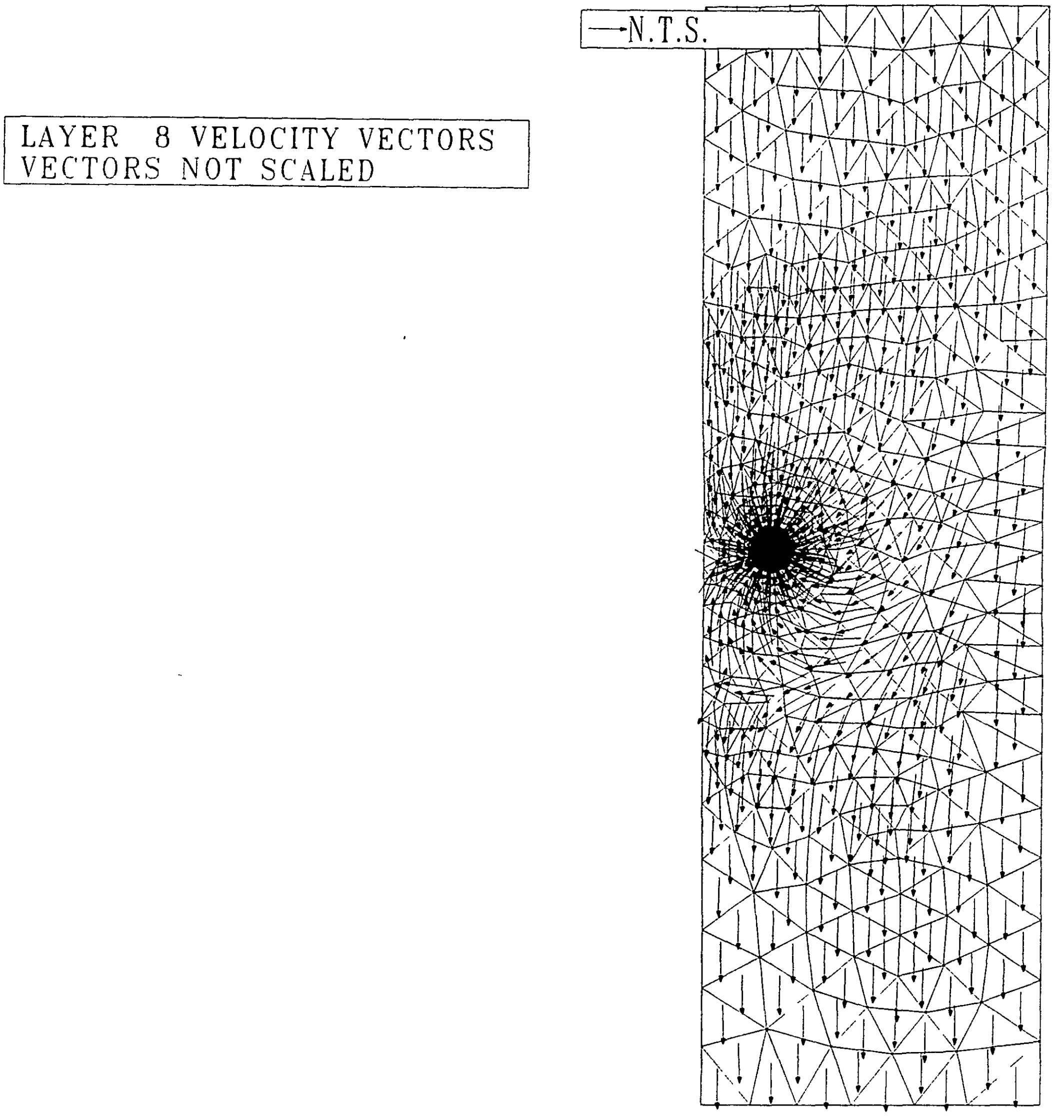
```
ONED 120 NODE 1 1 LEVEL 15 16
'specify recharge rate (ft/d)
RECH .0044 ELEM ALL
'define following properties of 1-d elements: #, K, Ss, Sy
PROP
20, 10000000.,0.,1.
'define following properties of material: #, Kx (ft/d), Ky, Kz, Ss, Sy
PROP
10, 297.2, 297.2, 59.53, .00001, .07
iter 10
goti
'save to file
SAVE SBP.SAV
XOUT
XCFI
```

APPENDIX A2: CAPTURE WIDTH AT VARIOUS ANISOTROPIES

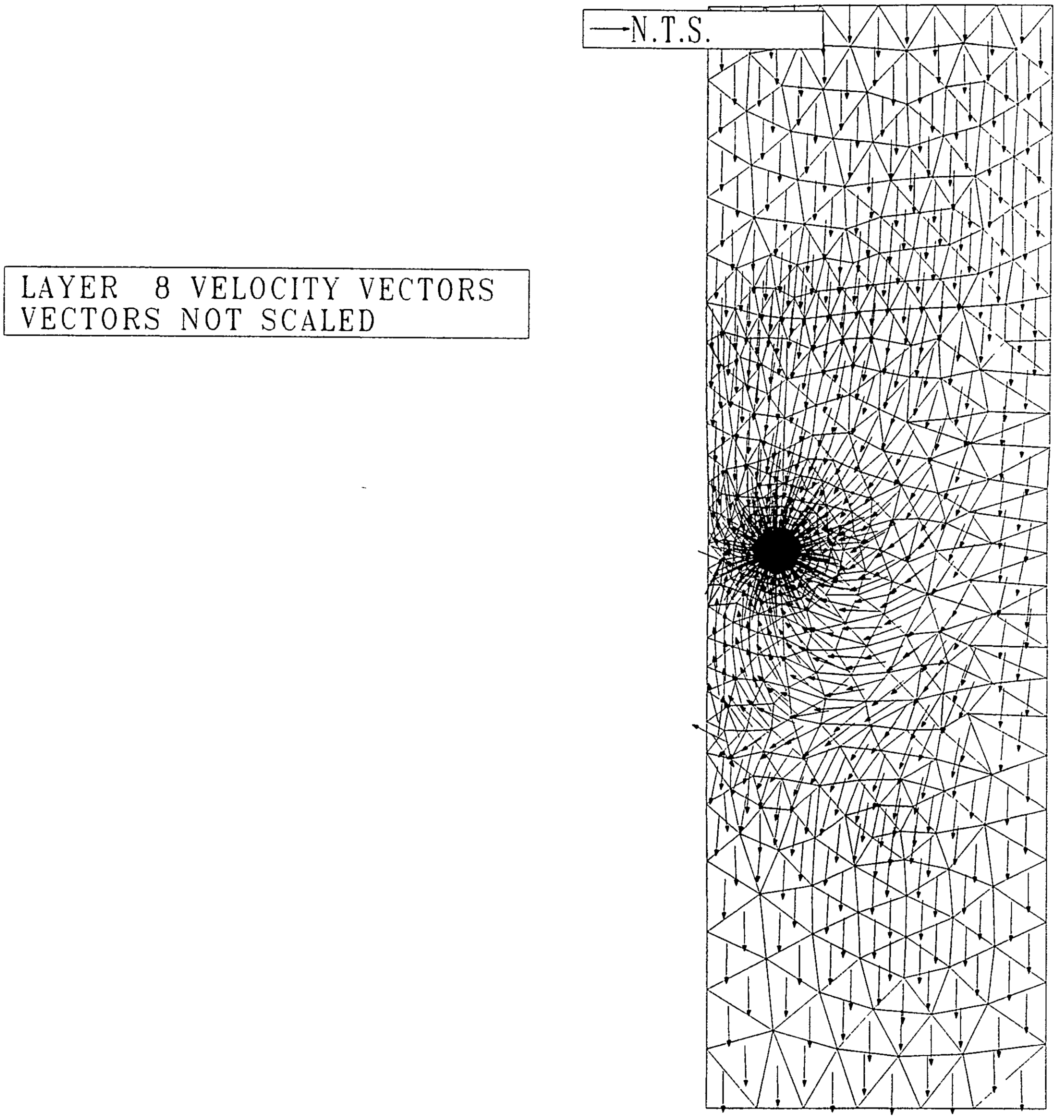
Velocity Vector Profile 2:1



Velocity Vector Profile 10:1



Velocity Vector Profile 20:1



APPENDIX A3: SAMPLE DYNTRACK COMMAND FILE- Capture Area

```
'COMMAND FILE TO IEG (SBP)PARTICLE TRACKING
'restore Dynflow file
REST SBP.SAV
'create an output file
OUTP SAVE SBPcap.OUT FORM
'read transport property file
DPRO READ PROP.DPR
'specify dispersion simulation only (turn off dispersion)
XDISP
'set radius of capture for well
RADI 10
'set particle weight
WEIGH 1000.
'set starting simulation time (units. days)
TIME 0.
'time step- set for 3 hours
DT 0.125
'print property set and node summary tables to std  output after each 40 time steps
PRAL 40
'seed particles at initial locations
PART
-45,200,-180
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-45,200,-120
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105,200,-125
PART
105,200,-120
PART
105,200,-115
PART
105,200,-110
PART
105,200,-105
PART
105,200,-90
PART
105,200,-80
PART
105,200,-70
PART
105,200,-65
PART
105,200,-60
PART
115,200,-180
PART
115,200,-175
PART
115,200,-170
PART
115,200,-155
PART
115,200,-140
PART
115,200,-125
PART
115,200,-120
PART
115,200,-115
PART
115,200,-110
PART
115,200,-105
PART
115,200,-90
PART
115,200,-80
PART
115,200,-70
PART
```

