**OAK RIDGE
NATIONAL
LABORATORY**

LOCKHEED MARTIN

**PADUCAH GASEOUS DIFFUSION PLANT
NORTHWEST PLUME INTERCEPTOR SYSTEM
EVALUATION**

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NORTHWEST PLUME INTERCEPTOR
SYSTEM EVALUATION**

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PREFACE

The capture zone analysis report for the Northwest Plume was performed under Work Breakdown Structure 7.1.02.18.04 (Activity Data Sheet 5311). This document provides information related to the evaluation of capture zone effectiveness for the Northwest Plume well fields using a numerical flow model.

1.0 INTRODUCTION

The Paducah Gaseous Diffusion Plant (PGDP) Northwest Plume Record of Decision (ROD) states groundwater will be pumped at a rate to reduce further contamination and initiate control of the northwest contamination plume (U.S. DOE 1993). Based on the ROD, four interceptor wells evenly divided between the north and south well fields were installed at the site (Fig.1.1). The initial design study, based on a hydraulic conductivity of 425 ft/d, suggested pumping rates of 100 gal/min per well field would be sufficient for plume containment (Douthitt and Philips 1994). However, during system startup hydraulic conductivities up to 8000 ft/d were estimated in the vicinity of the north well fields (Phillips 1996). The higher than expected hydraulic conductivities raised concerns that the interceptor system, operating as designed, would not be capable of containing the plume. Initial examination of water levels and contaminant concentrations in the vicinity of the two well fields demonstrated that due to the limited number of observation wells it was not possible to characterize well-field capture zones. To alleviate concerns, this study was commissioned to evaluate the capture zones of the north and south well fields operating at the design pumping rate of 100 gal/min per well field. Modified pumping rates capable of plume containment were to be determined if the design pumping rate proved deficient.

This report is organized as follows:

- Section 2 describes the project technical approach.
- Section 3 presents the site hydrogeologic conceptual model which serves as the framework for this study.
- Section 4 provides the rationale for model code selection.
- Sections 5 and 6 describe model configuration and calibration, respectively.
- Section 7 presents simulation results for various pumping scenarios.
- Section 8 discusses model strengths and limitations.
- Sections 9 and 10 present study conclusions and recommendations, respectively.

It is important to note that model predictions are in part a function of model configuration. Models configured differently can satisfy the same calibration criteria but yield different predictive results. In contrast to other site model configurations, this model includes a continuous higher hydraulic conductivity zone between the north and south well fields and anthropogenic recharge from the 001 Outfall ditch. It is possible that other model configurations that do not include these features can satisfy the same calibration criteria but result in different conclusions. Thus, results of this evaluation may not be unique.

Fig. 1.1. Northwest Plume interceptor system well fields.

2.0 TECHNICAL APPROACH

Higher than expected hydraulic conductivities (Phillips 1996) in the vicinity of the north and south well fields raised concerns that the Northwest Plume interceptor system, as presently operating, might not be containing groundwater contamination. To evaluate the impact of higher than expected hydraulic conductivities on capture zone geometries, the use of a sophisticated 3-dimensional groundwater flow and particle tracking model was suggested. Other approaches for evaluating plume hotspot containment such as potentiometric surface mapping and contaminant monitoring have proven ineffective due to the limited number of observation wells and minimal drawdown. To expedite evaluation, an existing 3-dimensional groundwater model was modified and used to perform the capture zone analysis (GeoTrans 1993). Details concerning model modification are presented in Sect. 5. After model modification, the model was calibrated by adjusting model input hydraulic conductivity and recharge parameter values until a reasonable match between observed (target) and model water-level elevations and plume geometry and particle traces were achieved. Model calibration procedures and results can be found in Sect. 6. Once calibrated, the model was used to predict the capture zones for the Northwest Plume interceptor system for various pumping scenarios including the current pumping regime. Section 7 contains capture zone analysis details. Based on model-predicted capture zones, modification to the present pumping regime were proposed.

3.0 CONCEPTUAL MODEL

Three hydrogeologic units, the upper continental recharge system (UCRS), the regional gravel aquifer (RGA), and the McNairy Formation, are present at the PGDP. Complete description of the geologic subunits composing these hydrogeologic units can be found in Clausen et al. (1992 and 1995). The UCRS is approximately 50 ft (15.2 m) thick and is primarily composed of clay and silt with interbedded sand and gravel lenses. Measured UCRS hydraulic conductivities ranging from 5.9×10^{-4} to 13.9 ft/d (2.1×10^{-7} to 4.9×10^{-3} cm/s) reveal the heterogeneity of this hydrogeologic unit. The bulk UCRS hydraulic conductivity is believed to be around 1.0 ft/d (3.5×10^{-4} cm/s) (GeoTrans 1992). Below the UCRS is the RGA, which ranges in thickness from 0 to 50 ft (0 to 15.2 m). Typical RGA hydraulic conductivities range between 50 to 1200 ft/d (1.8×10^{-2} to 0.4 cm/s) (Douthitt and Phillips 1994) with a bulk hydraulic conductivity of 425 ft/d (0.15 cm/s) (GeoTrans 1992). Hydraulic conductivities of up to 8000 ft/d (2.8 cm/s) have been estimated in a higher hydraulic conductivity zone in the vicinity of the north and south well fields (Phillips 1996). Because of the hydraulic conductivity contrast between the UCRS and RGA, groundwater flow is primarily vertical in the UCRS (Clausen et al. 1992 and 1995). Beneath the lower continental deposits resides the McNairy Formation which is composed of several hundred feet of fine sand, silt, and clay. Although the McNairy hydraulic conductivity has never been directly measured, based on analytical analysis the McNairy is thought to be much less conductive than the RGA (Davis 1994).

The UCRS and RGA hydrogeological units are bounded to the south by the Porters Creek Clay, a relatively impermeable unconformity (Clausen et al. 1992 and 1995). The Ohio River, located north of the site, is thought to be the ultimate discharge location for the majority of PGDP groundwater. There are no known hydrologic boundaries affecting the PGDP hydrogeologic units immediately east and west of the site.

Groundwater inflow to the PGDP hydrogeologic units comes from a combination of natural and anthropogenic recharge. Previous modeling studies estimated natural recharge at 4.7 in./year (11.9 cm/year) (McConnel 1992; GeoTrans 1992). Anthropogenic recharge associated with leaking underground fire protection and water supply lines, drainage ditches, and roof drains has never been quantified but is believed to be greater than natural recharge in the immediate vicinity of the PGDP (U.S. DOE 1996).

5.0 MODEL CONFIGURATION

This model was configured by modifying an existing groundwater model constructed by GeoTrans (GeoTrans 1992). The following sections discuss changes made to the GeoTrans model during model configuration. For brevity and to avoid repetitive discussions, wherever possible, references are made to the GeoTrans report.

5.1 MODEL DISCRETIZATION

To better simulate pumping of the two well fields, 52 rows and 11 columns were added to the GeoTrans model resulting in a 169 row $\times$ 102 column model grid (Fig. 5.1). A minimum 50 $\times$ 50-ft grid size was used in the vicinity of the pumping wells and was expanded to a maximum of 900 $\times$ 2200 ft at the Ohio River. Two layers representing the UCRS and RGA were used in the model rather than the three used in the GeoTrans model. The third layer in the GeoTrans model represented the McNairy formation. Analysis of the GeoTrans model water budget showed that only three to four percent of the water entering the RGA discharged to the McNairy. Additionally, particle tracking modeling showed that, according to the GeoTrans model, none of the contamination emanating from the C-400 and Northwest corner source areas reached the McNairy. Thus, the McNairy, as modeled by GeoTrans, had minimal influence on the flow system or contaminant transport and could be removed from the model without significantly affecting model results. GeoTrans established appropriate top and bottom elevations for the model layers from lithologic logs (GeoTrans 1992). The bottom of the RGA represents the bottom of the model. The model grid is oriented on the PGDP coordinate system.

5.2 BOUNDARY CONDITIONS

The following briefly discusses the various boundary conditions used in this model. All boundary conditions are identical to the boundary conditions used in the GeoTrans model (GeoTrans 1992). The rationale for selecting and assigning the various boundary conditions can be found in the GeoTrans report.

No-flow boundaries present in both model layers were assigned to the terrace face of the Plio-Pleistocene erosional surface along the southern edge of the model and on the northern side of the Ohio River (Figs. 5.2 and 5.3). The east and west sides of the model represent no-flow boundaries.

L2calbnd

Paducah Gaseous Diffusion Plant
Paducah, Kentucky

Legend

- VOC concentrations, > 10 ug/l
- VOC concentrations, > 1,000 ug/l
- Rivers and streams
- Buildings
- No Flow Cells

Fig. 5.1. Model grid.

Paducah Gaseous Diffusion Plant
Paducah, Kentucky

L1calbnd

Legend

- VOC concentrations, > 10 ug/l
- VOC concentrations, > 1,000 ug/l
- ~ Rivers and streams
- ▭ Buildings
- No Flow Cells
- ◇ Constant head boundaries
- ▭ River cells

Fig. 5.2. Model layer 1 boundary conditions.

Paducah Gaseous Diffusion Plant
Paducah, Kentucky

F312bnd

Legend

- VOC concentrations, > 10 ug/l
- VOC concentrations, > 1,000 ug/l
- Rivers and streams
- Buildings
- No Flow Cells
- ◇ Constant head boundary

Fig. 5.3. Model layer 2 boundary conditions.

The Ohio River, the settling pond at Tennessee Valley Authority (TVA), and Metropolis Lake are represented as constant head boundaries in the model. The Ohio River constant head boundary, which functions as the primary discharge location in the model, extends into both model layers and is assigned a constant head value of 290 ft (Figs. 5.2 and 5.3). Constant head boundaries representing the TVA settling pond and Metropolis Lake are located solely in model layer 1 and are assigned constant head values of 346 ft and 314 ft, respectively (Fig. 5.2).

Big and Little Bayou Creeks were specified in model layer 1 with MODFLOW's River package (Fig. 5.2). The River package simulates rivers, streams, or creeks as head-dependent boundaries whose base is the bottom of the surface water feature.

5.3 GROUNDWATER SOURCES AND SINKS

Unlike the GeoTrans model, which utilized a single recharge zone representing recharge from precipitation, recharge was applied to two zones within the model (Fig. 5.4).

Similar to the GeoTrans model, the first zone corresponds to recharge from precipitation, termed natural recharge. The second zone represents anthropogenic recharge which is known to occur, but at present, has not been characterized (U.S. DOE 1996). Anthropogenic recharge at the PGDP is expected to come from leaking underground utility lines, roof drains, and ditches. A number of anthropogenic recharge scenarios were evaluated during model configuration and calibration. Scenarios evaluated include configuring all of the facility and only those portions of the facility having water levels less than 10-ft below ground surface as anthropogenic recharge zones. The best match of particle traces to plume geometry occurred when only the 001 Outfall ditch was simulated as a source of anthropogenic recharge. Average flow in the unlined 001 Outfall ditch from 1987 through February 1996 was 1.9 million gallons per day (Mgd). During August 1991, the period against which the model was calibrated, average discharge was 1.4 Mgd. The potential for significant recharge to occur from the 001 Outfall ditch is great because the ditch is unlined and transmits a large quantity of water. No recharge was applied to a third zone representing areas of the PGDP where buildings and pavement are present. Predicted recharge rates for the two zones are presented in Sect. 6.

