

**Response to LQD/DEQ January 10, 2005 Comments**

**Irigaray Wellfield Restoration Report  
TFN 4 1/170**

**May 4, 2005**

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## **Introduction**

A numerical groundwater flow and transport model was used to evaluate the future movement of constituents derived from the Irigaray uranium insitu-leach (ISL) operation in Johnson County, Wyoming. Description of the model development, assumptions and results were provided in the Irigaray Mine Wellfield Restoration Report (COGEMA 2004). The previously submitted model results demonstrated that dissolved concentrations of uranium (U), selenium (Se), manganese (Mn), radium (Ra) and total dissolved solids (TDS) would remain below regulatory standards within 400 feet of the ISL wellfield.

WDEQ, in its review of the restoration report (January 2005), requested that ammonia be included in the modeling assessment. This letter report summarizes the results of the supplemental ammonia evaluation and modeling effort. Consistent with the Irigaray Restoration Report, this letter report is a combined effort of COGEMA Mining, Inc. and Petrotek Engineering Corporation.

## **Ammonia Chemistry**

The speciation of ammonia is a critical factor in assessing the fate and transport of ammonia. To evaluate ammonia species specifically related to Irigaray, COGEMA contracted Resource Technologies Group (RTG) to prepare a detailed discussion of ammonia geochemistry in the Irigaray environment. The RTG report (Attachment A) is referenced throughout this letter report. Tables used to convert from ammonium ( $\text{NH}_4$ ) to ammonia ( $\text{NH}_3$ ) are included in Appendix B of the RTG report. Those conversion tables are copied from the Administrative Rules of South Dakota, Un-ionized Ammonia Criteria Tables, January 1999.

Dissolved ammonia exists as an equilibrium of un-ionized ammonia ( $\text{NH}_3$ ) and ionized ammonium ions ( $\text{NH}_4^+$ ). The speciation is strongly dependent on pH and temperature and to a lesser extent on ionic strength. As pH increases, the relative proportion of un-ionized ammonia to total ammonia increases. Conversely, as temperature increases, the fraction of un-ionized ammonia decreases. A detailed description of ammonia chemistry is provided in Attachment A.

The WDEQ Class I water quality standard is 0.5 mg/l  $\text{NH}_3$  (as N). Water quality for the Irigaray wellfield monitoring program are typically reported as  $\text{NH}_4$  (as N). Under geochemical conditions prevalent within the Irigaray wellfield (pH from 7.17 to 7.80 and temperature from 12.8 to 17.7°C) the percentage of  $\text{NH}_3$  ranges

from 0.2 to 2.2 (Attachment A [Appendix B]). Outside of the wellfield, the pH is naturally higher, resulting in a higher fraction of  $\text{NH}_3$ . The conversion of  $\text{NH}_4$  concentration to  $\text{NH}_3$  will be required to assess potential impacts from ammonia to adjacent groundwater, as described below.

## Methodology

The methodology employed in the restoration report for U, Se, Mn, Ra and TDS was also used to demonstrate that residual ammonia will not degrade adjacent groundwater quality below the WDEQ Class I standard. The restoration model is designed to represent post-restoration, steady state conditions of groundwater flow within the UISS aquifer of the Wasatch Formation. The modeling effort is focused on advective and dispersive flow components, with no reliance on geochemical processes for mass removal. The model is constructed with three layers, corresponding to the mineralized zone and the overlying and underlying sand units of the UISS. All layers are simulated as confined. The flow field is calibrated to water level data from the site monitoring network. The model simulations were run for a period of 300 years. Detailed description of the model conceptualization, development and calibration are provided Section 5 and Appendix C of the Wellfield Restoration Report.

Initial conditions for the ammonia transport simulations included a uniform concentration of ammonia distributed across the footprint of the ISL wellfield within the mineralized zone layer. The initial wellfield concentration represents the average value within the wellfield (in accordance with the 2001 DEQ-LQD and DEQ-WQD Advisory Boards Clarification Paper). The average wellfield concentration of ammonia, reported as  $\text{NH}_4$  (as N), is 8.7 mg/l. All other portions of the model domain are simulated as having a concentration equivalent to background at the start of the simulation. The background concentration of ammonia outside the wellfield, reported as  $\text{NH}_4$  (as N), is 0.206 mg/l (0.041 mg/l  $\text{NH}_3$  as N at a pH of 8.86) (Attachment A [Appendix B]). Under average wellfield conditions (pH of 7.46 and temperature of 15.2°C) the 8.7 mg/l  $\text{NH}_4$  concentration is equivalent to an  $\text{NH}_3$  concentration of 0.07 mg/l, as N (Attachment A, Section 4.0). This value is already below the WDEQ Class I standard of 0.5 mg/l.

Based on the operational history of the Irigaray wellfield, a more conservative approach was also modeled. Ammonium bicarbonate was used as the lixiviant in Mine Units 1 through 5, in the northern portion of the wellfield. The practice was not used in Mine Units 6 through 9. Consequently, ammonia concentrations are higher in the northern portion of the wellfield. The average  $\text{NH}_4$  (as N) concentration in Mine Units 1 through 5 is 21.5 mg/l (0.17 mg/l  $\text{NH}_3$  as N; Attachment A, Section 4.0). As a maximum case scenario, transport simulations were also performed using this higher value for the initial concentration within the entire wellfield.

Ammonia migration has been demonstrated to be retarded due to the interaction of ammonium ions with formation clay. Drever in *The Geochemistry of Natural Waters* (1988) states the measured distribution coefficient ( $K_d$ ) of  $\text{NH}_4^+$  in sandstone aquifers ranged from 2 to 10 L/kg. Consistent with the approach used in the Wellfield Restoration Report, the lowest reasonable  $K_d$  available from literature was used. A  $K_d$  of 2 was used for the initial ammonia transport simulations. To be even more conservative, a sensitivity evaluation simulation with a  $K_d$  of 1 is also presented.

Dispersivity was incorporated into the transport simulations. A value of 25 feet, the same as used in the simulations for U, Se, Mn, Ra and TDS, was used to model ammonia transport. No diffusion was included in the simulations.

### **Factor for Conversion of $\text{NH}_4$ to $\text{NH}_3$**

As previously described, the initial ammonia concentrations used in the model are based on water quality data reported as the ammonium ion ( $\text{NH}_4$  as N). The model only addresses transport and attenuation of ammonia through advection, dispersion and sorption. The model does not consider speciation of ammonia. Therefore, a conversion factor must be applied to the simulated  $\text{NH}_4$  concentration to estimate the concentration of  $\text{NH}_3$ . The conversion factor is derived from site-specific pH and temperature data and the January 1999 un-ionized ammonia criteria tables from the Administrative Rules of South Dakota.

Geochemical conditions within the wellfield are such that the percentage of un-ionized ammonia is very small. The Irigaray wellfield pH ranges from 7.1 to 7.8 and averages 7.46, and the average temperature is 15.2°C (Attachment A [Appendix A]). At these conditions, the percentage of un-ionized ammonia is 0.81 (Attachment A [Appendix B]).

However, field-measured pH in the vicinity of the monitoring wells outside the wellfield is higher, averaging closer to 8.9 (Attachment A [Appendix A]). Assuming worst-case conditions (i.e., that the average temperature is approximately the same outside the wellfield as inside (15.2°C)), the percentage of un-ionized ammonia outside the wellfield is 20.0 (Attachment A [Appendix B]). Hence, a conservative conversion factor of 0.20 was used to convert simulated  $\text{NH}_4$  concentrations to  $\text{NH}_3$  (see Attachment A). This conversion factor is equivalent to a pH of between 8.9 and 9.0. As noted previously, a pH of 8.9 represents the measured pH at the monitoring wells located downgradient of the wellfield.

For the reasons discussed below, using the existing pH outside the wellfield (8.9) is very conservative. As the waters in the wellfield move to the northwest under the natural gradient, ammonia will be transported out of the wellfield. This is the basis for the transport simulations discussed in the following section. At the

same time, lower pH water will be transported out of the wellfield, resulting in pH values that should be lower than the current average of 8.9 units.

## Simulation Results

Ammonia transport was simulated using the wellfield average  $\text{NH}_4$  concentration of 8.7 mg/l and the average of the northern wellfield of 21.5 mg/l. Each of those scenarios were run with a  $K_d$  of 2 and 1. The simulated  $\text{NH}_4$  concentration was conservatively converted by a factor of 0.20 to represent  $\text{NH}_3$ . Results of the modeling indicate that residual concentrations of  $\text{NH}_3$  will be below regulatory limits at the prescribed boundary 400 feet from the wellfield.

Plots of  $\text{NH}_3$  concentration vs. time (converted from  $\text{NH}_4$ ) for the observation points (located approximately 400 ft from the wellfield boundary) were prepared for each of the simulations. Simulation results for the 300-year runs, including  $\text{NH}_4$  results and converted  $\text{NH}_3$  values, are presented on Table 1.

Figure 1 is the plot for simulation of a wellfield concentration of 8.7 mg/l and a  $K_d$  of 2. The plot shows that un-ionized ammonia will remain below the WDEQ standard for the duration of the model simulation period of 300 years. Similarly, concentration vs. time plots for the simulation of the higher wellfield concentration ( $\text{NH}_4$  of 21.5 mg/l) and a  $K_d$  of 2 is shown in Figure 2. None of the observation point concentrations exceed the WDEQ standard at any time in the model simulation.

To evaluate sensitivity, more conservative simulations were run with a  $K_d$  value of 1. Figure 3 shows the  $\text{NH}_3$  vs. time plots for the average wellfield concentration of 8.7 mg/l and a  $K_d$  of 1. Figure 4 shows the plots for the higher wellfield concentration and the  $K_d$  of 1. The model results show that none of the observation point concentrations exceed the WDEQ Class I standard for  $\text{NH}_3$ .

For summary purposes, Figure 5 presents results for the most critical observation point (OP-3) for a range of  $\text{NH}_3$  and  $K_d$  values.

## Summary

At the request of WDEQ, the numerical groundwater flow and transport model used to demonstrate that residual ammonia concentrations from the Irigaray operation will not significantly impact adjacent groundwater. A basecase simulation was run using the average wellfield  $\text{NH}_4$  concentration and a  $K_d$  of 2.

Additional sensitivity simulations were run using higher wellfield concentration and a lower  $K_d$ . All  $\text{NH}_4$  concentrations were converted to  $\text{NH}_3$  using a conservative factor of 0.20 (i.e., 20% of the ammonia will be present as  $\text{NH}_3$ ). Results of the modeling, using conservative parameter assignments and evaluation methodologies, demonstrate that residual concentrations of  $\text{NH}_3$  will

remain below the regulatory standard at all the observation points located 400 feet downgradient from the wellfield.

The modeling results are consistent with the site conceptual model and published data regarding the fate and transport of ammonium in aqueous systems. Because of (1) the low concentrations of  $\text{NH}_4$  in the wellfield, (2) the low pH in the wellfield (and associated small percentage of  $\text{NH}_3$  under those conditions), and (3) the limited mobility of  $\text{NH}_4$ , the transport of  $\text{NH}_4$  downgradient of the Irigaray Wellfield is expected to be very limited. Subsequently, expected residual concentrations of  $\text{NH}_3$  would be low, which is confirmed by the modeling presented in this report.

Table 1. Simulated NH<sub>4</sub> and Converted NH<sub>3</sub> Concentration at Observation Wells at 300 Years  
Irigaray ISL Wellfield, Wyoming

Observation Point	Simulation							
	Initial Wellfield NH <sub>4</sub> = 8.7mg/l				Initial Wellfield NH <sub>4</sub> = 21.5 mg/l			
	Kd=2 L/kg		Kd=1 L/kg		Kd=2 L/kg		Kd=1 L/kg	
	NH <sub>4</sub> (mg/l)	NH <sub>3</sub> (mg/l)*	NH <sub>4</sub> (mg/l)	NH <sub>3</sub> (mg/l)*	NH <sub>4</sub> (mg/l)	NH <sub>3</sub> (mg/l)*	NH <sub>4</sub> (mg/l)	NH <sub>3</sub> (mg/l)*
OP-1	0.206	0.0412	0.206	0.0412	0.206	0.0412	0.206	0.0412
OP-2	0.206	0.0412	0.214	0.0428	0.206	0.0412	0.227	0.0453
OP-3	0.220	0.0439	0.477	0.0954	0.240	0.0481	0.885	0.1770
OP-4	0.206	0.0412	0.208	0.0417	0.206	0.0412	0.212	0.0423
OP-5	0.206	0.0412	0.217	0.0433	0.206	0.0412	0.233	0.0465
OP-6	0.206	0.0413	0.242	0.0484	0.207	0.0413	0.297	0.0594
OP-7	0.206	0.0412	0.207	0.0415	0.206	0.0412	0.210	0.0419
OP-8	0.206	0.0412	0.206	0.0412	0.206	0.0412	0.206	0.0412
OP-9	0.206	0.0412	0.206	0.0413	0.206	0.0412	0.206	0.0413

Note: Background NH<sub>4</sub> concentration is 0.206 mg/l

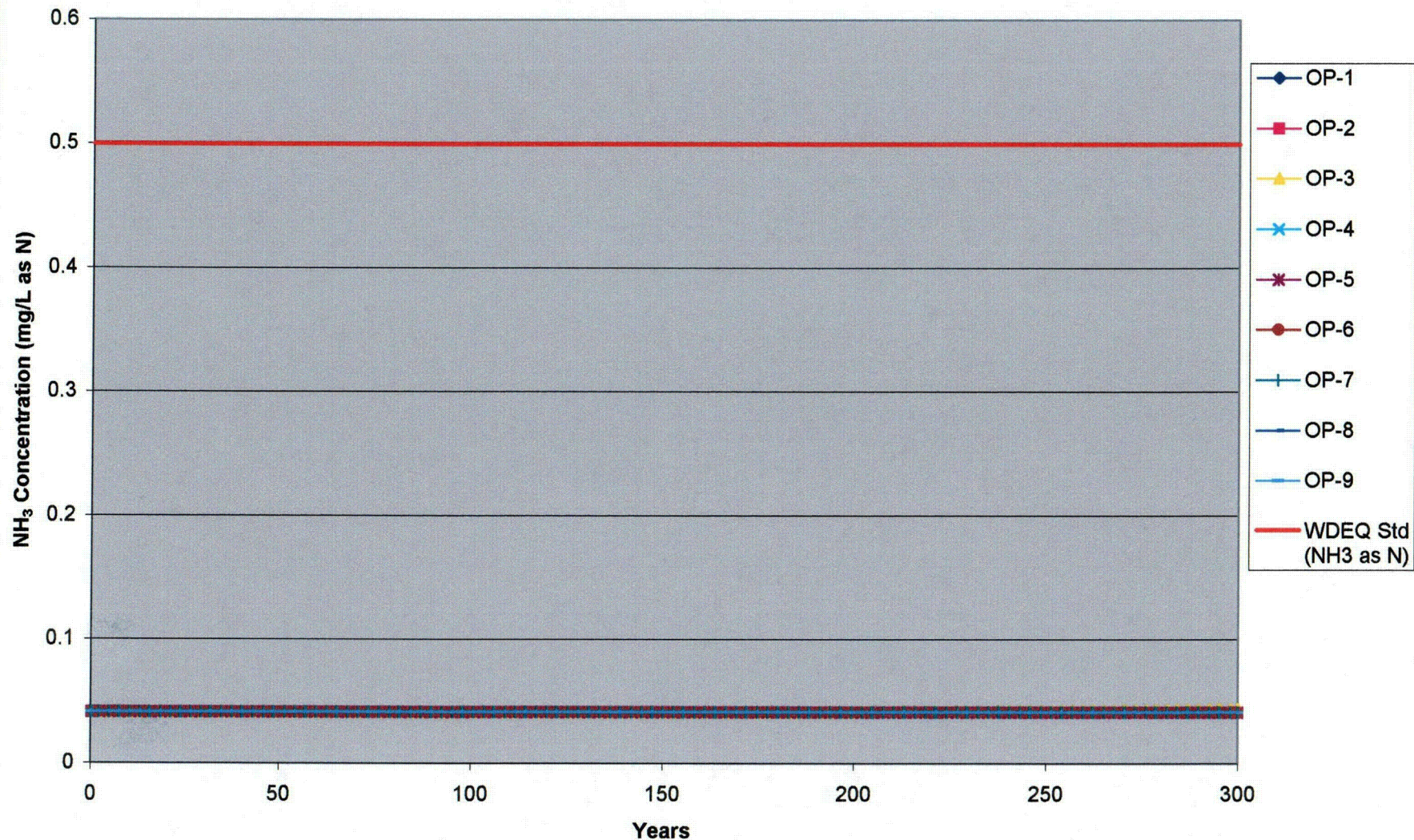
mg/l - milligrams per liter

Kd- Distribution coefficient

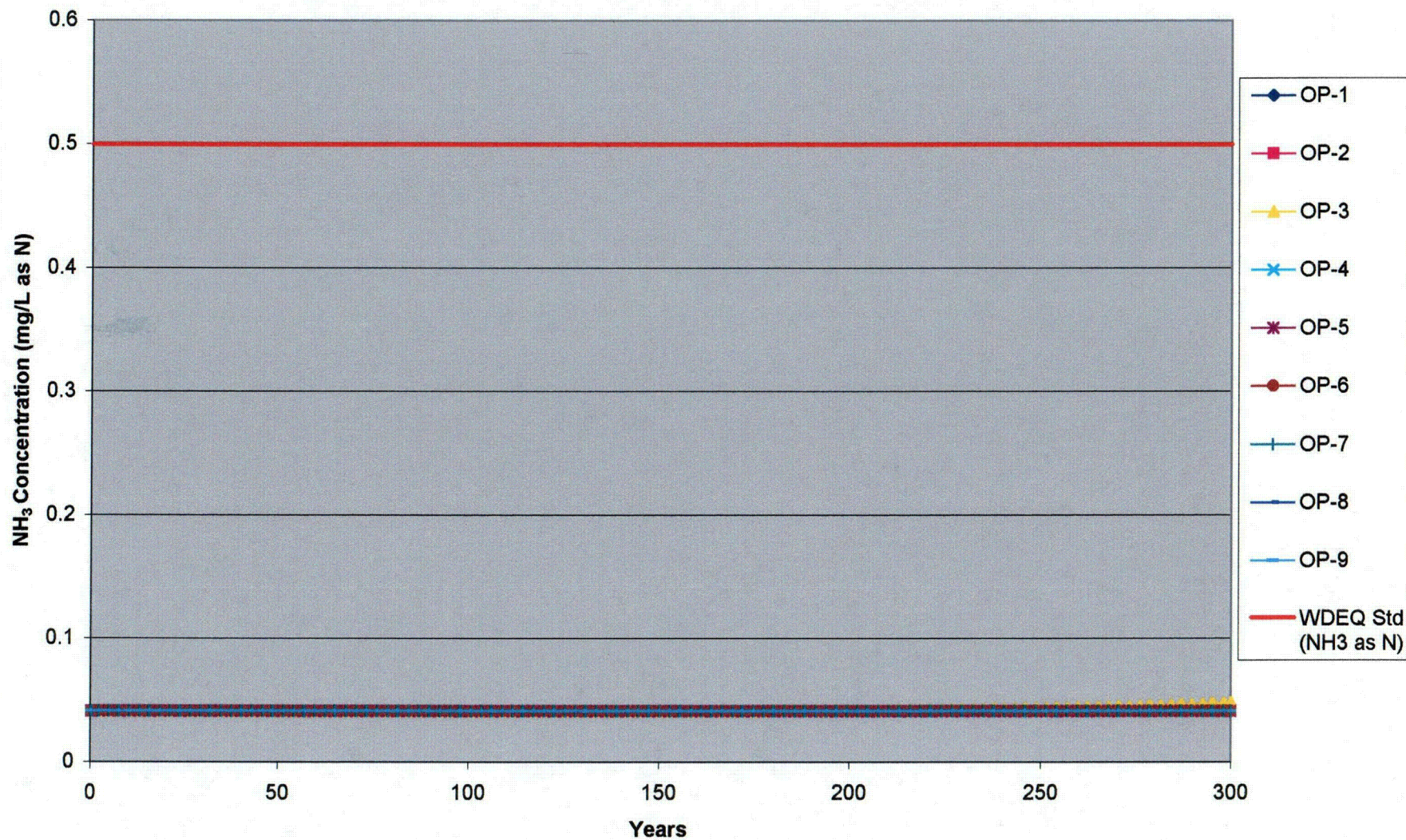
L/mg- liters per milligram

\* NH<sub>3</sub> concentration is calculated as 0.2 x NH<sub>4</sub> concentration