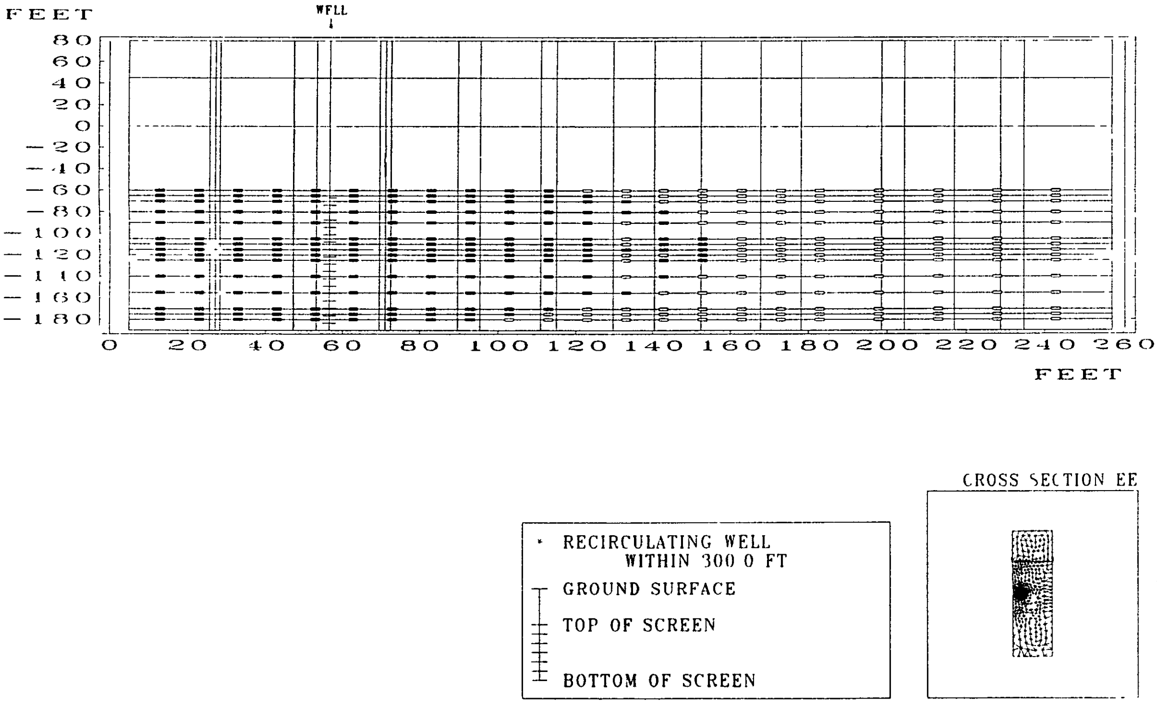
```
115,200,-65
PART
115,200,-60
PART
125,200,-180
PART
125,200,-175
PART
125,200,-170
PART
125,200,-155
PART
125,200,-140
PART
125,200,-125
PART
125,200,-120
PART
125,200,-115
PART
125,200,-110
PART
125,200,-105
PART
125,200,-90
PART
125,200,-80
PART
125,200,-70
PART
125,200,-65
PART
125,200,-60
PART
140,200,-180
PART
140,200,-175
PART
140,200,-170
PART
140,200,-155
PART
140,200,-140
PART
140,200,-125
PART
140,200,-120
PART
140,200,-115
PART
140,200,-110
PART
140,200,-105
PART
140,200,-90
PART
140,200,-80
PART
140,200,-70
PART
140,200,-65
PART
140,200,-60
PART
155,200,-180
PART
155,200,-175
PART
155,200,-170
PART
155,200,-155
PART
155,200,-140
PART
155,200,-125
PART
```

```
155,200,-120
PART
155,200,-115
PART
155,200,-110
PART
155,200,-105
PART
155,200,-90
PART
155,200,-80
PART
155,200,-70
PART
155,200,-65
PART
155,200,-60
PART
170,200,-180
PART
170,200,-175
PART
170,200,-170
PART
170,200,-155
PART
170,200,-140
PART
170,200,-125
PART
170,200,-120
PART
170,200,-115
PART
170,200,-110
PART
170,200,-105
PART
170,200,-90
PART
170,200,-80
PART
170,200,-70
PART
170,200,-65
PART
170,200,-60
PART
185,200,-180
PART
185,200,-175
PART
185,200,-170
PART
185,200,-155
PART
185,200,-140
PART
185,200,-125
PART
185,200,-120
PART
185,200,-115
PART
185,200,-110
PART
185,200,-105
PART
185,200,-90
PART
185,200,-80
PART
185,200,-70
PART
185,200,-65
PART
```

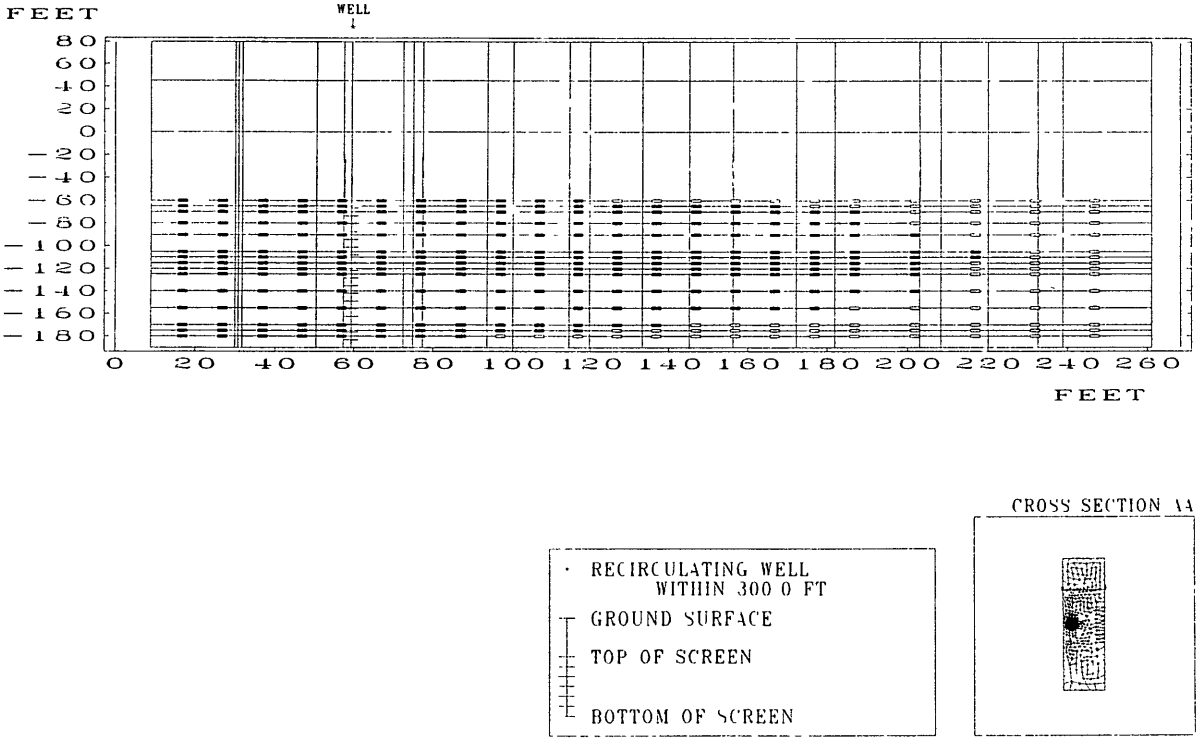
```
185,200,-60
'store particle tracks on file
RESU 25 SAVE SBPcap.RES
'set ending time of sequence
GOTI 100
GOTI 200
GOTI 300
GOTI 400
GOTI 500
'end storage of computation result
XRES
END
```