Four RGA interceptor wells, two each in the north and south well fields, are located within the model domain (Fig. 5.5). Each of the interceptor wells currently pumps at approximately 50 gal/min (9625 ft³/d) for a combined total of 200 gal/min (38,500 ft³/d), which is the maximum design capacity of the treatment system.

Paducah Gaseous Diffusion Plant
Paducah, Kentucky

Licalrec

Fig. 5.4. Model recharge distribution.

5.4 HYDRAULIC CONDUCTIVITY

Six hydraulic conductivity zones, two in model layer 1 and four in model layer 2, were used in the model (Figs. 5.6 and 5.7). With the exception of the two hydraulic conductivity zones representing the higher RGA hydraulic conductivity zone, inferred from the Northwest Plume aquifer test (Phillips 1996), the distribution of the various hydraulic conductivity zones in this model is similar to the GeoTrans model. The location and geometry of the higher hydraulic conductivity zone were determined from lithologic information, aquifer test results, and plume geometry. The two hydraulic conductivity zones within the higher hydraulic conductivity zone are based on aquifer test results and are an attempt to simplify a complex hydrogeologic system. Hydraulic conductivity values used in the model are presented in Sect. 6.

Fig. 5.6. Model layer 1 hydraulic conductivity distribution.

5-10

Paducah Gaseous Diffusion Plant
Paducah, Kentucky

L2calhc

- ~ Rivers and streams
 Buildings
 No Flow Cells
- Legend
 VOC concentrations, > 10 ug/l
 VOC concentrations, > 10,000 ug/l

Parameter	Calibrated value, ft/d	Parameter	Calibrated value, ft/d
RGA	425.00	RGA - channel edges	2500.00
RGA - Ohio River	21.40	RGA - channel middle	5000.00

Fig. 5.7. Model layer 2 hydraulic conductivity distribution.

6.0 MODEL CALIBRATION

The following sections discuss calibration procedure, estimates of aquifer properties, predicted water levels, and plume flow paths.

6.1 CALIBRATION PROCEDURE

The model was calibrated to August 15, 1991 water-level elevations and to the Northwest Plume geometry. The rationale for selecting these target water-level elevations can be found in the GeoTrans modeling report (GeoTrans 1992). During model calibration, parameter values representing hydraulic conductivity and recharge zones were adjusted to produce a model that best approximated target water-level elevations from 75 UCRS and RGA wells. Additionally, model input parameters were adjusted to obtain the best match between the Northwest plume geometry and particle traces originating from known contaminant sources. Any model that could not replicate the Northwest plume geometry, regardless of the match between target and model predicted heads, was discarded. The rationale was that if the model could not simulate plume geometry then the model could not be used for capture zone evaluation.

Parameter estimation using a non-linear regression technique developed by Doherty et al. (1994) was used to obtain estimates and 95% confidence intervals for all sensitive, non-correlated model input parameters. Table 6.1 lists model parameters and sensitivity and correlation status. A parameter is considered sensitive when changes in the parameter value produce measurable changes in the calibration error of the model, the difference between measured and model results. For example, both natural and anthropogenic recharge are sensitive parameters (Fig. 6.1). Small percentage changes in recharge rates produce measurable changes in the model calibration error.

Nonsensitive parameters have little or no influence on the model calibration error for all reasonable input values. An example of an insensitive parameter within the model is the hydraulic conductivity of the UCRS alluvium in the vicinity of the Big and Little Bayou Creeks (Fig. 6.1). Large percentage changes in UCRS alluvium hydraulic conductivity result in minimal changes in model calibration error, the difference between target and model heads. Because the nonsensitive parameters could not be estimated, reasonable values were determined from available data and held constant during model calibration (Table 6.1).

Correlated parameters have an optimum value that is dependent on the value of another model parameter. For example, in a Darcy column there are an infinite combination of discharge (recharge) and hydraulic conductivity values that will result in the same hydraulic head distribution. Because discharge and hydraulic conductivity are correlated, to

Table 6.1. Model parameter values and sensitivity and correlation status

Parameter	Parameter value, ft/d	Sensitive	Correlated
UCRS hydraulic conductivity	1.23	Yes	No
UCRS alluvium hydraulic conductivity	2.5	No	No
RGA hydraulic conductivity	425.0	Yes	No
RGA at the Ohio River hydraulic conductivity	21.4	Yes	Yes*
RGA channel edges hydraulic conductivity	2500.0	Yes	Yes*
RGA channel middle hydraulic conductivity	5000.0	No	No
Natural recharge	8.76×10^{-4}	Yes	No
Anthropogenic recharge	2.43×10^{-2}	Yes	No
Vertical RGA hydraulic conductivity**	8.75×10^{-4}	Yes***	No

Shaded text indicates parameters that can be and were estimated using parameter estimation techniques.

* These parameters were correlated to all other input parameters.

** All other hydraulic conductivities were assumed to be 10% of the corresponding horizontal hydraulic conductivity.

*** Proved to be so sensitive that small charges resulted in large increases in model calibration error, the difference between target and model heads.

Sensitivity Analysis

Fig. 6.1. Sensitivity analysis.

predict one it is necessary to know the other. Parameter estimation results demonstrated that the hydraulic conductivities of the RGA and the RGA channel edges were highly correlated to most of the other model input parameters and could not be estimated using parameter estimation techniques. Thus, reasonable values for these model input parameters were determined from available data and held constant during model calibration (Table 6.1).

6.2 ESTIMATES OF AQUIFER PROPERTIES

Parameter estimation was used to determine the best values for the remaining four sensitive, noncorrelated model input parameters (Table 6.1). Vertical hydraulic conductivities were not estimated because, while sensitive, small changes in hydraulic properties resulted in large changes in model error (the difference between target and model leads). Thus, parameter estimation could not improve upon the vertical hydraulic values used in the model. The hydraulic conductivity of the UCRS was estimated to be 1.23 ft/d (4.3×10^{-4} cm/s) with a 95% confidence interval between 0.88 to 1.71 ft/d (3.1×10^{-4} to 6.0×10^{-4} cm/s). Many of the slug tests performed on UCRS wells measured hydraulic conductivity values in this range suggesting the model input value is reasonable (CH2M Hill 1992). For comparison, in the GeoTrans model the UCRS was assigned a hydraulic conductivity value of 1.0 ft/d (3.5×10^{-4} cm/s).

The hydraulic conductivity of the RGA at the Ohio River was estimated to be 21.4 ft/d (7.6×10^{-4} cm/s) with a 95% confidence interval between 1.96 to 233.90 ft/d (6.9×10^{-4} to 8.3×10^{-2} cm/s). Because the RGA hydraulic conductivity near the river has not been measured it is difficult to assess the reliability of the prediction. However, even considering the extremes of the confidence interval, the predicted value is less than the RGA hydraulic conductivity value used in the model, suggesting that there is indeed a difference in hydraulic conductivity between the two zones and it is appropriate to include a separate hydraulic conductivity zone within the model for the RGA adjacent to the Ohio River. Further evidence is provided in Clausen et al. (1995) which presented data showing an increase in gradient near the Ohio River, which could be associated with a reduction in hydraulic conductivity. Deposition of sediment within the Ohio River could have deposited silt along the RGA/river interface. For comparison, in the GeoTrans model, the RGA at the Ohio River was assigned a hydraulic conductivity value of 96.0 ft/d (3.4×10^{-3} cm/s), which is within the parameter's predicted 95% confidence interval.

Recharge from precipitation (natural recharge) was estimated to be 8.76×10^{-4} ft/d (3.84 in./year) with a 95% confidence interval of 7.31×10^{-4} ft/d to 1.02×10^{-3} ft/d (3.02 in./year to 4.47 in./year). Previous modeling studies had estimated recharge from precipitation to be 1.07×10^{-3} ft/d (4.7 in./year) (McConnell 1992; GeoTrans 1992). However, previous modeling efforts lumped anthropogenic and natural recharge together

as one input parameter. Although never directly measured, anthropogenic recharge is expected to be greater than natural recharge at PGDP (U.S. DOE 1996). Thus, a recharge value that combines anthropogenic and natural recharge is expected to be greater than one representing natural recharge alone.

Parameter estimation predicted the recharge rate from the 001 Outfall Ditch to be 2.43×10^{-2} ft/d (106.4 in./year) with a 95% confidence interval of 1.94×10^{-2} ft/d to 2.91×10^{-2} ft/d (84.9 in./year to 127.4 in./year). Average flow in the 001 Outfall ditch during August 1991, the time period against which the model was calibrated, was 1.4 Mgd. The predicted recharge rate from the 001 Outfall represents approximately 25% of the 1.4 Mgd. Assuming a flow length of 5000 ft before leaving plant property, to maintain the model predicted recharge rate, the ditch would need to leak at a rate of 4.86×10^{-2} gal/min per linear foot. Given this minimal leakage rate, the predicted recharge rate from the 001 Outfall ditch is reasonable.

6.3 PREDICTED WATER LEVELS

Water-level calibration targets as well as calibration results for the overall model domain are listed in Table 6.2. Thirty targets are in the UCRS (model layer 1) and 45 targets are in the RGA (model layer 2). As expected, the match between layer 2 target and model water levels was better than the match between layer 1 target and model water levels. Model predicted water levels represent the water level at the center of a model node. Few, if any, of the wells from which target water levels were obtained are screened across elevations corresponding to the middle of the model nodes. The impact of screen elevation on being able to match target water levels is far greater in the UCRS relative to the RGA. Groundwater flow in the RGA is primarily horizontal (U.S. DOE 1996; Clausen et al. 1995; Clausen et al. 1992), meaning there is not much change vertically in water-level elevations from the top to the bottom of the RGA. Thus, essentially the same water level will be recorded regardless of where a well is screened vertically in the RGA. A strong vertical flow component is present in the UCRS as evidenced by near unity vertical hydraulic gradients (U.S. DOE 1996). A unity gradient means that every foot elevation change produces a foot change in water-level elevation. Consequently, water levels from wells screened at the top or bottom of the UCRS will be significantly different from wells screened at the middle of the UCRS, which corresponds to the model predicted water level.

The calibrated model was also evaluated using lump sum statistics such as the residual mean, residual standard deviation, sum of the differences squared, and absolute residual mean (Table 6.3). Lump sum statistics represent model calibration error as a single number. A perfectly calibrated model will produce a lump sum statistic of zero.

Table 6.3. Lump sum calibration statistics

Statistic	All	Layer 1	Layer 2
Residual Mean	-1.25	-1.65	-0.98
Residual Standard Deviation	3.60	5.48	1.24
Sum of the Differences Squared	1090	982	108
Absolute Residual Mean	2.50	4.30	1.29

Source of statistical formulas: Rumbaugh, J. O., and D. B. Rumbaugh. 1996. *Guide to Using Groundwater Vistas*. Environmental Simulations, Inc., Herndon, VA.

The fact that all the lump sum statistics, with the exception of the sum of the differences squared (which squares and sums the target and model differences), are near zero suggests that the calibration of the model is good. For comparison the sum of the differences squared, residual mean, and residual standard deviation for the GeoTrans model were 1387.0, 0.878, and 3.35, respectively.

