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Contract No. N62474-88-D-5086
Contract Task Order 0237

Prepared For

DEPARTMENT OF THE NAVY
Ms. Camille Garibaldi, Remedial Project Manager
Engineering Field Activity West
Naval Facilities Engineering Command
San Bruno, California

NAVAL AIR STATION MOFFETT FIELD, CALIFORNIA

IRON CURTAIN AREA GROUNDWATER FLOW MODEL

June 5, 1996

Prepared By

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June 6, 1996

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Naval Facilities Engineering Command
900 Commodore Way, Building 208
San Bruno, California 94066-5006

CLEAN Contract Number N62474-88-D-5086
Contract Task Order 0237

Subject: Iron Curtain Area Groundwater Flow Model

Dear Mr. Chao:

Enclosed are three copies of the Iron Curtain Area Groundwater Flow Model Report. Copies of the report are being forwarded to appropriate project personnel.

If you have any questions or comments, please call me at (303) 312-8828.

Sincerely,

Heidi J. Mueller

for James Wulff
Project Hydrogeologist

Enclosures (3)

cc: Don Chuck, EFA West
Stephen Fann, NFESC
Arun Gavaskar, Battelle

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1.0 PURPOSE

This modeling study supports the design of the pilot-scale permeable reaction wall (iron curtain). The iron curtain is a passive, in situ remedial technology that will be constructed at Site 9 of Moffett Federal Airfield (MFA) to serve as a long-term source control measure for solvent contamination. The iron curtain refers to the permeable "gate" in a funnel-and-gate system. A funnel-and-gate system uses relatively impermeable slurry walls to funnel groundwater and contaminants into a permeable reactive cell that is designed to break down solvent contamination through the chemical process of reductive dechlorinization. The reaction cell consists of 50 percent sand and 50 percent iron filings bounded by walls of pea gravel on the upgradient and downgradient sides of the cell.

The model will be used to predict the anticipated groundwater flow velocity through the reaction cell. Modeled flow velocities provide a design basis for the thickness of the iron curtain, based on the retention time that is required for the contaminants to break down to chlorine ions. The model will also be used to qualitatively assess the ability of the iron curtain to capture contaminants that originate upgradient of the system, specifically from the Building 88 area of Site 9.

Section 2.0 of this report discusses the model design. Sections 3.0 and 4.0 discuss boundary conditions and parameter values used in the model. Section 5.0 discusses model calibration. Section 6.0 presents the results of the model study. Sensitivity analyses are discussed in Section 7.0. A summary is provided in Section 8.0. References are provided in Section 9.0.

2.0 DESIGN

This modeling study employed the Modular Three-Dimensional Finite Difference Groundwater Flow Model (MODFLOW) (McDonald and Harbaugh 1988) to simulate flow through the A1/A2 aquifer and iron curtain system, and MODPATH (Pollack 1989) to calculate potential particle pathways through the iron curtain. These particle tracks are used to depict the extent of the iron curtain capture zone and determine the velocity of groundwater passing through the iron curtain.

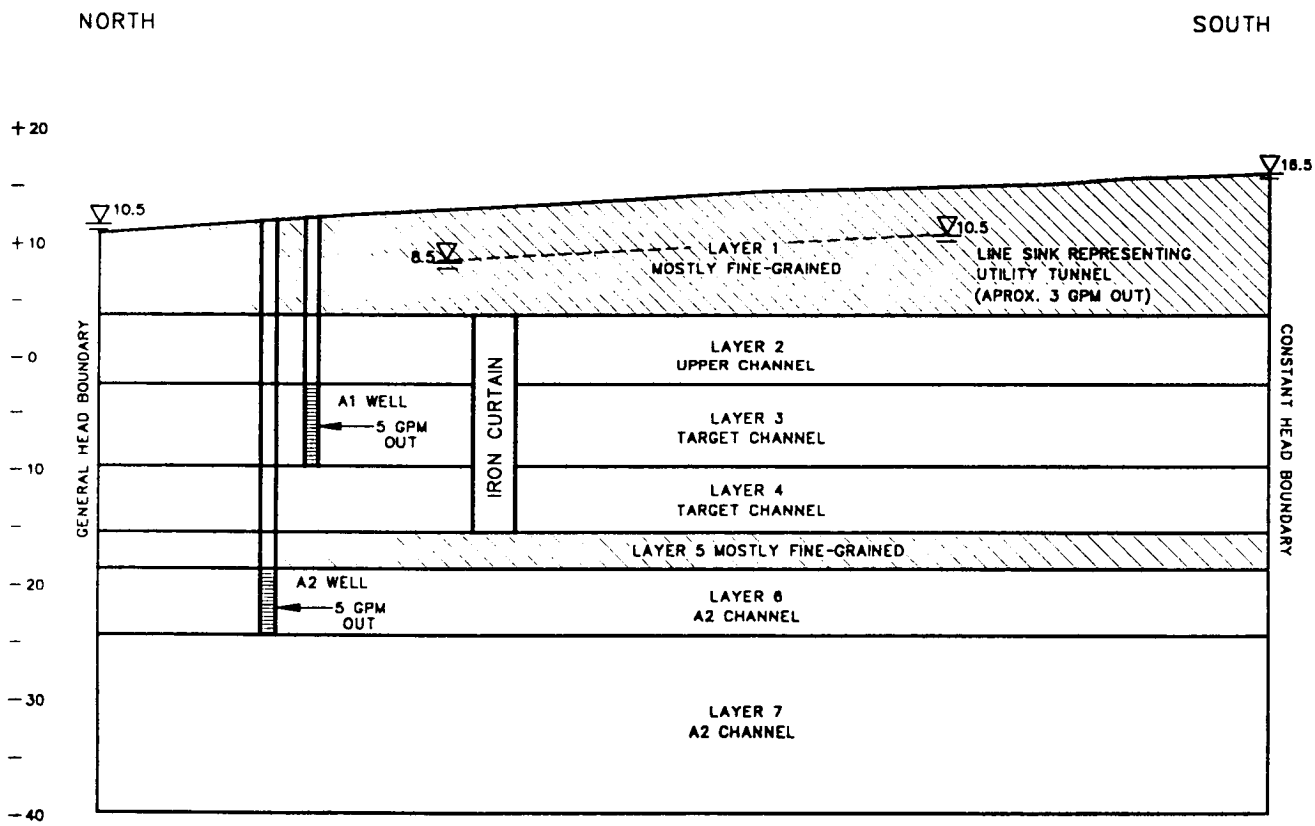
A three-dimensional model grid was used in this analysis because the iron curtain does not fully penetrate the A aquifer and a two-dimensional model would neglect the potential for groundwater flow and contaminant transport beneath the bottom of the iron curtain. The model was also constructed to account for the heterogeneity and anisotropy inherent in the aquifer material at MFA and the effects these material properties have on the ability of the iron curtain to capture contaminants.

A seven-layer grid, encompassing an area 1,000 feet (parallel to the direction of flow) by 700 feet (perpendicular to the direction of flow), was used to model the area surrounding the iron curtain site. The grid consists of 111 rows and 90 columns with a total of 69,930 model cells. A cell size of 3.75 by 2.5 feet was used in the center of the grid so that the individual components of the iron curtain could be represented in the model. The cell size was expanded to 20 by 20 feet in the corners of the model.

The lithology of the A aquifer within the model area consists of sand and gravel channel deposits which are incised into, and interbedded with, finer-grained deposits. These channels are believed to have a stringer-like morphology and may have been deposited by one or more flood events. The channel sands and gravels are lens-shaped in cross-section and grade laterally into silty sand and silt deposits. Lithologic data from approximately 20 cone penetrometer test (CPT) holes and 20 soil borings were used to define the spatial variability of aquifer properties within the iron curtain area. Away from the iron curtain area, channel maps (PRC 1993) were used to fill in the remaining grid.