APPENDIX A4: CAPTURE AREA AT VARIOUS ANISOTROPIES

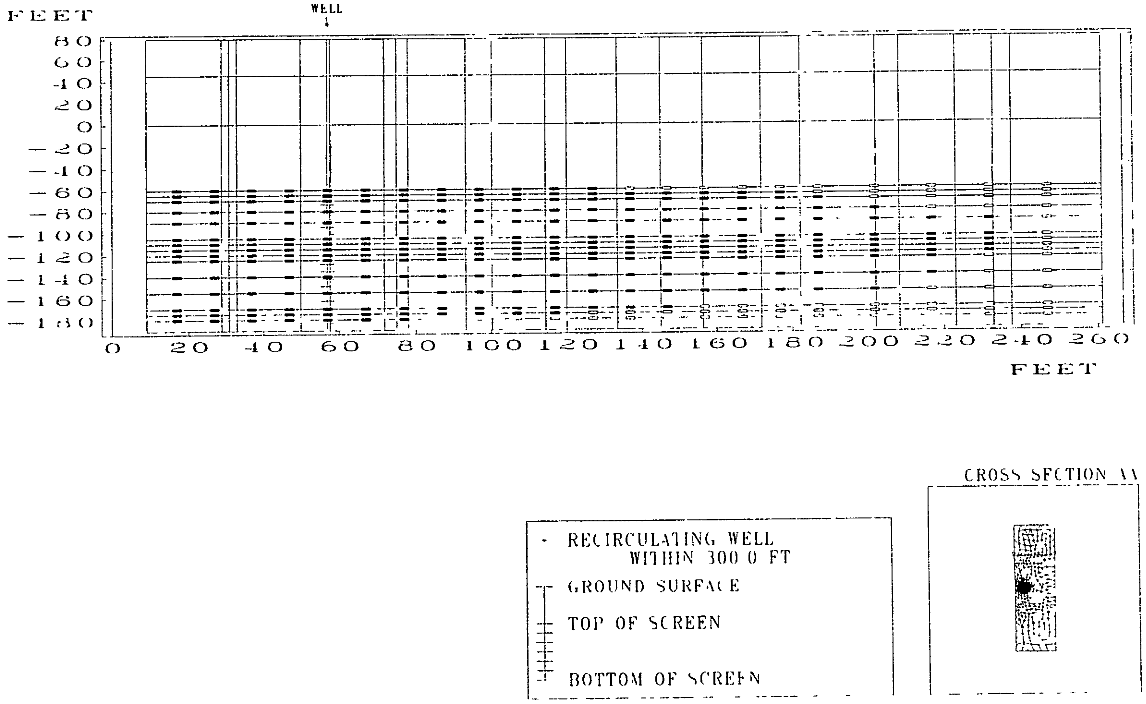
Particle Placements 2:1



Particle Placements 10:1



Particle Placements 20:1



APPENDIX A5: SAMPLE DYNTRACK COMMAND FILE- Radius of Influence/ Recirculation

```
'COMMAND FILE TO PARTICLE TRACKING
'restore Dynflow file
REST SBP.SAV
'create an output file
OUTP SAVE SBPrad OUT FORM
'read transport property file
DPRO READ PROP.DPR
'specify dispersion simulation only (turn off dispersion)
XDISP
'set radius of capture for well
RADI 10
'set particle weight
WEIGH 1000.
'set starting simulation time (units  days)
TIME 0
'time step- set for 1 hour
DT 0 042
'print property set and node summary tables to std  output after each 20 time steps
PRAL 20
'seed particles at initial locations- radially about well at recharge levels (2-4 and 14-16)
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
0.6840,-1.8794,-180
PART
0.3473,-1.9696,-180
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
-1.9696,0.3473,-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
-0.6840,1.8794,-180
PART
-0.3473,1.9696,-180
PART
0.0000,2.0000,-175
PART
0.3473,1.9696,-175
PART
0.6840,1.8794,-175
PART
1.0000,1.7321,-175
PART
1.2856,1.5321,-175
PART
1.5321,1.2856,-175
PART
1.7321,1.0000,-175
PART
1.8794,0.6840,-175
PART
1.9696,0.3473,-175
PART
2 0000,0.0000,-175
PART
1.9696,-0 3437,-175
PART
1.8794,-0.6840,-175
PART
1.7321,-1.0000,-175
PART
1.5321,-1.2856,-175
PART
1.2856,-1.5321,-175
PART
1.0000,-1.7321,-175
PART
0.6840,-1.8794,-175
PART
0.3473,-1.9696,-175
PART
0.0000,-2 0000,-175
PART
-0.3473,-1.9696,-175
PART
-0.6840,-1.8794,-175
PART
-1.0000,-1.7321,-175
PART
-1.2856,-1.5321,-175
PART
-1.5321,-1.2856,-175
PART
-1.7321,-1.0000,-175
PART
-1 8794,-0.6840,-175
PART
-1.9696,-0.3473,-175
```

```
PART
-2.0000,0.0000,-175
PART
-1.9696,0.3473,-175
PART
-1.8794,0.6840,-175
PART
-1.7321,1.0000,-175
PART
-1.5321,1.2856,-175
PART
-1.2856,1.5321,-175
PART
-1.0000,1.7321,-175
PART
-0.6840,1.8794,-175
PART
-0.3473,1.9696,-175
PART
0.0000,2.0000,-170
PART
0.3473,1 9696,-170
PART
0.6840,1.8794,-170
PART
1.0000,1.7321,-170
PART
1.2856,1 5321,-170
PART
1.5321,1.2856,-170
PART
1.7321,1.0000,-170
PART
1.8794,0.6840,-170
PART
1.9696,0.3473,-170
PART
2.0000,0.0000,-170
PART
1.9696,-0.3437,-170
PART
1.8794,-0.6840,-170
PART
1.7321,-1.0000,-170
PART
1 5321,-1.2856,-170
PART
1 2856,-1.5321,-170
PART
1.0000,-1.7321,-170
PART
0.6840,-1.8794,-170
PART
0.3473,-1.9696,-170
PART
0.0000,-2 0000,-170
PART
-0.3473,-1.9696,-170
PART
-0.6840,-1.8794,-170
PART
-1.0000,-1.7321,-170
PART
-1.2856,-1.5321,-170
PART
-1.5321,-1.2856,-170
PART
-1.7321,-1.0000,-170
PART
-1.8794,-0.6840,-170
PART
-1.9696,-0.3473,-170
PART
-2 0000,0 0000,-170
PART
-1 9696,0.3473,-170
```

```
PART
-1.8794,0.6840,-170
PART
-1.7321,1.0000,-170
PART
-1 5321,1.2856,-170
PART
-1.2856,1.5321,-170
PART
-1.0000,1.7321,-170
PART
-0.6840,1.8794,-170
PART
-0.3473,1.9696,-170
PART
0.0000,2.0000,-70
PART
0.3473,1.9696,-70
PART
0.6840,1.8794,-70
PART
1.0000,1.7321,-70
PART
1.2856,1.5321,-70
PART
1 5321,1.2856,-70
PART
1.7321,1.0000,-70
PART
1.8794,0.6840,-70
PART
1.9696,0 3473,-70
PART
2.0000,0.0000,-70
PART
1.9696,-0.3437,-70
PART
1 8794,-0 6840,-70
PART
1.7321,-1.0000,-70
PART
1.5321,-1.2856,-70
PART
1.2856,-1.5321,-70
PART
1.0000,-1.7321,-70
PART
0 6840,-1.8794,-70
PART
0.3473,-1.9696,-70
PART
0.0000,-2.0000,-70
PART
-0.3473,-1.9696,-70
PART
-0.6840,-1.8794,-70
PART
-1.0000,-1.7321,-70
PART
-1.2856,-1.5321,-70
PART
-1.5321,-1.2856,-70
PART
-1.7321,-1 0000,-70
PART
-1.8794,-0.6840,-70
PART
-1.9696,-0.3473,-70
PART
-2.0000,0.0000,-70
PART
-1.9696,0 3473,-70
PART
-1.8794,0.6840,-70
PART
-1.7321,1.0000,-70
```

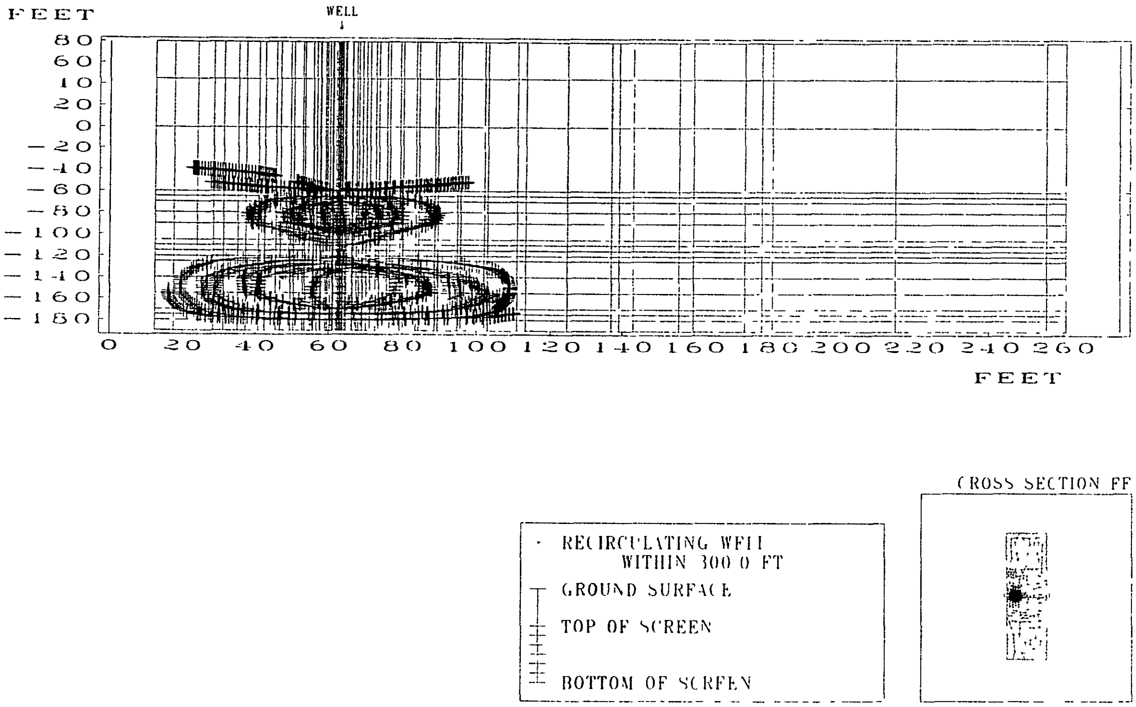
```
PART
-1.5321,1.2856,-70
PART
-1.2856,1 5321,-70
PART
-1.0000,1.7321,-70
PART
-0.6840,1.8794,-70
PART
-0.3473,1.9696,-70
PART
0.0000,2.0000,-65
PART
0.3473,1.9696,-65
PART
0.6840,1.8794,-65
PART
1.0000,1.7321,-65
PART
1.2856,1.5321,-65
PART
1.5321,1.2856,-65
PART
1.7321,1.0000,-65
PART
1.8794,0.6840,-65
PART
1.9696,0.3473,-65
PART
2.0000,0.0000,-65
PART
1.9696,-0.3437,-65
PART
1.8794,-0.6840,-65
PART
1.7321,-1.0000,-65
PART
1.5321,-1.2856,-65
PART
1.2856,-1.5321,-65
PART
1.0000,-1.7321,-65
PART
0.6840,-1 8794,-65
PART
0.3473,-1.9696,-65
PART
0.0000,-2.0000,-65
PART
-0.3473,-1.9696,-65
PART
-0.6840,-1.8794,-65
PART
-1.0000,-1.7321,-65
PART
-1 2856,-1.5321,-65
PART
-1.5321,-1.2856,-65
PART
-1.7321,-1.0000,-65
PART
-1.8794,-0 6840,-65
PART
-1.9696,-0.3473,-65
PART
-2.0000,0 0000,-65
PART
-1.9696,0.3473,-65
PART
-1.8794,0.6840,-65
PART
-1.7321,1.0000,-65
PART
-1.5321,1.2856,-65
PART
-1.2856,1.5321,-65
```

```
PART
-1.0000,1.7321,-65
PART
-0.6840,1.8794,-65
PART
-0 3473,1.9696,-65
PART
0.0000,2.0000,-60
PART
0.3473,1.9696,-60
PART
0.6840,1.8794,-60
PART
1.0000,1.7321,-60
PART
1.2856,1.5321,-60
PART
1.5321,1.2856,-60
PART
1.7321,1.0000,-60
PART
1.8794,0.6840,-60
PART
1 9696,0.3473,-60
PART
2.0000,0.0000,-60
PART
1.9696,-0.3437,-60
PART
1.8794,-0.6840,-60
PART
1.7321,-1.0000,-60
PART
1.5321,-1.2856,-60
PART
1.2856,-1.5321,-60
PART
1.0000,-1.7321,-60
PART
0.6840,-1.8794,-60
PART
0.3473,-1.9696,-60
PART
0.0000,-2.0000,-60
PART
-0.3473,-1.9696,-60
PART
-0 6840,-1.8794,-60
PART
-1.0000,-1.7321,-60
PART
-1.2856,-1 5321,-60
PART
-1.5321,-1.2856,-60
PART
-1.7321,-1 0000,-60
PART
-1.8794,-0.6840,-60
PART
-1.9696,-0.3473,-60
PART
-2.0000,0.0000,-60
PART
-1.9696,0.3473,-60
PART
-1.8794,0.6840,-60
PART
-1.7321,1.0000,-60
PART
-1.5321,1.2856,-60
PART
-1.2856,1.5321,-60
PART
-1.0000,1.7321,-60
PART
-0.6840,1.8794,-60
```