The model predicted UCRS and RGA potentiometric surfaces are similar to the UCRS and RGA target potentiometric surfaces (Figs. 6.2 through 6.5). Both the model and target UCRS potentiometric surface show a radial pattern surrounding a potentiometric high located over the northwest quadrant of the plant surrounded by a radial decreasing potentiometric surface. The similarities in the model and target potentiometric surfaces suggest that the calibration of the model is good.

Figure 6.6 is a plot of model vs target water levels. For a perfect calibration, the model and target water levels would be equal, and all the data points would lie on the 45° line. The data points, representing model and target water-level comparisons, cluster tightly around the 45° line, indicating that the calibration of the model is good.

6.4 PREDICTED PLUME FLOW PATHS

Dense non-aqueous phase liquid (DNAPL), primarily TCE, is speculated to be present at both the C-400 and Northwest Corner source areas (Clausen et al. 1995). Typically, most DNAPL is found at the base of a flow system, which at the PGDP would be the RGA, with minor amounts residing in the overlying strata, which at the PGDP would be the UCRS, as residual ganglia.

Figure 6.7 shows the model-predicted flow paths from the C-400 Building and Northwest corner source areas. The flow paths were determined using particle tracking. Particle tracking allows particles placed in the model-generated flow domain to move in a series of small steps dictated by the hydraulic gradients. Connecting the location of an individual particle for each time step results in a particle trace that corresponds to a flow path. All of the particles originating in the RGA from the C-400 Building and Northwest Corner source areas, where most of the DNAPL is expected to be located, follow the general path of the Northwest plume suggesting that the model reasonably simulates the flow field. However, in the immediate vicinity of the two source areas the plume path could not be exactly replicated. Data collected by Clausen et al. (1995) suggests that the plume originating from the C-400 Building intersects the plume originating from the Northwest Corner source area. Particle traces from the C-400 Building pass several hundred feet to the east of the Northwest Corner source area.

Figure

Potentiometric surface of the UCRS on August 15, 1991.

GeoTrans, inc.

Fig. 6.2. Potentiometric surface of the UCRS on August 15, 1991.

Paducah Gaseous Diffusion Plant
Paducah, Kentucky

Llcalwir

Legend

- VOC concentrations, > 10 ug/l
- VOC concentrations, > 1,000 ug/l
- Potentiometric surface, ft msl
- Rivers and streams
- Buildings
- No Flow Cells
- River cells
- Constant head boundaries

Fig. 6.3. Model predicted UCRS potentiometric surface.

Fig. 6.4. Potentiometric surface of the RGA on August 15, 1991.

Paducah Gaseous Diffusion Plant
Paducah, Kentucky

L2calwir

Legend

- VOC concentrations, > 10 ug/l
- VOC concentrations, > 1,000 ug/l
- Potentiometric surface, ft msl
- Rivers and streams
- Buildings
- No Flow Cells
- River cells
- Constant head boundaries

Fig. 6.5. Model predicted RGA potentiometric surface.

Fig. 6.6. Plot of model vs target water levels.

**Paducah Gaseous Diffusion Plant
Paducah, Kentucky**

Legend

- VOC concentrations, > 10 ug/l
- VOC concentrations, > 1,000 ug/l
- Particle traces
- Rivers and streams
- Buildings
- No Flow Cells
- Source areas

Fig. 6.7. Particle traces from source areas to the Ohio River.

Interestingly, a few of the particles originating in the UCRS in the vicinity of the C-400 Building, where residual DNAPL ganglia are likely to be found, flow east of the main plume in the RGA to the Ohio River. Low levels of volatile organic compound (VOC) contamination have been detected in RGA wells in the northeast portion of the PGDP suggesting that these flow paths are reasonable.

The eastern most contaminant flow path is represented by a concentration of particle traces (Fig. 6.7). It is likely that the flow paths of these particle traces are influenced by the no-flow boundary along the east side of the model domain. If the model domain were extended further to the east, these particle traces might follow the path of the Northeast plume. Thus, based on this model, it is possible that the C-400 Building source contributes to both the Northwest and Northeast plumes.

Contaminant concentrations within the two plumes support this hypothesis. Contaminant concentrations in the Northeast plume are less, relative to contaminant concentrations in the Northwest plume. Modeling shows that contamination located in the RGA under the C-400 Building follows the path of the Northwest plume. Conversely, contamination located in the UCRS under the C-400 Building follows the path of the Northeast plume. DNAPL, specifically TCE, is the source of the C-400 Building contamination. Based on expected DNAPL distribution patterns most of the free phase TCE should be located in the RGA. A smaller amount of free phase TCE should be located in the UCRS. Thus, while not conclusive, the modeling results suggests that the C-400 Building source contributes to both the Northwest and Northeast plumes. Other sources may also contribute to both plumes.

Of interest, modeling also showed that if anthropogenic recharge from the 001 Outfall ditch was removed from the model, particles originating in both the UCRS and RGA followed the Northwest plume. If anthropogenic recharge from the 001 Outfall ditch was increased, a greater percentage of the UCRS particles followed flow paths east of the Northwest plume. While not conclusive, these results suggest that anthropogenic recharge from the 001 Outfall ditch influences the Northeast plume.

It is important to note that the WAG 6 investigation identified other potential sources of anthropogenic recharge. While unquantified, it is likely that these sources in addition to the 001 Outfall ditch influence contaminant migration at the site.

7.0 PREDICTIVE SIMULATIONS

Three predictive simulations were performed to determine the capture zones of the Northwest Plume interceptor systems north and south well fields for various pumping scenarios. Each well field consists of two wells. The first simulation determined the capture zones for the wells operating under the current pumping scenario of 50 gal/min (9625 ft³/d) well. A second simulation determined the optimum pumping rates for the four wells, defined as the minimum rates needed to contain contamination emanating from source areas. The final simulation determined the optimal pumping rates required to contain contamination emanating from the two source areas using only the two wells in the south well field. All simulations assumed UCRS and RGA porosities of 0.40 and 0.25, respectively (Hughes et al. 1996 and McConnell 1992).

7.1 CURRENT PUMPING SCENARIO

Because of treatment system limitations, the combined pumping rate for both the north and south well fields presently can not exceed 200 gal/min (38,500 ft³/d). Pumping currently is divided evenly between the four wells at approximately 50 gal/min (9625 ft³/d) per well. Figure 7.1 shows the well field capture zones for interceptor system operating at maximum treatment capacity. Contamination emanating from the Northwest source area is contained by the south well field. The north well field capture zone contains groundwater contamination east of the C-400 Building. The C-400 Building, a known source area, lies between the two capture zones. Thus, as modeled, contamination emanating from the C-400 Building source eludes capture.

This analysis contradicts a previous study that predicted the plume and source areas would be contained at pumping rates of 50 gal/min (9625 ft³/d) per well (Phillips et al. 1996). The previous study assumed RGA hydraulic conductivities of approximately 1000 and 2500 ft/d (0.35 to 0.88 cm/s) for the south and north well fields, respectively. A pumping test conducted at the south and north well fields determined hydraulic conductivity to be approximately 1200 and 5000 ft/d (0.42 and 1.8 cm/s), respectively, in the vicinity of the well fields. Capture zone width is inversely proportional to hydraulic conductivity. Thus, based solely on the pumping test hydraulic conductivity data, for the same pumping rates, the capture zone widths for the north well field is expected to be about twice as small as those predicted by Phillips (1996).

Douthitt and Phillips (1994) predicted capture zone widths of 1200 ft for both the north and south wells fields when operated at 100 gal/min per well field. However, the measurement locations of the capture zone widths were not reported. This study's modeled north and south well field capture zones (measured parallel to the north PGDP perimeter fence) are approximately 500-ft and 650-ft wide, respectively. The plume hotspot

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Fig. 7.1. Capture zones for wells pumping at 50 gal/min.

(defined as TCE contributions greater than 1000 µg/L) at the same location, is approximately 2000-ft wide. Thus, as presently operated, the Northwest Plume interceptor system appears incapable of containing the plume hotspot.

7.2 OPTIMUM PUMPING SCENARIO FOR THE NORTH AND SOUTH WELL FIELDS

Optimum pumping rates for the wells in the north and south fields were determined to be 200 gal/min (38,500 ft³/d) per well and 75 gal/min (14,438 ft³/d) per well, respectively, for a combined pumping rate of 550 gal/min (105,875 ft³/d). At these pumping rates both the C-400 Building and Northwest Corner source areas are within the south well field capture zone (Fig. 7.2). Maintaining both source areas within the south well field capture zone is important because, in response to pumping, plume concentrations may sufficiently decline such that the north well field is no longer necessary. The north well field capture zone surrounds the south well field capture zone providing additional source area containment. Portions of the plume outside the capture zones, having VOC contaminant concentrations up to 1,000 µg/L, will ultimately discharge to the Ohio River. Because the source areas are contained, contaminated groundwater outside the capture zones will eventually be replaced with clean groundwater and contaminant concentrations will drop.

The optimum pumping rates required to contain the plume were determined using the calibrated model input parameters which individually represent the best value for a range of parameter values. For example, consider the hydraulic conductivity of the RGA. A value of 425 ft/d (0.15 cm/s) was used in the model to represent hydraulic conductivities that have been determined from aquifer tests to range from approximately 100 to 800 ft/d (3.5×10^{-2} to 0.28 cm/s). For robustness, the optimized pumping scheme should contain the plume for all RGA hydraulic conductivity values within this range. In addition to the RGA hydraulic conductivity, the optimized pumping scheme should also contain the plume over the expected range of all other model input parameters.

Capture zone analysis was performed for all the minimum and maximum input parameters listed in Table 7.1. Where possible, the extremes of the 95% confidence limits (as predicted using parameter optimization) were used as minimum and maximum model input values. For other input parameters, the range of measured values was used to determine minimum and maximum model input values. For the UCRS alluvium hydraulic conductivity (which has never been measured) the minimum and maximum input values were assumed to be an order of magnitude less and greater than the model input parameter. During a simulation, all input parameters other than the parameter of interest were held constant at their calibrated values. Complete capture was achieved for all simulations. This demonstrates that the optimum pumping rates are robust for a wide range of possible parameter values.

7-4

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Legend

- VOC concentrations, > 10 ug/l
- VOC concentrations, > 1,000 ug/l
- Particle traces, north well field
- Particle traces, south well field
- Rivers and streams
- Buildings
- No Flow Cells
- Source areas

Fig. 7.2. Capture zones for optimum pumping rates.