**Figure 1. Un-ionized Ammonia Concentration ( $\text{NH}_3$ , as N) at Irigaray Observation Points  
(Converted from  $\text{NH}_4$ , assuming that  $\text{NH}_3$  (as N) accounts for 20% of Total Ammonia)  
Simulated  $K_d=2$  and Wellfield  $\text{NH}_4$  Concentration at 8.7 mg/L (as N)**



**Figure 2. Un-ionized Ammonia Concentration ( $\text{NH}_3$ , as N) at Irigaray Observation Points  
(Converted from  $\text{NH}_4$ , assuming that  $\text{NH}_3$  (as N) accounts for 20% of Total Ammonia)  
Simulated  $K_d=2$  and Wellfield  $\text{NH}_4$  Concentration at 21.5 mg/L (as N)**



**Figure 3. Un-ionized Ammonia Concentration ( $\text{NH}_3$ , as N) at Irigaray Observation Points  
(Converted from  $\text{NH}_4$ , assuming that  $\text{NH}_3$  (as N) accounts for 20% of Total Ammonia)  
Simulated  $K_d=1$  and Wellfield  $\text{NH}_4$  Concentration at 8.7 mg/L (as N)**

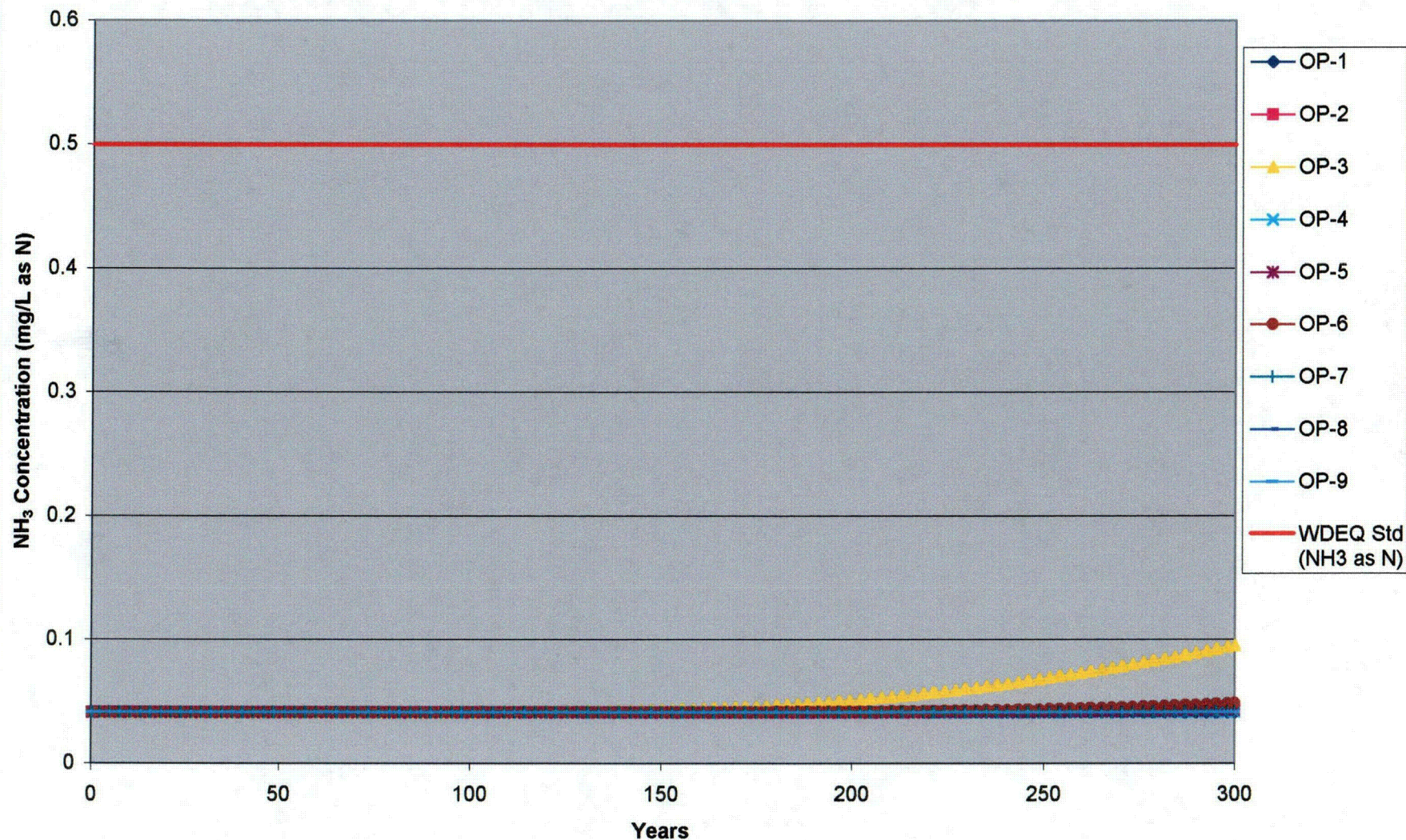


Figure 4. Un-ionized Ammonia Concentration ( $\text{NH}_3$ , as N) at Irigaray Observation Points  
(Converted from  $\text{NH}_4$ , assuming that  $\text{NH}_3$  (as N) accounts for 20% of Total Ammonia)  
Simulated  $K_d=1$  and Wellfield  $\text{NH}_4$  Concentration at 21.5 mg/L (as N)

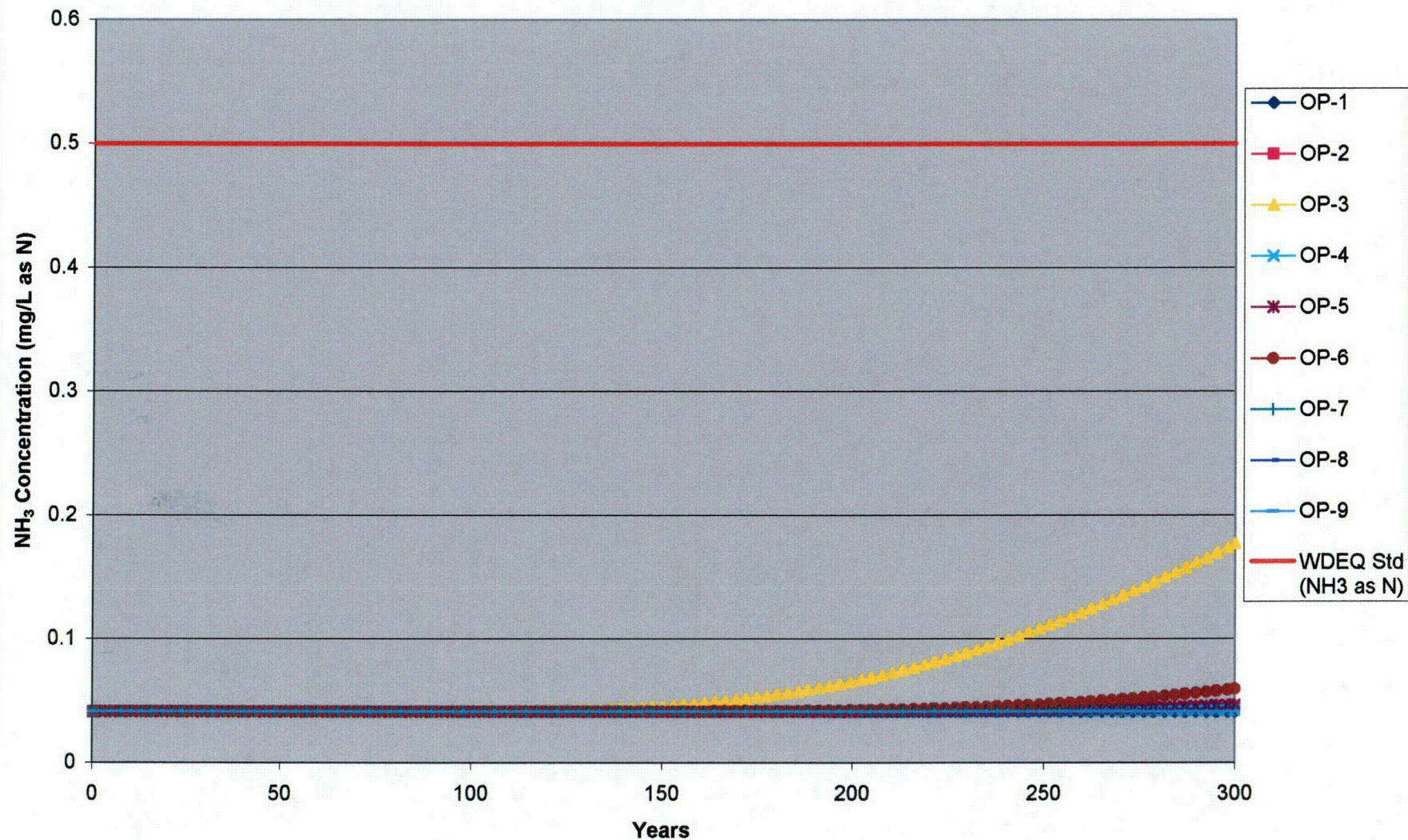
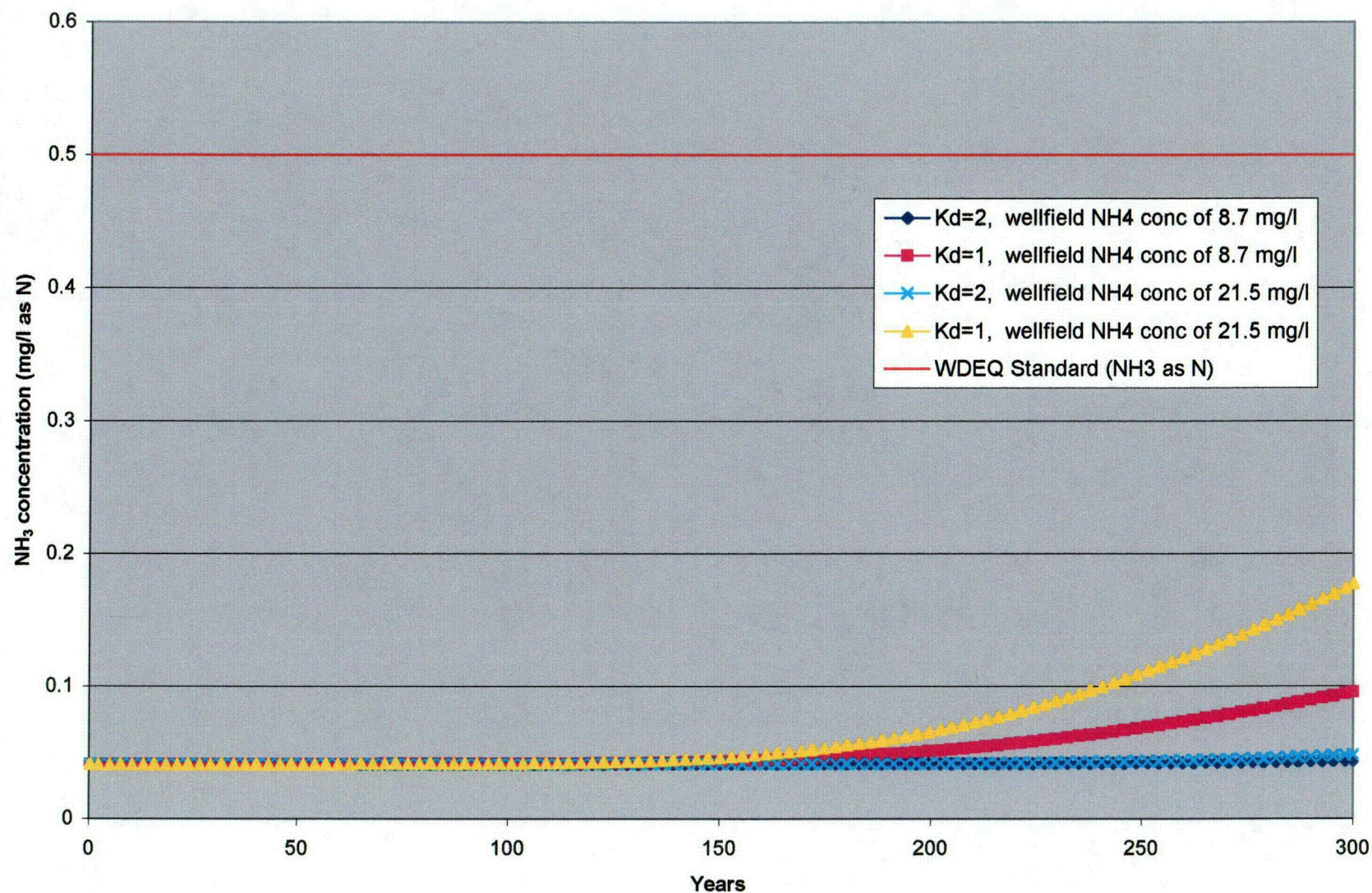


Figure 5. Comparison of Un-ionized Ammonia Concentration ( $\text{NH}_3$  as N) at OP-3 for All Simulations  
(Converted from  $\text{NH}_4$ , assuming that  $\text{NH}_3$  (as N) accounts for 20% of Total Ammonia)



**ATTACHMENT A**

**Resource Technologies Group (RTG)**

**Irigaray Aquifer Restoration:  
Impacts of Residual Ammonia**

**April 2005**



**RESOURCE  
TECHNOLOGIES  
GROUP, INC.**

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303-969-8511  
FAX 303-989-8188

April 20, 2005

Ms. Donna Wichers  
Cogema Resources Inc.  
935 Pendell Blvd., Second Floor  
Mills, Wyoming 82644

Dear Ms. Wichers,

RE: Evaluation of the Impact of Residual Ammonia on Post  
Restoration Groundwater Quality

Resource Technologies Group, Inc. (RTG) is pleased to have had the opportunity to prepare an initial evaluation of the impact of residual ammonia on post restoration groundwater quality.

The report of RTG's initial findings is attached for your review. The report was prepared using existing published scientific and wellfield data from the post restoration ground waters at the Cogema site. The calculations of ammonia concentrations in the report reflect the use of published speciation data for the distribution of the ammonia species as a function of pH and temperature. RTG has also used the most conservative assumptions for the interaction of ammonia with the host environment to determine the concentrations of ammonia at the well field boundaries.

Please feel free to call me (303-969-8511 x 301) if you require any additional or more detailed information on this subject.

Sincerely,

RESOURCE TECHNOLOGIES GROUP, INC.

Erich W. Tiepel, PhD  
President

**IRIGARAY**  
**AQUIFER RESTORATION:**

**Impacts Of Residual Ammonia**

## IRIGARAY AQUIFER RESTORATION:

### Impacts Of Residual Ammonia

#### 1.0 INTRODUCTION

The Irigaray In-situ Uranium mining operation used a system of injection and recovery wells to extract uranium from low grade ore bodies. The initial extraction solution (lixiviant) which was circulated through the first five Irigaray well fields (Production Units 1 through 5) was a solution containing ammonium bicarbonate. Traces of this solution remained in the aquifer after groundwater restoration methods were used to remove most of the ammonium carbonate solution from the aquifer. Low levels of ammonium ion remained in the groundwater upon completion of the restoration process.

This report will evaluate the effects of residual ammonium ion in the post-restoration groundwater and determine the speciation of ammonium ion ( $\text{NH}_4^+$ ) and un-ionized ammonia ( $\text{NH}_3$ ). This analysis will be used as input to determine potential migration effects of ammonia and the necessary requirements for compliance with applicable water quality regulations.

The input used in this evaluation is based on data submitted in the Irigaray Wellfield Restoration Report (COGEMA, July 2004) and groundwater field data supplied by COGEMA (Attachment A). Specific parameters from these data that were used in this analysis included:

##### 1. Wellfield Water Quality

- 8.7 ppm ( $\text{NH}_4^+$  as N); (11.2ppm as  $\text{NH}_4^+$ ) Avg. Conc. For the entire wellfield (Units 1-9)
- 21.5 ppm ( $\text{NH}_4^+$  as N); (27.6 ppm as  $\text{NH}_4^+$ ) Avg. Conc. in North End of Wellfield(Units 1-5)

##### 2. Wellfield Physical Parameters

- pH = 7.46 (Mean); (Range = 7.17 – 7.80)
- Avg. Temperature = 15.2°C; (Range 12.8 – 17.66°C)

##### 3. Wyoming Regulatory Limits for Groundwater Class Standards

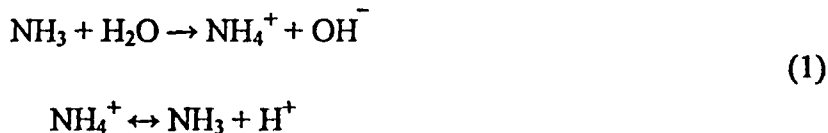
Ammonia = 0.5 mg/L (un-ionized  $\text{NH}_3$  as N)

## 2.0 AMMONIA CHEMISTRY

Ammonia (NH<sub>3</sub>) is found in the environment as a natural by-product of the decomposition of organic matter, such as plant and animal waste, and is the first decomposition product in the naturally occurring Nitrogen Cycle. In surface or groundwaters ammonia exists as a dissolved species. Under anaerobic conditions it will remain as ammonia (NH<sub>3</sub>) or the ammonium ion (NH<sub>4</sub><sup>+</sup>), but if exposed to oxygen and naturally occurring bacteria, it will undergo nitrification to produce nitrates (NO<sub>3</sub><sup>-</sup>).

Surface and groundwaters often contain naturally occurring nitrogen compounds such as ammonia depending on the source of the waters and on the availability of oxygen. Groundwater typically does not exhibit oxidation environments and any ammonia contained in groundwater usually remains as NH<sub>4</sub><sup>+</sup> or NH<sub>3</sub> under anaerobic conditions. Artificial introduction of ammonia compounds (such as ammonium bicarbonate) introduced into groundwater (such as the ammonium bicarbonate solution in the Irigaray lixiviant) also results in similar phenomenon to occur. The ammonium ion (NH<sub>4</sub><sup>+</sup>) will be stable in the groundwater in an anaerobic environment (minimal nitrification) and will exist in equilibrium as the dissociated ammonium ion (NH<sub>4</sub><sup>+</sup>) and the un-ionized species, NH<sub>3</sub>. Very little, if any, conversion of ammonia to nitrates has been found in groundwaters that contain low levels of ammonia.

Ammonia dissolved in groundwater exists as equilibrium of molecular (un-ionized) ammonia (NH<sub>3</sub>) and the ionized ammonium ion (NH<sub>4</sub><sup>+</sup>). This dissociation of ammonia is governed by the equilibrium reaction:



The equilibrium constant (K) for this reaction is:

$$K = \frac{[\text{NH}_3][\text{H}^+]}{[\text{NH}_4^+]} \quad (2)$$

As can be seen from this equation, the equilibrium distribution of NH<sub>3</sub> with NH<sub>4</sub><sup>+</sup> is strongly dependent on the hydrogen ion (H<sup>+</sup>) concentration, hence the pH.

The equilibrium constant K is also dependent on temperature and this relationship can be described with the following equation:

$$\text{pK} = 0.09018 + \frac{2729.92}{273.2 + T} \quad (3)$$

where  $pK = -\log_{10}K$  and  $T$  is temperature in degrees Celsius ( $^{\circ}C$ ).

From Equation 2, the definition of  $pK$ , and the definition of  $pH = -\log_{10} [H^+]$ , the following expressions can be derived for the fraction of total ammonia in each of the two forms:

$$f_{NH_3} = \frac{1}{1 + 10^{pK-pH}}$$

$$f_{NH_4^+} = \frac{1}{1 + 10^{pK-pH}} \quad (4)$$

$$f_{NH_3} + f_{NH_4^+} = 1$$

The individual fractions (speciation) of un-ionized ammonia ( $NH_3$ ) and the ammonium ion ( $NH_4^+$ ) vary markedly with temperature and pH. This relationship is shown in Figures 1.0 and 2.0 in different formats.