A schematic representation of the seven model layers is presented in Figure 1. All layers are horizontal, though the upper surface of layer 1 is bounded by a sloped water table. All layers are 6 or 7 feet thick, except layer 1 (variable), layer 5 (3 feet thick) and layer 7 (16 feet thick). The uppermost four layers of the model correspond to the A1 aquifer. The first layer represents a surficial silty clay layer that appears to be continuous across the site. This unit consists of a minimum of 5 feet of relatively impermeable silty clay. This unit may create locally confined groundwater conditions in the underlying aquifer where the unit is thickest (where the first permeable sediments lie at a depth of 10 to 15 feet).

Layers 2 through 4 contain A1 permeable zone sediments, though the majority of each layer contains silt and silty clay. Layer 2 contains a relatively wide (hundreds of feet) channel that crosses the site from southeast to northwest, which will be referred to as the upper channel. These channel sediments were found between depths of 5 and 13 feet below ground surface (bgs) east of the proposed iron curtain location. Layers 3 and 4 contain a north-south trending compound channel across which the iron curtain will be constructed. This channel will be referred to as the target channel. It is narrower (about 50 feet wide) but thicker than the upper channel. These channel sediments were found at depths of 10 to 26 feet bgs. The upper channel does not appear to intersect the target channel in the iron curtain based on lithologic data. Though these channel deposits may not intersect in the iron curtain area, they are almost certainly hydraulically connected, either because they intersect downgradient of the iron curtain area or they are connected through silt/clayey silt beds that envelope each channel.



LEGEND

HEAD

FINE-GRAINED LAYER

WELL SCREEN

FIGURE 1
NORTH-SOUTH SCHEMATIC
MODEL CROSS-SECTION

Layer 5 represents the discontinuous A1/A2 aquitard. Boring logs in the area show that it typically consists of 3 feet of silty clay or clayey silt between depth of 25 and 28 feet bgs in the iron curtain area. The model layer consists of silt below the target channel and silty clay away from the target channel. A layer thickness of 3 feet was assumed.

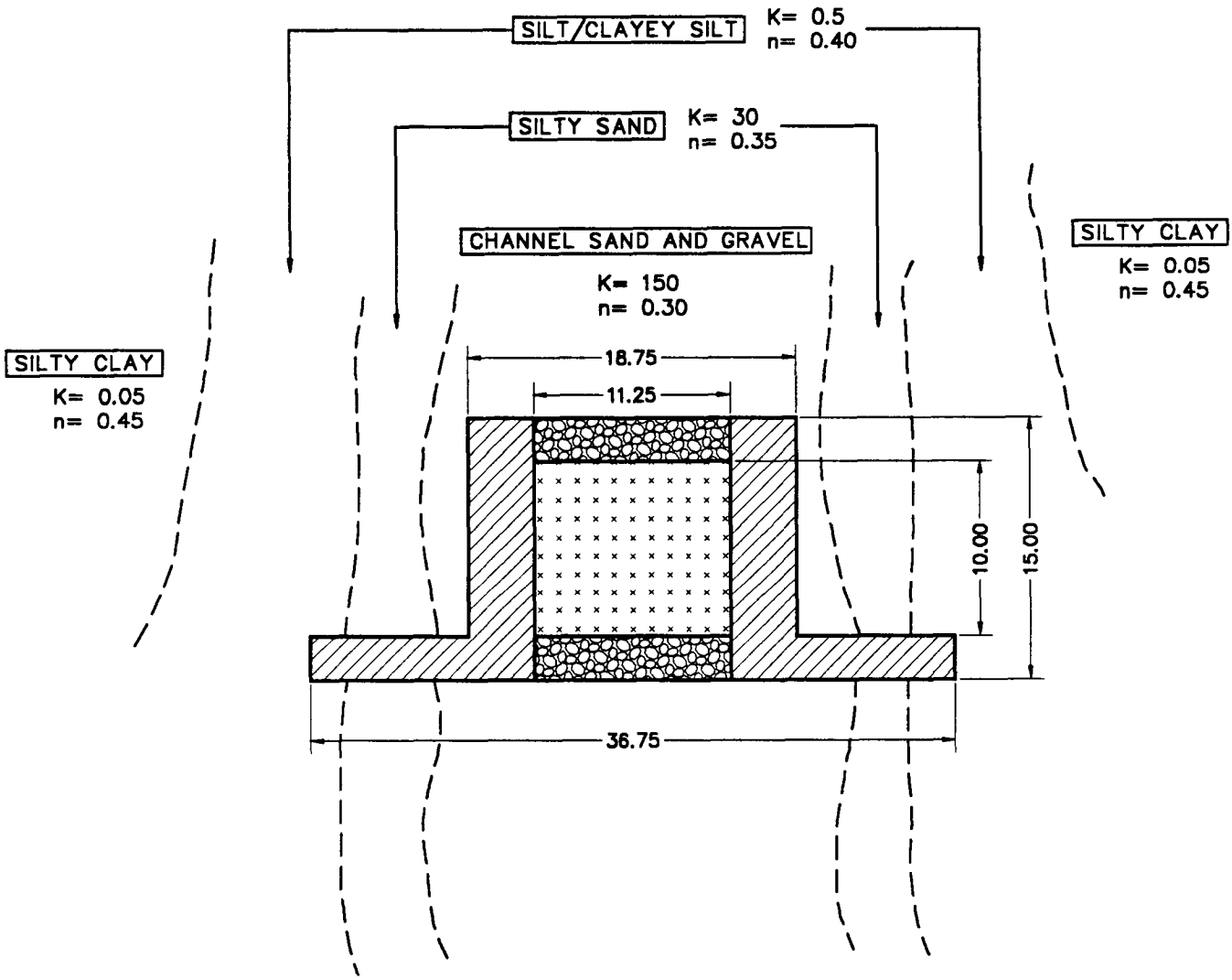
Layers 6 and 7 represent the A2 permeable zone. Layer 6 represents the upper 7 feet of the A2 permeable zone. In the iron curtain project area, this corresponds to a depth of approximately 35 feet bgs, which is as deep as CPT borings were conducted in the iron curtain area during this investigation. The 16-foot thick layer that represents the lower A2 aquifer (layer 7) is based on channel maps only. The seventh layer was added primarily to provide distance between a simulated extraction well in layer 6 and the lower (no-flow) model boundary.

The iron curtain is represented in layers 2, 3 and 4 of the model and is oriented perpendicular to the target channel. The total width of the funnel-and-gate system is 36.75 feet and the permeable cell, or gate, is 11.25 feet wide. The reactive cell is 10 feet wide perpendicular to flow and bounded by a 2.5 foot-thick wall of pea gravel on the upgradient and downgradient sides. Figure 2 depicts the configuration of the iron curtain in the model and its relationship to lithologic zones in layers 3 and 4. Figure 3 shows the major hydrologic features of the model in plan view.

3.0 BOUNDARY CONDITIONS

The model is bounded on the upgradient (southern) side by a constant head boundary equal to 16.5 feet and on the downgradient (northern) side by a general head boundary at which the head just outside the model boundary is equal to 10.5 feet. General head boundary conductances were zoned according to the hydraulic conductivity of the adjacent model cell and were equal to this hydraulic conductivity multiplied by the area of boundary cell face perpendicular to the direction of flow. The upper boundary of the model is the water table. The lateral and lower boundaries are zero-flux (no-flow) boundaries.