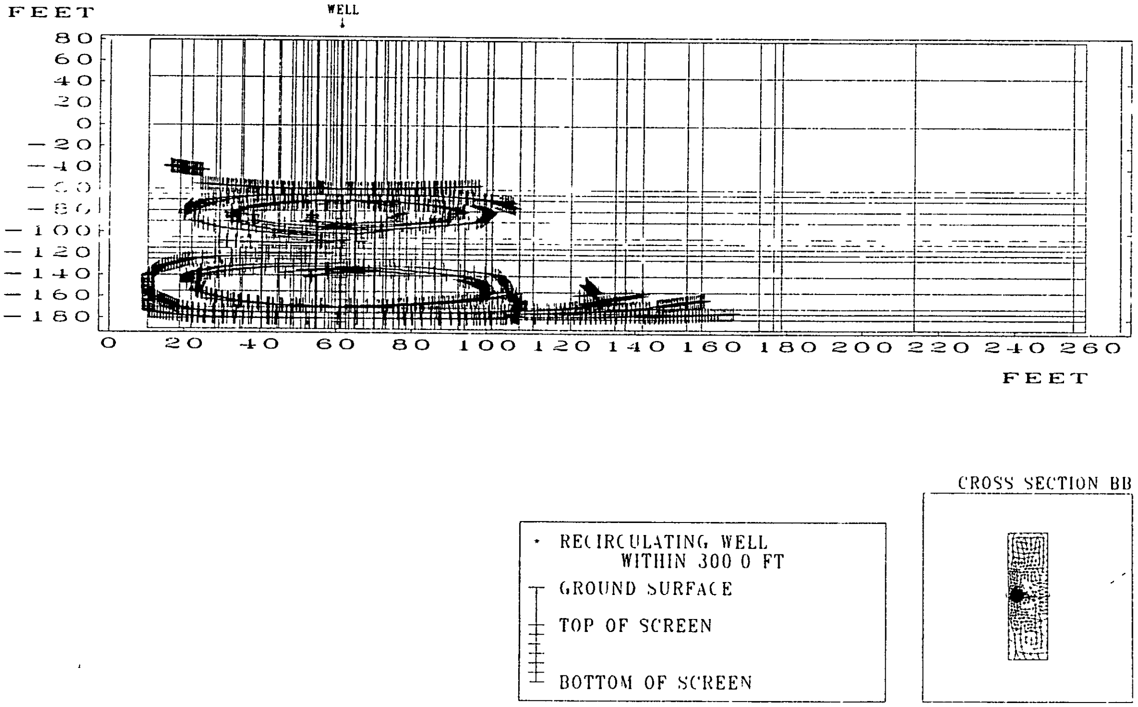
```
PART
-0.3473,1.9696,-60
'store particle tracks on file
RESU 10 SAVE SBPrad.RES
'set ending time of sequence
GOTI 25
GOTI 50
GOTI 75
GOTI 100
GOTI 125
GOTI 150
GOTI 175
'end storage of computation result
XRES
END
```

APPENDIX A6: RADIUS OF INFLUENCE AT VARIOUS ANISOTROPIES

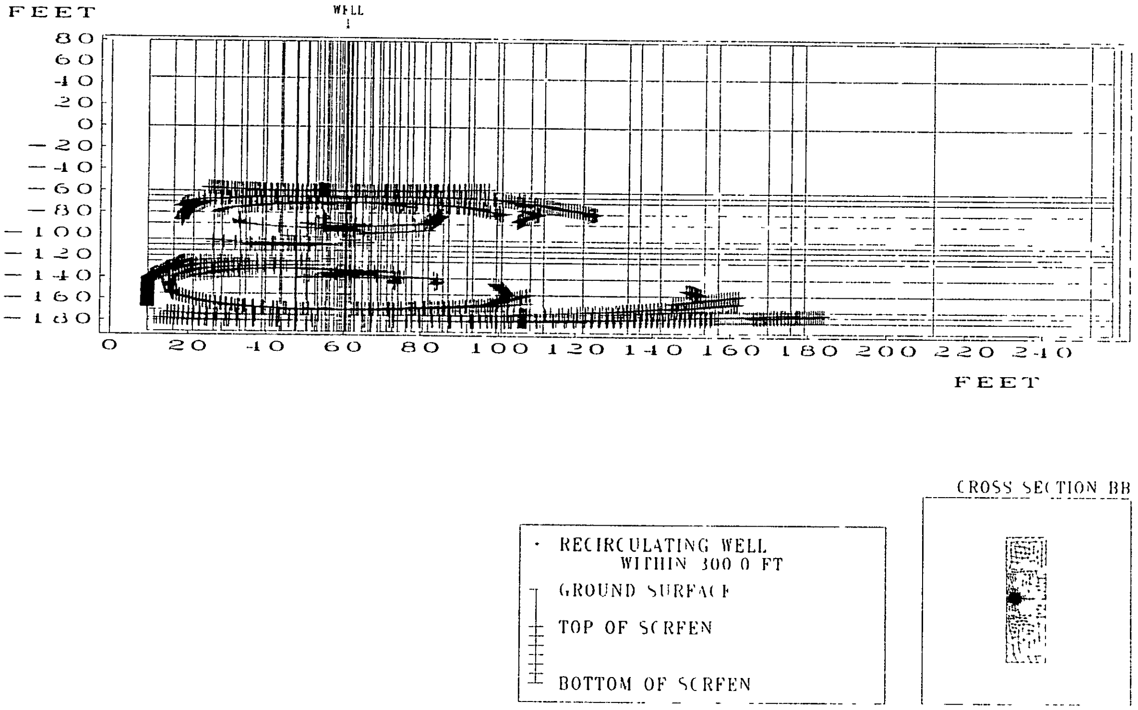
Particle Tracks 2:1



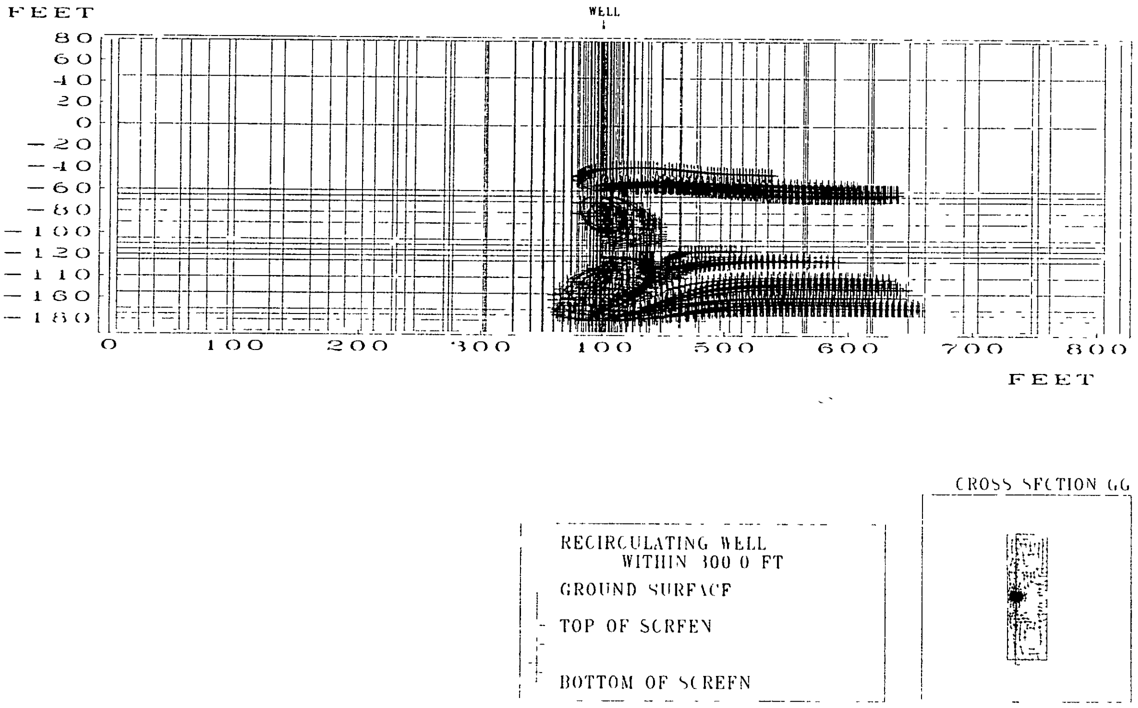
Particle Tracks 10:1



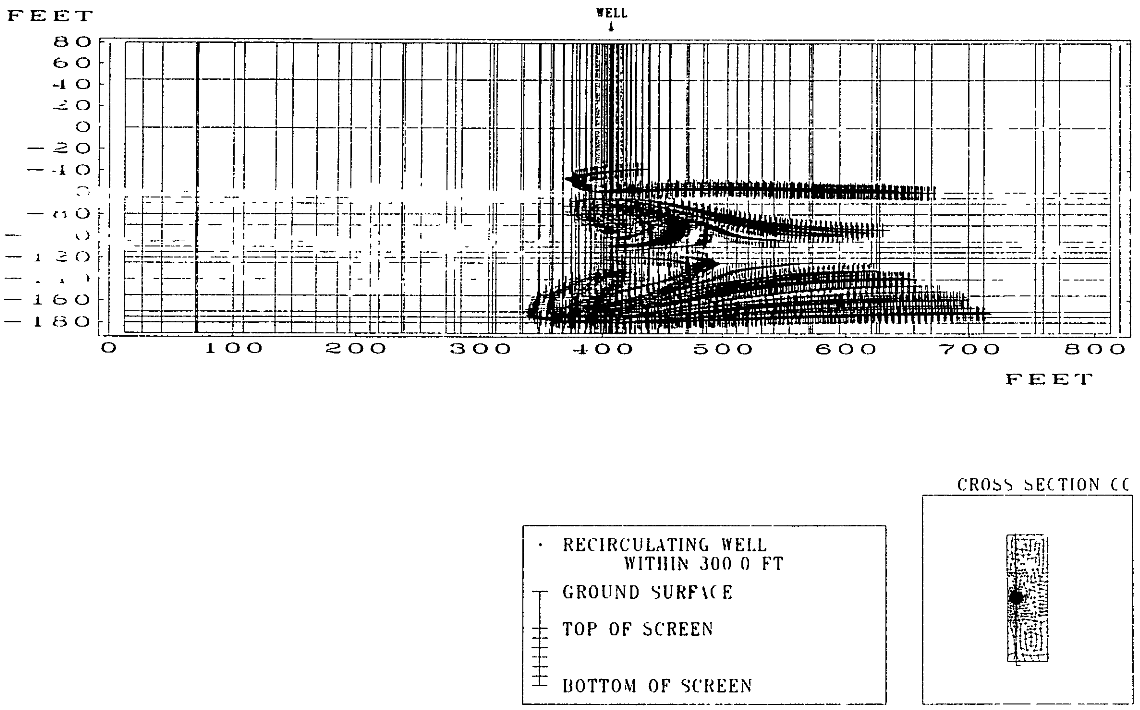
Particle Tracks 20:1



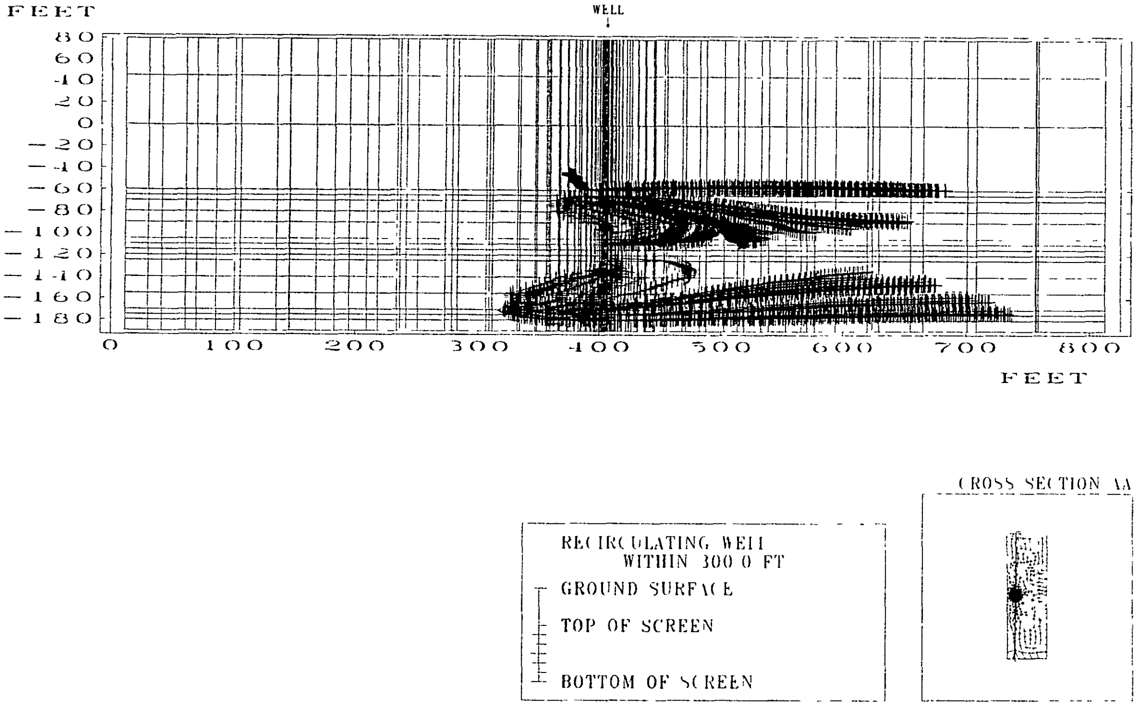
APPENDIX A7: PERCENT RECIRCULATION AT VARIOUS ANISOTROPIES
Particle Tracks 2:1