Ammonia speciation also depends on ionic strength, but in typical non-saline groundwaters, this effect is much smaller than the effects of pH and temperature. This effect is sufficiently small compared to the typical uncertainty in toxicity calculations in that it will not be considered here as a variable affecting ammonia speciation and ammonia toxicity.

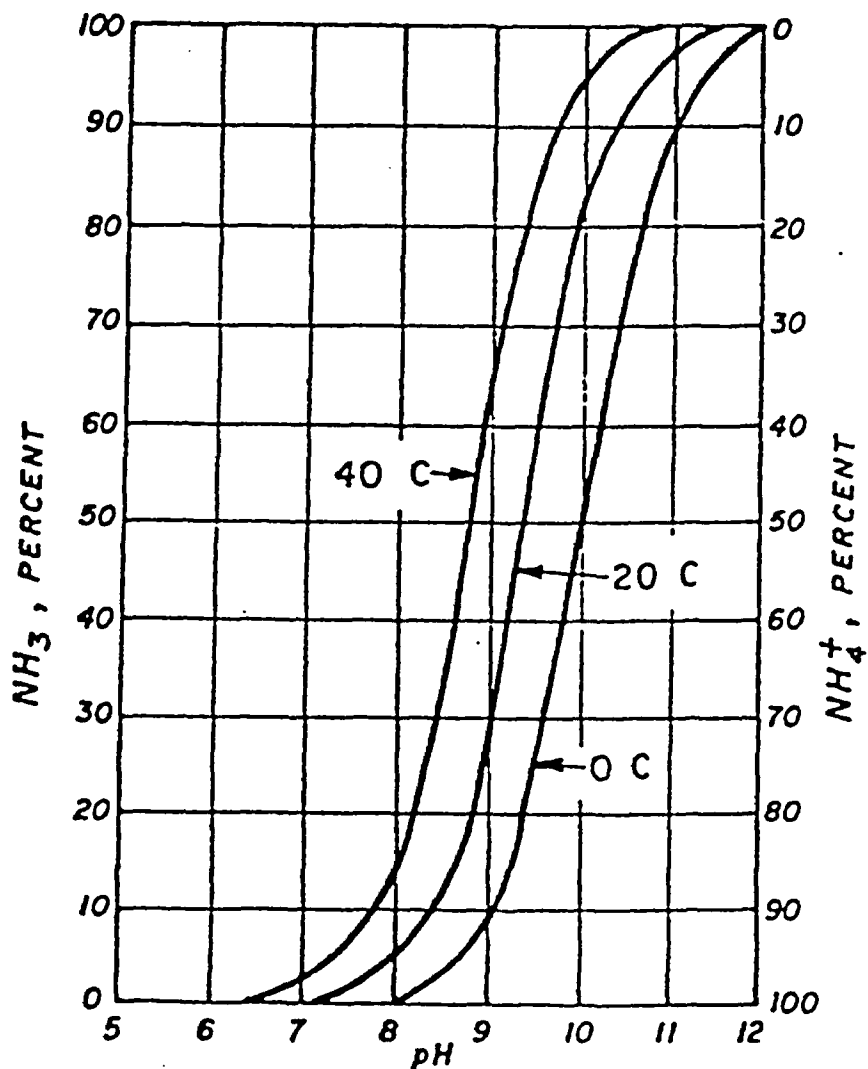
While the above distribution formulas can be used to determine the relative dissociation of  $NH_4^+$  to  $NH_3$ , it is more practical to develop tables or graphs which give these results. Figure 2.0 gives the fractional dependence of un-ionized ammonia and ammonium ion versus pH at a temperature of  $25^{\circ}C$ . Appendix B gives the full calculation of pH and temperature dependence using the above formulas for the combined effects of both temperature and pH. The Tables in Appendix B cover the pH range of 5-10 and a temperature range of  $10-20^{\circ}C$ .

### 3.0 AMMONIA TOXICITY

Ammonia ( $NH_3$ ) is generally considered to be non-toxic to humans and animals at the concentrations typically found in most surface and groundwater as in the post-restoration groundwaters at Irigaray.

**FIGURE 1.0**

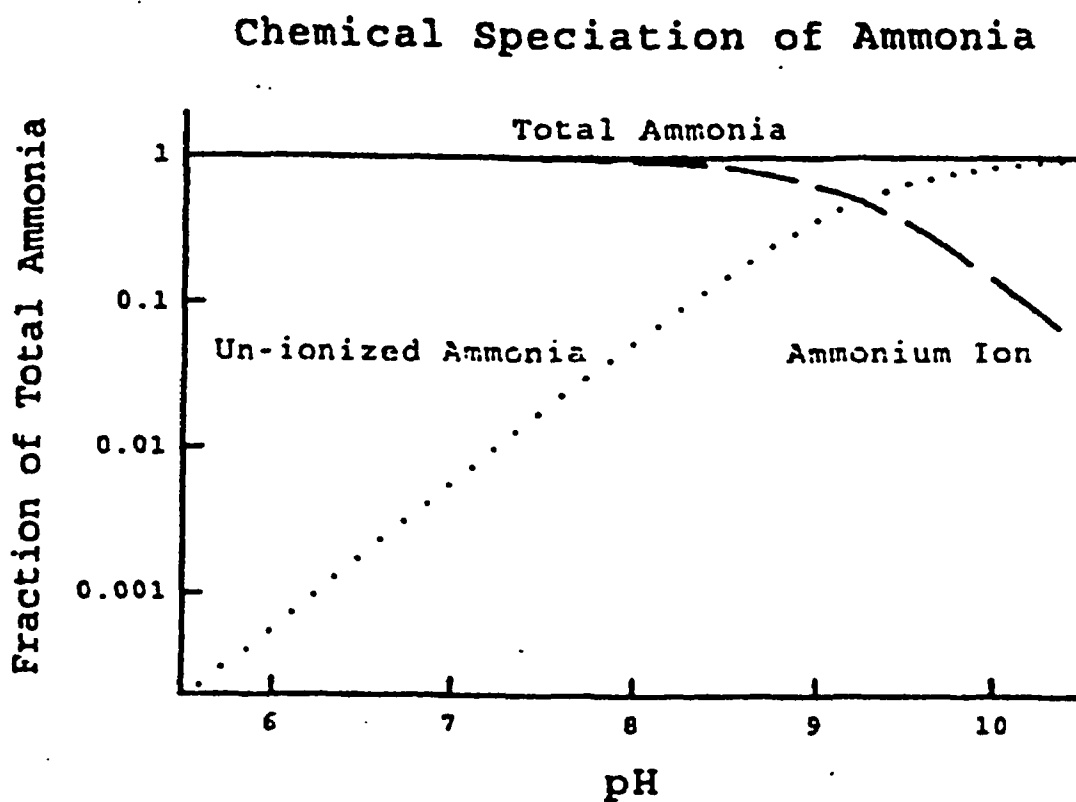
**EFFECTS OF pH AND TEMPERATURE ON DISTRIBUTION  
OF AMMONIA AND AMMONIUM ION IN WATER**



**Reference: Process Design Manual for Nitrogen Control USEPA, 1975**

FIGURE 2.0

T = 25°C



Reference: 1999 Update of Ambient Water Quality Criteria for Ammonia; EPA-822-R-99-014, December 1999

There is no ammonia standard for Primary Drinking Water as established by the Environmental Protection Agency (EPA). The most recent National Primary Drinking Water Regulations were reviewed for the list of drinking water contaminants and MCLs. National Secondary Drinking Water Regulations were also reviewed and ammonia was not listed as a Standard. Under the Drinking Water Contaminant Candidate List (CCL) ammonia was not found to be under consideration for future consideration as a Primary or Secondary Standard for Drinking Water. Even the list of Unregulated Contaminants, which is a list of potential future chemical species under consideration for regulation, did not mention ammonia.

Ammonia compounds (such as ammonium bicarbonate and other ammonium salts) are used in a variety of commercially available consumer goods and have been used as food additives in various products. Direct ammoniation, using  $\text{NH}_3$ , of cattle feed has been used in to enhance the nutrient value of certain low nutrient grasses and feedstock. High concentrations of ammonia in water (such as household ammonia solutions) are known to be an irritant and be corrosive due to the high pH that these solutions exhibit. High concentrations of ammonia also are a nuisance due to the strong odor of ammonia at high pH and can have health effects on humans or animals.

Ammonia toxicity to aquatic life is quite different than that for human and animals due to the mechanisms which un-ionized ammonia ( $\text{NH}_3$ ) can transport across sensitive biological membranes (such as gills). Ammonia toxicity to aquatic life is, therefore, highly dependant on the amount of un-ionized ammonia ( $\text{NH}_3$ ) present in the water.

Many studies have been conducted to determine the toxicity of un-ionized ammonia ( $\text{NH}_3$ ) to various aquatic life species. In general, it has been found that ammonia toxicity to aquatic life is highly dependent on the pH, temperature and, to some smaller extent, on the ionic strength of the water. For most non-saline groundwaters, the effect of ionic strength is minimal.

The speciation relationships between ammonia and the ammonium ion are important to ammonia toxicity because un-ionized ammonia ( $\text{NH}_3$ ) is much more toxic than the ammonium ion ( $\text{NH}_4^+$ ). Un-ionized ammonia is the more toxic form because it is a neutral molecule and thus is able to diffuse across the epithelial membranes of aquatic organisms much more readily than the charged ammonium ion. The ammonium ion ( $\text{NH}_4^+$ ) is considered to be much less toxic to aquatic life and is generally not a toxicity issue unless found at high concentrations.

Because of the importance of un-ionized ammonia, the convention in most scientific literature is to express ammonia toxicity in terms of un-ionized ammonia, and most water quality criteria and standards followed this convention. Observations that ammonia toxicity is relatively constant when expressed in terms of un-ionized ammonia come mainly from toxicity tests conducted at  $\text{pH} > 7.5$ . At lower pH, toxicity varies considerably when expressed in terms of un-ionized ammonia and under some conditions is relatively constant in terms of ammonium ion concentration.

#### 4.0 CALCULATIONS OF IRIGARAY WELLFIELD AMMONIA CONCENTRATIONS

For the conditions encountered at the Irigaray Wellfield, a calculation using the following average conditions of the Wellfield water quality parameters were made.

Avg.  $\text{NH}_4^+$  Data: From Irigaray Wellfield Restoration Report, Table 4-6 (COGEMA, July 2004). Avg. pH and Temperature Data: From Appendix A; Irigaray Field Water Quality Data. It is noted that, because pH is critical to assessment of aqueous nitrogen concentrations, pH measurements were conducted in the field using a flow-through cell.

Max.  $\text{NH}_4^+$  Data: From Irigaray Wellfield Restoration Report, Appendix A: Average of Rounds 1-4 Stability Data from only Irigaray Production Units 1 through 5 restoration wells (COGEMA, July 2004).

$$\text{Avg. } \text{NH}_4^+ = 8.7 \text{ (as N)}^{(1)} \quad (11.2 \text{ ppm as } \text{NH}_4^+)$$

$$\text{Max. } \text{NH}_4^+ = 21.5 \text{ ppm (as N)} \quad (27.6 \text{ ppm as } \text{NH}_4^+)$$

$$T = 15.2^\circ\text{C}$$

$$\text{pH} = 7.46$$

Note <sup>(1)</sup>: To change from "as N" concentrations to "as  $\text{NH}_4^+$ " concentrations multiply by 1.286.

At the above conditions, the un-ionized ammonia ( $\text{NH}_3$ ) concentrations are as follows:

$$\text{Avg. } \text{NH}_3 = 0.07 \text{ ppm (as N)}^{(2)} \quad (0.08 \text{ ppm as } \text{NH}_3)$$

$$\text{Max. } \text{NH}_3 = 0.17 \text{ ppm (as N)} \quad (0.21 \text{ ppm as } \text{NH}_3)$$

Note <sup>(2)</sup>: To change from "as N" concentrations to "as  $\text{NH}_3$ " concentrations multiply by 1.214.

Ammonia dissociation is sensitive to both pH and temperature and can significantly affect the amount of un-ionized  $\text{NH}_3$  which exists for any set of input parameters. For example, based on the average concentrations in the wellfield discussed above, a change in pH of 1.4 units to a value of pH = 8.86 (the average pH at the exterior monitor wells) results in an un-ionized ammonium concentrations as follows:

$$\text{Avg. } \text{NH}_3 = 1.56 \text{ ppm (as N)} \quad (1.77 \text{ ppm as } \text{NH}_3)$$

$$\text{Max. NH}_3 = 3.60 \text{ ppm (as N)} \quad (4.37 \text{ ppm as NH}_3)$$

At a lower pH of 6.8, the concentrations change to:

$$\text{Avg. NH}_3 = 0.015 \text{ ppm (as N)} \quad (0.018 \text{ ppm as NH}_3)$$

$$\text{Max. NH}_3 = 0.037 \text{ ppm (as N)} \quad (0.045 \text{ ppm as NH}_3)$$

The temperature effect on ammonia distribution is less pronounced but still significant. For example, at the above conditions of the Irigaray Wellfield at a pH of 7.46, lowering the temperature by 3°C from 15.2°C to 12.2°C results in the following un-ionized ammonia concentrations.

$$\text{Avg. NH}_3 = 0.051 \text{ ppm (as N)} \quad (0.062 \text{ ppm as NH}_3)$$

$$\text{Avg. NH}_3 = 0.23 \text{ ppm (as N)} \quad (0.28 \text{ ppm as NH}_3)$$

Raising the temperature 3°C from 15.2°C to 18.2°C at a pH of 7.46 results in the following un-ionized ammonia conditions.

$$\text{Avg. NH}_3 = 0.22 \text{ ppm (as N)} \quad (0.27 \text{ ppm as NH}_3)$$

$$\text{Max NH}_3 = 0.57 \text{ ppm (as N)} \quad (0.70 \text{ ppm as NH}_3)$$

As can be seen from Figure 1, the un-ionized fraction of ammonia for any given concentration changes by a factor of approximately 10 over a pH range of  $7.5 \pm 1.0$  with lower un-ionized concentrations occurring at lower pH. Temperature changes over the range of  $15.2^\circ \pm 3.0^\circ\text{C}$  have a lesser effect of only 20% with lower temperatures resulting in lower un-ionized  $\text{NH}_3$  concentrations. These combined effects of both pH and temperature can be seen in Figure 3.

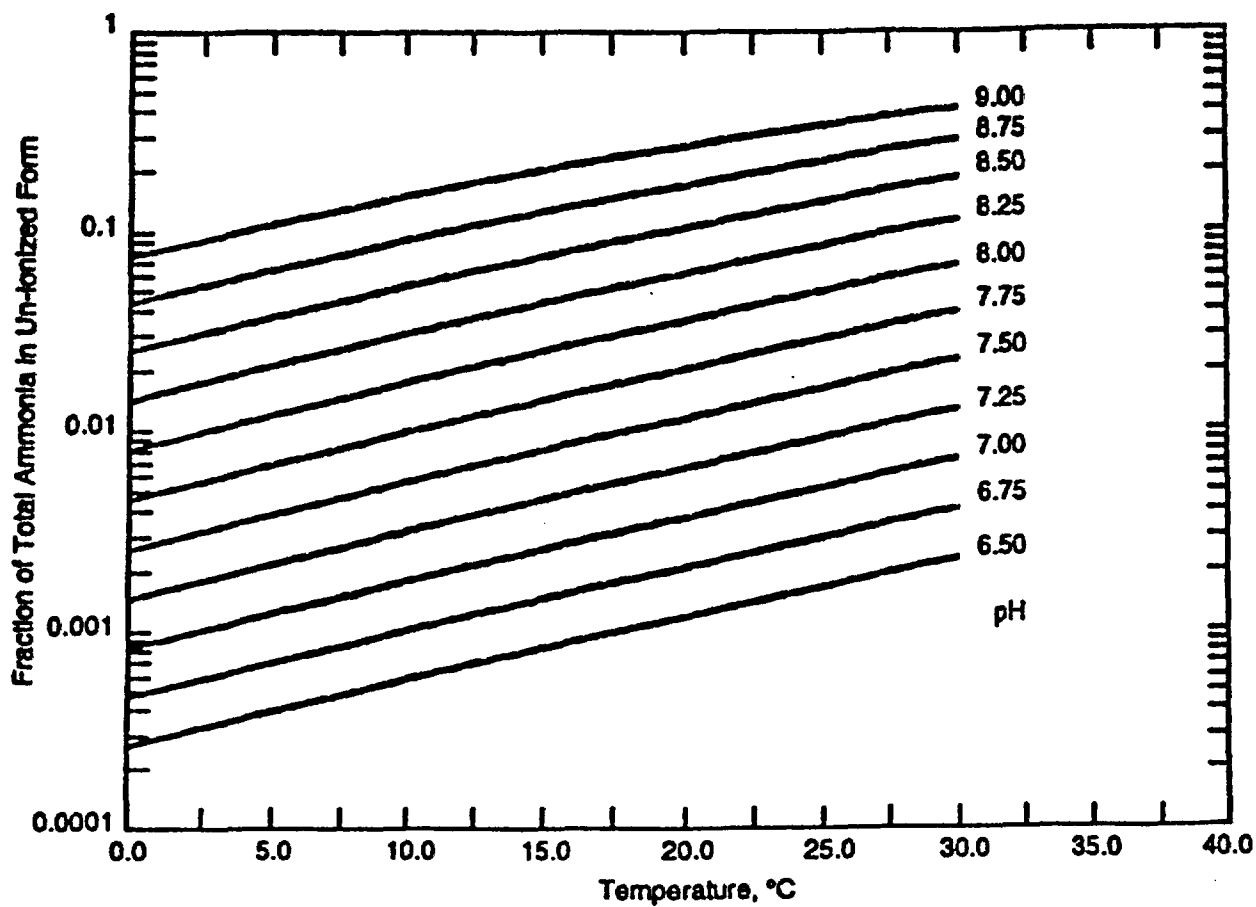
## 5.0 CONCLUSIONS

1. At the average conditions of ammonia concentration, pH and temperature found in the post-restoration Irigaray Wellfield, the concentrations of un-ionized ammonia ( $\text{NH}_3$ ) are below the regulatory limit of 0.5 ppm as un-ionized  $\text{NH}_3$  (as N)
2. pH and temperature play a significant role in the distribution of the ammonia species with pH having a larger effect than temperature.
3. Discharges of Irigaray post-restoration groundwater at the wellfield average for ammonia, or even at the maximum concentration, ammonia concentrations are below the Wyoming groundwater limit for un-ionized  $\text{NH}_3$  of 0.5 ppm (as N).

4. Dissipation of un-ionized  $\text{NH}_3$  through the natural movement of groundwater will further reduce the  $\text{NH}_3$  concentrations over time.
5. Ammonia migration has been demonstrated to be retarded due to the interaction of the ammonium ion with formation clays (Drever, J.I, 1988; *The Geochemistry of Natural Waters*, PP 96-97; Hem, J.D., 1989; *Study and Interpretation of the Chemical Characteristics of Natural Waters*; USGS Water Supply Paper 2254; PP 124-126). The most conservative approach to retardation would be to assume that there are no interactions with the clays in the formation. Using this assumption, the ammonium ion would be considered mobile and a retardation factor of 1.0 (mobile ion) would be used. Transport analysis using this very conservative approach (no retardation) still will result in very low un-ionized  $\text{NH}_3$  values at the wellfield perimeter.
6. The condition for formation of nitrates and nitrites from ammonia do not exist in the aquifer due to the lack of oxygen, nitrificates in bacteria and due to the reducing conditions in the formation. It is expected that little, if any,  $\text{NH}_3$  conversion to  $\text{NO}_2^-$  or  $\text{NO}_3^-$  would occur in the formation. This is further demonstrated by the  $\text{NO}_2^-$  and  $\text{NO}_3^-$  values in the Irigaray Wellfields that are less than detectable (Table 4-6, Irigaray Wellfield Restoration Report, COGEMA 2004).