An internal line sink representing a utility tunnel was incorporated into layer 1 of the model. The utility tunnel crosses the site from southwest to northeast. The northeastern portion of the tunnel is below the water table. Water table elevations from a piezometer network that was installed at the iron curtain site indicate that the water table is depressed in the vicinity of this utility tunnel. Groundwater seepage has been observed in a portion of the tunnel that crosses the site and a sump pump at the end of the tunnel pumps at an average of 5 to 7 gallons per minute (gpm) during the dry season. The line sink was represented by a diagonal line of general head boundary cells. The heads



ALL MEASUREMENTS IN FEET
ALL HYDRAULIC CONDUCTIVITIES IN FT/D

LEGEND

K	HYDRAULIC CONDUCTIVITY		
n	TOTAL POROSITY		
— — —	BOUNDARY OF GEOLOGIC UNIT		
	SLURRY WALL	K= 0.003	n= 0.45
	IRON	K= 283	n= 0.33
	GRAVEL PACK	K= 2830	n= 0.33

5' 0 5' 10'
SCALE IN FEET

FIGURE 2
PLAN VIEW SHOWING
DIMENSIONS AND PROPERTIES OF
IRON CURTAIN IN MODEL

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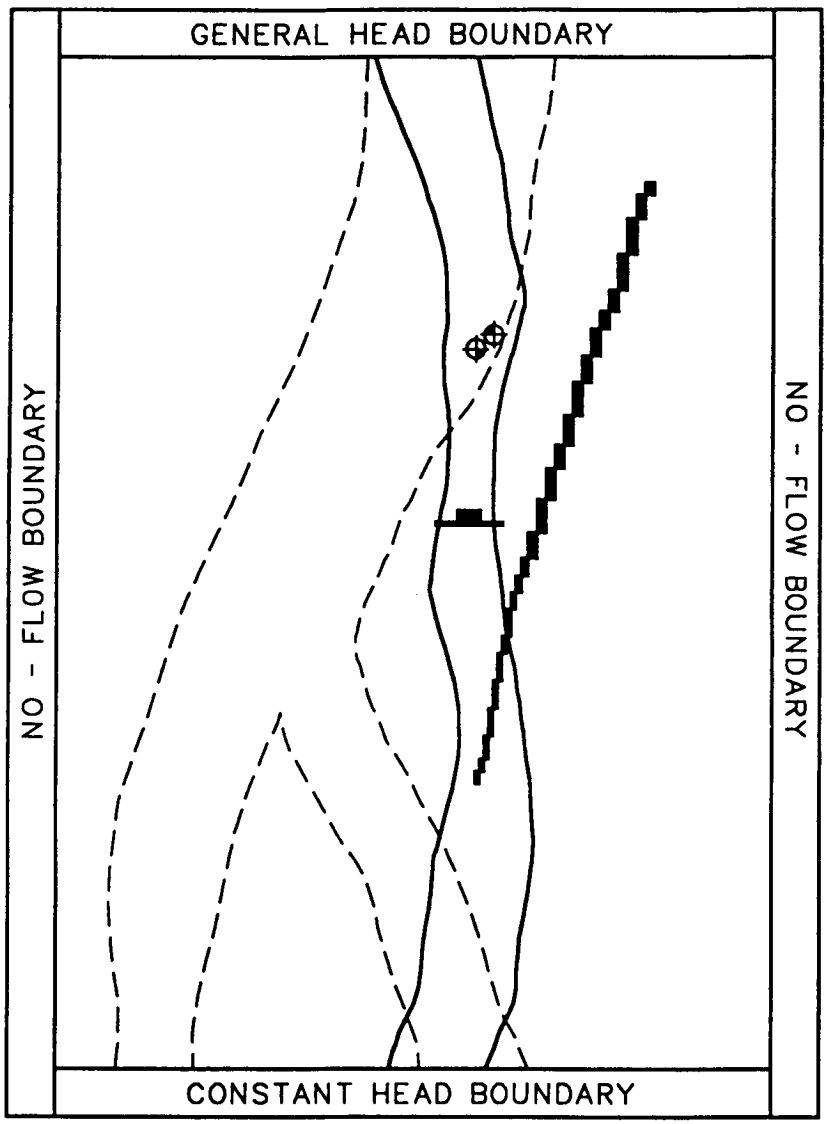

LEGEND

- TARGET CHANNEL BOUNDARY (LAYERS 3 AND 4)
- UPPER CHANNEL BOUNDARY (LAYER 2)
- IRON CURTAIN (LAYERS 2, 3 AND 4)
- UTILITY TUNNEL (LAYER 1)
- A1 EXTRACTION WELL (LAYER 3)
- A2 EXTRACTION WELL (LAYER 6)

FIGURE 3
MAJOR HYDROLOGIC FEATURES
OF MODFLOW MODEL
PLAN VIEW

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assigned to the cells are approximately equal to the estimated elevation of the tunnel floor. General head boundary cell conductances were varied through several orders of magnitude until the discharge into the tunnel was approximately 3 gpm. This value was chosen because a portion of the tunnel that is below the water table is located outside of model domain. Therefore, the line sink should not account for a discharge equal to that pumped out of the sump. The final value of conductance applied to the general head boundary cells that represent the line sink was 400 square feet per day (ft^2/d).

4.0 PARAMETER VALUES

Four geologic units are represented in the model: sand and gravel, silty sand, silt, and silty clay. The hydraulic conductivities assigned to the channel materials (sand and gravel in the center of the channels, silty sand at the edges) are within the range of conductivities calculated at observation wells from an aquifer test conducted at A1 permeable zone well W9-35 in 1992. The data were collected and reduced by the IT Corporation (IT) as part of the remedial investigation (RI) of the west side aquifers (IT 1993). Transmissivity values were calculated from transmissivities obtained from the Cooper-Jacob Method (pumping well) and the Hantush-Jacob Method (observation wells). An average aquifer thickness of 8 feet was assumed. The average value of hydraulic conductivity derived from one pumping well (W9-35) and three observation wells (piezometers PZ9.8-2, PZ9.8-4, and PZ9.8-6) was 53 feet per day (ft/d), the low value was 13 ft/d, and the high value was 169 ft/d. Based on the high and low values and the location and lithology of the observation well borings, a hydraulic conductivity of 150 ft/d was used for sand and gravel, and 30 ft/d was used for silty sand.

Estimates of the horizontal hydraulic conductivity of the A1/A2 aquitard (which is largely composed of silt) were obtained from slug tests conducted in wells screened across the aquitard at several locations at Site 9 (IT 1993). IT analyzed these data using the method of Cooper and others. The estimates ranged from 0.1 ft/d to 1.4 ft/d. Based on this range, a value of 0.5 ft/d was assigned to silt in the model. No site-specific data are available to estimate the hydraulic conductivity of silty clay. A value of 0.05 ft/d was assumed. This value is conservative in that it may overestimate the potential for transport through silty clay; however, the areal extent of this geologic unit is significant only in the low-permeability model layers (layers 1 and 5).

Porosity values were based on total porosities for different lithologic types obtained from laboratory samples during the west side aquifer investigation (PRC 1993). A value of 0.30 was assigned to sand and gravel (based on three samples); a value of 0.35 was assigned to silty sand (based on four samples); a value of 0.40 was assigned to silt (based on two samples); and a value of 0.45 was assigned to silty clay (based on 14 samples).

The material properties of the iron curtain components (slurry wall, pea gravel, and the iron/sand mixture that is used as the reactive medium) were similar to values used in previous modeling studies. A hydraulic conductivity of 283 ft/d and a porosity of 0.33 were assumed for the reactive medium. A hydraulic conductivity of 2830 ft/d and a porosity of 0.33 were assumed for the pea gravel. A hydraulic conductivity of 0.003 ft/d and a porosity of 0.45 were assumed for the slurry walls.

Vertical anisotropy, or the ratio of horizontal to vertical hydraulic conductivity, is one important parameter for which data do not exist. Vertical hydraulic conductivity data can only be derived from laboratory tests (which do not reflect site conditions because the samples are disturbed) or specially designed aquifer tests (which have not been conducted at the site). In the absence of this data, a ratio of 10:1 (horizontal:vertical) was assumed. Horizontal anisotropy (the ratio of hydraulic conductivity in the longitudinal and transverse directions) was assumed to be 1:1.

5.0 CALIBRATION

The model hydraulic gradient was calibrated to an average hydraulic gradient of 0.0057, which was calculated from head maps of the western side of MFA. The downgradient general head boundary was varied from 8.5 feet to 11 feet while the zoned boundary conductance values were kept constant. A gradient of 0.0058 was achieved with a general head of 10.5 feet at the downgradient boundary. The model was not calibrated to a set of head values because the existing monitoring wells were too few (four) and far between within the model area to provide a meaningful head map.