Table 7.1. Model calibrated, minimum, and maximum input parameter values, ft/d

Parameter	Calibrated value	Minimum value	Maximum value
UCRS hydraulic conductivity	1.23	0.88	1.71
UCRS alluvium hydraulic conductivity	2.50	0.25	25.00
RGA hydraulic conductivity	425.00	53.00	1475.00
RGA at the Ohio River hydraulic conductivity	21.40	1.96	233.90
RGA channel edges hydraulic conductivity	2500.00	1000.00	5000.00
RGA channel middle hydraulic conductivity	5000.00	2500.00	8000.00
Natural recharge	8.76×10^{-4}	7.31×10^{-4}	1.02×10^{-3}
Industrial recharge	2.43×10^{-2}	1.94×10^{-2}	2.91×10^{-2}

Particle tracking suggests that approximately ten years will be required to remove one pore volume of contaminated groundwater from the aquifer. A pore volume is defined here as the volume of contaminated groundwater located within the capture zones between the well fields and source areas. Time to remove one pore volume for both well fields is similar primarily because of variability in hydraulic conductivity. The south well field capture zone extends into the lower hydraulic conductivity portions (425 ft/d (0.15 cm/s) of the RGA. In contrast, the north well field capture zone is confined primarily within the highly transmissive zone where hydraulic conductivities are believed to be between 2500 and 5000 ft/d (0.88 to 1.8 cm/s). All else being equal, the higher the hydraulic conductivity the faster the capture zone development. Thus, even though the north well field is further from the source areas, the time required to remove one pore volume is similar to the south well field. Pore volume removal rates should not be equated with the time required to remediate to current drinking water standards. Numerous studies suggest that when DNAPL is present tens to hundreds of pore volumes will need to be removed to achieve drinking water standards (National Research Council 1994).

Particle tracking also suggests that approximately eleven years will be required for all groundwater contamination located outside capture zones to reach the Ohio River. Again, this time should not be equated with the time required to achieve drinking water standards. Because of matrix diffusion, it will take more than 11 years to achieve drinking water standards outside the well field capture zones (National Research Council 1994).

7.3 OPTIMUM PUMPING SCENARIO FOR THE SOUTH WELL FIELD

Because the previous simulation demonstrated that both source areas can be contained by the south well field, in the future it may be desirable to turn off the north well field and rely solely on the south well field for containment. Optimum south well field pumping rates were determined to be 75 gal/min per well for a combined pumping rate of 150 gal/min. At these pumping rates, both the C-400 Building and Northwest source areas are within the south well field capture zone (Fig. 7.3). Particle tracking demonstrated that ten years will be required to remove one pore volume of contaminated water from the aquifer. Similar to the previous simulation, complete capture was achieved for the full range of parameter values listed in Table 7.1.

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Legend

- VOC concentrations, > 10 ug/l
- VOC concentrations, > 1,000 ug/l
- Rivers and streams
- Buildings
- No Flow Cells
- South well field
- Source areas

Fig. 7.3. Capture zone for south well field pumping at optimum rates.

8.0 MODEL EVALUATION

Calibration results demonstrate that the model adequately simulates the groundwater flow regime at the PGDP and can be used to predict the capture zones of the north and south well fields. However, the overall mass balance error for the model (the difference between water entering and leaving the model domain) was 10%. In some portions of the model, the mass balance error approached 50%. Mass balance errors for most models are under 1%. Although not reported, the original GeoTrans model suffered from the same mass balance problem, which is related to the large head differences between model layers 1 and 2, representing the UCRS and RGA, respectively.

9.0 CONCLUSIONS

Results of the interceptor system evaluation support the following conclusions :

- As presently operated, the interceptor system is marginally effective in containing the Northwest plume hotspot. This conclusion contradicts a previous study which suggested that containment was possible at 50 gal/min/well (Phillips 1996). The difference in conclusions can be attributed to a high hydraulic conductivity zone in the vicinity of the two well fields.
- Pumping rates of 75 gal/min per well in the south well field and 200 gal/min per well in the north well field are necessary to contain the plume.
- The south well field alone is capable of containing contamination emanating from the C-400 Building and Northwest Corner source areas at a well field pumping rate of 150 gal/min.
- Approximately ten years will be required to remove one pore volume of contaminated groundwater from the aquifer. A pore volume is defined as the volume of contaminated groundwater located within the capture zone between the well field and source area.
- Model results may only be valid for periods of low Ohio River stage and may not adequately portray actual capture zones during periods of high river stage during which RGA groundwater flow is primarily eastward.

10.0 RECOMMENDATIONS

- Groundwater modeling suggests that anthropogenic recharge associated with the 001 Outfall ditch could be contributory to the development of the Northeast plume. A study should be conducted to characterize the interaction of the 001 Outfall and other ditches with shallow groundwater. Additionally, predictive modeling should be undertaken to develop a better understanding of how changes in ditch discharge rates affect contaminant migration at the site.
- To alleviate potential mass balance problems future groundwater models should simulate the UCRS with multiple model layers rather than with a single model layer.
- The model simulated the PGDP flow system as a steady-state flow system. In reality the flow system is transient and responds to precipitation events, fluctuating leakage rates from ditches and underground utilities and changes in Ohio River stage. Investigations should be undertaken to determine if these perturbations cause significant temporal changes in the PGDP flow field. If any of these perturbations prove to be significant then a transient flow model that includes these temporal perturbations should be constructed and used to evaluate the interceptor system.
- Efforts should be made to better characterize the interaction of the Terrace Gravels and the PGDP groundwater flow system. Additionally, predictive modeling should be undertaken to develop an understanding of how temporal changes in Terrace Gravel discharge rates affect contaminant migration at the site.
- In addition to anthropogenic recharge, the presence of a zone of higher RGA hydraulic conductivity zone between the two well fields greatly influenced model particle paths. Without the combination of anthropogenic recharge and the higher hydraulic conductivity zone, particle traces did not follow the path of the Northwest Plume. Future modeling should focus on evaluating the effects of heterogeneity, such as the higher hydraulic conductivity zone, on groundwater flow and plume configuration.
- The eastern no-flow model boundary influences the migration paths of particles migrating from C-400 to the northeast. Better simulation of the flow system and portrayal of the Northeast Plume configuration may be possible by expanding the eastern no-flow model boundary to the east.
- Although the McNairy Formation, as represented in the GeoTrans model, was determined to minimally influence groundwater flow and contaminant transport, future models should include the McNairy Formation so that the hydraulic relationship between it and the other hydrogeologic units can be better understood.

11.0 REFERENCES

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APPENDIX A

REPORT COMMENTS AND RESPONSES

U.S. DEPARTMENT OF ENERGY OAK RIDGE OPERATIONS		DESIGN REVIEW RECORD	
Project Title: <u>Paducah Gaseous Diffusion Plant Northwest Plume Interceptor System Evaluation</u>		Date: <u>11/6/96</u>	
Job Title: <u>Alan Laase and Jay Clausen</u>		Transmittal No.: _____	
Item No.	Drawing or spec. no. & paragraph	Comments	A-E Action
1	Drew Diefendorf LMER General Comment	<p>My comments on the report are based on the observation that we continue to mold the conceptual hydrogeologic model of the site to fit our arguments. The report clearly supports my concern that:</p> <ol style="list-style-type: none"> 1. We have not adequately defined the recharge effects from the terrace deposits and Bayou and Little Bayou Creeks. 2. The industrial hydrogeology, in particular, anthropogenic sources and sinks of groundwater have not been adequately defined. <p>Both of these issues were noted as objectives for the Phase I Hydrogeologic investigation, but were never achieved. While the modeling effort included potential effects from the 001 Outfall, it did not include effects from other natural and anthropogenic sources and sinks as outlined above.</p>	<p>Agree, but models are supposed to be molded to our conceptual model when there is a lack of data. We agree recharge has not been adequately defined at the site, however in the absence of hard data assumptions were used in the model. The objective of this model was to assess the Northwest Plume capture zones with the available data, not to define recharge rates. The current modeling effort utilized the assumptions of hydraulic conductivity for the creeks assigned by GeoTrans in 1992. These assumptions were agreed upon by LMES during modeling development by GeoTrans and appear reasonable in the absence of real data. Modeling is an iterative process where one builds upon the assumptions as new data is collected until a point is reached that additional data won't effect the model outcome. We feel we made an attempt to build upon the previous modeling activities by incorporating data and conceptual ideas where appropriate. Until LMES can convince DOE and regulators for the need of recharge data we will have to make assumptions. The alternative is to not model until we have all of the hard data covering all aspects of the hydrologic cycle. We don't feel this approach would be acceptable to our client, DOE.</p> <p>Text will be added to state a number of recharge scenarios were simulated. However, the best results were achieved by adding recharge along the 001 Outfall and no recharge in the central portion of the plant where large buildings and pavement exist. We agree anthropogenic recharge needs to be quantified but it was beyond the scope of this project to assess the impact of recharge. We tried a number of recharge scenarios. The scenario modeled resulted in the best match of the Northwest plume. In our opinion, if plume geometry is not simulated correctly it makes little sense to perform capture zone analysis. Are our assumptions correct? Given the data available, namely discharge rates from Outfall 011, and the inputs had the desired effect of shifting the modeled plume into alignment with the actual plume the assumptions appear reasonable.</p>

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Item No.	Drawing or spec. no. & paragraph	Comments	A-E Action
2	Drew Diefendorf LMER General Comment	The discovery of the heretofore undocumented channel seems somewhat contrived. Where is the geometry of this channel documented in previous reports.? While it is probable that channel deposits exist within the RGA, it is also probable that they occur as a far more complex system of remnant channel cutoffs, lenses and other somewhat anastomosing bodies wherein the RGA can generally be treated as a singular, albeit heterogeneous, hydrologic unit.	The text will be changed to explain that the high hydraulic conductivity zone is an oversimplification of actual field conditions. Text referencing a "channel" will be deleted throughout the document. Our attempt was to introduce heterogeneity into the model without adding too many complexities. We understand in reality that a braided river deposit will consist of a number of high hydraulic conductivity zones which may or may not be continuous due to reworking of material. Also, we considered that these deposits are likely distributed in three dimensions and consist of singular bodies superimposed next to each other. The hydraulic conductivity values used in the model are based on the high end of the pump test transmissivity data results presented in Phillips (1996). The well field aquifer tests revealed higher than expected hydraulic conductivity values. Given that the plume is continuous between the well fields isn't it also reasonable to expect that the higher hydraulic zone conductivity zone is also continuous? Given the model results agree quite well with actual plume configuration and are much better than previous modeling efforts by GeoTrans, McConnel, Wang, and Jacobs we feel this is a reasonable assumption. Furthermore, existing braided river channels are quite sinuous. We don't believe it is unreasonable to assume the normal east west system had a northerly bend in the area of the Northwest plume and then bent back to the west in the vicinity of the Ohio River. Also, transverse distribution of gravels as bars is common in braided river deposits. Another explanation could be that the high K zone represents an single storm event. If the material is coarse enough it is possible that subsequent storm events lacked the energy to rework these deposits. Additionally, some cross sections perpendicular to the Northwest Plume in Clausen et al. 1995 (KY/ER-66) seem to suggest an erosional low at the top of the McNairy Formation, although this is based on drive point data. Until detailed coring of transects in the Northwest Plume are completed this possibility cannot be definitively proven. On the other hand, until an alternative hypothesis is presented that can explain the current plume configuration and can be simulated with a model we stand by our hypothesis and current modeling results until proven otherwise.