Particle Tracks 10:1



Particle Tracks 20:1



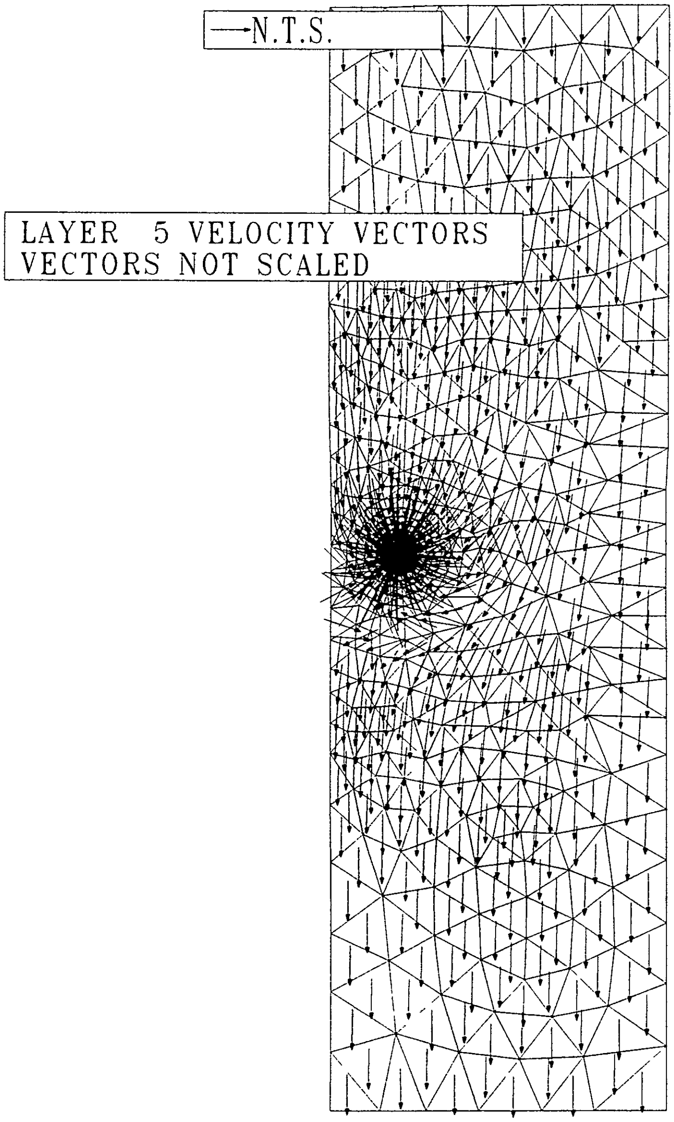
APPENDIX B1: SAMPLE DYNFLOW COMMAND FILE

```
'EG&G MODEL
'create output file of session
OUTP EGG.OUT
'read plan view finite element grid
GRID READ GRID5.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 (relative to mean sea 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 383 - 389 level all
FIX NODE 476 - 482 level all
!set initial head value for all nodes (water table elevation)
INIT 35.
'fix head boundaries upgradient and downgradient of well
'hydraulic gradient 0.0014 ft/ft (about 1 ft/day) - overall 1.12 ft. head drop
across 800 ft. grid extent)
INIT 34.44 NODE 476 - 482 level all
INIT 35.56 NODE 383 - 389 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 (total 88gpm, only one cell)
'note: need to divide flux by number of levels
FLUX -4236. NODE 1 LEVEL 4 - 7
FLUX 4236. NODE 1 LEVEL 11 - 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
```

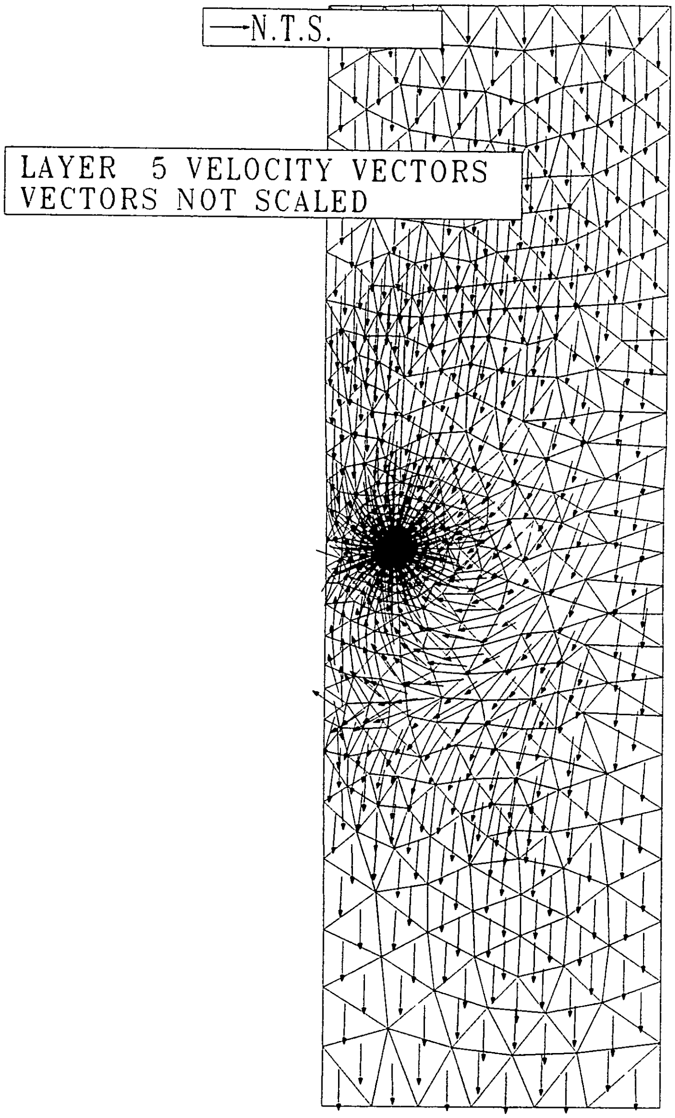
```
PROP
20, 10000000.,0.,1.
'define following properties of material: #, Kx (ft/d), Ky, Kz, Ss, Sy
PROP
10, 297.2, 297.2, 59.53, .00001, .07
iter 10
goti
'save to file
SAVE EGG.SAV
XOUT
XCFI
```