6.0 RESULTS

MODPATH particle tracking software was used to depict contaminant transport pathways through the iron curtain area under three scenarios: without the iron curtain (pre-construction conditions), with the iron curtain, and with the iron curtain and a pair of hypothetical extraction wells pumping 5 gpm from both the A1 and A2 aquifer zones. The wells were located approximately 200 feet downgradient from the iron curtain. Particle tracking was conducted at a local and site-wide scale for each scenario.

Local-scale particle tracking focused on the area immediately surrounding the iron curtain and is used to estimate groundwater velocity through the iron curtain. Five particles were positioned in the center of the target channel approximately 70 feet upgradient of the iron curtain in layer 3 of the model.

Particle locations were marked at 1-day intervals. Particle (groundwater) velocity through the iron curtain was estimated by counting the number of markers between a line upgradient of the iron curtain (y-coordinate = 556.76) and downgradient of the iron curtain (y-coordinate = 613.51). The distance between these lines (56.75 feet) was divided by the fewest number of markers along any of the particle tracks to obtain the maximum particle velocity.

Particle velocities calculated for the three scenarios were 3.1 ft/d under pre-construction conditions; 4.1 ft/d with the iron curtain; and 5.5 ft/d with the iron curtain and extraction wells. Table 1 provides information on velocities, gradients, and discharges calculated for each of the three scenarios. Figures 4 through 6 depict the particle traces for the three scenarios. Groundwater table contours (in tenths of a foot) are also superimposed on these plots.

Site-wide scale particle tracking was conducted to evaluate particle transport and capture throughout the western side of MFA. Contaminants are represented by particles placed in layers 2, 3, 4, and 6 near the upgradient boundary of the model. Ten particles were arrayed in a line in each of the four layers for a total of 40 particles. The particle starting locations spanned channel deposits and the lower permeability lithologies adjacent to the channels. Particles that entered cells containing the iron curtain were removed from the model, so the influence of the iron curtain would be visible. Table 2 provides information on the starting location of each particle, its destination, and its travel time. Particle travel times can be used to compare the speed of particle transport in different regions of the grid and to draw inferences about the effect of the iron curtain on contaminant transport. However, unlike the actual contaminants of interest, particles in MODPATH cannot be retarded or degraded. Therefore, the particle travel times cannot be used as quantitative estimates of actual contaminant travel times.

Figures 7 through 9 are particle tracking plots that provide a qualitative view of the capture zones under each scenario. Figures 7 through 9 superimpose particle tracks from all layers. Particle locations are marked a 1-year intervals. The model results suggest that the iron curtain would primarily treat A1 groundwater from the channel that the iron curtain intercepts (the target channel). Twelve of the 40 particles were captured by the iron curtain in the iron curtain scenario. Eight of these 12 particles originated in, or adjacent to, the target channel (in the permeable deposits in layers 3 and 4). One particle was captured from the upper channel (permeable deposits in layer 2). Three particles that originated in low permeability deposits were captured in the iron curtain, two of which originated in layer 6 (the A2 aquifer). Additional particles were captured by the iron curtain in

TABLE 1

MODEL RESULTS

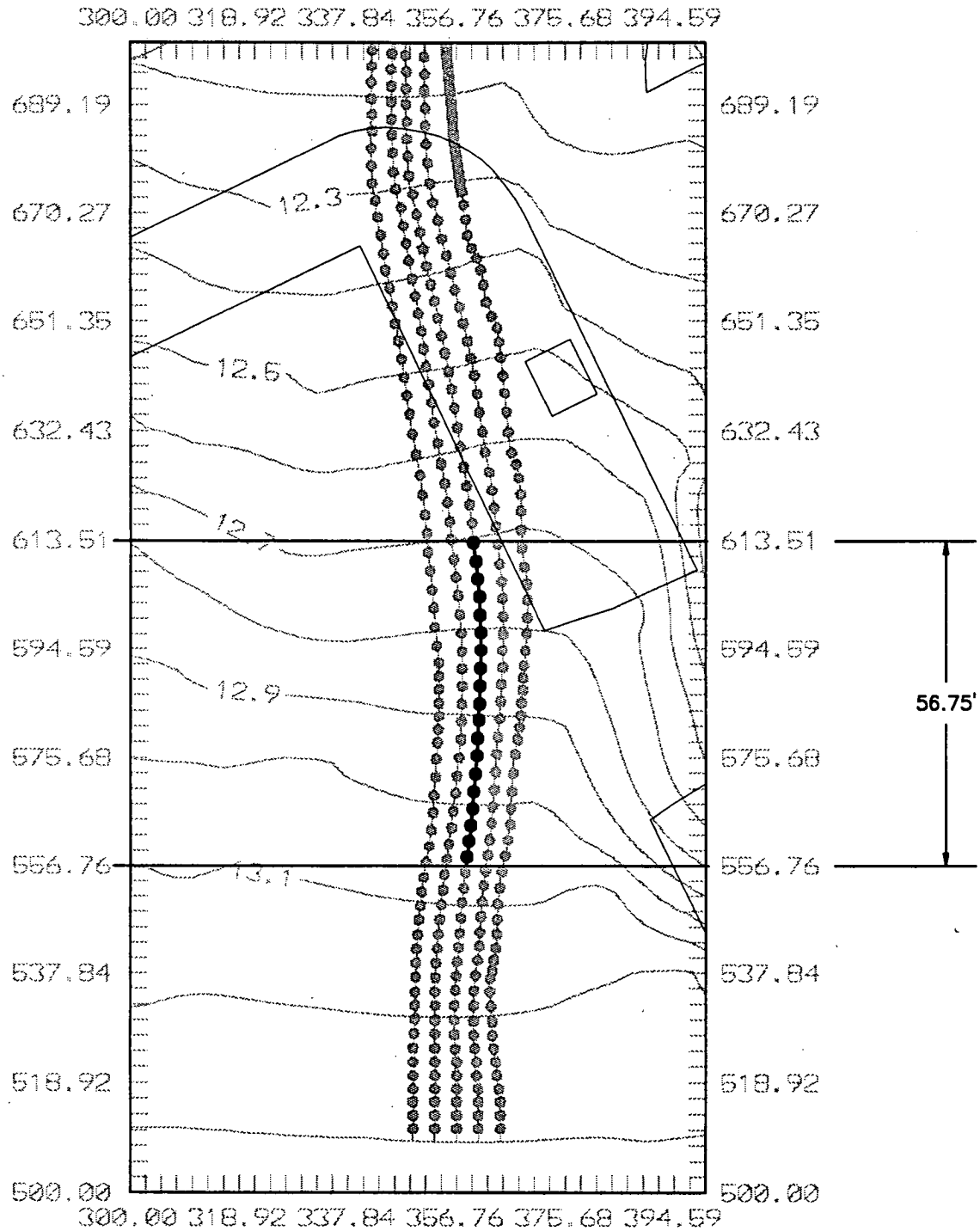
Scenario	Particle Velocity (ft/day)	Gradient[1]	Discharge through Iron Curtain[2] (gallons per minute)	Number of Particles Captured[2] (out of 40)	Water Balance Error[3] (percent)
Pre-construction	3.1	0.0058	0.8	4	+3.1
Iron Curtain	4.1	0.0058	1.7	12	+2.2
Iron Curtain and Extraction Wells	5.5	0.0072	2.4	16	-0.4

Notes:

[1] Gradient calculated across the center 500 feet of the model grid (along Y-axis)

[2] The iron curtain is not included in the pre-construction scenario. However, the discharge through the front face of the iron curtain in the iron curtain scenarios was compared to the discharge through the equivalent cross-sectional area of the aquifer in the pre-construction scenario. This was accomplished by summing the individual discharges through the model cells that constitute the front face of the iron curtain. Similarly, the number of particles that pass through these cells was determined for pre-construction conditions and compared to the number of cells that pass through the iron curtain.