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Item No.	Drawing or spec. no. & paragraph	Comments	A-E Action
3	Drew Diefendorf LMER General Comment	There appears to be some difficulty in evaluating piezometric levels in the vicinity of the recovery field. This needs to be explained and addressed. If we cannot measure the effects of pumping in the field as seems to be the case, how can we apply useable field data to a model or its calibration.? It's difficult to convince me, if you can't measure draw down adequately with the current monitoring system, how will you prove the effectiveness of doubling of the recovery rate?	Text will be added to explain the difficulty in assessing the cone of depression given the small head changes. The drawdown from pumping activities has no relevance to the model. The model was calibrated with head data collected prior to pumping activities. One needs to keep in mind that drawdown and the development of a cone of depression will not be the same as the capture zone in our type of hydrologic system. Even if we could measure drawdown it won't tell you the extent of the capture zone. Contaminants can be captured beyond the drawdown since the stream tubes up gradient of the well field will be bent towards the pumping wells. The only way it appears to assess the extent of the capture zone is through modeling or possibly with the colloidal bore-scope.
4	Drew Diefendorf LMER General Comment	Where are the plots of current potentiometric surfaces to support arguments that the centroid is not being captured?	We didn't intend to include since the focus of the report was on the model results.
5	Drew Diefendorf LMER General Comment	Given the important implications of this work, it is recommended that the modeling effort be peer reviewed by appropriate modeling folks within the ER program before it is used for decision making purposes.	The document was reviewed by individuals from LMES, Jacobs, DOE and its subcontractors. We agree review by a LMES modeler would be desirable but as far as we are aware there are no individuals within the LMES ER program at Paducah or elsewhere with modeling expertise.
6	Ken Davis LMES Section 3.0, Conceptual Model	Section 3.0, Conceptual Model: If you want to include it, I have derived a horizontal K for the McNairy of $1.8 \times 10E-2$ ft/d ($6.3 \times 10E-6$ cm/s). Reference is "The McNairy Formation in the Area of the Paducah Gaseous Diffusion Plant", Sept., 1996.	Thanks, we will reference this number in the text.
7	Ken Davis LMES Section 5.2, Boundary Conditions	Although I was an early proponent, I now believe modeling the terrace as a no-flow boundary to be an error. The boundary assumption for the terrace significantly detracts from the acceptance of the results, in my view.	We disagree modeling the terrace as a no flow boundary detracts from the results. Changing the boundary conditions of the terrace will have minimal impact on the groundwater flow direction in the vicinity of the two extraction well fields. Compare the results of the two GeoTrans models, one which used an active cell the latter as a no flow boundary. We agree some flow likely occurs across the terrace but there is insufficient data to quantify it. Although optimization could have been performed to assess the flow across the terrace we felt this was beyond the scope of the project. However, future modeling should address this concern.

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Item No.	Drawing or spec. no. & paragraph	Comments	A-E Action
8	Ken Davis LMES General Comment	All PGDP groundwater flow models are most sensitive to our assumptions of RGA K and recharge (Fig. 6.1). Until we come to terms with at least one of these parameters, utilization of modeling - as attempted here - will be stymied. Realistically, DOE isn't going to foot the bill to adequately define either with field research.	Agree, but as stated in the responses to comments #1 and #2 we have to use the data we have at hand and to employ reasonable assumptions where hard data is lacking.
9	Ken Davis LMES General Comment	I think the attempt to incorporate a model of RGA K (Fig. 5.7) is the correct response with these limitations. From time-to-time, I have supported building a model just as you have done. However, now that I see it, I don't like it. My conceptual model of RGA deposition won't allow for the NW Plume channel. So...I think we either need to research depositional systems and agree to an RGA model or you need to burden this report with the lithologic evidence for the NW Plume channel. Otherwise, the assumptions of RGA K are too speculative to be comfortable with.	See response to comment #2. We believe the way we modeled the system is reasonable given the agreement between the modeled results and the actual plume configuration. The alternative was to utilize the existing models with no changes, which we deemed to be unacceptable given that they did not accurately portray the known flow system based on the orientation of the Northwest plume. If the model can't accurately portray the plume geometry then this seems to us to cast doubt on the capture zone analysis.
10	Ken Davis LMES General Comment	Other hydraulic controls are just as likely to explain the location and shape of the NW Plume. I now think the west-to-east flow that develops during high Ohio River stage indicates the presence of a hydraulic 'driver' northwest of the plant that explains the 'banana' curve to the plume.	We agree, the eastward flow has an impact on the plume. However, this a transient feature which only lasts for several months and does not occur every year. So the impact on the flow system and the plume orientation will be temporary. The majority of the time the Ohio River stage is at or near base level conditions which result in a general northward flow direction. So, some other feature likely explains the "banana" curve which we believe to be heterogeneity.
11	Ken Davis LMES General Comment	The absence of change in the south well field capture zone modeled without the north well field (Fig. 7.3) versus with the north well field (Fig. 7.2) doesn't appear right. Were the capture zones in Fig. 7.2 modeled with both well fields running concurrently? They should have been.	The two well fields, operating at the simulated pumping rates, do not "compete" for water. Running one well field without the other will not change the shape of the others capture zone. The correct well fields were operational for all simulations.
12	Ken Davis LMES General Comment	I think this report should go forward. Up front, we need to highlight the critical assumptions that lead to the results: 1) the Northwest Plume channel with high K and 2) the recharge model for plant site. Although the intent is to evaluate the NW Plume containment system, perhaps the value of this report is to demonstrate the application of modeling and the need for further model development at PGDP.	We agree and will add the caveats up front in the introduction. As mentioned in the recommendation we feel much would be gained in understanding recharge and heterogeneity by simply sitting down with the model for several months and playing around with the input parameters.
13	Ross Miller LMES Page 6-10, 6.3:	Good opening paragraph.	Thanks.

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Item No.	Drawing or spec. no. & paragraph	Comments	A-E Action
14	Ross Miller LMES Page 6-17, middle paragraph	I agree. I suspect the C-400 area is contributing to the Northeast Plume. However, I would tread carefully here as the Tc-99 fingerprint at C-400 does not indicate this area as a major contributor to the Northeast Plume.	We agree with your concern text will be changed to reflect the uncertainty based on the assumptions inherit to the model. The model runs suggest that changes in the discharge rate at Outfall 011 have a major impact on the RGA hydraulics. This in turn impacts recharge to the RGA and ultimately groundwater flow directions and contaminant transport from C-400. The lagoon did not come on line until 1977 prior to this discharge was into the N/S ditch. Most of the plant upgrades which resulted in the recovery of Tc-99 occurred prior to 1977. Thus, groundwater contamination from C-400 which contained Tc-99 would have migrated to the Northwest away from C-400. Thus, only post 1977 water and contaminants would be contributing to the Northeast Plume. This seems to support the lower levels of Tc-99 seen in the Northeast Plume and the lesser longitudinal extent as compared to the Northwest Plume. If one uses the 1977 date as the start of the Northeast Plume the longitudinal extent is in agreement with expected average flow velocities of 1 ft/day.
15	Ross Miller LMES Page 6-17, last paragraph	No doubt the 001 Outfall influences the hydraulics in the UCRS and RGA. However, as pointed out in the WAG 6, Phase I hydrogeological study, there are many anthropogenic recharge areas as potential contributors to flow paths of the plume(s). I suggest eliminating your statement relating to 001 as I believe it will be very difficult to defend this position. Rather, reword stating that Outfall 001 was used as an "assumptive means" to duplicate a complex recharge system.	We will clarify the text to state this was the only scenario, of several tried, which had the desired impact of mimicking the Northwest Plume orientation and location. We would like to point out that the leakance rate fits reasonably well with the known discharge rate for this Outfall. We agree that other areas of anthropogenic recharge may also effect the flow system but given the limited time and budget we could only assess several scenarios.
16	Ross Miller LMES Page 7-1, 7.1, first paragraph	The last sentence is misleading; would rewrite.	The text will be changed to clarify the point we are trying to make, which is that it appears there is a zone of non capture between the two well fields, ie. contaminants from C-400 are migrating past both the south and north well field at the current 50 gpm pumping rate. In reality we believe the contaminants from C-400 migrate directly under SWMUs 7&30, unfortunately we could not get the modeled plume to perfectly simulate the actual plume.
17	Ross Miller, LMES Page 8-1, 8.0	I would move those paragraphs relating to future recommendation to Section 10.0.	Agree, we will move these to the Recommendation section.
18	Ross Miller LMES General Comment	I definitely believe your report has enhanced our understanding of the Northwest Plume and also identified areas of potential data gaps. I am not a modeler and do not claim to be one. However, I do understand the limitations and use of models (see attached letter dated 6/17/96, "Groundwater Modeling, The Real World") and suggest you include some general caveats to that effect.	Thanks, we will add some text indicating that modeling is an iterative process. Thus, earlier modeling attempts are not necessarily wrong but rather are limited by the data available and understanding of the hydrologic system for that point in time.

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19	Bruce Phillips Jacobs Eng. Pg. vi, 2nd paragraph; Pg. 7-1, 3rd paragraph; Pg. 7-3, 1st full sentence; Pg. 9-1, 1st bullet	<p>In the text locations noted, it is stated that model results suggest the plume "hotspot" is not contained at the current pumping rate. However, based on Fig. 7.1, the current pumping rates are adequate for "hotspot" containment. Based on Fig. 7.1, the capture zone widths for the North and South Well Fields are approximately 500 ft and 1,000 ft respectively. The plume cores defined by TCE greater than 1,000 µg/l have widths of approximately 350 ft and 600 ft in the North and South Well Fields respectively.</p> <p>Page 7-1 (3rd para., 3rd sent.) incorrectly reports values of hydraulic conductivity estimated from the aquifer test (see comment #2 below). In the preliminary capture zone analysis reported in Phillips (1996), hydraulic conductivity values of 1,000 ft/d and 2,500 ft/d for the South and North Well Fields, respectively, were used based on results of the Hantush-Jacob analyses of the aquifer test. Based on the Hantush-Jacobs solution, conductivities in the south ranged from 800 to 1300 ft/d with a geometric mean of about 1,050 ft/d. Hydraulic conductivities in the north ranged from 2,685 to 3,025 ft/d with a geometric mean of 2,850 ft/d. The Hantush-Jacobs values are more appropriate since the RGA is confined by a leaky aquitard - it's more consistent with the conceptual model.</p>	<p>While most of the plume "hotspot" is contained the C-400 Building, a known source area, is located between the simulated capture zones. Therefore, as simulated, contamination emanating from this source area will allude capture. Based on the location of the C-400 Building with respect to the capture zones containment was deemed inadequate.</p> <p>North well field transmissivities ranged from 75,208 158,563 ft²/d (Phillips 1996). Based on a north well field RGA thickness of 20 ft (Phillips 1996), north well field hydraulic conductivities ranged from 3,760 to 7,928 ft/d. Similarly, based on a transmissivity range of 25,088 to 49,328 ft²/d and a thickness of 30 ft south well field hydraulic conductivities ranged from 836 to 1,644 ft/d. The text will be modified to reflect these ranges.</p> <p>Phillips (1996) did not specify which aquifer analysis method yielded the most accurate hydraulic conductivity predictions. Therefore, we assumed all values within a hydraulic conductivity range were possible.</p> <p>A number of error sources can introduce variability in pumping test results. Sources of error include errors in adjusting drawdowns, position of the best-fit curve with respect to the plot of draw down verses time, and assumed RGA aquifer thickness. As a consequence, the predicted hydraulic conductivity ranges for the two pumping tests is probably larger than that reported in Phillips (1996). Thus, use of model hydraulic conductivity values minimally out of range of the Phillips (1996) values is acceptable.</p>
20	Bruce Phillips Jacobs Eng. Pg. 1-1, 1st paragraph; Pg. 3-1, 1st paragraph;	In the paragraphs noted, it is stated that Phillips, 1996 estimated hydraulic conductivities in the RGA up to 8,000 ft/d. The range of hydraulic conductivities in the south was from 800 ft/d to 1,430 ft/d with a geometric mean of 1,175 ft/d. The range of hydraulic conductivities in the north was from 2,685 ft/d to 5,700 ft/d with a geometric mean of 3,740 ft/d.	<p>Figure 5 in Phillips (1996) shows RGA thickness in the vicinity of the north well field to be approximately 20 ft. Based on this thickness north well field hydraulic conductivities range from 3,760 to 7,928 ft/d. Thus the statement that Phillips (1996) estimated hydraulic conductivities up to 8,000 ft/d is correct.</p> <p>See comment response 1 for additional detail.</p>
21	Bruce Phillips Jacobs Eng. Pg. 3-1, 1st para., 6th sentence	The range of thickness of the RGA is approximately 0 ft to 50 ft.	Agree, text will be changed.
22	Bruce Phillips Jacobs Eng. Pg. 3-1, 2nd para., 1st sentence	While the Porters Creek Clay provides an overlying confining layer for the McNairy Formation south of the PGDP, it does not "bound" the hydrogeological unit as implied here.	Agreed, the text will be changed accordingly.