APPENDIX B2: CAPTURE WIDTH AT VARIOUS ANISOTROPIES

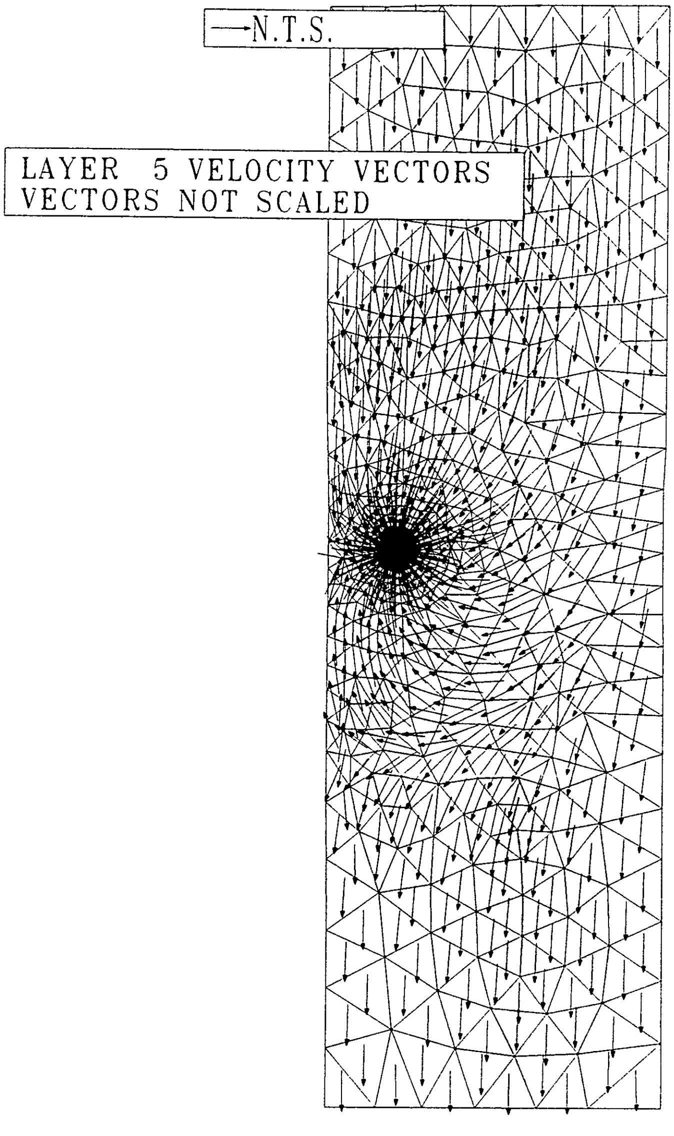
Velocity Vector Profiles 2:1



Velocity Vector Profiles 10:1



Velocity Vector Profiles 20:1



APPENDIX B3: SAMPLE DYNTRACK COMMAND FILE- Capture Area

```
'COMMAND FILE TO PARTICLE TRACKING
'restore Dynflow file
REST EGG.SAV
'create an output file
OUTP SAVE EGGcap.OUT FORM
'read transport property file
DPRO READ PROP DPR
'specify advection simulation only (turn off dispersion)
XDISP
'set radius of capture for well
RADI 20
'set particle weight
WEIGH 1000
'set starting simulation time (units: days)
TIME 0
'time step- set for 1 hour
DT 0.042
'print property set and node summary tables to std  output after each 40 time steps
PRAL 40
'seed particles at initial locations
PART
-45,200,-180
PART
-45,200,-160
PART
-45,200,-155
PART
-45,200,-150
PART
-45,200,-145
PART
-45,200,-140
PART
-45,200,-135
PART
-45,200,-117.5
PART
-45,200,-100
PART
-45,200,-95
PART
-45,200,-90
PART
-45,200,-85
PART
-45,200,-80
PART
-45,200,-75
PART
-45,200,-65
PART
-35,200,-180
PART
-35,200,-160
PART
-35,200,-155
PART
-35,200,-150
PART
-35,200,-145
PART
-35,200,-140
PART
-35,200,-135
PART
-35,200,-117.5
PART
-35,200,-100
PART
-35,200,-95
PART
-35,200,-90
```

```
PART
-35,200,-85
PART
-35,200,-80
PART
-35,200,-75
PART
-35,200,-65
PART
-25,200,-180
PART
-25,200,-160
PART
-25,200,-155
PART
-25,200,-150
PART
-25,200,-145
PART
-25,200,-140
PART
-25,200,-135
PART
-25,200,-117 5
PART
-25,200,-100
PART
-25,200,-95
PART
-25,200,-90
PART
-25,200,-85
PART
-25,200,-80
PART
-25,200,-75
PART
-25,200,-65
PART
-15,200,-180
PART
-15,200,-160
PART
-15,200,-155
PART
-15,200,-150
PART
-15,200,-145
PART
-15,200,-140
PART
-15,200,-135
PART
-15,200,-117 5
PART
-15,200,-100
PART
-15,200,-95
PART
-15,200,-90
PART
-15,200,-85
PART
-15,200,-80
PART
-15,200,-75
PART
-15,200,-65
PART
-5,200,-180
PART
-5,200,-160
PART
-5,200,-155
PART
-5,200,-150
```

```
PART
-5,200,-145
PART
-5,200,-140
PART
-5,200,-135
PART
-5,200,-117.5
PART
-5,200,-100
PART
-5,200,-95
PART
-5,200,-90
PART
-5,200,-85
PART
-5,200,-80
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PART
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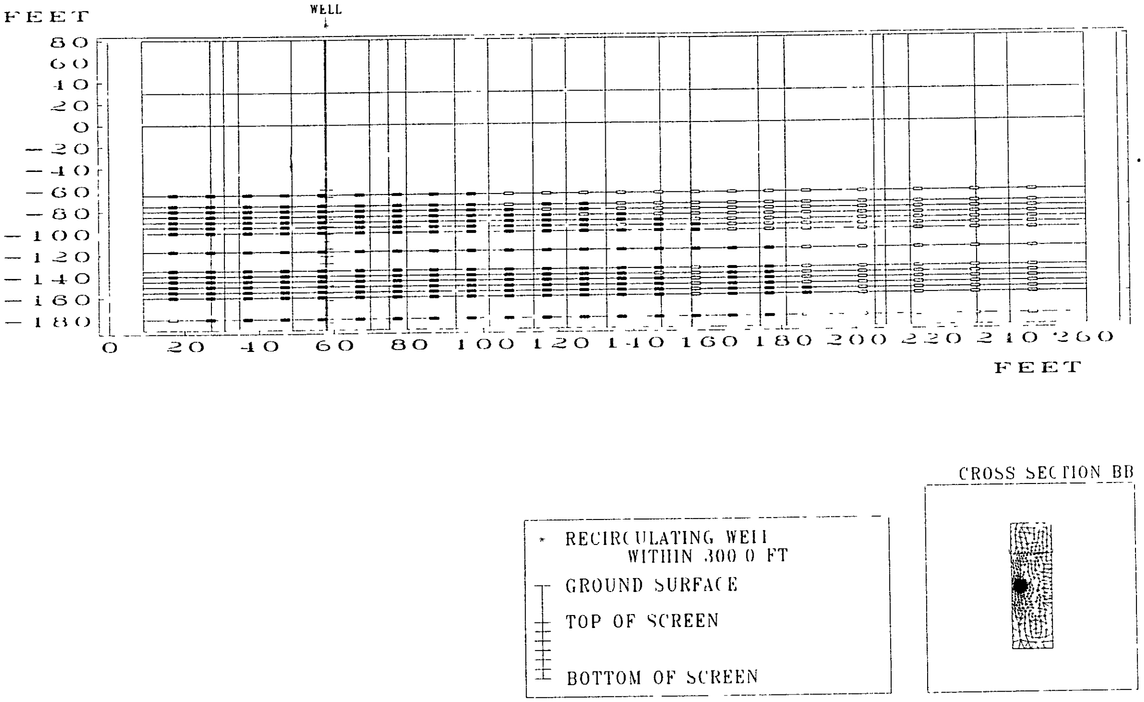
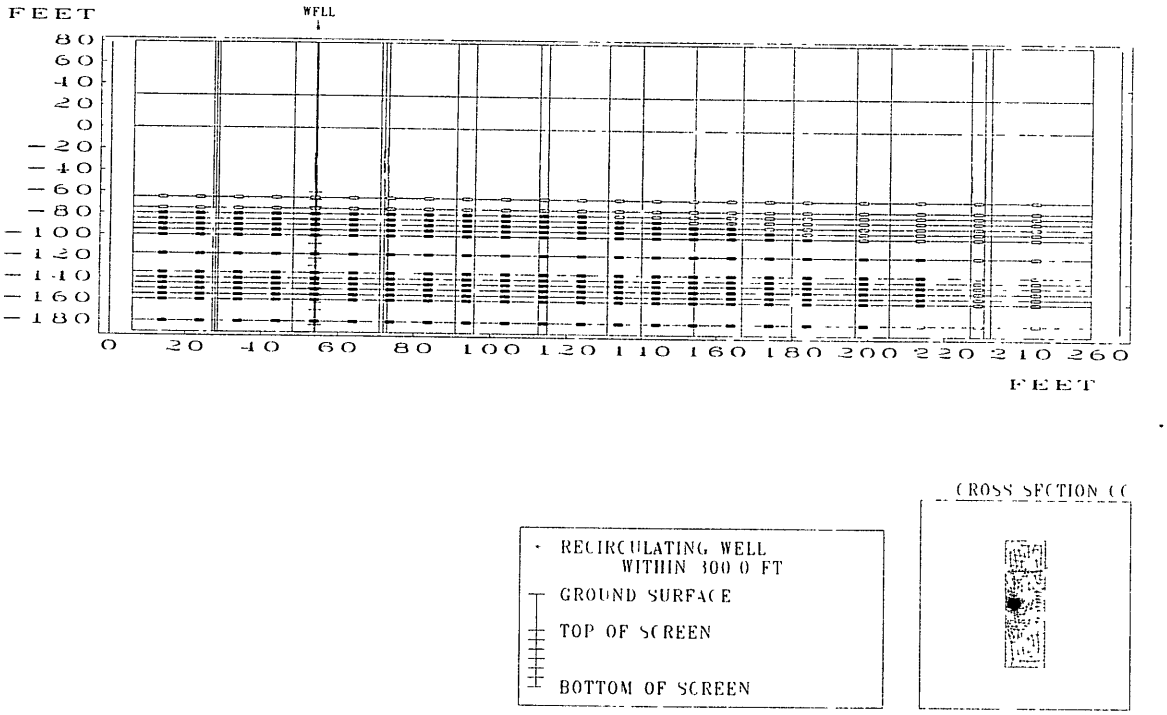
PART
185,200,-117 5
PART
185,200,-100
PART
185,200,-95
PART
185,200,-90
PART
185,200,-85
PART
185,200,-80
PART
185,200,-75
PART
185,200,-65
```

```
'store partıcle tracks on fıle
RESU 50 SAVE EGGcap.RES
'set endıng tıme of sequence
GOTI 25
GOTI 50
GOTI 75
GOTI 100
GOTI 125
GOTI 150
GOTI 175
GOTI 200
GOTI 225
GOTI 250
GOTI 275
GOTI 300
GOTI 325
GOTI 350
GOTI 375
GOTI 400
GOTI 425
GOTI 450
GOTI 475
GOTI 500
'end storage of computatıon result
XRES
END
```

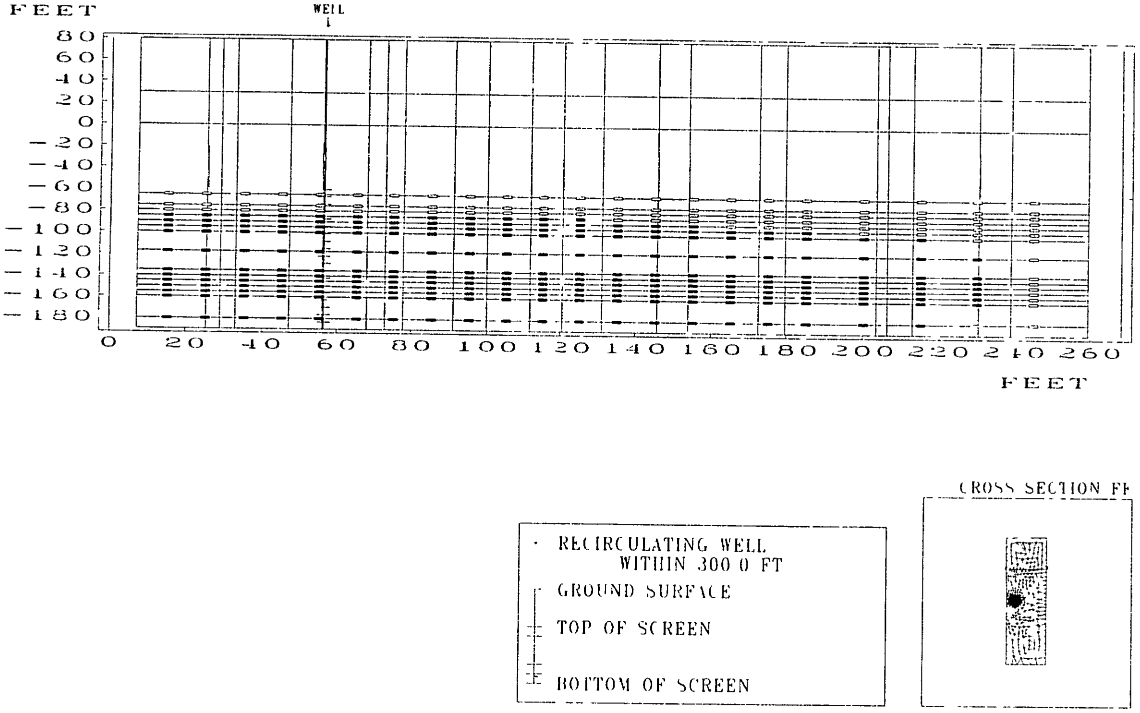
APPENDIX B4: CAPTURE AREA AT VARIOUS ANISOTROPIES
Particle Placements 2:1