[3] Water balance error for the simulation as calculated by MODFLOW



LEGEND

PARTICLE TRACK-MARKERS REPRESENT ONE DAY OF TRAVEL TIME

$\frac{56.75 \text{ FEET}}{18.5 \text{ DAYS}}$ = 3.1 FEET/DAY

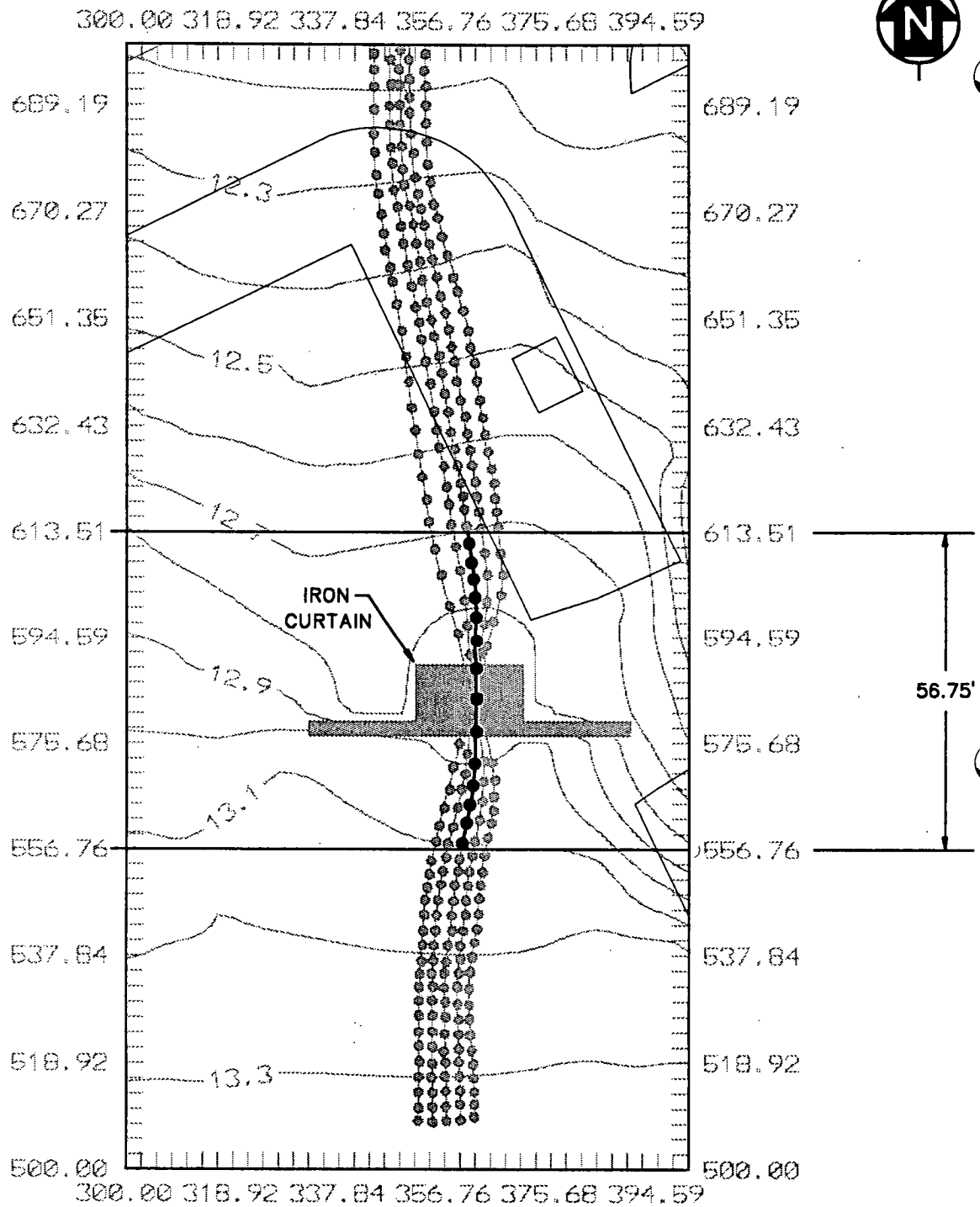
GROUNDWATER CONTOURS IN FEET ABOVE MSL

NOT TO SCALE

FIGURE 4
LOCAL SCALE PARTICLE TRACKING RESULTS
FOR PRE-CONSTRUCTION SCENARIO

FILE NAME: FILE NAME

DATE: DAY MONTH DATE, YEAR



LEGEND

PARTICLE TRACK-MARKERS REPRESENT ONE DAY OF TRAVEL

$\frac{56.75 \text{ FEET}}{14 \text{ DAYS}}$ = 4.1 FEET/DAY

GROUNDWATER CONTOURS IN FEET ABOVE MSL

NOT TO SCALE

FIGURE 5
LOCAL SCALE PARTICLE TRACKING RESULTS FOR IRON CURTAIN SCENARIO

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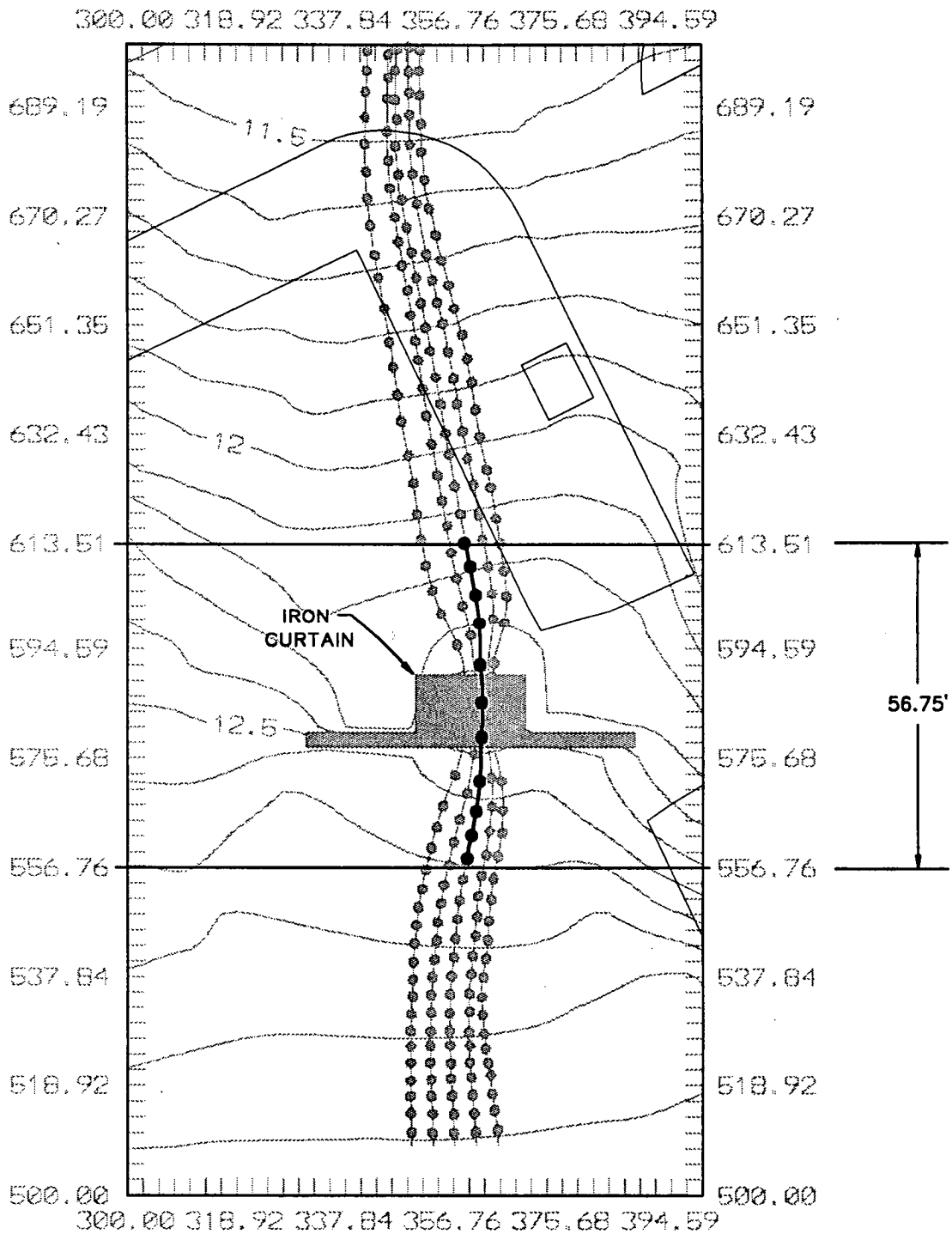