**FIGURE 3.0**

**Effects of pH and Temperature on Un-ionized Ammonia**



**Reference: Nitrogen Control Manual EPA / 625 / R-93 / 010**

## **APPENDIX A**

### **Irigaray Field Water Quality Data**

**IRIGARAY MINE**
**Field Measurement of Water Quality Parameters**
**Mining Wells**
**15**

Well I.D.:	Production Unit:	Date of Test	Time	Well T.D.	1- Casing Displmnt Gallons	Subm. Pump GPM	CUM Pumped Gallons	# of C.D.'s Pumped	Sample Flowrate l/min	pH	Cond. mS/cm	Turbidity NTU	Dissolved Oxygen mg/l	Temp deg C	Salinity %	TDS g/l	ORP mV
AP-4	Unit 1	05/21/02	11:40	264	139	7.5	576	4.1	0.300	7.47	1.500	12.5	0.07	15.28	0.07	0.960	-142
BP-4	Unit 1	05/21/02	10:30	268	141	12.0	930	6.6	0.250	7.80	0.776	39.0	0.08	14.74	0.03	0.495	-168
DI-27	Unit 3	05/21/02	13:40	234	118	17.4	652	5.5	0.450	7.47	1.870	25.0	0.01	16.32	0.09	1.180	-230
DI-90	Unit 2	05/21/02	13:15	235	133	8.1	652	4.9	0.350	7.17	1.850	50.0	2.58	17.02	0.09	1.180	-71
DP-28	Unit 2	05/21/02	12:05	252	132	12.0	753	5.7	0.300	7.36	1.570	19.3	0.03	16.76	0.07	1.010	-184
FP-5	Unit 3	05/21/02	14:21	287	146	11.9	548	3.8	0.400	7.59	0.919	69.0	0.01	15.10	0.04	0.579	-162
FI-62	Unit 4	05/21/02	15:15	281	139	6.2	362	2.6	0.350	7.64	0.805	47.0	0.15	17.66	0.03	0.514	-195
GI-76	Unit 5	05/23/02	8:50	204	124	12.5	814	6.6	0.450	7.77	0.752	6.5	0.00	14.16	0.03	0.482	-187
HI-57	Unit 6	05/22/02	16:02	292	141	14.3	640	4.5	0.300	7.40	0.968	1.9	5.34	15.53	0.04	0.619	-122
HI-53	Unit 6	05/22/02	17:00	316	154	2.1	335	2.2	0.300	7.20	0.910	30.2	2.20	15.64	0.04	0.583	-23
JP-26	Unit 7	05/23/02	8:18	204	108	13.7	700	6.5	0.400	7.33	0.750	0.7	0.40	14.72	0.03	0.481	-32
JP-57	Unit 7	05/23/02	9:05	211	136	12.1	536	3.9	0.450	7.68	0.591	0.8	4.94	14.25	0.02	0.379	-155
KP-44	Unit 8	05/23/02	10:15	249	136	8.0	520	3.8	0.375	7.39	0.781	1.5	0.00	13.46	0.03	0.501	-120
LI-51	Unit 9	05/23/02	11:00	292	150	15.1	570	3.8	0.400	7.41	0.902	1.9	0.00	12.80	0.04	0.577	-149
LP-22	Unit 9	05/23/02	10:03	287	150	11.9	915	6.1	0.350	7.27	0.880	1.4	0.00	14.55	0.04	0.564	-119

**Exterior Ring Monitoring Wells**
**9**
**Average**
**7.46**
**15.20**
**-137.27**

Well I.D.:	Production Unit:	Date of Test	Time	Well T.D.	1- Casing Displmnt Gallons	Subm. Pump GPM	CUM Pumped Gallons	# of C.D.'s Pumped	Sample Flowrate l/min	pH	Cond. mS/cm	Turbidity NTU	Dissolved Oxygen mg/l	Temp deg C	Salinity %	TDS g/l	ORP mV
M-17	1 N	05/22/02	9:14	252	120	8.2	656	5.5	0.400	8.94	0.606	5.1	0.44	11.65	0.03	0.387	-56
M-07	1N	05/22/02	8:56	240	145	13.0	662	4.6	0.300	7.83	2.250	7.0	1.20	11.53	0.11	1.440	-115
M-02	2 W	05/22/02	10:07	260	130	12.1	485	3.7	0.400	8.96	0.722	35.0	0.10	11.89	0.03	0.462	-162
M-010	4 W	05/22/02	10:33	295	154	7.1	537	3.5	0.300	8.90	0.590	24.7	0.81	11.66	0.02	0.377	-93
M-04	2 E	05/22/02	14:53	298	148	12.2	538	3.6	0.350	8.90	0.884	31.0	4.18	11.41	0.04	0.566	-138
M-15	5 W	05/22/02	12:40	296	163	8.0	652	4.0	0.350	8.97	0.591	19.7	0.73	12.10	0.02	0.378	-152
M-23	5 E	05/22/02	13:58	324	146	7.1	462	3.2	0.350	9.10	0.559	20.4	2.35	11.64	0.02	0.357	-160
M-24	6 E	05/22/02	14:14	375	159	8.5	555	3.5	0.300	9.10	0.500	3.3	1.30	11.50	0.02	0.320	-50
M-25	6 W	05/22/02	12:01	205	116	10.1	588	5.1	0.350	9.00	0.554	38.4	7.36	12.05	0.02	0.354	-131

**Notes**

Used Horiba U-22 multimeter to measure pH, Conductivity, Turbidity, DO, Temp, Salinity, TDS and ORP.

**Average**
**8.86**
**11.71**
**-117.44**

## **APPENDIX B**

### **Un-ionized Ammonia Criteria Tables**

**pH Range = 5.0 – 10.0**

**Temperature Range = 10 - 20°C**

**Reference: Administrative Rules of South Dakota, Un-ionized ammonia criteria tables (ARSI) 74:51:01) Appendix A, effective January 27, 1999.**

Temp °C	pH	Unionized %
10.0	5.0	0.001863
10.0	5.1	0.002346
10.0	5.2	0.002953
10.0	5.3	0.003718
10.0	5.4	0.004680
10.0	5.5	0.005892
10.0	5.6	0.007417
10.0	5.7	0.009337
10.0	5.8	0.011755
10.0	5.9	0.014798
10.0	6.0	0.018629
10.0	6.1	0.023451
10.0	6.2	0.029521
10.0	6.3	0.037162
10.0	6.4	0.046780
10.0	6.5	0.058885
10.0	6.6	0.074121
10.0	6.7	0.093295
10.0	6.8	0.117423
10.0	6.9	0.147781
10.0	7.0	0.185974
10.0	7.1	0.234014
10.0	7.2	0.294428
10.0	7.3	0.370380
10.0	7.4	0.465833
10.0	7.5	0.585742
10.0	7.6	0.736288
10.0	7.7	0.925166
10.0	7.8	1.161929
10.0	7.9	1.458393
10.0	8.0	1.829101
10.0	8.1	2.291843
10.0	8.2	2.868236
10.0	8.3	3.584270
10.0	8.4	4.470831
10.0	8.5	5.564026
10.0	8.6	6.905202
10.0	8.7	8.540426
10.0	8.8	10.519133
10.0	8.9	12.891670
10.0	9.0	15.705387
10.0	9.1	18.999268
10.0	9.2	22.797165
10.0	9.3	27.100220
10.0	9.4	31.880127
10.0	9.5	37.074326
10.0	9.6	42.585770
10.0	9.7	48.287796
10.0	9.8	54.034760
10.0	9.9	59.676407
10.0	10.0	65.073166
10.0	10.1	70.109451

Temp °C	pH	Unionized %
10.5	5.0	0.001938
10.5	5.1	0.002439
10.5	5.2	0.003071
10.5	5.3	0.003866
10.5	5.4	0.004867
10.5	5.5	0.006127
10.5	5.6	0.007713
10.5	5.7	0.009710
10.5	5.8	0.012224
10.5	5.9	0.015388
10.5	6.0	0.019372
10.5	6.1	0.024387
10.5	6.2	0.030699
10.5	6.3	0.038644
10.5	6.4	0.048645
10.5	6.5	0.061233
10.5	6.6	0.077076
10.5	6.7	0.097013
10.5	6.8	0.122101
10.5	6.9	0.153668
10.5	7.0	0.193379
10.5	7.1	0.243328
10.5	7.2	0.306138
10.5	7.3	0.385099
10.5	7.4	0.484328
10.5	7.5	0.608968
10.5	7.6	0.765438
10.5	7.7	0.916722
10.5	7.8	1.207726
10.5	7.9	1.515695
10.5	8.0	1.900685
10.5	8.1	2.381100
10.5	8.2	2.979254
10.5	8.3	3.721942
10.5	8.4	4.640923
10.5	8.5	5.773191
10.5	8.6	7.160964
10.5	8.7	8.850996
10.5	8.8	10.893088
10.5	8.9	13.337388
10.5	9.0	16.230255
10.5	9.1	19.608612
10.5	9.2	23.492996
10.5	9.3	27.879974
10.5	9.4	32.735641
10.5	9.5	37.991486
10.5	9.6	43.544922
10.5	9.7	49.265182
10.5	9.8	55.004745
10.5	9.9	60.614120
10.5	10.0	65.956970
10.5	10.1	70.922760

Temp °C	pH	Unionized %
11.0	5.0	0.002015
11.0	5.1	0.002536
11.0	5.2	0.003193
11.0	5.3	0.004019
11.0	5.4	0.005060
11.0	5.5	0.006390
11.0	5.6	0.008020
11.0	5.7	0.010096
11.0	5.8	0.012710
11.0	5.9	0.016000
11.0	6.0	0.020142
11.0	6.1	0.025356
11.0	6.2	0.031919
11.0	6.3	0.040180
11.0	6.4	0.050578
11.0	6.5	0.063666
11.0	6.6	0.080137
11.0	6.7	0.100865
11.0	6.8	0.126949
11.0	6.9	0.159766
11.0	7.0	0.201050
11.0	7.1	0.252975
11.0	7.2	0.318268
11.0	7.3	0.400345
11.0	7.4	0.503483
11.0	7.5	0.633021
11.0	7.6	0.795621
11.0	7.7	0.999567
11.0	7.8	1.255130
11.0	7.9	1.574994
11.0	8.0	1.974744
11.0	8.1	2.473405
11.0	8.2	3.094016
11.0	8.3	3.864173
11.0	8.4	4.186510
11.0	8.5	5.988933
11.0	8.6	7.424474
11.0	8.7	9.170552
11.0	8.8	11.277250
11.0	8.9	13.794406
11.0	9.0	16.767227
11.0	9.1	20.230377
11.0	9.2	24.200836
11.0	9.3	28.670441
11.0	9.4	33.599640
11.0	9.5	38.913986
11.0	9.6	44.505478
11.0	9.7	50.239424
11.0	9.8	55.967484
11.0	9.9	61.540726
11.0	10.0	66.826706
11.0	10.1	71.720001

Temp °C	pH	Unionized %
11.5	5.0	0.002094
11.5	5.1	0.002637
11.5	5.2	0.003319
11.5	5.3	0.004179
11.5	5.4	0.005261
11.5	5.5	0.006623
11.5	5.6	0.008337
11.5	5.7	0.010496
11.5	5.8	0.013213
11.5	5.9	0.016633
11.5	6.0	0.020939
11.5	6.1	0.026360
11.5	6.2	0.033183
11.5	6.3	0.041771
11.5	6.4	0.052580
11.5	6.5	0.066186
11.5	6.6	0.083308
11.5	6.7	0.104856
11.5	6.8	0.131970
11.5	6.9	0.166084
11.5	7.0	0.208997
11.5	7.1	0.262969
11.5	7.2	0.330833
11.5	7.3	0.416136
11.5	7.4	0.523320
11.5	7.5	0.657929
11.5	7.6	0.826873
11.5	7.7	1.038746
11.5	7.8	1.304193
11.5	7.9	1.636356
11.5	8.0	2.051356
11.5	8.1	2.568856
11.5	8.2	3.212626
11.5	8.3	4.011085
11.5	8.4	4.997746
11.5	8.5	6.211401
11.5	8.6	7.695907
11.5	8.7	9.499279
11.5	8.8	11.671788
11.5	8.9	14.262853
11.5	9.0	17.316345
11.5	9.1	20.864471
11.5	9.2	24.920502
11.5	9.3	29.471359
11.5	9.4	34.471710
11.5	9.5	39.841202
11.5	9.6	45.466766
11.5	9.7	51.210495
11.5	9.8	56.922424
11.5	9.9	62.455872
11.5	10.0	67.682114
11.5	10.1	72.501129

Temp °C	pH	Unionized %
12.0	5.0	0.002177
12.0	5.1	0.002741
12.0	5.2	0.003450
12.0	5.3	0.004344
12.0	5.4	0.005468
12.0	5.5	0.006884
12.0	5.6	0.008666
12.0	5.7	0.010910
12.0	5.8	0.013734
12.0	5.9	0.017290
12.0	6.0	0.021766
12.0	6.1	0.027400
12.0	6.2	0.034492
12.0	6.3	0.043419
12.0	6.4	0.054655
12.0	6.5	0.068796
12.0	6.6	0.086594
12.0	6.7	0.108990
12.0	6.8	0.137172
12.0	6.9	0.172627
12.0	7.0	0.217228
12.0	7.1	0.273320
12.0	7.2	0.343845
12.0	7.3	0.432490
12.0	7.4	0.543863
12.0	7.5	0.683719
12.0	7.6	0.859228
12.0	7.7	1.079301
12.0	7.8	1.354971
12.0	7.9	1.699842
12.0	8.0	2.130595
12.0	8.1	2.667542
12.0	8.2	3.335194
12.0	8.3	4.162807
12.0	8.4	5.184772
12.0	8.5	6.440766
12.0	8.6	7.975429
12.0	8.7	9.837313
12.0	8.8	12.076824
12.0	8.9	14.742795
12.0	9.0	17.877609
12.0	9.1	21.510818
12.0	9.2	25.651764
12.0	9.3	30.282303
12.0	9.4	35.351288
12.0	9.5	40.772552
12.0	9.6	46.428116
12.0	9.7	52.177094
12.0	9.8	57.868942
12.0	9.9	63.359085
12.0	10.0	68.522949
12.0	10.1	73.266113

Temp °C	pH	Unionized %
12.5	5.0	0.002263
12.5	5.1	0.002848
12.5	5.2	0.003586
12.5	5.3	0.004514
12.5	5.4	0.005683
12.5	5.5	0.007155
12.5	5.6	0.009007
12.5	5.7	0.011339
12.5	5.8	0.014274
12.5	5.9	0.017970
12.5	6.0	0.022621
12.5	6.1	0.028477
12.5	6.2	0.035848
12.5	6.3	0.045125
12.5	6.4	0.056803
12.5	6.5	0.071500
12.5	6.6	0.089996
12.5	6.7	0.113271
12.5	6.8	0.142558
12.5	6.9	0.179404
12.5	7.0	0.225751
12.5	7.1	0.284037
12.5	7.2	0.357319
12.5	7.3	0.449421
12.5	7.4	0.565129
12.5	7.5	0.710415
12.5	7.6	0.892716
12.5	7.7	1.121268
12.5	7.8	1.407505
12.5	7.9	1.765508
12.5	8.0	2.212527
12.5	8.1	2.769537
12.5	8.2	3.461811
12.5	8.3	4.319439
12.5	8.4	5.377696
12.5	8.5	6.677136
12.5	8.6	8.263145
12.5	8.7	10.184763
12.5	8.8	12.492405
12.5	8.9	15.234232
12.5	9.0	18.450928
12.5	9.1	22.169205
12.5	9.2	26.394272
12.5	9.3	31.102768
12.5	9.4	36.237701
12.5	9.5	41.707199
12.5	9.6	47.388672
12.5	9.7	53.138611
12.5	9.8	58.806381
12.5	9.9	64.249832
12.5	10.0	69.348877
12.5	10.1	74.014801

Temp °C	pH	Unionized %
13.0	5.0	0.002351
13.0	5.1	0.002960
13.0	5.2	0.003726
13.0	5.3	0.004691
13.0	5.4	0.005906
13.0	5.5	0.007435
13.0	5.6	0.009360
13.0	5.7	0.011783
13.0	5.8	0.014834
13.0	5.9	0.018674
13.0	6.0	0.023508
13.0	6.1	0.029592
13.0	6.2	0.037252
13.0	6.3	0.046893
13.0	6.4	0.059027
13.0	6.5	0.074299
13.0	6.6	0.093519
13.0	6.7	0.117705
13.0	6.8	0.148136
13.0	6.9	0.186421
13.0	7.0	0.234576
13.0	7.1	0.295134
13.0	7.2	0.371268
13.0	7.3	0.466949
13.0	7.4	0.587144
13.0	7.5	0.738047
13.0	7.6	0.927373
13.0	7.7	1.164695
13.0	7.8	1.461854
13.0	7.9	1.833423
13.0	8.0	2.297234
13.0	8.1	2.874942
13.0	8.2	3.592588
13.0	8.3	4.481112
13.0	8.4	5.576673
13.0	8.5	6.920680
13.0	8.6	8.559232
13.0	8.7	10.541792
13.0	8.8	12.918694
13.0	8.9	15.737243
13.0	9.01	9.036301
13.0	9.1	22.839508
13.0	9.2	27.147751
13.0	9.3	31.932358
13.0	9.4	37.130447
13.0	9.5	42.644577
13.0	9.6	48.347839
13.0	9.7	59.094498
13.0	9.8	59.734268
13.0	9.9	65.127808
13.0	10.0	70.159790
13.0	10.1	74.747238

Temp °C	pH	Unionized %
13.0	5.0	0.002351
13.0	5.1	0.002960
13.0	5.2	0.003726
13.0	5.3	0.004691
13.0	5.4	0.005906
13.0	5.5	0.007435
13.0	5.6	0.009360
13.0	5.7	0.011783
13.0	5.8	0.014834
13.0	5.9	0.018674
13.0	6.0	0.023508
13.0	6.1	0.029592
13.0	6.2	0.037252
13.0	6.3	0.046893
13.0	6.4	0.059027
13.0	6.5	0.074299
13.0	6.6	0.093519
13.0	6.7	0.117705
13.0	6.8	0.148136
13.0	6.9	0.186421
13.0	7.0	0.234576
13.0	7.1	0.295134
13.0	7.2	0.371268
13.0	7.3	0.466949
13.0	7.4	0.587144
13.0	7.5	0.738047
13.0	7.6	0.927373
13.0	7.7	1.164695
13.0	7.8	1.461854
13.0	7.9	1.833423
13.0	8.0	2.297234
13.0	8.1	2.874942
13.0	8.2	3.592588
13.0	8.3	4.481112
13.0	8.4	5.576673
13.0	8.5	6.920680
13.0	8.6	8.559232
13.0	8.7	10.541792
13.0	8.8	12.918694
13.0	8.9	15.737243
13.0	9.01	9.036301
13.0	9.1	22.839508
13.0	9.2	27.147751
13.0	9.3	31.932358
13.0	9.4	37.130447
13.0	9.5	42.644577
13.0	9.6	48.347839
13.0	9.7	59.094498
13.0	9.8	59.734268
13.0	9.9	65.127808
13.0	10.0	70.159790
13.0	10.1	74.747238

Temp °C	pH	Unionized %
13.5	5.0	0.002443
13.5	5.1	0.003076
13.5	5.2	0.003872
13.5	5.3	0.004874
13.5	5.4	0.006137
13.5	5.5	0.007725
13.5	5.6	0.009725
13.5	5.7	0.012243
13.5	5.8	0.015413
13.5	5.9	0.019403
13.5	6.0	0.024425
13.5	6.1	0.030748
13.5	6.2	0.038706
13.5	6.3	0.048723
13.5	6.4	0.061330
13.5	6.5	0.077198
13.5	6.6	0.097167
13.5	6.7	0.122295
13.5	6.8	0.153912
13.5	6.9	0.193686
13.5	7.0	0.243713
13.5	7.1	0.306623
13.5	7.2	0.385709
13.5	7.3	0.485094
13.5	7.4	0.609930
13.5	7.5	0.766644
13.5	7.6	0.963235
13.5	7.7	1.209622
13.5	7.8	1.518067
13.5	7.9	1.903648
13.5	8.0	2.384792
13.5	8.1	2.983849
13.5	8.2	3.727636
13.5	8.3	4.647949
13.5	8.4	5.781829
13.5	8.5	7.171528
13.5	8.6	8.863815
13.5	8.7	10.908510
13.5	8.8	13.355752
13.5	8.9	16.251862
13.5	9.0	19.633667
13.5	9.1	23.521530
13.5	9.2	27.911911
13.5	9.3	32.770599
13.5	9.4	38.028915
13.5	9.5	43.583969
13.5	9.6	49.304855
13.5	9.7	55.044052
13.5	9.8	60.651993
13.5	9.9	65.992615
13.5	10.0	70.955490
13.5	10.1	75.463333