Particle Placements 10:1



Particle Placements 20:1



APPENDIX B5: SAMPLE DYNTRACK COMMAND FILE- Radius of Influence/ Recirculation

```
'COMMAND FILE TO PARTICLE TRACKING
'restore Dynflow file
REST EGG.SAV
'create an output file
OUTP SAVE EGGrad.OUT FORM
'read transport property file
DPRO READ PROP.DPR
'specify dispersion simulation only (turn off dispersion)
XDISP
'set radius of capture for well
RADI 10
'set particle weight
WEIGH 1000.
'set starting simulation time (units: days)
TIME 0.
'time step- set for 1 hour
DT 0.042
'print property set and node summary tables to std. output after each 20 time steps
PRAL 20
'seed particles at initial locations- radially about well at recharge levels (2-4 and 14-16)
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
0.6840,-1 8794,-95
PART
0.3473,-1.9696,-95
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
-1.9696,0.3473,-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
-0.6840,1.8794,-95
PART
-0 3473,1.9696,-95
PART
0.0000,2.0000,-90
PART
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PART
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PART
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PART
0.3473,-1.9696,-90
PART
0.0000,-2.0000,-90
PART
-0.3473,-1.9696,-90
PART
-0.6840,-1.8794,-90
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-1.0000,-1.7321,-90
PART
-1.2856,-1.5321,-90
PART
-1.5321,-1.2856,-90
PART
-1.7321,-1.0000,-90
PART
-1.8794,-0.6840,-90
PART
-1.9696,-0.3473,-90
```

```
PART
-2.0000,0.0000,-90
PART
-1.9696,0.3473,-90
PART
-1.8794,0.6840,-90
PART
-1.7321,1.0000,-90
PART
-1.5321,1.2856,-90
PART
-1.2856,1.5321,-90
PART
-1.0000,1.7321,-90
PART
-0.6840,1.8794,-90
PART
-0.3473,1.9696,-90
PART
0.0000,2.0000,-85
PART
0.3473,1.9696,-85
PART
0.6840,1.8794,-85
PART
1.0000,1.7321,-85
PART
1.2856,1.5321,-85
PART
1.5321,1.2856,-85
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PART
1.8794,0.6840,-85
PART
1.9696,0.3473,-85
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PART
1.8794,-0.6840,-85
PART
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PART
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PART
1.2856,-1.5321,-85
PART
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PART
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PART
0.3473,-1.9696,-85
PART
0.0000,-2.0000,-85
PART
-0.3473,-1.9696,-85
PART
-0.6840,-1.8794,-85
PART
-1.0000,-1.7321,-85
PART
-1.2856,-1.5321,-85
PART
-1.5321,-1.2856,-85
PART
-1.7321,-1.0000,-85
PART
-1.8794,-0.6840,-85
PART
-1.9696,-0.3473,-85
PART
-2.0000,0.0000,-85
PART
-1.9696,0.3473,-85
```

```
PART
-1.8794,0.6840,-85
PART
-1.7321,1.0000,-85
PART
-1.5321,1 2856,-85
PART
-1.2856,1.5321,-85
PART
-1.0000,1.7321,-85
PART
-0.6840,1.8794,-85
PART
-0.3473,1.9696,-85
PART
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PART
0.3473,1.9696,-80
PART
0.6840,1.8794,-80
PART
1.0000,1.7321,-80
PART
1.2856,1.5321,-80
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1.5321,1.2856,-80
PART
1.7321,1.0000,-80
PART
1.8794,0.6840,-80
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1.9696,0.3473,-80
PART
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PART
1.9696,-0.3437,-80
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PART
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PART
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PART
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PART
-1.0000,-1.7321,-80
PART
-1.2856,-1.5321,-80
PART
-1.5321,-1.2856,-80
PART
-1.7321,-1.0000,-80
PART
-1.8794,-0.6840,-80
PART
-1.9696,-0.3473,-80
PART
-2.0000,0 0000,-80
PART
-1.9696,0 3473,-80
PART
-1.8794,0.6840,-80
PART
-1.7321,1.0000,-80
```