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23	Bruce Phillips Jacobs Eng. Pg. 5-5, 4th paragraph.	Why were the lagoons not considered as sources of anthropogenic recharge? It has been postulated that C-616 may contribute technetium to ground water via recharge.	Borescope measurements at MW173 and MW186 indicated northward groundwater flow, which is not consistent with leaking lagoons. Thus, the lagoon was not simulated as a source of recharge. Characterization efforts should be undertaken to determine if this is a valid assumption.
24	Bruce Phillips Jacobs Eng. Pg. 5-8, 1st paragraph; Fig. 5.7	The text noted states the hydraulic conductivity zones within the "channel" are based on expected fluvial depositional patterns but these patterns are not discussed in the text. The depositional system responsible for the lower continental deposits (approximately 6 mile wide belt with gravel and sand from 0 to 60 ft thick) has often been interpreted as braided to coarse-grained meandering fluvial system. It would be unrealistic to include only one sinuous channel deposit within an area dominated by channel facies. If the high conductivity zones depicted in Fig. 5.7 are meant to represent a meandering channel deposit, I would expect the high conductivity zone to be more broadly represented as the channel migrated across the area.	Agreed, the text will be modified to state that the modeling approach is an oversimplification of the depositional environment. Also, all text implying a "single" channel will be modified. However, it is possible that a single storm event resulted in coarse material being deposited linearly between the two well fields. Subsequent storm events may have lacked the energy to rework these deposits.
25	Bruce Phillips Jacobs Eng. Pg. 6-17, 1st full paragraph, 8th sentence	While portions of the NE Plume complex may be related to dissolved phase contamination from the UCRS, the plume core along the southern margin of the plume complex has higher concentrations of TCE at the base of the RGA, indicating a likely RGA source.	A higher concentration in part of the NE plume does not necessarily indicate a DNAPL source in the RGA. While flow within the RGA is primarily horizontal vertical stratification must occur. Groundwater entering the RGA near the southern site boundary moves vertically as it flows toward the Ohio River to accommodate "new" groundwater entering the RGA. Thus, it is possible to have stratified, both horizontally and vertically, contaminant concentrations without having a DNAPL source in the RGA. The text will be reworded that this is one of several hypothesis. Agreed, sources other than C-400 could be and are likely feeding this plume. However, our focus was not on the Northeast Plume. We only mentioned this because of the interesting result.
26	Caroline Barber Jacobs Eng. Page 2-1	Why have conventional methods of hot spot containment evaluation (such as potentiometric surface mapping and contaminant monitoring proven) proven ineffective?	Text will be added that the current configuration of monitoring wells is not conducive for evaluating drawdown at the current pumping rates. The low pumping rates hardly stress the aquifer and result in negligible drawdown. Additionally, cyclical trends in contaminant levels are not conducive to isopleth mapping of TCE levels.
27	Caroline Barber Jacobs Eng. Page 5-1	The McNairy Formation should have been included in this model.	As discussed in the text, because of how the GeoTrans model was configured the McNairy did not influence groundwater flow or contaminant migration in the vicinity of the two well fields. Thus, no benefit would have been gained by including the McNairy in the model.

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28	Caroline Barber Jacobs Eng. Page 5-5, Sect 5-3, Para. 2	Why was just ditch 001 used to estimate industrial recharge? What are these simplifying assumptions based upon? The industrial hydrologic survey could not put a number on this recharge, and could not even bracket it very well. Please explain.	As stated in the report, the 001 Outfall ditch is expected to leak significant quantities of water because the ditches length (5000-ft), it is unlined and transmits a large quantity of water. Other ditches also undoubtedly leak. However, because of ditch lengths and water volumes transmitted leakage rates from the other ditches are not expected to be as significant. You are correct that the industrial hydrology study did not quantify leakage rates from industrial features and identifying the leakage rates as critical information needed to accurately simulate the site. Ken Davis, EIMS, provided the Outfall 001 discharge rates.
29	Caroline Barber Jacobs Eng. Page 5-8	I'm not sure it makes sense to use 'plume geometry' to justify the delineation of a high conductivity channel, and then use particle tracking to justify that the model is correctly tracking the plumes. Putting such a high conductivity channel into the model where the plumes are located will naturally tend to make to model track the plumes that direction.	The text will be changed from a channel to high conductivity zone. The high hydraulic conductivity zone was located using a combination of plume geometry and aquifer test results. The well field aquifer tests revealed higher than expected hydraulic conductivity values. Given that the plume is continuous between the well fields isn't it also reasonable to expect that the higher hydraulic zone conductivity zone is also continuous?
30	Caroline Barber Jacobs Eng. Page 5-8, Sect. 5.4	This type of conductivity zonation will force the plume directions. I think this zonation is an over simplification of the system.	We agree that the model configuration will dictate model predictions. However, the zonation employed is probably no more of an over simplification of the system than that used in other site models. The system simplifications are acceptable given the available data.
31	Caroline Barber Jacobs Eng. Page 5-10, Fig. 5.7	The delineation of the relic channels within the RGA using conductivity zones seems to be almost entirely based upon the graphical depiction of the plumes' geometries. This needs to be documented using detailed cross sections along with the pump test data, to justify making these conductivity zones match the plumes so exactly. Please add lithologic data and cross sections to justify the delineation of these conductivity zones.	Limited lithologic information, most of the water-quality data in the area was obtained using drive-point techniques, makes it difficult to prove or disprove the existence of a higher hydraulic conductivity channel solely based on lithologic descriptions. As stated in comment response 29, given the higher than expected hydraulic conductivities at the two well fields and that the plume is continuous between the well fields isn't it also reasonable to expect that the higher hydraulic zone conductivity zone is also continuous? Additional documentation concerning lithology will not be added to the report since it is beyond the scope of this project.
32	Caroline Barber Jacobs Eng. Page 6-1, Sect. 6.3	Why was the model calibrated to the same time as the 1992 analysis? It would have been a good idea to do a thorough analysis of all of the water level data available to date, as well as Ohio River stage data, to determine what the optimum calibration time is.	GeoTrans 1992 calibration target values are reasonable calibration targets. Analysis of the hydrologic data in the manner suggested is beyond the scope of this project. Given the recent understanding of the significance in change in flow direction a transient model may be appropriate and thus there are no optimum steady-state calibration targets.
33	Caroline Barber Jacobs Eng. Page 6-2, Fig. 6.1	This figure is meaningless if it is not in color. Unless all users of this document can get color copies, perhaps this figure could be modified to be understandable in black and white copies.	The document will be distributed with color figures since these are easier to portray the information than in black and white.

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34	Caroline Barber Jacobs Eng. Page 6-5, Sect. 6.4	This simulates the flow field of the NW Plume because it is forced that way by the hydraulic conductivity zonation put into the model.	See comment response to 29 and 30.
35	Caroline Barber Jacobs Eng. Page 8-1, Para. 1	Past models have already addressed these deficiencies. The UCRS update suggested here was already done by another DOE model developed by the Jacobs EM Team (DOE, 1994), which simulates the UCRS as two discrete layers.	We are pleased to see that others also recognized the deficiencies of the GeoTrans model and implemented corrective measures.
36	Caroline Barber Jacobs Eng. Page 8-1, Para. 4	A thorough evaluation of water level data and Ohio River stage data would have been beneficial here. Potentiometric surface maps would have been helpful as well. Please explain about the shifting of the RGA ground water flow from a northerly direction to an easterly one.	Agree, this information would be beneficial but this is beyond the scope of this project. This information has been included in the Annual Report for the Northwest Plume O&M, DOE/OR/07-1531&D1.
37	Caroline Barber Jacobs Eng. Page 8-2, Para 1	The Jacobs EM Team model already includes the terrace gravels, and has incorporated in its structure, the most recent lithology data from the WAGs 1&7 investigation, as well as the Northeast Plume investigation. There is no reason to further update this model when another model already incorporates this data.	We were not aware the (DOE 1994) model had been updated with this information.
38	Caroline Barber Jacobs Eng. Page 8-2, Para. 2	A current model already includes the McNairy Formation in its structure. This has already been incorporated into the model developed by the Jacobs Em team.	Thank you for the information.
39	Caroline Barber Jacobs Eng. Page 10-1, Bullets 1,2,3,4	Most of these recommended 'updates' have been already incorporated into the model developed by the Jacobs EM team. It would have been helpful to have used a model that incorporated much of the data gathered since 1992. It is not clear why recommendations for updates are made without mentioning the DOE already possesses a model which incorporates these updates?	See comment #37. Additionally, when LMES was presented with the information from the DOE, 1994 model we had some concerns about the results. Specifically, the hydraulic conductivities used in the model were too low and the model did not accurately depict the geometry of the Northeast Plume. We were not aware any changes had been made to this model since 1994.
40	Catherine Woehr Jacobs Eng. Pg. 3-1, para 1. Last sent.	"Although the McNairy hydraulic conductivity has never been measured...." Suggest adding "at the PGDP", as I believe the McNairy hydraulic conductivity has been measured in the laboratory) by the USGS.	Agreed, the sentence will be changed to state the hydraulic conductivity of the McNairy has never been measured in situ at the site.
41	Catherine Woehr Jacobs Eng. Pg. 5-5, Sect. 5.3	Groundwater sources and sinks: suggest adding a figure showing the location of Ditch 001 as well as the locations of other potentially significant anthropogenic sources of recharge in the vicinity of the NW Plume. Was any attempt made to quantify and incorporate into the model the amount of recharge coming from the C-616 lagoons? Their proximity to the bend in the Northwest Plume could be coincidental but should be addressed.	The ditch is shown in Fig. 5.4 although it is hard to see since it is a line. Although anthropogenic recharge is believed important at the site, the sources, locations, and discharge quantities have yet to be characterized. See Comment Response # 23 and #28.
42	Catherine Woehr Jacobs Eng. General Comment	The report needs more justification, (including cross-sections and/or gravel/sand percentage maps) for the mapped geometry of the relic channel shown in Fig. 5-10. Please further explain, as the existence of a single channel with a narrow, very high K zone does not conform to the generalized depositional history presented in the Groundwater Phase III report (which hypothesized braided channel deposits) and it represents a large change from the original 1993 GeoTrans model. Would a single channel adequately account for the configuration of the Tc-99 plume as well?	See comment response 31. We don't see any particular disagreement with idea of highly conductive zones within the RGA orientated in a north-south direction as a conflict with a braided depositional environment. The only change from the GeoTrans, (1992) model is the inclusion of heterogeneity. This heterogeneity causes the simulated plume to reasonably track the real plume. The configuration of the Tc-99 plume has never been adequately defined and to date has been developed through extensive creativity.