LEGEND

PARTICLE TRACK-MARKERS REPRESENT ONE DAY OF TRAVEL TIME

$\frac{56.75 \text{ FEET}}{10.25 \text{ DAYS}} = 5.5$ FEET/DAY

GROUNDWATER CONTOURS IN FEET ABOVE MSL

NOT TO SCALE

FIGURE 6
LOCAL SCALE PARTICLE TRACKING RESULTS FOR IRON CURTAIN AND EXTRACTION WELLS SCENARIO

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TABLE 2

PARTICLE STARTING LOCATION, DESTINATION, AND TRAVEL TIME

Particle Starting Location					Pre-Construction Scenario		Iron Curtain Scenario		Iron Curtain and Extraction Well Scenario	
Initial Cell Address			Lithology	Position Relative to Channel	Destination	Travel Time (years)	Destination	Travel Time (years)	Destination	Travel Time (years)
Layer	Row	Column								
2	102	40	Silt	West	B	11.1	B	11.3	A1	15.2
2	102	44	Silty Sand	West	B	2.1	B	2.1	A1	1.6
2	102	48	Silty Sand	West	B	1.5	B	1.5	A1	1.1
2	102	52	Sand and Gravel	Center	B	1.0	B	1.0	A1	0.7
2	102	56	Sand and Gravel	Center	B	1.5	IC	0.7	IC	0.7
2	102	60	Sand and Gravel	Center	UT	0.3	UT	0.3	UT	0.2
2	102	62	Sand and Gravel	Center	UT	0.7	UT	0.7	IC	0.4
2	102	64	Silt	East	UT	4.7	UT	4.4	UT	3.7
2	102	66	Silt	East	UT	10.1	UT	9.5	UT	8.1
2	102	68	Silt	East	UT	20.0	UT	19.7	UT	14.1
3	104	42	Silt	West	B	15.5	B	16.0	A1	13.8
3	104	46	Silty Sand	West	B	3.4	B	3.4	A1	3.0
3	104	50	Silty Sand	West	B	1.9	B	2.0	A1	0.6
3	104	55	Sand and Gravel	Center	B	1.0	IC	0.4	IC	0.4
3	104	59	Sand and Gravel	Center	UT	0.7	UT	0.8	IC	0.5
3	104	61	Sand and Gravel	Center	B	1.5	IC	0.6	IC	0.6
3	104	63	Silty Sand	East	UT	1.6	UT	1.7	IC	0.7
3	104	65	Silty Sand	East	UT	9.3	UT	7.4	UT	4.0
3	104	67	Silty Sand	East	UT	4.8	UT	7.4	UT	3.5
3	104	69	Silt	East	B	11.3	B	13.5	UT	10.2
4	106	40	Silt	West	B	4.6	IC	4.4	IC	6.8
4	106	44	Silty Sand	West	B	2.5	IC	2.2	IC	2.3
4	106	48	Silty Sand	West	B	1.3	IC	0.9	IC	0.9

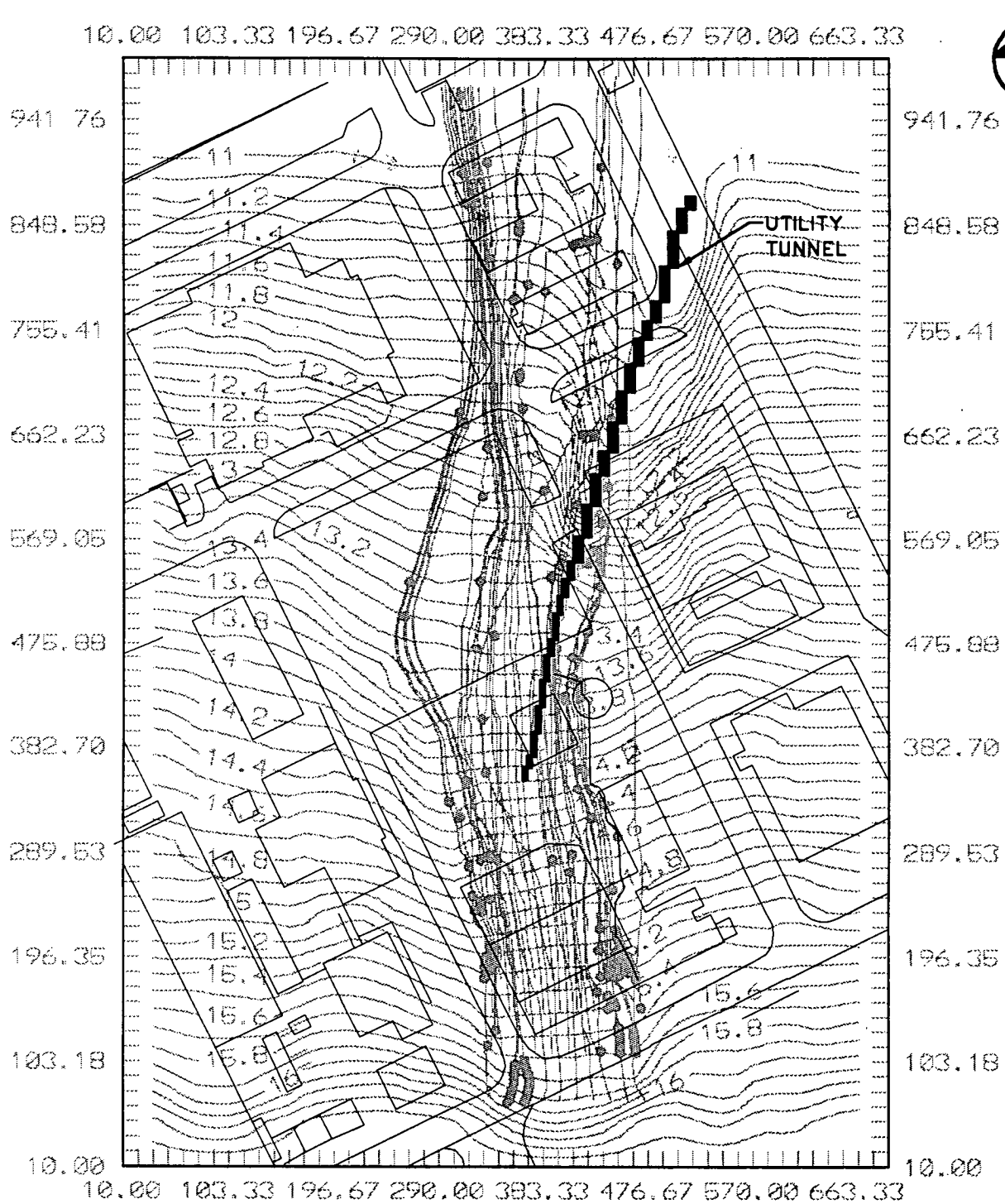
TABLE 2 (Continued)