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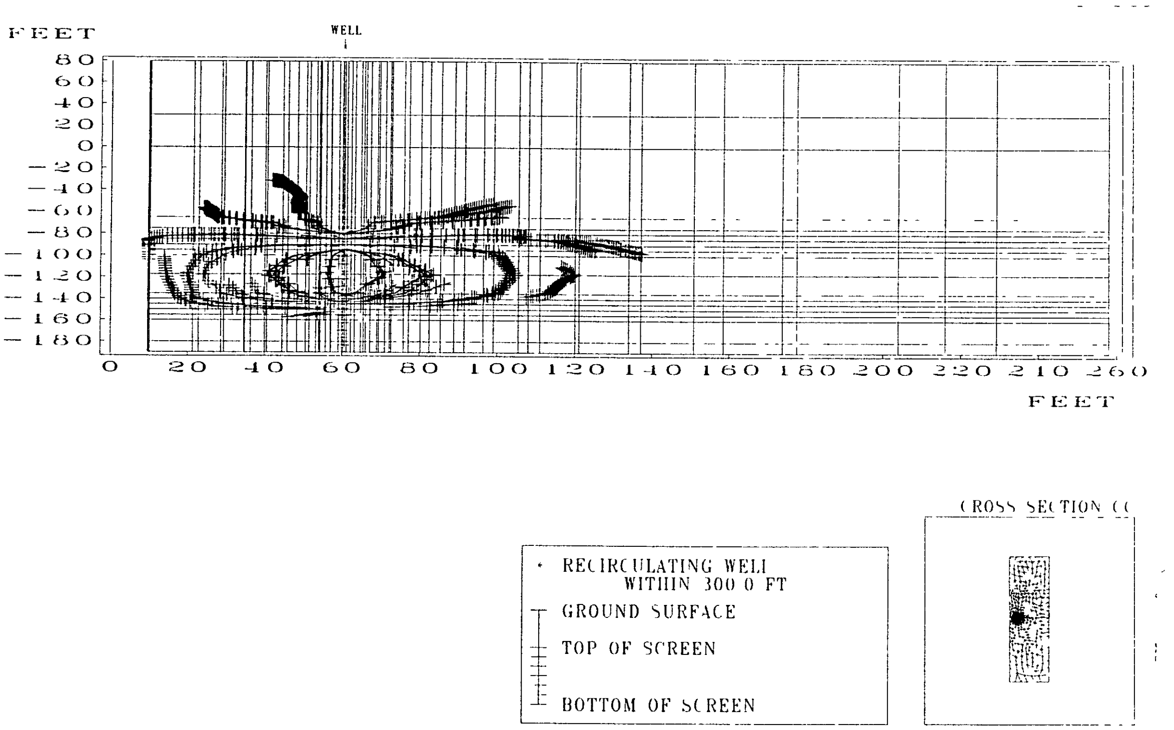
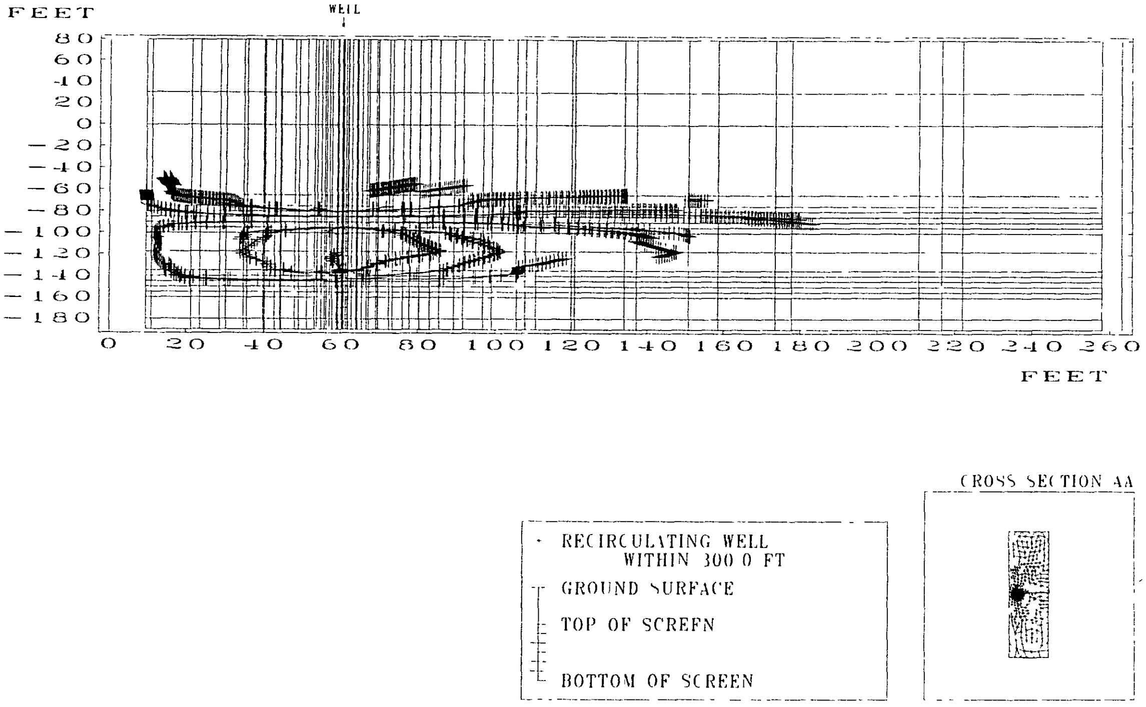
PART
-1.5321,1.2856,-80
PART
-1.2856,1.5321,-80
PART
-1.0000,1.7321,-80
PART
-0.6840,1.8794,-80
PART
-0.3473,1.9696,-80
'store particle tracks on file
RESU 10 SAVE EGGrad RES
'set ending time of sequence
GOTI 25
GOTI 50
GOTI 75
GOTI 100
GOTI 125
GOTI 150
GOTI 175
'end storage of computation result
XRES
END
```

APPENDIX B6: RADIUS OF INFLUENCE AT VARIOUS ANISOTROPIES

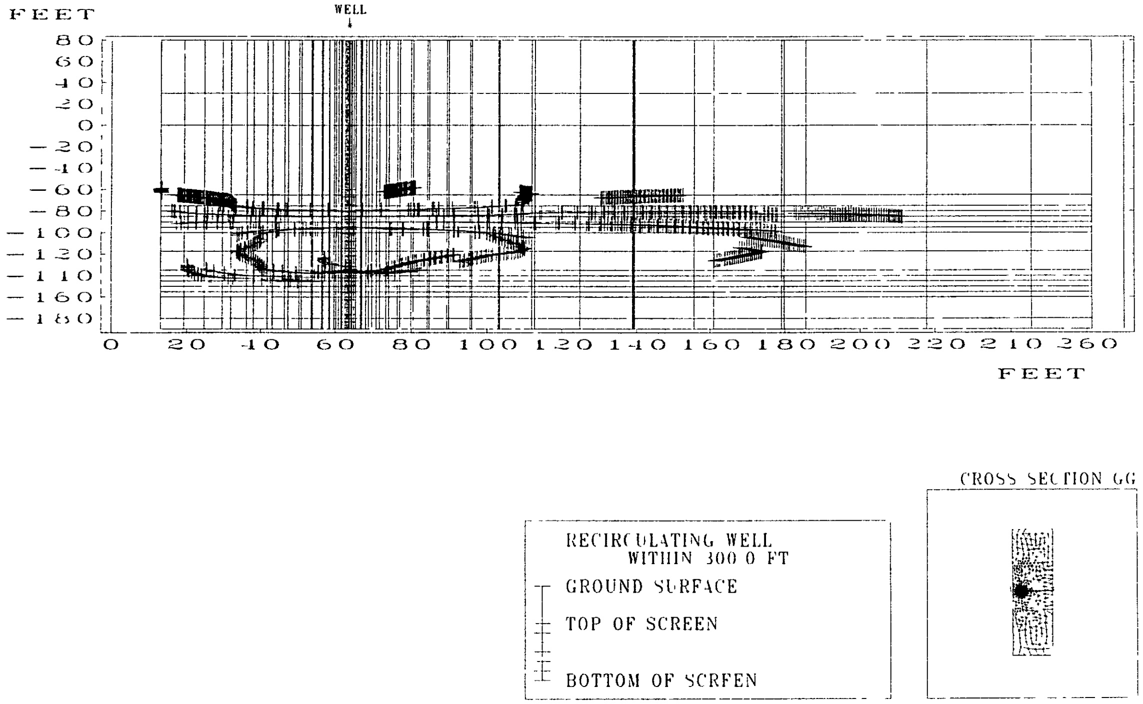
Particle Tracks 2:1



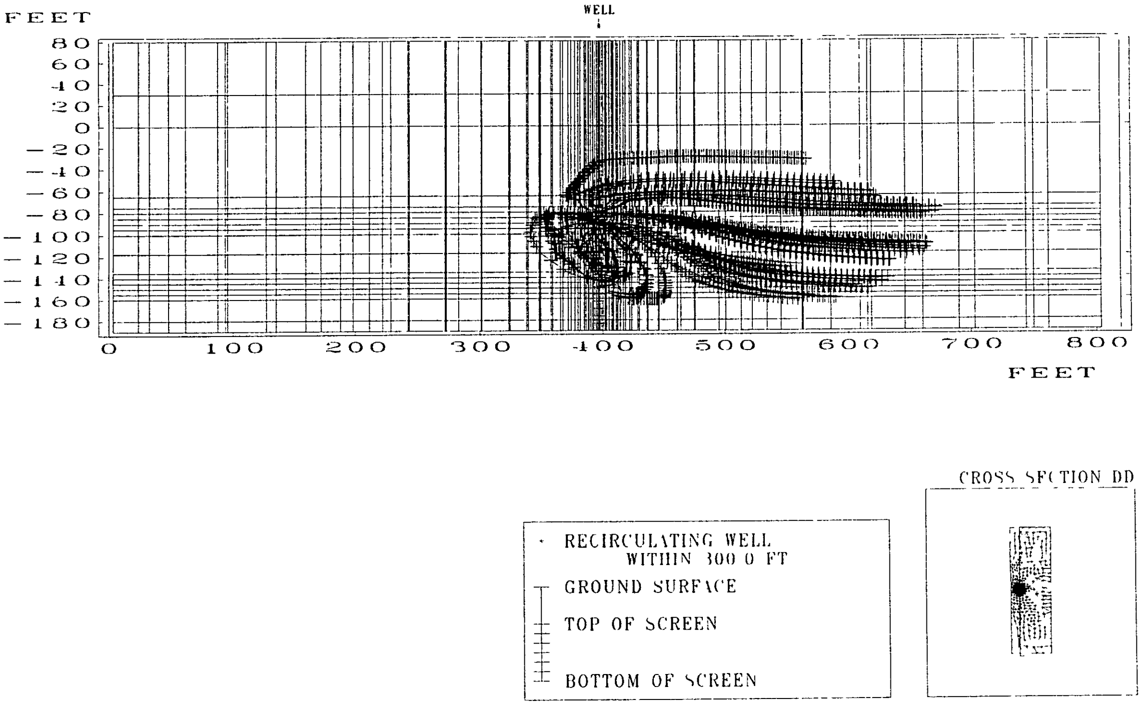
Particle Tracks 10:1



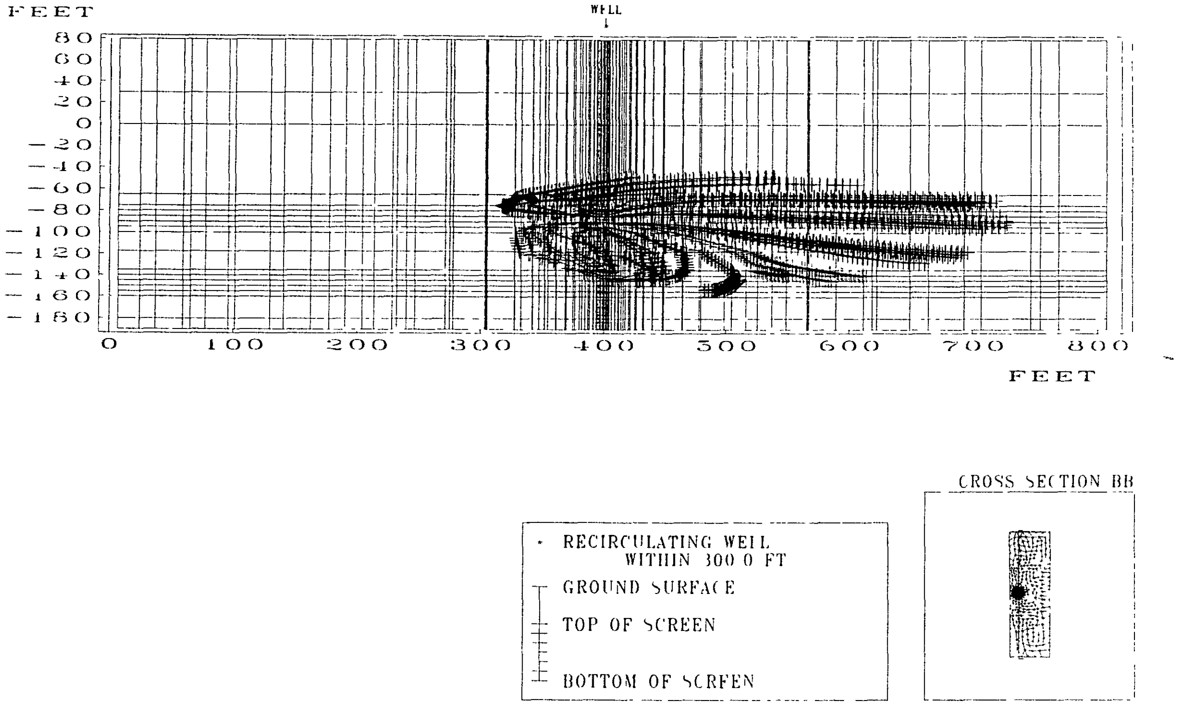
Particle Tracks 20:1



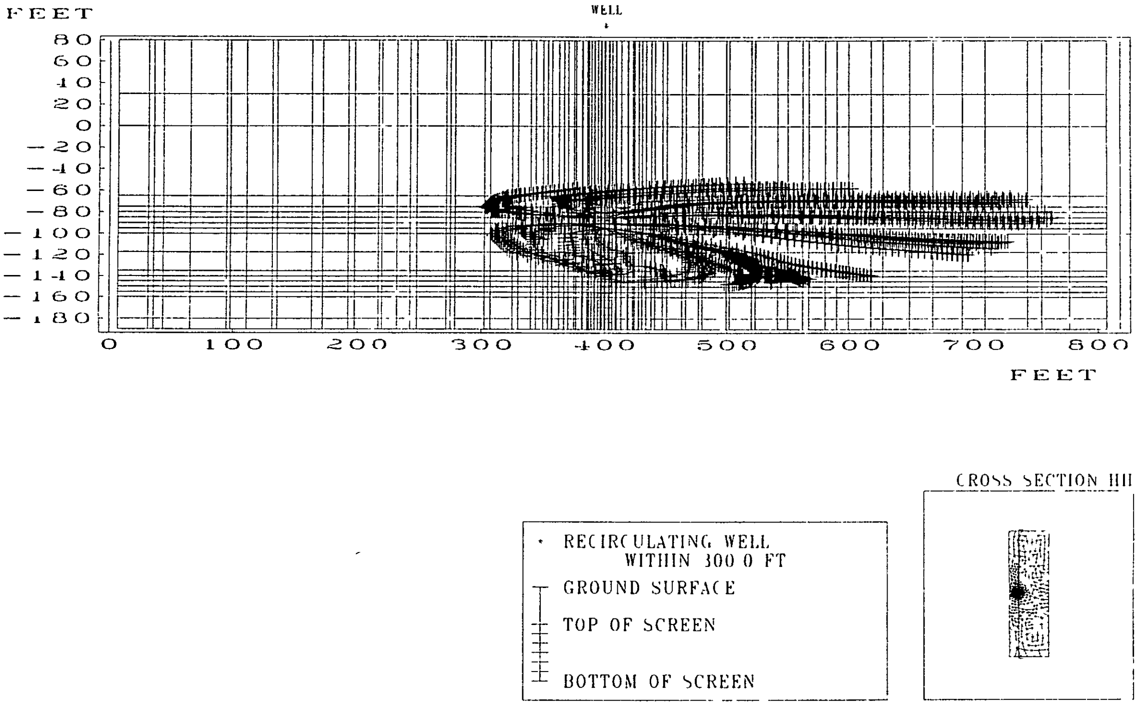
APPENDIX B7: PERCENT RECIRCULATION AT VARIOUS ANISOTROPIES
Particle Tracks 2:1



Particle Tracks 10:1



Particle Tracks 20:1



APPENDIX C: CS-10 DYNTRACK PROPERTY FILE

```
'dyntrack property file:
' Prop. #, Disp. (long.), Disp. (trans-horiz.), Disp. Ratio (vert./horiz.),
effect. porosity, retardation
10,0.,0.,0.,0.35,1.00
20,0.,0.,0.,1.,1.00
```