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43	Steve Miller Jacobs Eng. General Comment	<p>The report indicates that the ROD stated the interceptor system shall be operated to contain the hotspot of the plume. The language in the ROD was carefully chosen to not state control of the hotspot. For example the language "ground water will be pumped at a rate to reduce further contamination" and "The primary objective of the interim action is to stabilize the site by <u>initiating</u> control of the of the northwest contamination plume." were used. Although the ROD also indicates the rates will be adjusted to optimized the system, DOE didn't commit to control of the high concentration area. Before the system is modified or a final action is recommended, the DOE may wish to obtain additional information such as a baseline risk assessment and ecological risk assessment. Please revise the text to accurately reflect the ROD language.</p> <p>The author may wish to indicate if the additional rates will mobilize DNAPL. I don't believe the air stripper is designed to treat DNAPL at this time.</p> <p>Also, if a mass reduction technology is implemented at the C-400 area, the source of contamination at the NW Plume would be reduced over time.</p>	<p>The text will be changed to exactly what is stated in the ROD: We will make it clear that the current Northwest Plume O&M system has met the objective of "initiating" control of the plume. However, keep in mind the first bullet in the ROD states "the first location, immediately north of the plant on the US DOE property is intended to control the source". It is our assessment that the current pumping rates may not be adequate to meet this objective.</p> <p>No changes to text but increased rates would be insufficient to mobilize DNAPL.</p> <p>Agreed, that if mass reduction technology is successful at the C-400 Building contamination at the NW Plume would be reduced over time.</p>
44	Eric Evans Jacobs Eng. General Comment	<p>It appears that the authors did not evaluate recent groundwater modeling studies that have been conducted at PGDP. The Jacobs ER Team has constructed, calibrated, and documented a site-wide, groundwater flow model that contains several improvements over the GeoTrans model including: (1) greater vertical resolution and lithologic detail in the UCRS; (2) more accurate definition of the Porters Creek terrace location; and (3) explicit simulation of the McNairy formation. Because of these improvements, I think that this model would have been a better starting place for the capture zone analysis. The authors should discuss the rationale for choosing the GeoTrans model for their analyses.</p>	See Comment Response #37 & #39.

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45	Eric Evans Jacobs Eng. General Comment	The results of the capture zone analyses are strongly controlled by the two high hydraulic conductivity zones (i.e., 2,500 and 5,000 ft/day) that represent the postulated ancestral channel. Both of these values are unrealistically high. The hydraulic conductivity values that were assigned in these zones were based on the aquifer test conducted at the well fields. The assignment of the two high hydraulic conductivity zones was based on the results of the aquifer test analyses conducted at the two well fields (Phillips 1995). The authors should have relied on the aquifer test results calculated using the Hantush and Jacob leaky artesian solution. This solution accounts for the vertical flow of water from the UCRS to the RGA. The other solutions that were used to calculate transmissivity values do not account for this vertical flow. If the vertical flow from the UCRS to the RGA was not important, then the anthropogenic recharge discussed by the authors would have little effect on water levels and velocities in the RGA. The transmissivity values derived using the Hantush and Jacob leaky artesian solution and presented in the aquifer test report are 32,504 and 79,780 ft ² /day, for the south and north well fields, respectively. Assuming a RGA thickness of 50 feet (based on cross-sections at the well fields), these transmissivity values would yield hydraulic conductivity values of 650 and 1,595 ft/day for the south and north well fields, respectively. These values are much more reasonable for the RGA and are more consistent with other measured values at the PGPD. Because recharge and hydraulic conductivity are directly related, an infinite number of hydraulic conductivity and recharge rate combinations will yield equivalent hydraulic head distributions during the model calibration. Consequently, one of the two parameters must be constrained during the model calibration procedure. The authors chose to fix the hydraulic conductivity values in the two high hydraulic conductivity zones, and the values were not adjusted during the calibration procedure.	While the K values used in the model are on the high end of Phillips' (1996) values we disagree that the K values used are unrealistically high and thus invalidate the model results. See Comment Response # 19. Although, we modeled the heterogeneity as a single high K zone, we acknowledge that in reality we have deposits several tens to 100s of feet with high K zones that may be superimposed next to different deposits with varying K's. However, the level of data needed to model each deposit does not exist to allow modeling of heterogeneity in this manner, thus we oversimplified the system. The depositional environment can easily account for several orders of magnitude in variation in K values. The size range of material observed at the site is from silty sand up to cobbles. Thus, the physical data, i.e., very coarse soil samples, as well as the pump test results support the use of a high K number. Keep in mind that each subsequent pumping test at the site has resulted in an increase in T by an order of magnitude, much to our surprise each time. As our understanding of the system involves we are better able to predict where we expect the highest T zones.
45 cont.	Eric Evans Jacobs Eng.	Because the authors applied hydraulic conductivity values that are unrealistically high and that are not supported by field data, the model calibration and the modeling results are inaccurate and do not represent actual hydrogeologic conditions. For a given pumping rate, the capture zones that were simulated by the model will be more narrow than the actual capture zones. Consequently, the revised pumping rates presented by the authors will be much higher than those needed for proper capture. The authors need to recalibrate the model using lower hydraulic conductivity values in the postulated ancestral channel and rerun the predictive simulations before using the modeling results to make decisions.	See comment response # 19. The model will not be recalibrated. Two criteria were used to evaluate model calibration. The simulated plume had to reasonably match the orientation of the observed plume and model predicted heads had to reasonably match 1991 water-levels. A range of channel hydraulic conductivities were modeled with the model values used producing the best plume match. Text will be added to the calibration section elaborating on calibration procedure.
46	Eric Evans Jacobs Eng. pg. 4-1, line 11	PEST, and other parameter estimation codes, do not necessarily produce the "best" or most realistic set of input parameters. As applied in the PGDP modeling study, PEST estimates model input parameters that minimize the discrepancy between observed and simulated water levels for the given model configuration (i.e., boundary conditions, location and number of parameter zones, etc.).	As stated in the text, PEST determines the best set of input parameters for a given model configuration. If the model was configured differently then PEST would predict an alternative set of best parameter values. Therefore, the sentence is correct and needs no modification.
47	Eric Evans Jacobs Eng. pg 5-1	Discuss the boundary conditions in the McNairy.	The McNairy was not included in the model. A sentence will be added stating that the top of the McNairy represented the bottom of the model.

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48	Eric Evans Jacobs Eng. pg. 5-8	The assignment of the high hydraulic conductivity zone in the RGA representing the inferred channel is based on speculation. Please provide more direct and <u>specific</u> evidence that supports your delineation of this zone.	See comment responses # 31 and #42..
49	Eric Evans Jacobs Eng. pg. 6-1; par. 3	Discuss the fact that the "modeling results" that are used during the sensitivity analysis are calculated water levels.	Text will be added stating that model calibration error is the difference between modeled and target heads.
50	Eric Evans Jacobs Eng. Table 6.1	Did you check the correlation between recharge and hydraulic conductivity? The two are almost always highly correlated.	The text states that the channel hydraulic conductivities were correlated to most other input parameters. The table reflects only the status of the channel hydraulic conductivities and not the other input parameters.
51	Michael Kladias Jacobs Eng. Executive Summary Par 3, line 3.	Statement regarding eastward flow in the RGA may be incorrect. Please include a contour plot depicting observed eastward flow directions in the RGA. Contoured heads in January 1992, (stage=326 ft) do not reveal dominant eastward flow directions, only a flow reversal along (perpendicular to) the Ohio River.	Agree, the January head data does not show eastward flow, however potentiometric maps for May and June, 1996 as well as several other prior years indicates eastward flow exists at certain times. Reference to this discussion in DOE/OR-07-1531&D1 will be included. Additionally, potentiometric maps will not be added to this report.
52	Michael Kladias Jacobs Eng. Section 1, Par 1, Line 8	Change sentence to state that hydraulic conductivities are estimated to be 8,000 ft/d, I doubt that they were measured directly. Also, Phillips (1996) suggested that higher transmissivities may be found in the north well field, estimated transmissivities in the south well field were a factor of 2 to 3 lower than the north. The value of 8,000 ft/d may not be representative of a large area. Also the values estimated in the north should be used with caution since aquifer thickness is small and non-uniform. Please address these issues and include more detail from Phillips (1996).	Agreed, text will be changed from measured directly to estimated. The text will be reworded so as not imply that K's of 8000 ft/day are representative of a large area but rather represent a possible upper bound. The Phillips (1996) report will be referenced where appropriate. See comment response # 19 & 20.
53	Michael Kladias Jacobs Eng. Section 2, Par 1, Line 9.	Should be stated in the text why the GeoTrans Model was modified and why this model was chosen over any other models developed for the PGDP.	See comment responses # 37, 39, and 44.
54	Michael Kladias Jacobs Eng. Section 3, Par 1, Line 8	Please state exactly what is meant by bulk hydraulic conductivity. I think these values are model estimated and represent volumetric averaged values or homogeneous equivalents.	Bulk hydraulic conductivity, as noted in the comment, represents homogeneous equivalent hydraulic conductivity. The authors believe bulk hydraulic conductivity is self explanatory and needs no further definition.
55	Michael Kladias Jacobs Eng. Section 3, Par 1, Line 19	Text states that the McNairy formation hydraulic conductivity has never been measured, but GeoTrans (1992) states that average slug test values (from regional studies) are about 0.24 ft/d (CH2M Hill 1991). This suggests that the McNairy is as permeable as the UCRS is in some locations. Please address this issue.	Text will be changed to say that McNairy hydraulic conductivity values have not been measured in situ at PGDP. The regional slug test data referenced in the comment has been judged unreliable and nonrepresentative (Kilby and McConnell, 1993 in KY/ER-34). In some areas it may be possible that the upper McNairy is as permeable as the UCRS. However, both the UCRS and McNairy have significantly lower hydraulic conductivities than the RGA.
56	Michael Kladias Jacobs Eng. Section 3, Par 2, Line 1.	This statement is incorrect, I do not believe the PCC bounds the McNairy formation in the south. Please restate that only the UCRS and RGA terminate in the south at the PCC Terrace.	Text will be changed.