PARTICLE STARTING LOCATION, DESTINATION, AND TRAVEL TIME

Particle Starting Location					Pre-Construction Scenario		Iron Curtain Scenario		Iron Curtain and Extraction Well Scenario	
Initial Cell Address			Lithology	Position Relative to Channel	Destination	Travel Time (years)	Destination	Travel Time (years)	Destination	Travel Time (years)
Layer	Row	Column								
4	106	52	Sand and Gravel	Center	B	1.5	IC	0.5	IC	0.4
4	106	56	Sand and Gravel	Center	B	1.2	IC	0.5	IC	0.4
4	106	60	Silty Sand	East	B	10.7	IC	1.5	IC	0.4
4	106	62	Silty Sand	East	UT	4.5	IC	1.9	IC	1.3
4	106	64	Silt	East	UT	4.2	UT	5.0	IC	1.6
4	106	66	Silt	East	UT	21.3	UT	22.0	UT	16.5
4	106	68	Silty Clay	East	UT	13.2	UT	13.7	UT	12.7
6	108	42	Silt	West	B	4.3	B	3.7	A2	2.4
6	108	46	Silty Clay	West	B	20.7	IC	21.4	IC	19.1
6	108	50	Silty Clay	West	B	49.5	IC	50.3	IC	50.2
6	108	54	Sand and Gravel	West	B	1.9	B	2.0	A2	0.8
6	108	58	Sand and Gravel	Center	B	5.9	B	5.9	A2	0.6
6	108	61	Sand and Gravel	Center	B	0.9	B	0.9	B	2.0
6	108	63	Sand and Gravel	Center	B	2.9	B	3.0	B	1.5
6	108	65	Sand and Gravel	Center	B	1.2	B	1.2	B	1.1
6	108	67	Sand and Gravel	Center	UT	4.3	UT	4.4	UT	9.3
6	108	69	Silty Sand	East	B	1.0	B	1.0	B	1.1

Notes:

B Particle passed through model to the downgradient boundary
UT Utility tunnel
IC Iron curtain
A1 A1 extraction well
A2 A2 extraction well



LEGEND

PARTICLE TRACK-MARKERS REPRESENT ONE YEAR OF TRAVEL TIME

GROUNDWATER CONTOURS IN FEET ABOVE MSL

FIGURE 7
SITE-WIDE SCALE PARTICLE TRACKING RESULTS FOR PRE-CONSTRUCTION SCENARIO

NOT TO SCALE

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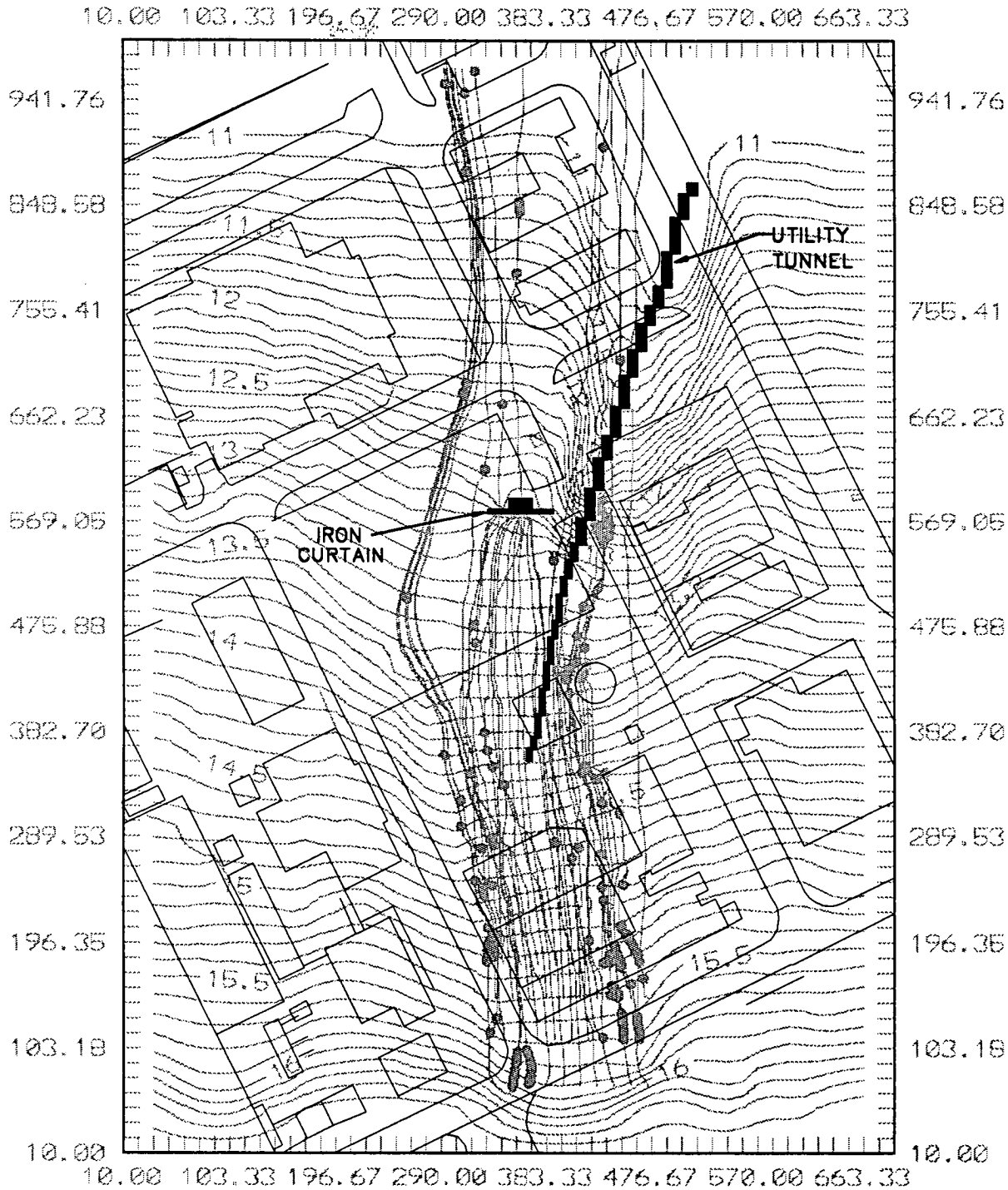
DATE: 04-29-96 DDJ DN



LEGEND

PARTICLE TRACK-MARKERS REPRESENT ONE YEAR OF TRAVEL TIME

GROUNDWATER CONTOURS IN FEET ABOVE MSL

NOT TO SCALE

FIGURE 8
STATE-WIDE SCALE PARTICLE TRACKING RESULTS FOR IRON CURTAIN SCENARIO

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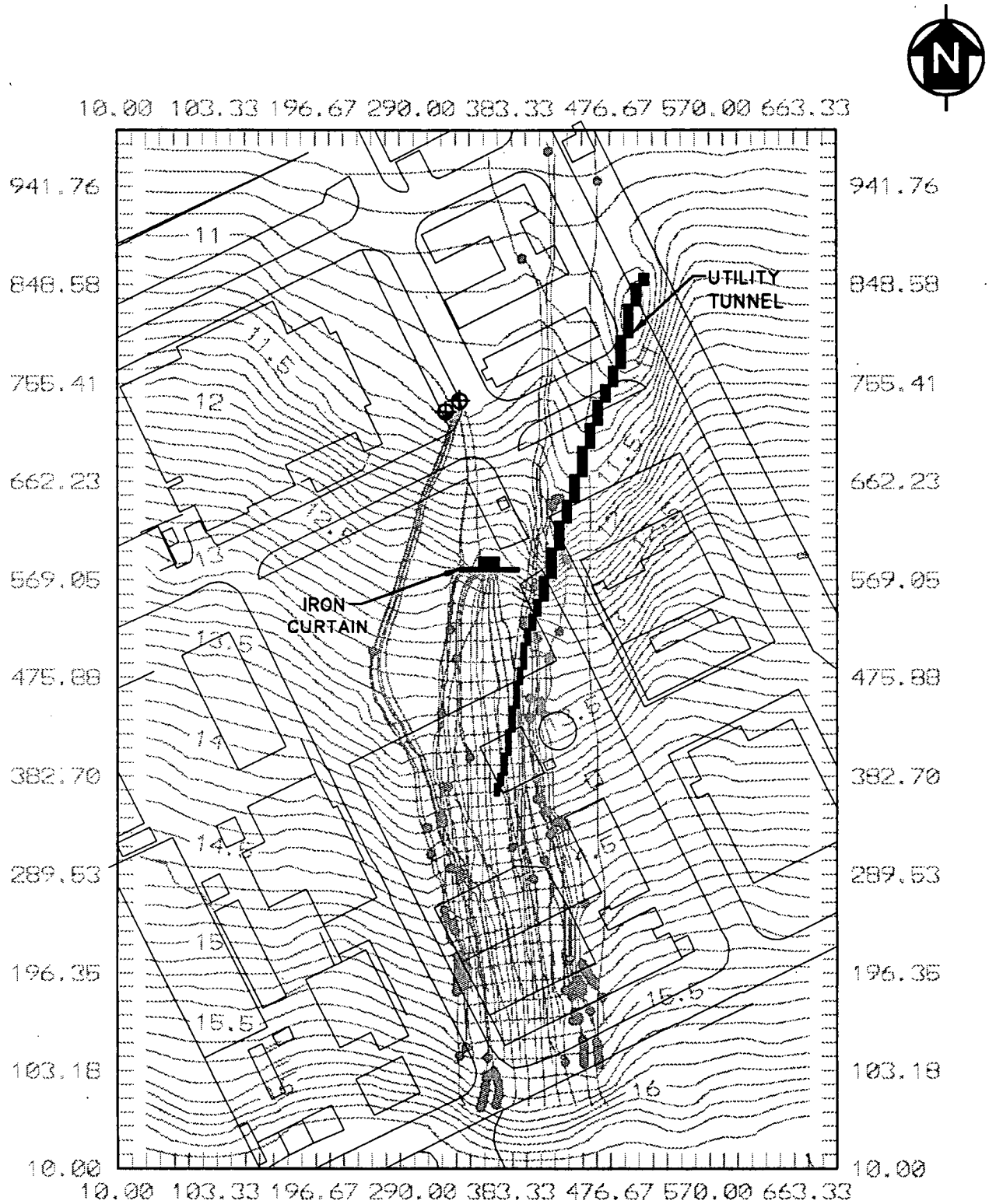
DATE: 04-29-90 DDJ DN