Temp °C	pH	Unionized %
14.0	5.0	0.002538
14.0	5.1	0.003195
14.0	5.2	0.004023
14.0	5.3	0.005064
14.0	5.4	0.006375
14.0	5.5	0.008026
14.0	5.6	0.010104
14.0	5.7	0.012719
14.0	5.8	0.016012
14.0	5.9	0.020157
14.0	6.0	0.025375
14.0	6.1	0.031944
14.0	6.2	0.040211
14.0	6.3	0.050618
14.0	6.4	0.063715
14.0	6.5	0.080199
14.0	6.6	0.100944
14.0	6.7	0.127048
14.0	6.8	0.159891
14.0	6.9	0.201207
14.0	7.0	0.253172
14.0	7.1	0.318516
14.0	7.2	0.400657
14.0	7.3	0.503873
14.0	7.4	0.633511
14.0	7.5	0.796236
14.0	7.6	1.000338
14.0	7.7	1.256096
14.0	7.8	1.576203
14.0	7.9	1.976254
14.0	8.0	2.475287
14.0	8.1	3.096354
14.0	8.2	3.867069
14.0	8.3	4.820082
14.0	8.4	5.993320
14.0	8.5	7.429831
14.0	8.6	9.177052
14.0	8.7	11.285058
14.0	8.8	13.803685
14.0	8.9	16.778107
14.0	9.0	20.242950
14.0	9.1	24.215134
14.0	9.2	28.686386
14.0	9.3	33.617050
14.0	9.4	38.932526
14.0	9.5	44.524719
14.0	9.6	50.259125
14.0	9.7	55.986694
14.0	9.8	61.559189
14.0	9.9	66.843964
14.0	10.0	71.735809
14.0	10.1	76.163239

Temp °C	pH	Unionized %
14.5	5.0	0.002637
14.5	5.1	0.003319
14.5	5.2	0.004179
14.5	5.3	0.005260
14.5	5.4	0.006622
14.5	5.5	0.008337
14.5	5.6	0.010495
14.5	5.7	0.013213
14.5	5.8	0.016633
14.5	5.9	0.020939
14.5	6.0	0.026359
14.5	6.1	0.033182
14.5	6.2	0.041769
14.5	6.3	0.052579
14.5	6.4	0.066184
14.5	6.5	0.083306
14.5	6.6	0.104853
14.5	6.7	0.131966
14.5	6.8	0.166079
14.5	6.9	0.208991
14.5	7.0	0.262961
14.5	7.1	0.330823
14.5	7.2	0.416125
14.5	7.3	0.523305
14.5	7.4	0.657910
14.5	7.5	0.826850
14.5	7.6	1.038716
14.5	7.7	1.304158
14.5	7.8	1.636310
14.5	7.9	2.051298
14.5	8.0	2.568785
14.5	8.1	3.212536
14.5	8.2	4.010974
14.5	8.3	4.997609
14.5	8.4	6.211236
14.5	8.5	7.695704
14.5	8.6	9.499033
14.5	8.7	11.671494
14.5	8.8	14.262504
14.5	8.9	17.315933
14.5	9.0	20.863998
14.5	9.1	24.919968
14.5	9.2	29.470764
14.5	9.3	34.471069
14.5	9.4	39.840515
14.5	9.5	45.466049
14.5	9.6	51.209763
14.5	9.7	56.921707
14.5	9.8	62.455200
14.5	9.9	67.681503
14.5	10.0	72.500580
14.5	10.1	76.846893

Temp °C	pH	Unionized %
15.0	5.0	0.002738
15.0	5.1	0.003447
15.0	5.2	0.004340
15.0	5.3	0.005464
15.0	5.4	0.006878
15.0	5.5	0.008659
15.0	5.6	0.010901
15.0	5.7	0.013723
15.0	5.8	0.017275
15.0	5.9	0.021748
15.0	6.0	0.027377
15.0	6.1	0.034463
15.0	6.2	0.043382
15.0	6.3	0.054609
15.0	6.4	0.068739
15.0	6.5	0.086522
15.0	6.6	0.108900
15.0	6.7	0.137058
15.0	6.8	0.172484
15.0	6.9	0.217048
15.0	7.0	0.273093
15.0	7.1	0.343560
15.0	7.2	0.432131
15.0	7.3	0.543412
15.0	7.4	0.683153
15.0	7.5	0.858519
15.0	7.6	1.078414
15.0	7.7	1.353860
15.0	7.8	1.698453
15.0	7.9	2.128860
15.0	8.0	2.665380
15.0	8.1	3.332511
15.0	8.2	4.159486
15.0	8.3	5.180678
15.0	8.4	6.435757
15.0	8.5	7.969327
15.0	8.6	9.829939
15.0	8.7	12.067986
15.0	8.8	14.732332
15.0	8.9	17.865387
15.0	9.0	21.496765
15.0	9.1	25.635895
15.0	9.2	30.264740
15.0	9.3	35.332260
15.0	9.4	40.752441
15.0	9.5	46.407425
15.0	9.6	52.156326
15.0	9.7	57.848663
15.0	9.8	63.339767
15.0	9.9	68.505005
15.0	10.0	73.249847
15.0	10.1	77.514450

Temp °C	pH	Unionized %
15.5	5.0	0.002844
15.5	5.1	0.003580
15.5	5.2	0.004507
15.5	5.3	0.005674
15.5	5.4	0.007143
15.5	5.5	0.008992
15.5	5.6	0.011320
15.5	5.7	0.014251
15.5	5.8	0.017940
15.5	5.9	0.022585
15.5	6.0	0.028431
15.5	6.1	0.035789
15.5	6.2	0.045052
15.5	6.3	0.056710
15.5	6.4	0.071383
15.5	6.5	0.089849
15.5	6.6	0.113087
15.5	6.7	0.142327
15.5	6.8	0.179112
15.5	6.9	0.225384
15.5	7.0	0.283575
15.5	7.1	0.356739
15.5	7.2	0.448692
15.5	7.3	0.564214
15.5	7.4	0.709266
15.5	7.5	0.891276
15.5	7.6	1.119464
15.5	7.7	1.405247
15.5	7.8	1.762685
15.5	7.9	2.209003
15.5	8.0	2.765151
15.5	8.1	3.456368
15.5	8.2	4.312708
15.5	8.3	5.369413
15.5	8.4	6.666994
15.5	8.5	8.250807
15.5	8.6	10.169873
15.5	8.7	12.474609
15.5	8.8	15.213197
15.5	8.9	18.426422
15.5	9.0	22.141098
15.5	9.1	26.362610
15.5	9.2	31.067855
15.5	9.3	36.200058
15.5	9.4	41.667587
15.5	9.5	47.348053
15.5	9.6	53.098038
15.5	9.7	58.766891
15.5	9.8	64.212418
15.5	9.9	69.314270
15.5	10.0	73.983475
15.5	10.1	78.166016

Temp °C	pH	Unionized %
16.0	5.0	0.002953
16.0	5.1	0.003717
16.0	5.2	0.004680
16.0	5.3	0.005892
16.0	5.4	0.007417
16.0	5.5	0.009337
16.0	5.6	0.011755
16.0	5.7	0.014798
16.0	5.8	0.018629
16.0	5.9	0.023451
16.0	6.0	0.029521
16.0	6.1	0.037162
16.0	6.2	0.046779
16.0	6.3	0.058884
16.0	6.4	0.074120
16.0	6.5	0.093293
16.0	6.6	0.117420
16.0	6.7	0.147779
16.0	6.8	0.185971
16.0	6.9	0.234010
16.0	7.0	0.294422
16.0	7.1	0.370373
16.0	7.2	0.465825
16.0	7.3	0.585732
16.0	7.4	0.736275
16.0	7.5	0.925150
16.0	7.6	1.161910
16.0	7.7	1.458368
16.0	7.8	1.829067
16.0	7.9	2.291803
16.0	8.0	2.868185
16.0	8.1	3.584208
16.0	8.2	4.470758
16.0	8.3	5.563936
16.0	8.4	6.905092
16.0	8.5	8.540292
16.0	8.6	10.518970
16.0	8.7	12.891467
16.0	8.8	15.705150
16.0	8.9	18.998993
16.0	9.0	22.796860
16.0	9.1	27.099869
16.0	9.2	31.879730
16.0	9.3	37.073914
16.0	9.4	42.585342
16.0	9.5	48.287354
16.0	9.6	54.034348
16.0	9.7	59.675995
16.0	9.8	65.072754
16.0	9.9	70.109070
16.0	10.0	74.701492
16.0	10.1	78.801666

Temp °C	pH	Unionized %
16.5	5.0	0.003066
16.5	5.1	0.003860
16.5	5.2	0.004859
16.5	5.3	0.006117
16.5	5.4	0.007701
16.5	5.5	0.009694
16.5	5.6	0.012204
16.5	5.7	0.015363
16.5	5.8	0.019340
16.5	5.9	0.024347
16.5	6.0	0.030649
16.5	6.1	0.038582
16.5	6.2	0.048567
16.5	6.3	0.061134
16.5	6.4	0.076951
16.5	6.5	0.096856
16.5	6.6	0.121903
16.5	6.7	0.153419
16.5	6.8	0.193066
16.5	6.9	0.242934
16.5	7.0	0.305643
16.5	7.1	0.384476
16.5	7.2	0.483545
16.5	7.3	0.607986
16.5	7.4	0.764204
16.5	7.5	0.960175
16.5	7.6	1.205789
16.5	7.7	1.513271
16.5	7.8	1.897657
16.5	7.9	2.377325
16.5	8.0	2.974561
16.5	8.1	3.716127
16.5	8.2	4.633736
16.5	8.3	5.764360
16.5	8.4	7.150168
16.5	8.5	8.837895
16.5	8.6	10.877323
16.5	8.7	13.318614
16.5	8.8	16.208176
16.5	8.9	19.583008
16.5	9.0	23.463806
16.5	9.1	27.847305
16.5	9.2	32.699860
16.5	9.3	37.953217
16.5	9.4	43.504990
16.5	9.5	49.224564
16.5	9.6	54.964523
16.5	9.7	60.575333
16.5	9.8	65.920471
16.5	9.9	70.889236
16.5	10.0	75.403809
16.5	10.1	79.421509

Temp °C	pH	Unionized %
17.0	5.0	0.003183
17.0	5.1	0.004007
17.0	5.2	0.005044
17.0	5.3	0.006350
17.0	5.4	0.007994
17.0	5.5	0.010063
17.0	5.6	0.012669
17.0	5.7	0.015948
17.0	5.8	0.020077
17.0	5.9	0.025274
17.0	6.0	0.031816
17.0	6.1	0.040051
17.0	6.2	0.050416
17.0	6.3	0.063461
17.0	6.4	0.079880
17.0	6.5	0.100542
17.0	6.6	0.126541
17.0	6.7	0.159254
17.0	6.8	0.200405
17.0	6.9	0.252164
17.0	7.0	0.317249
17.0	7.1	0.399064
17.0	7.2	0.501872
17.0	7.3	0.630999
17.0	7.4	0.793084
17.0	7.5	0.996386
17.0	7.6	1.251145
17.0	7.7	1.570012
17.0	7.8	1.968523
17.0	7.9	2.465652
17.0	8.0	3.084377
17.0	8.1	3.852230
17.0	8.2	4.801769
17.0	8.3	5.970829
17.0	8.4	7.402375
17.0	8.5	9.143778
17.0	8.6	11.245087
17.0	8.7	13.756176
17.0	8.8	16.722351
17.0	8.9	20.178467
17.0	9.0	24.141815
17.0	9.1	28.604660
17.0	9.2	33.527878
17.0	9.3	38.837479
17.0	9.4	44.425980
17.0	9.5	50.159134
17.0	9.6	55.888123
17.0	9.7	61.464508
17.0	9.8	66.755280
17.0	9.9	71.654678
17.0	10.0	76.090561
17.0	10.1	80.025818

Temp °C	pH	Unionized %
17.5	5.0	0.003303
17.5	5.1	0.004159
17.5	5.2	0.005235
17.5	5.3	0.006591
17.5	5.4	0.008297
17.5	5.5	0.010445
17.5	5.6	0.013150
17.5	5.7	0.016554
17.5	5.8	0.020839
17.5	5.9	0.026233
17.5	6.0	0.033023
17.5	6.1	0.041570
17.5	6.2	0.052328
17.5	6.3	0.065868
17.5	6.4	0.082909
17.5	6.5	0.104354
17.5	6.6	0.131338
17.5	6.7	0.165289
17.5	6.8	0.207997
17.5	6.9	0.261711
17.5	7.0	0.329251
17.5	7.1	0.414149
17.5	7.2	0.520824
17.5	7.3	0.654794
17.5	7.4	0.822941
17.5	7.5	1.033816
17.5	7.6	1.298021
17.5	7.7	1.628636
17.5	7.8	2.041718
17.5	7.9	2.556851
17.5	8.0	3.197714
17.5	8.1	3.992620
17.5	8.2	4.974972
17.5	8.3	6.183463
17.5	8.4	7.661833
17.5	8.5	9.458030
17.5	8.6	11.622317
17.5	8.7	14.204165
17.5	8.8	17.247635
17.5	8.9	20.785217
17.5	9.0	24.830673
17.5	9.1	29.371536
17.5	9.2	34.363205
17.5	9.3	39.726044
17.5	9.4	45.347610
17.5	9.5	51.090378
17.5	9.6	56.804504
17.5	9.7	62.343094
17.5	9.8	67.576859
17.5	9.9	72.405212
17.5	10.0	76.761780
17.5	10.1	80.614670

Temp °C	pH	Unionized %
18.0	5.0	0.003428
18.0	5.1	0.004316
18.0	5.2	0.005433
18.0	5.3	0.006840
18.0	5.4	0.008611
18.0	5.5	0.010840
18.0	5.6	0.013647
18.0	5.7	0.017180
18.0	5.8	0.021627
18.0	5.9	0.027225
18.0	6.0	0.034272
18.0	6.1	0.043142
18.0	6.2	0.054307
18.0	6.3	0.068358
18.0	6.4	0.086042
18.0	6.5	0.108297
18.0	6.6	0.136299
18.0	6.7	0.171530
18.0	6.8	0.215847
18.0	6.9	0.271583
18.0	7.0	0.341662
18.0	7.1	0.429747
18.0	7.2	0.540417
18.0	7.3	0.679393
18.0	7.4	0.853802
18.0	7.5	1.072500
18.0	7.6	1.346457
18.0	7.7	1.689198
18.0	7.8	2.117311
18.0	7.9	2.650998
18.0	8.0	3.314652
18.0	8.1	4.137386
18.0	8.2	5.153449
18.0	8.3	6.402369
18.0	8.4	7.928659
18.0	8.5	9.780784
18.0	8.6	12.009131
18.0	8.7	14.662650
18.0	8.8	17.783981
18.0	8.9	21.403122
18.0	9.0	25.530090
18.0	9.1	30.147568
18.0	9.2	35.205383
18.0	9.3	40.618317
18.0	9.4	46.269226
18.0	9.5	52.017624
18.0	9.6	57.713058
18.0	9.7	63.210632
18.0	9.8	68.384949
18.0	9.9	73.140808
18.0	10.0	77.417435
18.0	10.1	81.188278

Temp °C	pH	Unionized %
18.5	5.0	0.003558
18.5	5.1	0.004479
18.5	5.2	0.005638
18.5	5.3	0.007098
18.5	5.4	0.008938
18.5	5.5	0.011249
18.5	5.6	0.014161
18.5	5.7	0.017827
18.5	5.8	0.022442
18.5	5.9	0.028251
18.5	6.0	0.035563
18.5	6.1	0.044768
18.5	6.2	0.056352
18.5	6.3	0.070933
18.5	6.4	0.089283
18.5	6.5	0.112378
18.5	6.6	0.141430
18.5	6.7	0.177984
18.5	6.8	0.223965
18.5	6.9	0.281792
18.5	7.0	0.354495
18.5	7.1	0.445873
18.5	7.2	0.560673
18.5	7.3	0.704822
18.5	7.4	0.885700
18.5	7.5	1.112477
18.5	7.6	1.396502
18.5	7.7	1.751756
18.5	7.8	2.195369
18.5	7.9	2.748181
18.5	8.0	3.435305
18.5	8.1	4.286656
18.5	8.2	5.337334
18.5	8.3	6.627704
18.5	8.4	8.203004
18.5	8.5	10.112186
18.5	8.6	12.405654
18.5	8.7	15.131721
18.5	8.8	18.331451
18.5	8.9	22.032166
18.5	9.0	26.239914
18.5	9.1	30.932434
18.5	9.2	36.053970
18.5	9.3	41.513794
18.5	9.4	47.190277
18.5	9.5	52.940353
18.5	9.6	58.613419
18.5	9.7	64.066788
18.5	9.8	69.179413
18.5	9.9	73.861420
18.5	10.0	78.057785
18.5	10.1	81.746918

Temp °C	pH	Unionized %
19.0	5.0	0.003691
19.0	5.1	0.004647
19.0	5.2	0.005850
19.0	5.3	0.007365
19.0	5.4	0.009271
19.0	5.5	0.011671
19.0	5.6	0.014693
19.0	5.7	0.018497
19.0	5.8	0.023285
19.0	5.9	0.029312
19.0	6.0	0.036899
19.0	6.1	0.046448
19.0	6.2	0.058468
19.0	6.3	0.073596
19.0	6.4	0.092633
19.0	6.5	0.116590
19.0	6.6	0.146734
19.0	6.7	0.184657
19.0	6.8	0.232358
19.0	6.9	0.292345
19.0	7.0	0.367762
19.0	7.1	0.462544
19.0	7.2	0.581611
19.0	7.3	0.731103
19.0	7.4	0.918663
19.0	7.5	1.153782
19.0	7.6	1.448197
19.0	7.7	1.816360
19.0	7.8	2.275956
19.0	7.9	2.848468
19.0	8.0	3.559750
19.0	8.1	4.440523
19.0	8.2	5.526737
19.0	8.3	6.859577
19.0	8.4	8.484982
19.0	8.5	10.452319
19.0	8.6	12.811934
19.0	8.7	15.611368
19.0	8.8	18.889954
19.0	8.9	22.672104
19.0	9.0	26.959808
19.0	9.1	31.725708
19.0	9.2	36.908401
19.0	9.3	42.411789
19.0	9.4	48.110046
19.0	9.5	53.857910
19.0	9.6	59.504974
19.0	9.7	64.911179
19.0	9.8	69.960052
19.0	9.9	74.567047
19.0	10.0	78.682816
19.0	10.1	82.290680

Temp °C	pH	Unionized %
19.5	5.0	0.003829
19.5	5.1	0.004821
19.5	5.2	0.006069
19.5	5.3	0.007640
19.5	5.4	0.009618
19.5	5.5	0.012108
19.5	5.6	0.015243
19.5	5.7	0.019189
19.5	5.8	0.024156
19.5	5.9	0.030409
19.5	6.0	0.038279
19.5	6.1	0.048186
19.5	6.2	0.060655
19.5	6.3	0.076348
19.5	6.4	0.096098
19.5	6.5	0.120950
19.5	6.6	0.152219
19.5	6.7	0.191556
19.5	6.8	0.241035
19.5	6.9	0.303255
19.5	7.0	0.381475
19.5	7.1	0.479775
19.5	7.2	0.603251
19.5	7.3	0.758262
19.5	7.4	0.952724
19.5	7.5	1.196454
19.5	7.6	1.501593
19.5	7.7	1.883069
19.5	7.8	2.359138
19.5	7.9	2.951945
19.5	8.0	3.688086
19.5	8.1	4.599098
19.5	8.2	5.721779
19.5	8.3	7.098123
19.5	8.4	8.774726
19.5	8.5	10.801306
19.5	8.6	13.228066
19.5	8.7	16.101639
19.5	8.8	19.459457
19.5	8.9	23.322845
19.5	9.0	27.689545
19.5	9.1	32.526993
19.5	9.2	37.768173
19.5	9.3	43.311752
19.5	9.4	49.027985
19.5	9.5	54.769760
19.5	9.6	60.387299
19.5	9.7	65.743530
19.5	9.8	70.726624
19.5	9.9	75.257629
19.5	10.0	79.292679
19.5	10.1	82.819885

Temp °C	pH	Unionized %
20.0	5.0	0.003972
20.0	5.1	0.005001
20.0	5.2	0.006295
20.0	5.3	0.007925
20.0	5.4	0.009977
20.0	5.5	0.012560
20.0	5.6	0.015811
20.0	5.7	0.019905
20.0	5.8	0.025057
20.0	5.9	0.031543
20.0	6.0	0.039707
20.0	6.1	0.049983
20.0	6.2	0.062916
20.0	6.3	0.079194
20.0	6.4	0.099679
20.0	6.5	0.125455
20.0	6.6	0.157887
20.0	6.7	0.198687
20.0	6.8	0.250003
20.0	6.9	0.314531
20.0	7.0	0.395649
20.0	7.1	0.497582
20.0	7.2	0.625611
20.0	7.3	0.786323
20.0	7.4	0.987909
20.0	7.5	1.240528
20.0	7.6	1.556730
20.0	7.7	1.951939
20.0	7.8	2.444984
20.0	7.9	3.058684
20.0	8.0	3.820394
20.0	8.1	4.762475
20.0	8.2	5.922563
20.0	8.3	7.343440
20.0	8.4	9.072329
20.0	8.5	11.159234
20.0	8.6	13.654114
20.0	8.7	16.602524
20.0	8.8	20.039825
20.0	8.9	23.984131
20.0	9.0	28.428741
20.0	9.1	33.335800
20.0	9.2	38.632690
20.0	9.3	44.213013
20.0	9.4	49.943390
20.0	9.5	55.675278
20.0	9.6	61.259903
20.0	9.7	66.563471
20.0	9.8	71.479034
20.0	9.9	75.933243
20.0	10.0	79.887543
20.0	10.1	83.334732



PERMIT TO MINE NO. 478

July 26, 2004

Mr. Don McKenzie, District III Supervisor  
Land Quality Division  
Department of Environmental Quality  
1866 S. Sheridan Avenue  
Sheridan, Wyoming 82801

**RE: Irigaray Mine Wellfield Restoration Report, Permit to Mine No. 478**

Dear Mr. McKenzie,

COGEMA Mining, Inc. (COGEMA) hereby submits three copies of the report entitled "Wellfield Restoration Report, Irigaray Mine". This is the final report for the conclusion of groundwater restoration activities in all commercial wellfields at the Irigaray in situ leach uranium mine, Production Units 1 through 9, Permit to Mine No. 478.