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57	Michael Kladias Jacobs Eng. Section 5.1, Par 1 Line 1.	Please state if any other models, such as those by McConnell or the Jacobs ER Team (DOE 1994,1996), were examined during recalibration. Also see comment 3.	No.
58	Michael Kladias Jacobs Eng. Section 5.1, Par 1, Line 11.	Text states that the in the original implementation of the GeoTrans model the effects of the McNairy were insignificant. Explain why this still applies with the recalibrated model. If the GeoTrans model was incorrectly calibrated how do you know the effects of McNairy were handled correctly? Please provide additional information as to why the McNairy can be deleted. See comment 5.	<p>What is meant by "incorrectly calibrated"? The GeoTrans model was, according to the GeoTrans modelers, successfully calibrated against target observations. Rather than incorrectly calibrated, within the GeoTrans model the McNairy was perhaps incorrectly configured. GeoTrans represented the McNairy as a series of constant head nodes. Therefore, within the GeoTrans model RGA hydraulic head values control movement of water into the McNairy. The GeoTrans model and this model were calibrated to the same RGA target hydraulic head values. Although there were differences in the degree of RGA calibration, both models reasonably matched the RGA target values. Thus, for the two models, it is unlikely that there would have been significant differences in flow between the RGA and McNairy.</p> <p>The authors do not believe that additional justification for removing the McNairy beyond that already presented is warranted. Thus, no changes will be made to the text.</p>
59	Michael Kladias Jacobs Eng. Section 5.2, Par 1, Line 1.	What is the rationale for not adjusting boundary conditions in the GeoTrans (1992) model? The Jacobs ER Team model (DOE, 1994) showed that with updated structural data, the intake channel near TVA actually cuts into the alluvial deposits along the Ohio River. This results in improved simulated flow directions in the RGA.	We weren't aware of any updated structural data.
60	Michael Kladias Jacobs Eng. Section 5.3, Par 2, Line 9	What is the reference for the 001 Outfall ditch leakage rate of 1.4 mg/d?	See comment response # 28.
61	Michael Kladias Jacobs Eng. Section 5.3, Par 2, Line 13.	Why was recharge not eliminated in areas where caps or liners exist (WAG22, SWMU 3) in addition to building and paved areas?	See comment response # 1 and 23.
62	Michael Kladias Jacobs Eng. Section 5.4, Par 1, Line 6.	See comment 2.	See comment response #19, 20, and 52.
63	Michael Kladias Jacobs Eng. Section 6.1, Par 1, Line 1.	Please explain why 1991 data was used instead of more recent water level data from 1992 that may yield better spatial coverage of water levels? Was any evaluation performed to determine a more suitable steady-state calibration period, i.e., September or October?	The spatial distribution of data was deemed sufficient and an analysis to determine suitable target data was beyond the scope of the project. The 1991 date was deemed by LMES and GeoTrans to be indicative of base level conditions.

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64	Michael Kladias Jacobs Eng. Section 6.1, Par 1, Line 1.	<p>Doherty et al. (1994) states the following with regard to confidence limits: "...parameter confidence limits are calculated on the basis of the same linearity assumptions which was used to derive the equations for parameter improvement. No account is taken of parameter upper and lower bounds in calculation of 95% confidence intervals. Thus an upper or lower confidence limit can lie well outside a parameter's allowed domain.</p> <p>The parameter confidence intervals are highly dependent on the assumptions underpinning the model. If the model has too few parameters to accurately simulate a particular system, the optimized objective function will be large and so too will be the parameters covariances and , with them, the parameter confidence intervals. The sole purpose of the confidence intervals provided by PEST is as a means of comparing the certainty with which different parameters values are estimated. They have no physical significance. In many cases the confidence limits (error estimate) are far greater than the actual parameter value in question. Please explain how these confidence intervals relate to an uncertainty analysis that should evaluate the potential range in a parameter based on field observations or measurements. Also, why was the observed range in parameters not used in the uncertainty analysis?</p>	<p>Although it is possible for 95% confidence parameter extremes to be outside expected parameter ranges this is not the case with this model. With the exception of the RGA Ohio River hydraulic conductivity, the model input parameter 95% confidence intervals are relatively narrow suggesting confident and reasonable predictions. The 95% confidence interval for the RGA Ohio River hydraulic conductivity spans two orders of magnitude with the extremes being believable values. Thus, estimated parameter 95% confidence interval extremes are with reasonable limits and are, for this model, meaningful.</p> <p>The applicability of 95% confidence intervals for sensitivity analysis is currently being debated among inverse modeler practitioners and developers with no clear consensus. Some practitioners/developers prefer actual parameter ranges and others prefer 95% confidence intervals.</p> <p>For parameters such as recharge and Ohio River hydraulic conductivity which have never been directly measured at the site observed parameter ranges are not available. We believe, for these parameters, use of 95% confidence intervals is more reasonable than arbitrarily selecting minimum and maximum values.</p>
65	Michael Kladias Jacobs Eng. Section 6.1, Par 3, Line 4, Fig. 6.1	What is the rationale for including RGA channel (middle) zone in the model since it is completely insensitive and statistically insignificant to the model? Typically, insensitive zones are to be coupled with sensitive zones to add credibility to model estimated values. How was "optimized value" of the zone selected?	The two channel hydraulic conductivity zones are insensitive with respect to hydraulic head but are sensitive to particle migration. The two channel hydraulic conductivity values used in the model resulted in the best match between particle traces and plume geometry.
66	Michael Kladias Jacobs Eng. Section 6.1, Par 3, Line 4, Fig. 6.1	As described in the report in Section 3 the primary flow direction in the UCRS is downward. Why were vertical conductances not estimated in the model and/or sensitivity analyses performed on this parameter? If flow is primarily downward, the vertical conductance between model layers 1 and 2 should be extremely sensitive. Please address the sensitivity if vertical conductance values.	Vertical hydraulic conductivities proved to be extremely sensitive. In fact, minimal changes in the input values resulted in nonconvergence. Vertical hydraulic conductivity values will be listed in Table 6.1 along with input parameters and an explanation as to why the parameter was not estimated using inverse techniques will be included.
67	Michael Kladias Jacobs Eng. Section 6.2, Par 2, Line 6	Explain how the model predicted confidence limits justify the value actually used in the calibrated model. The confidence limits only indicate to the user the range in values that are statistically significant to the model calibration. See comment 14.	See comment response #64.
68	Michael Kladias Jacobs Eng. Section 6.2, Par 4, Line 4.	See comment 10.	See comment response #28.

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69	Michael Kladias Jacobs Eng. Section 6.3, Table 6.3	These calibration statistics are only marginally improved over the GeoTrans (1992) calibration. Please post the residuals on the calibrated head plots for model layers 1 and 2. The Residual Mean of -1.25 may indicate significant spatial bias, please explain if any bias exists and why? It appears that the model generally over predicts water levels. Also please explain or provide a reference for how the calibration statistics are calculated.	Because of readability the residuals will not be added to the hydraulic head plots for layer 1 and 2. The information requested can be obtained from the scatter plot shown in Fig. 6.6. A reference will be added to Table 6.3 referencing the statistic formula source.
70	Michael Kladias Jacobs Eng. Section 6.4, Par 4, Line 1.	Please show additional particle traces to delineate exactly how the model represents the Northeast Plume. From the figures included in this report it does not appear that the model accurately simulates Northeast Plume flow directions.	It was never the intent of this model to simulate the Northeast plume. The authors simply wanted to illuminate the possibility that the C-400 Building could be a source of both the northeast and northwest plumes. No claims to accurate portrayal of the Northeast plume are made in the report. The report states that if the eastern model boundary was located further to the east the particle traces might follow the path of the northeast plume.
71	Michael Kladias Jacobs Eng. Section 6.4, Par 4, Line 4.	Given this statement that the model does not simulate the Northeast Plume, how does this affect the results for the Northwest Plume presented in this report?	See comment response #70.
72	Michael Kladias Jacobs Eng. Section 6.4, Par 4, Line 5.	How is this statement relevant, since the model may never simulate the Northeast Plume in its current form?	See comment response #70
73	Michael Kladias Jacobs Eng. Section 6.4, Par 5, Line 6.	How can this statement be made since potential errors as stated in Section 8 may exist in the model because the UCRS is possibly under-discretized? Please qualify this statement.	The statement is already qualified by the use of terms such as "of interest", "while not conclusive", "could be responsible". The paragraph is not intended to be definitive.
74	Michael Kladias Jacobs Eng. Section 7.2, Par 3, Line 1	See comment 14.	See comment response #64.
75	Michael Kladias Jacobs Eng. Section 7.2, Par 4, Line 1	How does a travel time or pore volume exchange time of 10 years correspond to the source timing for the Northwest Plume. Is this travel time reasonable and why hasn't the plume already reached the Ohio River at that rate? Also state what porosity was used to compute pore volume exaggerate and travel times.	Porosities will be added to the report. Given the correlation of Ohio River stage and RGA water-levels it is possible that the plume has already reached the Ohio River but can not be detected because of the mixing of river and RGA water. Thus, the front of the plume is probably a poor indicator of groundwater travel times.

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76	Michael Kladias Jacobs Eng. Section 8, Par 1, Line 3.	According to Konikow (1978) "Ideally the error in the water balance is less than 0.1%. However, an error of around 1% is usually considered acceptable." In large domain models containing large inflows and outflows, the solver head convergence criteria must be set to an exceptionally small value to reduce overall and subregional model errors. Errors of 50% are unacceptable and suggest that the model was not fully converged. What attempts were made to reduce the flow balance error? How are the results presented in this report justified if the mass errors are so large? The large mass balance errors are most likely the results of a large convergence criteria and extremely high hydraulic conductivities in the RGA. Explain how additional layers will reduce the mass balance errors since the overall flow from the UCRS to the RGA should not change?	We recognize that the mass balance of the model is less than ideal and expended considerable effort attempting to locate and reduce the error. The error is not associated with large convergence criteria or the addition of high hydraulic conductivity zones as implied in the comment. The convergence criteria for the model was 10^{-3} feet. The GeoTrans model did not include high hydraulic conductivity zones and suffered from the same mass balance problems. Evaluation of cell-by-cell flow terms showed that the greatest mass balance error was associated with areas of the model having the greatest UCRS to RGA head differential. The combination of large head differential and relatively small vertical hydraulic conductivity results in large mass balance errors. Adding additional UCRS model layers would reduce the head differential between model layers and thus the mass balance error.
77	Michael Kladias Jacobs Eng. Section 8, Par 6, Line 4 and Section 8, Par 7, Line 1	Both the terrace gravels and the McNairy formation were simulated in the Jacobs ER Team model (DOE 1996). Both were found to be extremely important to the model calibration. The Jacobs ER Team model resulted in a much closer fit to observed data than the GeoTrans model (RSS=148.4, STD=1.37, RMEAN=-0.196 ft). Since a re-calibration effort was undertaken in this study why wasn't the Jacobs ER Team model used or the GeoTrans (1992) model revised to include these features?	As stated previously, changing the extent of the GeoTrans model domain was beyond the scope of this project. At the time the decision was made to use the GeoTrans model we were not aware of the "improved" features in the Jacobs model.
78	Michael Kladias Jacobs Eng. Section 10, Par 2	See Comment 27.	See comment response #77.
79	Michael Kladias Jacobs Eng. Section 10, Par 4	See Comment 27	See comment response #27.
80	Michael Kladias Jacobs Eng Figures	Consider black and white figures for easier report reproduction.	Given figure detail, color figures improve report comprehension.

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