LEGEND

- A1 EXTRACTION WELL (LAYER 3)
- A2 EXTRACTION WELL (LAYER 6)
- PARTICLE TRACK-MARKERS REPRESENT ONE YEAR OF TRAVEL TIME

GROUNDWATER CONTOURS IN FEET ABOVE MSL

NOT TO SCALE

FIGURE 9
SITE-WIDE SCALE PARTICLE RESULTS FOR IRON CURTAIN AND EXTRACTION WELLS SCENARIO

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DATE: 04-29-96 DDJ DN

layers 2, 3 and 4 with the inclusion of the downgradient extraction well pair, implying an increase in iron curtain capture zone. Particle tracks were influenced by heterogeneity of the sediments and the location and strength of hydraulic sinks. The iron curtain was most effective at treating particles that originated in the lower part of the A1 aquifer (layer 4). An upward gradient directed toward the utility tunnel appears to have a significant impact on contaminant movement. Many particles in layers two and three were discharged to the utility tunnel, while most particles in layer 4 were captured by the iron curtain.

Two particles that originated in the silty clay deposits in the A2 aquifer migrated into the A1 zone, to be captured by the iron curtain. The travel times associated with these particles were much greater than those associated with particles that originated in permeable deposits and were subsequently captured by the iron curtain. The travel times of these particles were not greatly reduced by having a downgradient extraction well pair in operation. These results suggest that some contaminants in the low permeability deposits of the A2 aquifer will eventually discharge to the iron curtain, but this process should require a lengthy time frame, even if active stresses are applied to the aquifer. All of the particles that originated in A2 permeable deposits passed through the model, implying that there is little opportunity for this swiftly flowing groundwater to migrate vertically into the A1 to be captured by the iron curtain.

7.0 SENSITIVITY ANALYSIS

A sensitivity analysis was conducted on three parameters: hydraulic conductivity of the channel sand and gravel, vertical anisotropy, and the conductance of the general head boundary cells that constitute the utility tunnel. All of the analyses were conducted on the iron curtain scenario (without extraction wells). The particle velocities obtained during the sensitivity analyses are compared to the 4.1 ft/d value obtained from the iron curtain scenario in Table 3.

Vertical anisotropy and utility tunnel conductances were tested because there are no data to substantiate the values used in the model. The hydraulic conductivity of the channel sand and gravel, however, was based on aquifer test results from the iron curtain area, which should provide a reasonable estimate of this parameter. This parameter was included in the sensitivity analysis because the hydraulic conductivity of the most permeable deposits should have a significant effect on the particle velocity obtained from the model.

TABLE 3

SENSITIVITY ANALYSIS

Parameter Varied	Hydraulic Conductivity of Channel Sand and Gravel (ft/day)	Vertical Anisotropy Ratio	Conductance of Cells Representing Utility Tunnel (ft^2/day)	Particle Velocity (ft/day)
Base Case	150	10:1	400	4.1
Hydraulic Conductivity of Channel Sand and Gravel	75	10:1	400	2.1
Hydraulic Conductivity of Channel Sand and Gravel	300	10:1	400	7.3
Vertical Anisotropy Ratio	150	1:1	400	3.2
Vertical Anisotropy Ratio	150	100:1	400	4.7
Conductance of Utility Tunnel Cells	150	10:1	40	4.1
Conductance of Utility Tunnel Cells	150	10:1	4,000	4.1

Notes: Shaded cells denotes varied parameters

The hydraulic conductivity value assigned to the channel sand and gravel during the model runs was 150 ft/d, which is close to the high value of 169 ft/d calculated from the aquifer test results. The high value was assigned rather than the average value of 53 ft/d because it was assumed that many of the observation wells from which the average hydraulic conductivity value was calculated were located in silty sand, which was included in the model as a separate geologic unit. The values of sand and gravel hydraulic conductivity that were tested in the sensitivity analysis were 300 ft/d and 75 ft/d, which should provide a reasonable range of velocities to use for the design basis of the iron curtain. Particle velocity was relatively sensitive to this parameter, increasing with an increase in the hydraulic conductivity assigned to the sand and gravel lithologic type. The resulting range was 2.1 to 7.3 ft/d.

Vertical anisotropy ratios of 1:1 and 100:1 were used to bracket the ratio of 10:1 used in the model. Particle velocity was moderately sensitive to this parameter, increasing with an increase in anisotropy. Particle velocity was insensitive to changes in the conductance assigned to the general head cells representing the utility tunnel. Values of 40 ft^2/d and 4,000 ft^2/d did not alter the calculated particle velocity of 4.1 ft/d.

8.0 SUMMARY

A three-dimensional numerical model was constructed to support the iron curtain design. The MODFLOW groundwater flow model was used in conjunction with MODPATH particle tracking software to obtain estimates of flow velocity through a section of channel before and after construction of the iron curtain. An additional scenario including an extraction well pair was included to evaluate the change in flow velocity that may accompany the future implementation of an extraction well system in close proximity to the iron curtain. The following particle (groundwater) velocities were calculated: 3.1 ft/d before construction of the iron curtain; 4.1 ft/d after construction of the iron curtain; 5.5 ft/d after construction of the iron curtain and installation of an extraction well pair.

Roughly one-third of the particles that originated in A1 and A2 permeable zones in the Building 88 area were captured by the iron curtain, in the two scenarios that included the iron curtain. The iron curtain was most effective at capturing particles that originated in the target channel, particularly from the lower portion of the channel (layer 4). The capture zone of the iron curtain appears to increase with the addition of a downgradient well pair. Discharge to the utility tunnel caused an upward gradient within the iron curtain area. This allowed contaminants from the finer-grained portion of the A2 aquifer to migrate upward and discharge to the iron curtain.

Sensitivity analyses were conducted on three parameters: hydraulic conductivity of the most permeable lithologic type (channel sand and gravel), vertical anisotropy, and general head boundary cell conductances that control infiltration to the utility tunnel. Particle velocity was very sensitive to changes in hydraulic conductivity, moderately sensitive to changes in vertical anisotropy, and insensitive to changes in utility tunnel conductance. The range of velocity values obtained by varying the hydraulic conductivity of the channel sand and gravel was approximately 2 ft/d to 7 ft/d. This provides a reasonable range in the estimate of flow velocity through the iron curtain.

9.0 REFERENCES

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