The attached report includes supporting data, discussion and modeling results to demonstrate that groundwater restoration in Production Units 1 through 9 meets, and in some cases exceeds, the requirements for groundwater restoration approval by the WDEQ. We respectfully request that the WDEQ review the report and grant COGEMA an unconditional approval for the restoration project.

If you think it beneficial, COGEMA and our consultants are ready to meet with your staff as early as possible in the review process to discuss the project results and to answer any questions. We are anxious to move forward with this process and we look forward to working with your staff towards the approval of a very significant and successful endeavor.

Sincerely,

Donna L. Wichers  
General Manager

# WELLFIELD RESTORATION REPORT IRIGARAY MINE

JULY 2004

*Prepared by:*

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**WELLFIELD RESTORATION REPORT**  
COGEMA Mining, Inc. Irigaray Project

**TABLE OF CONTENTS**

<b>1.0 INTRODUCTION .....</b>	<b>1-1</b>
1.1 Background.....	1-1
1.2 Statement of Need for Restoration Approval .....	1-2
1.3 Purpose and Objectives.....	1-2
1.4 Report Organization.....	1-3
 <b>2.0 REGULATORY HISTORY .....</b>	 <b>2-1</b>
2.1 Permitting History .....	2-1
2.2 Regulatory History .....	2-1
2.3 Historical Groundwater Classifications, Aquifer Exemption .....	2-2
2.4 Recent Regulatory Developments .....	2-3
2.4.1 Groundwater Classification .....	2-3
2.4.2 Restoration Law vs. Regulations .....	2-3
2.5 Regulatory Considerations for Irigaray Restoration .....	2-4
 <b>3.0 SUMMARY OF SITE SETTING, GEOLOGY AND HYDROLOGY .....</b>	 <b>3-1</b>
3.1 Site Setting .....	3-1
3.2 Regional Geology .....	3-1
3.3 Site Geology .....	3-2
3.4 Site Hydrology.....	3-3
 <b>4.0 OPERATIONAL HISTORY AND RESTORATION RESULTS .....</b>	 <b>4-1</b>
4.1 Mining History .....	4-1
4.1.1 Wellfield Operations.....	4-1
4.1.2 Baseline Water Quality .....	4-1
4.2 Restoration Program.....	4-3
4.2.1 Goals of the Restoration Program .....	4-3
4.2.2 Target Restoration Values .....	4-3
4.2.3 Restoration Process Technology Applied .....	4-4
4.3 Restoration Operations.....	4-6
4.3.1 Total Volume Processed.....	4-6
4.3.2 Operational Summaries, Irigaray Wellfields .....	4-6
4.3.2.1 Restoration History of Units 1 through 3 .....	4-7
4.3.2.2 Restoration History of Units 4 and 5 .....	4-7
4.3.2.3 Restoration History of Unit 6 .....	4-8
4.3.2.4 Restoration History of Unit 7 .....	4-9
4.3.2.5 Restoration History of Unit 8 .....	4-9
4.3.2.6 Restoration History of Unit 9 .....	4-10
4.3.3 Water Quality Monitoring During Restoration.....	4-10

4.3.3.1 One Zone Water Quality .....	4-11
4.3.3.2 One Zone Perimeter Monitor Wells.....	4-12
4.3.3.3 Shallow Zone Monitoring .....	4-12
4.3.3.4 Deep Monitor Zone .....	4-13
4.3.4 Water Level Monitoring During Restoration .....	4-13
4.4 Restoration Results.....	4-14
4.4.1 Post-Mining Water Quality .....	4-14
4.4.2 Restoration Water Quality.....	4-15
4.4.3 Stabilization Monitoring Water Quality .....	4-15
4.4.4 Summary and Conclusions.....	4-18

## **5.0 ASSESSMENT OF FUTURE GROUNDWATER QUALITY: SUMMARY OF GROUNDWATER FLOW AND SOLUTE TRANSPORT MODEL.....**

5.1 Model Objectives and Strategy .....	5-1
5.2 Model Codes.....	5-2
5.3 Model Development.....	5-2
5.4 Calibration.....	5-3
5.5 Validation .....	5-3
5.6 Solute Transport Simulations.....	5-4
5.6.1 Transport Simulation Results .....	5-6
5.6.1.1 Selenium .....	5-6
5.6.1.2 Manganese .....	5-7
5.6.1.3 Uranium .....	5-7
5.6.1.4 Radium-226 .....	5-8
5.6.1.5 TDS .....	5-8
5.7 Sensitivity Analyses .....	5-8
5.7.1 Hydraulic Conductivity/Hydraulic Gradient.....	5-9
5.7.2 Horizontal to Vertical Hydraulic Conductivity Ratio .....	5-9
5.7.3 Porosity.....	5-10
5.7.4 Mineralized Zone Thickness .....	5-10
5.7.5 Dispersivity.....	5-10
5.7.6 Distribution Coefficient.....	5-11
5.8 Modeling Summary/Conclusions .....	5-11

<b>6.0 SUMMARY AND CONCLUSIONS .....</b>	<b>6-1</b>
6.1 Summary .....	6-1
6.2 Conclusions .....	6-2

## **LIST OF APPENDICIES**

Appendix A - Groundwater Restoration Analytical Results  
Appendix B - Detailed Site Setting, Geology and Hydrology  
Appendix C - Groundwater Flow and Solute Transport Modeling Report

Appendix D - MODFLOW Input/Output for Calibration Runs  
Appendix E - MT3D Output with Input Echo – All Model Transport Runs

### LIST OF TABLES

- 4-1 Target Restoration Values
- 4-2 Comparison of Baseline Ranges: Units 1-9 vs. Units 1-6
- 4-3 Total Volumes Processed and Key Operational Dates
- 4-4 Irigaray Mine Monitor Wells
- 4-5 Historical Water Level Data
- 4-6 Restoration Water Quality Results
- 4-7 Restoration Results Compared with Target Restoration Values Units 1-9
- 5-1 Input Parameters for the Irigaray Groundwater Flow Model
- 5-2 Calibration Targets, Residuals and Statistics for the Irigaray Groundwater Flow Model
- 5-3 Summary of Model Input Concentrations and Maximum Simulated Concentrations vs. WDEQ Standards

### LIST OF PLATES

<u>Plate</u>	<u>Title</u>
1	Regional Location/Facilities Map – Irigaray Mine

### LIST OF FIGURES

<u>Figure</u>	<u>Title</u>
1-1	Site Location Map – Irigaray Mine
1-2	Regional Location Map – Irigaray Mine
1-3	Local Location Map – Irigaray Mine
1-4	Facility Map – Irigaray Mine
2-1	Wellfield and Mine Unit Map
4-1	Ore Zone Baseline Wells and Designated Restoration/Sampled Wells
4-2	Conductivity and Uranium Concentrations: Units 1-3 GWS & RO Phases
4-3	Conductivity and Uranium Concentrations: Units 4&5
4-4	Conductivity and Uranium Concentrations: Unit 6
4-5	Conductivity and Uranium Concentrations: Unit 7
4-6	Conductivity and Uranium Concentrations: Unit 8
4-7	Conductivity and Uranium Concentrations: Unit 9
5-1	Model Domain, Grid and Boundary Conditions
5-2	Cross-Sectional View - Model Layers
5-3	Simulated Head Distribution and Groundwater Flowpaths
5-4	Model Residuals for the Calibration Simulation

- 5-5 Comparison of the Head Distribution for the Calibration and Validation Simulations
- 5-6 Location of Model Observation Points
- 5-7 Initial Conditions, Selenium Transport Simulation
- 5-8 Modeled Selenium Distribution at 24 years
- 5-9 Modeled Selenium Distribution at 100 years
- 5-10 Modeled Selenium Distribution at 300 years
- 5-11 Modeled Selenium Concentration vs. Time-400 feet from the Irigaray ISL Wellfield
- 5-12 Simulated Migration of the Selenium Plume
- 5-13 Vertical Distribution of Selenium Simulated at Observation OP3
- 5-14 Modeled Manganese Distribution at 100 years
- 5-15 Modeled Manganese Concentration vs. Time-400 feet from the Irigaray ISL Wellfield
- 5-16 Modeled Uranium Distribution at 300 years
- 5-17 Modeled Uranium Concentration vs. Time-400 feet from the Irigaray ISL Wellfield
- 5-18 Modeled Radium-226 Distribution at 1,000 years
- 5-19 Modeled Radium-226 Concentration vs. Time-400 feet from the Irigaray ISL Wellfield
- 5-20 Modeled TDS Distribution at 100 years
- 5-21 Modeled TDS Concentration vs. Time-400 feet from the Irigaray ISL Wellfield
- 5-22 Sensitivity Analysis-Hydraulic Conductivity-Selenium at Observation Point OP3
- 5-23 Sensitivity Analysis-Horizontal to Vertical Hydraulic Conductivity Ratio-Selenium at Observation Point OP3
- 5-24 Sensitivity Analysis-Porosity-Selenium at Observation Point OP3
- 5-25 Sensitivity Analysis-Mineralized Zone Thickness-Selenium at Observation Point OP3
- 5-26 Sensitivity Analysis-Dispersivity-Selenium at Observation Point OP3
- 5-27 Sensitivity of Dispersivity on Average Selenium Concentration of the Modeled Aquifer at Observation Point OP3
- 5-28 Sensitivity Analysis-Distribution Coefficient-Selenium at Observation Point OP3

## LIST OF ABBREVIATIONS

AMSL – Above Mean Sea Level  
BL – Baseline  
cm/s – centimeters per second  
COC – Contaminants of Concern  
COGEMA – COGEMA Mining, Inc.  
EPA - Environmental Protection Agency  
FITCO - Fuel International Trading Company  
ft/d – feet per day  
ft<sup>2</sup>/d – feet squared per day  
gpm – gallons per minute  
ISL – In-situ Leach  
K – hydraulic conductivity  
Kd – distribution coefficient  
l/kg – liters per kilogram  
LQD – Land Quality Division  
mg/l – milligrams per liter  
MRC - Malapai Resources Company  
MW – Monitoring Well  
NRC – Nuclear Regulatory Commission  
OP – Observation Point  
PCG2 – Preconjugate Gradient Solver  
pCi/l – picocuries per liter  
PEC – Petrotek Engineering Corporation  
PRB – Powder River Basin  
RSS – Residual Sum of Squares  
S - Storativity  
T – transmissivity  
TDS – Total Dissolved Solids  
TW – Trend Well  
UIC – Underground Injection Control  
UISS – Upper Irigaray Sandstone  
WDEQ – Wyoming Department of Environmental Quality  
WDEQ/WQCC – Wyoming Department of Environmental Quality/Water Quality Control Commission  
WDEQ/LQD – Wyoming Department of Environmental Quality/Land Quality Division  
WNI - Western Nuclear, Inc.

## **1.0 INTRODUCTION**

COGEMA Mining, Inc. (COGEMA) has prepared this technical demonstration supporting completion of the wellfield restoration operations at the Irigaray in-situ uranium mine in Johnson County, Wyoming. Wellfield restoration operations were initiated in 1990 (under a previous owner) and completed in 2002. Groundwater within the production zone has been restored to the pre-mining class of use, using Best Practicable Technology, as required by the Wyoming Department of Environmental Quality (WDEQ). An average of 13.7 pore volumes of water were treated for each of the nine Irigaray wellfields during restoration activities. Restoration operations have resulted in acceptable post-restoration water quality for 28 of 29 constituents that have restoration standards, the only exception being manganese.

Stability monitoring, completed in 2003, demonstrates no strongly increasing concentration trends for 33 of the 34 monitored constituents, indicating that post-restoration conditions are stable. The one constituent that is increasing to a significant degree (manganese) has only a secondary WDEQ standard. The Mn trends observed are not expected to impact the class of use in any manner. In fact, the Mn trend is an indicator of reducing conditions in the aquifer, which is beneficial.

Groundwater flow and solute transport modeling performed to assess the impact of residual concentrations of selected constituents (Mn, Se, U, Ra-226 and TDS) over the long term (300 to 1,000 years) shows that restored groundwater in the mineralized zone does not pose a threat to groundwater class of use outside the simulated monitoring locations (similar to the monitoring well locations) 400 feet downgradient from the wellfield. Furthermore, there is no threat to groundwater class of use outside the permit (aquifer exemption) boundary, which is 1,400 to 2,600 feet downgradient from the wellfield.

This report, including supporting data, discussion and modeling results demonstrates that groundwater restoration at the Irigaray in-situ uranium mine meets the requirements for restoration approval by WDEQ.

## **1.1 BACKGROUND**

COGEMA operates the Irigaray in-situ leach (ISL) uranium mine in Johnson County, Wyoming (Figures 1-1 through 1-3). The Irigaray operation includes surface facilities and treatment plant, well houses, trunklines/pipelines, and mining and monitoring wells typical of ISL operations (Plate 1 and Figure 1-4).

The Irigaray project was originally owned and operated by Westinghouse Electric Corporation (Westinghouse). Commercial permits and licenses were issued to Westinghouse in August, 1978. In 1987, Malapai Resources Company purchased the Irigaray project from Westinghouse. The property was later sold to Fuel International Trading Company (FITCO), a subsidiary of Electricité de France, in September 1990.

At that time, FITCO entered into an agreement whereby Total Minerals Corporation became the operator.

In July, 1993 COGEMA Resources, Inc. acquired Total Minerals Corporation and became the operator of the Irigaray project. In November 1993, the name of Total Minerals Corporation was changed to COGEMA Mining, Inc.

## **1.2 STATEMENT OF NEED FOR RESTORATION APPROVAL**

To date, the State of Wyoming has issued few unconditional restoration approvals for ISL wellfields. The few approvals have not been due to lack of effort on the part of the operators, or interest in approval by the State, but rather the difficult regulatory constraints within the ISL mine permitting program. As a result, ISL operators continue to expend tremendous effort and expense towards restoration without clear regulatory goals. This situation is and has been detrimental to both the State of Wyoming and the ISL industry.

Historically, the Wyoming Department of Environmental Quality/Land Quality Division (WDEQ/LQD) mining permits stated that, after mining operations are completed, the groundwater in ISL minefields must be restored to pre-mining baseline quality or, if that cannot be achieved, restoration must be to the pre-mining use. However, because of inconsistencies regarding initial aquifer classification (e.g., some wells/wellfields were classified as Class I, and others as Class III, Class IV, or Class V), determination of baseline class of use has been difficult within the historical regulatory framework. At numerous ISL sites, the issue of groundwater classification was further complicated because the mining aquifers have been exempted, specifically withdrawing consideration of the aquifers as underground sources of drinking water within the mine permit boundaries. With regard to Irigaray, the aquifer was exempted by rule with the State's primacy of the EPA's UIC program, several years after operations commenced. Regulatory issues directly related to Irigaray are discussed in Section 2.0 of this report.

The unconditional approval of the Irigaray restoration will show that ISL mining and restoration within the State of Wyoming can be accomplished, which is currently needed.

## **1.3 PURPOSE AND OBJECTIVES**

The purposes of this report are:

- To discuss the significant beneficial results from historical restoration operations performed at Irigaray,
- To document that COGEMA's restoration activities at Irigaray have resulted in groundwater quality consistent with the pre-mining class of use, and,

- To provide the supporting discussion and data such that LQD has a strong basis for granting unconditional approval of the Irigaray restoration activities.

To further support restoration approval, the results from a ground-water modeling study performed to evaluate transport of selected ground-water constituents downgradient of the wellfield are summarized in Section 5.0 and presented in detail in Appendix C.

The approach taken for the modeling evaluation is to develop an advective transport model that is independent of geochemical reactions. This approach is extremely conservative and results in overprediction of constituent concentrations downgradient of the site. A simplistic advection/dispersion model has been used to provide results that are more easily understood from a technical and regulatory standpoint, which will benefit all stakeholders. Because the modeling results demonstrate that there is no threat to Class-1 waters outside the permit (aquifer exemption) boundary, use of more complicated geochemical codes that would result in a smaller residual concentration "footprint", is not warranted.

## **1.4 REPORT ORGANIZATION**

This report includes six sections, the first being this introduction. The permitting and regulatory histories of the Irigaray operation are summarized in Section 2. The physical setting of the site, geology and hydrology are summarized in Section 3. Section 4 includes a summary of operational history, a detailed presentation of restoration operations, and historical water quality information. An assessment of future water quality changes for a limited number of key constituents remaining in the wellfield after restoration, and the benefit of concentration reduction due to advection and dispersion downgradient of the wellfield is presented in Section 5. Section 6 includes a summary and conclusions.

Specific water quality information pertinent to this report is included as Appendix A. A detailed presentation of the hydrogeologic conceptual model for the site is included in Appendix B. The ground-water modeling report, including a detailed presentation of the model assumptions, construction, and operation, is included in Appendix C. Model input and output are included in Appendix D and E, respectively.

COGEMA (and former operators) have been involved with the project for many years, and have a detailed understanding of the project history. For this reason, the majority of Sections 1, 2, 3, 4, 6 and Appendix A, including associated figures and tables, were prepared by COGEMA. Section 5 of the report and Appendices B through E were prepared by Petrotek Engineering Corporation and HydroSolutions, Inc. Technical references are included in Appendix B and C.

## **2.0 REGULATORY HISTORY**

### **2.1 PERMITTING HISTORY**

Wyoming Mineral Corporation, a subsidiary of Westinghouse Electric Corporation (Westinghouse), originally permitted the commercial-scale Irigaray in situ leach (ISL) project in 1977 through 1978. Permit to Mine No. 478 was issued by the Department of Environmental Quality (DEQ), Land Quality Division (LQD) on August 18, 1978. The NRC Source Material License SUA-1341 was subsequently issued in November 1978. Commercial production at Irigaray commenced in November 1978, although the A-wellfield (now Production Unit 1) had previously been operated as a research and development wellfield under DEQ-LQD License to Explore by Dozing No. 8, and NRC License SUA-1204.

The DEQ Permit to Mine allowed Westinghouse to mine a 30-acre area using ISL techniques. The area was limited due to concerns regarding the restorability of the original ammonium bicarbonate lixiviant used at the site. The NRC also limited the mine acreage, but to a 50 acre limit. Although the restorability of ammonium and sodium bicarbonate lixiviants were subsequently proven, the Irigaray mine site today consists of exactly 30 acres of wellfield (see Figure 2-1). An expansion past the original 30 acres was never requested due to downturns in the uranium market.

Since 1978, two major amendments to Permit No. 478 have been issued by the DEQ. These are A1 (1983, to incorporate lands that encompass the 517 test site and roads, and other updates), and A2 (1988, to incorporate the Christensen Ranch). Numerous amendments have been issued to the NRC license since 1978. In 1996, COGEMA submitted to both DEQ and NRC an updated permit document (NRC renewal application). This essentially combined the critical elements of the original Irigaray permit document with the Christensen Ranch permit documents. This document was subsequently accepted by both agencies in 1997.

### **2.2 REGULATORY HISTORY**

At the time that ISL mining gained popularity in the state of Wyoming (mid-'70's), there were no laws or regulations specific to ISL mining. The research and development activities at Irigaray were conducted under a License to Explore by Dozing permit (LE8) issued by DEQ. The commercial Permit to Mine issued by DEQ in 1978 was based upon standard surface mining regulations. In 1979 and 1980, state laws and regulations were put in place that addressed ISL mining. Both DEQ-WQD and DEQ-LQD issued rules to regulate the ISL industry. WQD Chapters 8 and 9 regulations provided a groundwater classification and groundwater pollution control permitting process. DEQ-LQD, as required by statute passed in 1979, took the lead role in regulation of ISL with their new set of regulations, Chapter 11, promulgated in 1980. Since their initial development in 1980, these ISL regulations have not been amended.

## 2.3 HISTORICAL GROUNDWATER CLASSIFICATIONS, AQUIFER EXEMPTION

As described above, the Irigaray Mine was permitted prior to the promulgation of the DEQ laws and regulations for ISL mining, and prior to the promulgation and implementation of EPA's UIC program (1980-1981). DEQ obtained primacy for the implementation of EPA's UIC program in the 1983-1984 time period. Because the Irigaray site was already permitted and operational prior to the DEQ and EPA's UIC programs implementation, an aquifer exemption specific to the Irigaray permit area was never issued by EPA or DEQ. Instead, it appears that the Irigaray permit area was incorporated (exempted) by rule at the time that primacy for the UIC program was issued to the State of Wyoming, DEQ.

The basis for the UIC program in Wyoming is DEQ's groundwater classification system provided in Chapter VIII of Water Quality Division's rules and regulations. However, again because the Irigaray site pre-dates Chapter VIII by several years, a water quality classification was not issued by DEQ for the Irigaray wellfields when the project was first permitted. The first water quality classification was done in 1987 by DEQ-WQD for Production Unit 7. Production Units 6, 8 and 9 were classified by DEQ-WQD in 1988. And, almost 15 years after initial ISL activity at Irigaray, a groundwater classification was issued by DEQ-WQD in 1990 for Production Units 1 through 5. A summary of DEQ-WQD's groundwater classifications for the Irigaray wellfields is as follows:

### ♦ Irigaray Units 1 through 5: (1990) *Classification not done prior to permit issuance as production pre-dated DEQ-WQD Chapter VIII by 5 years*

- All groundwater in the ore zone is CLASS I, except for water in the vicinity of well AP-4 which is CLASS IV(a) due to radium >100 pCi/l.
  - Selenium exceeds CLASS I for 3 other wells, but no separate classification was given. The company was told to restore selenium to baseline.
  - Iron exceeds CLASS I for at least 12 baseline wells, but it was noted by DEQ that iron could be treated for domestic use.
  - Radium-226 exceeded CLASS I in ALL wells, but only well AP-4 was greater than 100 pCi/l. DEQ considered radium-226 treatable for domestic use if the concentration is less than 100 pCi/l.

### ♦ Irigaray Units 6, 8 and 9: (1988)

- All groundwater in the Unit 6 ore zone is CLASS I, except wells HI-57 and HP-59 which are CLASS III due to sulfate and TDS. All groundwater in Units 8 and 9 are CLASS I.

- Although noted by DEQ, but not considered for the classification, all wells exceeded Class I for radium-226 and several wells exceeded Class I for iron, manganese, selenium and arsenic.

#### ♦ Irigaray Unit 7: (1987)

- All groundwater in the ore zone is CLASS I; radium should be returned to background in any case.
- Although noted by DEQ, but not considered for the classification, all wells exceeded Class I for radium-226.

In summary, despite baseline concentrations of radium-226, iron, selenium, manganese and arsenic above the DEQ-WQD's Chapter VIII Class I (Drinking Water) classification, and radium-226 above Class II (Agriculture) and III (Livestock), the groundwater within the production zone was still essentially classified as Class I Drinking Water.

## 2.4 RECENT REGULATORY DEVELOPMENTS

### 2.4.1 Groundwater Classification

In November, 2001, a joint DEQ Land Quality Division – Water Quality Division Advisory Board policy was issued with regard to in-situ groundwater classification and restoration. In this policy it was recognized that treating a groundwater source which contains radium at background concentrations commonly found in a uranium production zone could produce a solids filtrate or wastewater that would be prohibited for unrestricted release. Therefore, the concept of treatability for radium-226 no longer appeared applicable. The policy, dated November 14, 2001, specifically states that radium will not be considered as treatable due to concerns with the safe disposal of any water treatment by-products (applies to Section 5 of DEQ-WQD Chapter VIII rules and regulations). Because the radium-226 concentrations at baseline within Production Units 1 through 9 were all above 5 pCi/l (Class I, II and III standards), the applicable groundwater classification for these units is Class V.

### 2.4.2 Restoration Law vs. Regulations

There has been a long-standing debate regarding the wording of the DEQ-LQD and DEQ-WQD rules and regulations as compared to the definition of groundwater restoration provided in the Wyoming Statutes [W.S. §35-11-103(f)(iii)]. The statute defines groundwater restoration as "the condition achieved when the quality of all groundwater affected by the injection of recovery fluids is returned to a quality of use equal to or better than, and consistent with the uses for which the water was suitable prior to the operation by employing the best practicable technology." Best Practicable Technology (BPT) is further defined in W.S. §35-11-103(f)(i) as "a technology based process justifiable in terms of existing performance and achievability in relation to health and safety which minimizes, to the extent safe and practicable, disturbances and

adverse impacts of the operation on human or animal life, fish, wildlife, plant life and related environmental values." The DEQ-LQD regulations [Chapter 11, Section 3(d)(1)(A and B)] that were written subsequent to passage of the statute first require restoration to background or better; if background cannot be achieved then the affected groundwater will at a minimum be returned to a quality of use equal to and consistent with uses for which the water was suitable prior to the commencement of the operation. Industry has always viewed the regulations as more stringent than the statute due to the requirement to first restore to background concentrations or better instead of restoring to the quality of use, which is the standard in law. Although a revision to the ISL rules and regulations is anticipated to correct this language (approved by DEQ-LQD Advisory Board in August 2003), the new rules have not yet been promulgated as of this writing. Regardless, it was recognized in the November 14, 2001 joint policy of the DEQ-LQD and DEQ-WQD Advisory Boards that the standard for restoration is to return the groundwater to the pre-mining class of use. Therefore, the determination of the appropriate pre-mining class of use for the Irigaray site is critical to a determination of restoration acceptability.

## **2.5 REGULATORY CONSIDERATIONS FOR IRIGARAY RESTORATION**

In summary, the key regulatory considerations for the determination of Irigaray restoration acceptability are as follows:

- ◆ Authorization to inject, prior to promulgation of the UIC program, was granted by WDEQ. Consistent with aquifer exemptions at ISL operations in Texas and Nebraska, and as discussed in this report, COGEMA considers that the aquifer exemption boundary is the permit boundary.
- ◆ The Irigaray site was permitted prior to the existence of DEQ's current laws, rules and regulations for in situ leach mining and EPA's UIC program. If necessary, this should be taken into consideration when determining whether the standards of restoration have been met, considering the standards were imposed after permit issuance.
- ◆ Groundwater classifications conducted post-permit issuance were incorrect. The Irigaray groundwater should never have been classified as Class I Drinking Water, but as Class V Mineral Producing, or at the very least Class IV Industrial. Based on the pre-mining water quality at Irigaray, it is COGEMA's interpretation that the pre-mining use of the wellfields is Class V Mineral Producing.

In summary, based on the technical results of the restoration, and considering the regulatory history of the site, it is COGEMA's opinion that an unconditional restoration approval is appropriate for the Irigaray site.

### **3.0 SUMMARY OF SITE SETTING, GEOLOGY AND HYDROLOGY**

This section provides a brief summary of the site setting, regional and site geology, and hydrology specific to the Irigaray project. A more detailed presentation is included as Appendix B.

#### **3.1 SITE SETTING**

The Irigaray permit area consists of almost 700 acres located within the southern portion of the Powder River Basin in Wyoming. The Irigaray project is located approximately 43 miles southeast of the city of Buffalo, Wyoming in Johnson County (Figure 1-1). Access to the property is via gravel roads from the north and south. The Irigaray property is remotely located from any significant population centers, and the nearest resident is located at the Irigaray Ranch, located four miles to the north of the project.

Surface configuration of the Irigaray property is characterized by rolling uplands which are dissected by sharp, deeply cut drainages. The primary drainage within the Irigaray permit boundary is Willow Creek, an ephemeral tributary to the Powder River (Figure 1-2). Surface elevation is approximately 4,300 feet amsl (Figure 1-3). Surface and mineral ownership within the Irigaray permit boundary is approximately half privately owned and the other half is BLM and State owned lands. The Irigaray permit area was historically used for livestock grazing prior to mining.

#### **3.2 REGIONAL GEOLOGY**

The Irigaray project area is located in the west-central portion of the Powder River Basin. Structurally the Powder River Basin is a broad north-south aligned asymmetrical syncline whose axis lies west of its center. A broad northward plunging anticline has its axis parallel to and slightly east of the Pumpkin Buttes alignment and is intersected by a broad westward plunging arch. Strata in the Irigaray area dips northwesterly at one to two degrees, consistent with the position on the northwest flank of the anticline. Numerous cross-sections through the Irigaray area give no indication that detectable faulting has occurred in Tertiary sediments of the area.

Structural and stratigraphic development in the area was associated with tectonic events during Late Cretaceous times extending through the Eocene Epoch. Surrounding uplifts (i.e., Central Rocky Mountain Region) created a basin in which up to 8,000 feet of non-marine clastic sediments were deposited. Four distinct stratigraphic units are recognized in the Powder River Basin as a result of surrounding tectonic activities. These are the Cretaceous Lance Formation, Paleocene Fort Union Formation, Eocene Wasatch Formation, and Oligocene White River Formation. A more detailed description of geologic events forming the Powder River Basin is given in Appendix B.

### 3.3 SITE GEOLOGY

Post-Oligocene erosion in the project area has removed 900 to 1,300 feet of the Wasatch Formation. Surficial geology of the area is made up of Quaternary alluvial and Tertiary Wasatch outcrops. The White River Formation has been removed from the Powder River Basin in the vicinity with the exception of a thin cap on top of the Pumpkin Buttes. Shallow subsurface geology consists of fluvial deposits of the Eocene Wasatch Formation, Paleocene Fort Union and Cretaceous Lance Formation.

The subsurface Wasatch sediments, which contain the uranium deposits being mined, are a complex, interrelated sequence of shales, mudstones, siltstones, sandstones and thin lignite coal seams. A generalized shallow stratigraphic column is presented below.

<b>Generalized Stratigraphic Column and Description Surface to the UISS Irigaray Mine</b>		
<i>Geologic Section (Classification)</i>	<i>Typical Thickness (feet)</i>	<i>Description</i>
Overburden Unit	60 – 125	Interbedded, discontinuous sand and claystone
Units 1 Sand (Shallow/upper monitor zone)	5 – 50	Fine-grained, discontinuous sandstone
Interburden Unit	20 – 30	Interbedded claystone, sandstone, and coal
Coal Unit	5	Fractured, soft coal seams 1-2 feet thick
Claystone Unit	18 – 25	Gray, hard claystone
Upper Irigaray Sandstone (UISS) (Mining zone)	75 - 130	Fine to medium-grained arkosic sandstone

Roll-type uranium mineralization at the Irigaray site is present in fluvial channel sands in the "Upper" and "Lower" sandstone units of the Wasatch formation. The "Upper" unit, termed the Upper Irigaray Sandstone (UISS), is the largest and most economically important, although the Lower Irigaray Sandstone does contain mineralization. At present, only the "Upper" unit has been mined. The channel sands trend to the north, which is also the general direction of the regional dip and hydraulic gradient. The host environment of the upper unit consists of arkosic, fine to coarse grained, poorly sorted sands. The UISS shows a series of vertically graded sands from coarse at the bottom to fine at the top and at least two periods of downcutting and subsequent filling. Because of the mainly fluvial depositional environment, horizontal and vertical facies changes occur rapidly, making it difficult to correlate the highly lenticular beds across the site. The mineralization has been stratigraphically confined by persistent layers of shales, mudstones or claystones. The top of mineralization is on the average about 200 feet

below the surface. The UISS (host sand) averages approximately 100 feet in total thickness, whereas the mineralized section within the UISS typically is 18 feet thick. The calcite content of the host ranges from 1 to 3 percent.

Mineralization occurs along the margins of the large tongue of sand altered by oxidizing groundwater flow. This tongue measures some three miles in width near the center of the Irigaray property and extends from the southern boundary for a strike length of ten miles. Uranium deposition as uraninite and coffinite occurred where the groundwater encountered reducing conditions. Uranium is localized at the interface (roll front) between the oxidized and reduced sandstone. The oxidized zone is difficult to distinguish from the reduced zone; the sandstone on the oxidized side has a tan to yellowish green bleached color whereas the reduced portion is characterized by a gray color. Lack of strong red and brown coloration in oxidized material is due to the generally low pyrite content (less than 0.5 percent). In contrast to many uranium deposits of similar origin, no molybdenum mineralization has been found at the Irigaray site to date. Arsenic and selenium are present within and adjacent to the uranium mineralization. Barite, as  $\text{BaSO}_4$ , is also found with the uranium mineralization.

### **3.4 SITE HYDROLOGY**

Historical studies (See Appendix B) have stated that the general direction of groundwater flow in the PRB is to the north. It has been postulated that regional flow systems (e.g., the Wasatch, Fort Union, and deeper sediments) generally flow to the northern portion of the PRB and discharge via unknown avenues in Montana. The hydraulic communication between the flow systems has been reported to vary from none to direct. Flow direction in those sediments near outcrop areas generally has been characterized as toward the center of the PRB. The specific discharge areas have not been clearly identified in historical studies, and the degree of interaction between surface and groundwater in the PRB was not fully defined.

More recent studies performed in the PRB regarding regional groundwater flow and the impact of groundwater on surface water bodies have concluded the following: (1) groundwater flow in the PRB is more appropriately evaluated on a local, rather than regional scale, both with regard to flow direction and gradient, (2) vertical flow in the Wasatch is limited, (3) most flow occurs horizontally (e.g., to the north) in specific stratigraphic units, (4) regional and local potentiometric data must be from the same stratigraphic horizon to assess the flow direction and gradient, and (5) interaction between surface and groundwater appears to be limited.

For these reasons, only wells completed in the UISS were utilized to assess the hydraulic gradient in the vicinity of Irigaray. Water level data from over 60 monitoring and trend wells in the vicinity of the Irigaray wellfield, and 4 monitoring wells approximately 3,700 feet to the north of the wellfield (517 Area – Plate 1) were used to construct a semi-regional potentiometric map (Appendix B).

On a semi-regional scale, groundwater flow occurs to the north-northwest, and the gradient is on the order of 0.004 to 0.006 ft/ft. This groundwater flow direction is consistent with results numerous hydrogeologic studies specific to Irigaray (Appendix B). On a local scale, site data indicate a general west-northwest flow direction with an approximate gradient of 0.005 ft/ft.

Formation and hydraulic properties for the UISS have been studied extensively prior to, and during mining operations. A summary of laboratory results for the UISS follows.

<b>Average Permeability, Porosity, and Density for UISS Core Samples (after Morris &amp; Bahr, 1975)</b>				
<i>Sample Description</i>	<i>Horizontal Permeability (md)</i>	<i>Vertical Permeability (md)</i>	<i>Porosity (percent)</i>	<i>Density (g/cc)</i>
Clay & Silt above UISS	0.3	0.5	16.6	na
Mineralized Zone	806	607	23.4	1.96
Non-mineralized Zone	3312	2256	29.0	1.86

As documented in numerous reports related to ISL mining, the UISS is a confined aquifer. Extensive site data suggest the average hydraulic conductivity values for the UISS range from 0.46 ft/d to 0.55 ft/d, and the average storativity is approximately  $2.0 \times 10^{-4}$ .

## **4.0 OPERATIONAL HISTORY AND RESTORATION RESULTS**

### **4.1 MINING HISTORY**

#### **4.1.1 Wellfield Operations**

As stated earlier, the 30-acre Irigaray wellfield consists of nine contiguous wellfields, or Production Units. Commercial mining was initiated in the A-field (Unit 1; Figure 2-1) in October of 1978. The A-Wellfield had previously been operated for research and development during 1976 and 1977. Wellfield activation continued through November 1979 with the construction and operation of the B (also Unit 1), C, D, F and G wellfields. These wellfields comprise the areas now known as Production Units 1 through 5.

The lixiviant used for the initial operations in Units 1 through 5 was ammonium bicarbonate, with hydrogen peroxide as the oxidant (1977 through 1980). In May 1980, after feasibility testing in the E-Wellfield, the lixiviant system for the entire site was converted to sodium bicarbonate chemistry with gaseous oxygen as the oxidant. Following the completion of mining, the E-Wellfield was restored. Regulatory acceptance of the E-Wellfield restoration was granted in 1986.

In late 1981, all Irigaray mining activities were suspended. In February 1982, the wellfields were placed in a temporary standby status. The standby period continued until August 1987 when mining was re-activated in Units 1 through 5. Mining in Production Units 6, 7, 8 and 9 was initiated in the first half of 1988.

Mining operations were completed in Units 1 through 5 in June of 1989. Mining operations continued in Units 6 through 9 until the start of a temporary suspension in February 1990. Mining in Units 6 through 9 resumed three years later in August of 1993. Commercial mining operations continued in Units 6 through 9 until the end of November 1994, at which time the wellfields were placed on standby while awaiting restoration.

#### **4.1.2 Baseline Water Quality**

Prior to mining, the water quality of the ore zone, overlying monitor zone and underlying monitor zone was established for each operational area. At Irigaray, water quality within the ore zone was determined from representative injection or recovery wells located across a staggered well fence perpendicular to the uranium roll front. Section 4.1.3 of the original Permit 478 for Irigaray specified that one baseline well would be drilled for each production cell across any given width of the mining unit. Main water quality fences were to be located at intervals of approximately 600 feet along the ore zone as the wellfields were expanded. Staggering the wells both north and south gave coverage throughout the wellfields. The baseline wells were sampled to establish the pre-mining use category of the ore zone, as well as the water quality target values for restoration. Baseline water quality was established individually for all monitor wells.

The original Irigaray permit also specified that each "baseline well" would be sampled a minimum of three times at a frequency of no less than one-week apart. This resulted in wells with three baseline samples ranging from one week apart to three months apart. Later, when operations resumed in Production Units 6 through 9 in 1987, the WDEQ required two additional samples from baseline wells in new wellfields to augment the original three sample baseline.

The baseline water quality samples for Production Units 1 through 5 were obtained during the years of 1976 through 1979. Baseline water quality samples for Units 6 through 9 were obtained in 1979, 1980 and 1987. The initial baseline sampling of Units 6 through 9 was conducted in 1979 and 1980 before the development of the area was suspended. Additional sampling was conducted in 1987 to confirm and augment the existing baseline data prior to the commencement of mining. Separate baseline water quality packages were subsequently approved for Units 6, 7, 8 and 9. The baseline data for Units 1 through 6 (original data) were approved in the Permit 478 document. The individual wells utilized to establish the ore zone baseline water quality are listed below.

#### IRIGARAY UNITS 1-9 ORE ZONE BASELINE WELLS

Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9
AP-3	DI-4	DI-21	FI-60	GI-76	HI-50	JP-15	KI-128	LI-51
AP-4	DI-12	DI-27	FI-62	GI-82	HI-53	JP-26	KP-29	LP-13
AP-5	DP-7		FI-64	GI-105	HI-57	JP-47	KP-44	LP-20
AP-10	EI-34		FI-66	GI-122	HI-62	JP-50	KP-50	LP-22
			FI-67		HP-24	JP-53	KP-63	LP-24
					HP-59	JP-57	KP-70	LP-43
					HP-87	JP-63		LP-63

Locations of these wells may be found on Figure 4-1 of this report.

The baseline analysis suite typically followed the WDEQ Guideline 8 list of parameters for uranium mines. As some of the very early baselines were obtained prior to the development of WDEQ Guideline 8, some parameters were not analyzed. The analytical results for each individual baseline well located in Units 1 through 5 are contained in "Appendix 1 of the Aquifer Restoration and Decommissioning Plan for Units 1 through 5, May 1991" and the original Permit 478 application document. Individual analysis for wells in Units 6 through 9 are contained in "Appendix 2 of the Aquifer Restoration and Decommissioning Plan for Units 4 through 9, March 1995" and individual wellfield data packages. These baseline data have been combined and are presented in Appendix A, Table A-1 of this report. In summary, 200 samples were obtained from 46 wells to characterize the baseline water quality of the ore zone in 30 acres of wellfield. This equates to an average of 1.5 baseline wells per acre of wellfield and 4.3 samples per well, which is consistent with current practices for baseline characterization in ISL wellfields.

## **4.2 RESTORATION PROGRAM**

### **4.2.1 Goals of the Restoration Program**

The stated goal for restoration in the Permit to Mine No. 478 application document is to return the quality of groundwater to baseline concentrations, using the best practicable technology and economic reasonableness. If this primary goal cannot be achieved, the groundwater will, at a minimum, be returned to the pre-mining use category.

As noted earlier in Section 2.0, various pre-mining use categories were established for the Irigaray production units. Although these units were primarily classified as Class I drinking water, we now know that this classification was in error due to high concentrations of uranium, radium-226 and other constituents. The classification that is appropriate for these uranium ISL wellfields is Class V, Mineral Commercial.

### **4.2.2 Target Restoration Values**

Target Restoration Values for Irigaray were established and accepted by the regulatory agencies in Table R1-1 of Permit to Mine No. 478, renamed as Table 6.1 in the January 1996 permit renewal document. Table 4-1 of this report presents the Target Restoration Values as given in Tables R1-1 and 6.1 of the prior permit documents. For twenty-five of the twenty-nine parameters listed, the baseline range was the established Target Restoration Value. For the other four parameters (ammonia, bicarbonate, chloride and uranium), the Target Restoration Values were based upon the final E-Field restoration stabilization values. This baseline range was compiled using data from ore zone baseline wells located in Production Units 1 through 6 and the E-wellfield.

In May 2003, COGEMA Mining, Inc. met with WDEQ personnel to discuss the restoration status of the Irigaray and Christensen Ranch projects. At that time, it was proposed and agreed that one restoration report package (this report) would be submitted for the Irigaray project. This would entail combining all baseline data from Units 1 through 9 together for a larger database. It was recognized that the data from Units 1 through 9 are more meaningful when combined as a whole than if presented as several individual packages. Thus, a combined baseline data set was compiled from the ore zone baseline wells located in Production Units 1 through 9 and is included in Table 4-2. E-Field baseline wells were not included in the Units 1 through 9 data set so as to reflect only the wellfields addressed by this report.

Table 4-2 also contains a comparison of the Units 1 through 9 baseline range with the Units 1 through 6 baseline range (the approved restoration targets for Irigaray). As can be seen from the table, the two data sets generally agree. However, the range is broader for parameters such as sodium, sulfate and total dissolved solids, which is a reflection of 200 sample values versus the 81 sample values associated with the original restoration baseline range used for the permit.

The baseline ranges for Units 1 through 9 as shown in Table 4-2 are used in this report as the Target Restoration Values.

#### **4.2.3 Restoration Process Technology Applied**

Best practicable technology (BPT) was applied throughout the Irigaray groundwater restoration program. The process employed was completely justifiable in terms of performance and achievability in relation to health, safety and minimization of adverse impacts to the environment.

The restoration program followed the four-phase approach approved in the "*Aquifer Restoration and Decommissioning Plan for Units 1 through 5, May 1991*" (May 1991 Plan) and in the "*Aquifer Restoration And Wellfield Decommissioning Plan - Irigaray Mine - Production Units 4 Through 9, submitted in March 1995*" (March 1995 Plan). The four phases were:

1. Groundwater Sweep
2. Permeate Injection (with reductant addition as necessary)
3. Aquifer Recirculation
4. Post-Restoration Stabilization

In the first three 'process' phases, the groundwater was actively recovered and treated as necessary for re-injection or disposal. The final phase involved the monitoring of designated restoration wells to assess the restoration efforts and the stability of the ore-zone water quality.

The first phase of restoration, groundwater sweep, was conducted to recall the mining solution (lixiviant) from the affected aquifer (termed ore or mineralized zone) and from the area surrounding the ore zone that may have been affected by flaring of lixiviant during mining. Groundwater sweep involves the 100% consumptive removal of the wellfield groundwater with no re-injection. The process is termed groundwater sweep because the removal of water from the ore zone creates a hydrologic sink, wherein the surrounding groundwater "sweeps" into the mined ore zone, recharging the zone with native connate water. The water recovered during groundwater sweep was treated for discharge under an NPDES permit, or transferred to the on-site evaporation ponds.

The second restoration phase, Reverse Osmosis (RO) permeate injection, is the primary means of reducing the level of total dissolved solids in the affected aquifer. During this phase, groundwater was extracted from the wellfield and treated using ion exchange and state-of-the-art reverse osmosis technology. These systems removed metals, radionuclides and dissolved solids and generated a high-purity water product (permeate). The permeate was treated with caustic soda to raise the pH to a level consistent with the restoration target and then re-injected into the affected aquifer. When deemed necessary, a chemical reductant (hydrogen sulfide gas) was added to the injection stream to attenuate trace metal concentrations. The RO permeate injection

phase was operated to minimize the consumptive removal of groundwater while still maintaining a hydrologic sink (cone of depression) within the wellfield. During this phase, the wellfield was typically over-recovered by ten to thirty percent, thus continuing the beneficial effect of groundwater sweep from the perimeter of the operating area.

During the aquifer recirculation phase, the aquifer water was simply circulated within the wellfield to provide consistent water quality. Recovered groundwater was commingled and redirected to the injection wells without additional purification treatment. This activity was the end of active restoration.

During the stabilization phase, the only wellfield activity was well sampling for the monitoring program. The sample results demonstrate that the chemical constituents in the groundwater of the ore zone are in equilibrium with their immediate surroundings. The above phases of restoration were used to treat the affected wellfield groundwater for a specified sequence and volume to reach the restoration goals, based on prior Irigaray restoration experience. For Irigaray Production Units 1 through 5, the May 1991 plan called for the following treatment sequence:

- Groundwater Sweep – three (3) pore volume displacements (PVD) of treatment
  - RO Permeate Injection – three (3) PVD
  - Recirculation – one (1) PVD
- Total = 7 PVD of treatment

In the March 1995 plan, the proposed treatment sequence for Units 6 through 9 was:

- Groundwater Sweep – one (1) PVD
  - RO Permeate Injection – five (5) PVD
  - Recirculation – one (1) PVD
- Total = 7 PVD of treatment

Essentially the difference between the two programs was to shorten the groundwater sweep phase and expand the RO treatment phase. Based on the results of the Irigaray Production Units 1-5 groundwater sweep, COGEMA concluded that some amount of groundwater sweep is necessary to recall mining solutions from the periphery of the wellfield, but once these solutions are recalled, continued groundwater sweep is inefficient and an unnecessary consumptive use of groundwater. Therefore the plan was changed in 1995 to include only one PVD of groundwater sweep, with an increase in the number of PVD of RO permeate injection to five.

Even though the planned restoration programs for Units 1-5 and 6-9 involved a total of 7 PVD of treatment, the actual results of the restoration program utilized more PVD of treatment, as described in the following sections.

## 4.3 RESTORATION OPERATIONS

### 4.3.1 Total Volume Processed

A summary of the gallons processed for each phase of restoration is given in Table 4-3. A total volume of 840,175,000 gallons was processed over eleven and a half years of active restoration operations.

To equate the gallons processed to a pore volume displacement (PVD) estimate, the affected area of the production zone (one pore volume) was calculated as follows:

$PV = (WA) (AT) (FF) (P) (CONV)$  where:

PV = pore volume  
WA = wellfield area in square feet (ft<sup>2</sup>)  
AT = average thickness in feet (ft)  
FF = flare factor of 1.44 [effectively adds 44% to the volume to account for a 20% horizontal flare of lixiviant and a 20% vertical flare of lixiviant]  
P = average porosity (26%)  
CONV = conversion from ft<sup>3</sup> to gallons (7.48)

Based on an average thickness of 16.8 feet for all nine production units and an average porosity of 26% the above calculation applied to the Irigaray Wellfield Units 1-9 results in a calculated PV of approximately 61,483,000 gallons. A breakdown of determined pore volume by Production Unit is given below. It is noted that the flare factor of 1.44 is a regulatory requirement from WDEQ. Based on historical operations and data, actual values for horizontal and vertical flare are 0% and 10%, respectively. Because of the required 1.44 flare factor, COGEMA has processed a volume of water during restoration that greatly exceeds the amount that would be required based on historical operational data.

AREA	KGALLONS/PVD
PU 1-3	11,746
PU 4-5	10,212
PU 6	13,417
PU 7	13,200
PU 8	4,386
PU 9	8,522
TOTAL	61,483

### 4.3.2 Operational Summaries, Irigaray Wellfields

Due to operational and facility considerations, the restoration activities in Irigaray Units 1 through 9 were operated, monitored and controlled as six operating areas. Units 1

through 3 were managed as one distinct area. Production Units 4 and 5 were managed as another distinct area. Production Units 6, 7, 8 and 9 were all managed as separate areas. The history of the restoration activities at Irigaray is consequently reported by these six functional groupings. In addition to the volumes of groundwater recovered during restoration, Table 4-3 also provides a summary of the key-dates of each restoration phase for the various wellfield groupings. The restoration history is detailed further in Sections 4.3.2.1 through 4.3.2.6.

#### **4.3.2.1 Restoration History of Units 1 through 3**

Groundwater restoration began in May 1990 with the groundwater sweep (GWS) phase for Production Units 1 through 3. A total of 4.2 pore volume displacements (49 million gallons) of GWS were completed before the Reverse Osmosis (RO) permeate injection phase was started in late-April 1991.

In total, 13.2 pore volumes (155 million gallons) of groundwater were recovered and treated during the permeate injection phase of Units 1 through 3. Hydrogen sulfide gas was added to the injection stream during the first two pore volumes (June and July 1991). In total, 22,000 pounds of hydrogen sulfide were introduced at an average concentration of 200 mg/l. Permeate injection continued until October 22, 1992. Figure 4-2 illustrates the trends of conductivity and uranium concentration in Units 1 through 3 during the GWS and RO permeate injection phases as determined by the average of the baseline well analytical results obtained at each PVD. The trend for both conductivity and uranium appeared to be stabilizing after the last four PVD of permeate injection, therefore continued RO treatment beyond the total 13.2 PVD was not considered effective in terms of the cost/benefit ratio. A decision was made to progress to aquifer recirculation and stabilization.

The aquifer recirculation phase immediately followed the permeate injection phase. The recirculation of one pore volume was completed on November 30, 1992. In total, 18.4 PVD (216 million gallons) of groundwater were recovered from the aquifer during the active restoration phases of Units 1 through 3.

The post-restoration stabilization phase began immediately after aquifer recirculation. Final stability samples were obtained nine-months later in September 1993.

#### **4.3.2.2 Restoration History of Units 4 and 5**

Groundwater restoration of Units 4 and 5 began in June 1991 with the initiation of the groundwater sweep phase. A total of 3.0 pore volume displacements (30.5 million gallons) of GWS were completed before August 1993 when the restoration activity was suspended to allow additional production activity in Units 6 through 9. Although the GWS phase was considered technically complete, additional GWS occurred on a limited basis between April 15, 1995 and October 4, 1995. In total, 3.4 PVD's (34.4 million gallons) of groundwater were removed during the GWS activities of Units 4 and 5.

Reverse Osmosis (RO) permeate injection phase was started in October, 1995. This restoration phase continued through August 1998. In total, 9.5 pore volumes (97.5 million gallons) of groundwater were recovered and treated during this phase in Units 4 and 5. Based on the positive response to permeate injection, the formation was not treated with a chemical reductant. Figure 4-3 illustrates the trends of conductivity and uranium concentration in Units 4 and 5 during the GWS and RO permeate injection phases as determined by the recovery stream samples taken weekly. The trend for conductivity stabilized during the last five PVD of permeate injection and did not improve during this time. Uranium was somewhat erratic and actually increased during the last two PVD of treatment. Based on the lack of improvement in overall conductivity in the last 5 PVD of a total of 9.5 PVD additional RO treatment was not considered effective in terms of the cost/benefit ratio. A decision was made to progress to aquifer recirculation and stabilization.

The aquifer recirculation phase of Units 4 and 5 occurred between August 29 and September 29, 1998. The recirculation of one pore volume (10.5 million gallons) was completed. In total, 13.9 PVD (142 million gallons) of groundwater were recovered from the aquifer during the active restoration phases of Units 4 and 5.

The post-restoration stabilization phase began immediately after aquifer recirculation. Final stability samples were obtained nine-months later in late-June and mid-July of 1999.

#### **4.3.2.3 Restoration History of Unit 6**

Groundwater restoration of Unit 6 began in January 1996 with the initiation of groundwater sweep. A total of 1.4 pore volume displacements (18.5 million gallons) of groundwater were withdrawn from the aquifer before completion in August 1998.

The unit was maintained on standby status until the commencement of the permeate injection phase in July, 2000. This restoration phase continued through October 11, 2001. In total, 7.1 pore volumes (95.5 million gallons) of groundwater were recovered and treated during the permeate injection phase of Unit 6. Based on the positive response to permeate injection, the formation was not treated with a chemical reductant. Figure 4-4 illustrates the trends of conductivity and uranium concentration in Unit 6 during the permeate injection phase as determined by the recovery well sample average determined each month. The trend for conductivity and uranium essentially stabilized after 3 PVD of treatment and did not significantly improve during the total 7.1 PVD of treatment. Additional RO treatment was not considered effective in terms of the cost/benefit ratio. A decision was made to progress to aquifer recirculation and stabilization.

The aquifer recirculation phase of Unit 6 occurred between October 11, 2001 and November 15, 2001. The recirculation of one PVD (over 13 million gallons) was

completed. In total, 9.5 PVD (127 million gallons) of groundwater were recovered from the aquifer during the active restoration phases of Unit 6.

The post-restoration stabilization phase began immediately after aquifer recirculation. Final stability samples were obtained nine-months later in August of 2002.

#### **4.3.2.4 Restoration History of Unit 7**

Groundwater restoration of Unit 7 began in April 1995 with the initiation of groundwater sweep (GWS). A total of 1.6 pore volume displacements (21.4 million gallons) of groundwater were withdrawn from the aquifer before completion in September 1997.

The unit was maintained on standby status until the commencement of the permeate injection phase in February 2000. This restoration phase continued through July 2001. In total, 11.7 pore volumes (155 million gallons) of groundwater were recovered and treated during the permeate injection phase of Unit 7. Based on the positive response to permeate injection, the formation was not treated with a chemical reductant. Figure 4-5 illustrates the trends of conductivity and uranium concentration in Unit 7 during the permeate injection phase as determined by the recovery well sample average determined each month. The trends for both conductivity and uranium stabilized during the last 2 PVD of treatment. Additional RO treatment was not considered effective in terms of the cost/benefit ratio. A decision was made to progress to aquifer recirculation and stabilization.

The aquifer recirculation phase of Unit 7 occurred between July 12, 2001 and August 30, 2001. The recirculation of 13.3 million gallons (1.0 PV) was completed. In total, 14.3 PVD (189 million gallons) of groundwater were recovered from the aquifer during the active restoration phases of Unit 7.

The post-restoration stabilization phase began immediately after aquifer recirculation. Final stability samples were obtained nine months later in June of 2002.

#### **4.3.2.5 Restoration History of Unit 8**

Groundwater restoration of Unit 8 began in April 1995 with the initiation of groundwater sweep (GWS). A total of 1.4 pore volume displacements (6.3 million gallons) of groundwater were withdrawn from the aquifer before completion in September 1997.

The unit was maintained on standby status until the commencement of the permeate injection phase in March 1999. This restoration phase continued through June 2000. In total, 10.2 pore volumes (45 million gallons) of groundwater were recovered and treated during the permeate injection phase of Unit 8. Based on the positive response to permeate injection, the formation was not treated with a chemical reductant. Figure 4-6 illustrates the trends of conductivity and uranium concentration in Unit 8 during the permeate injection phase as determined by the recovery well sample average determined each month. The trends for both conductivity and uranium stabilized during

the last 2 PVD of treatment. Additional RO treatment was not considered effective in terms of the cost/benefit ratio. A decision was made to progress to aquifer recirculation and stabilization. The aquifer recirculation phase of Unit 8 occurred in July and August 2000. The recirculation of 0.9 PVD (3.7 million gallons) was completed. In total, 12.5 PVD (54.9 million gallons) of groundwater were recovered from the aquifer during the active restoration phases of Unit 8.

The post-restoration stabilization phase began immediately after aquifer recirculation. Final stability samples were obtained nine-months later in June of 2001.

#### **4.3.2.6 Restoration History of Unit 9**

Groundwater restoration of Unit 9 began in April 1995 with the initiation of groundwater sweep (GWS). A total of 1.7 pore volume displacements (14.3 million gallons) of groundwater were withdrawn from the aquifer before completion in September 1997.

The unit was maintained on standby status until the commencement of the permeate injection phase in November 1998. This restoration phase continued through April 2000. In total, 10.7 pore volumes (91.4 million gallons) of groundwater were recovered and treated during the permeate injection phase of Unit 9. Based on the positive response to permeate injection, the formation was not treated with a chemical reductant. Figure 4-7 illustrates the trends of conductivity and uranium concentration in Unit 9 during the permeate injection phase as determined by the recovery well sample average determined each month. The trends for both conductivity and uranium stabilized during the last 2 PVD of treatment. Additional RO treatment was not considered effective in terms of the cost/benefit ratio. A decision was made to progress to aquifer recirculation and stabilization.

The aquifer recirculation phase of Unit 9 occurred in May of 2000. The recirculation of 0.5 PVD (4.7 million gallons) was completed. In total, 13 PVD (110 million gallons) of groundwater were recovered from the aquifer during the active restoration phases of Unit 9.

The post-restoration stabilization phase began immediately after aquifer recirculation. Final stability samples were obtained nine-months later in January of 2001.

#### **4.3.3 Water Quality Monitoring During Restoration**

The groundwater monitoring plan for the restoration program of Irigaray Units 1 through 3 was provided in "*Table 6 of the Aquifer Restoration and Decommissioning Plan, Irigaray Mine, Units 1 Through 5, May 1991*". The groundwater monitoring plan for the restoration program of Units 4 through 9 was provided in "*Table 6 of the Aquifer Restoration and Decommissioning Plan, Irigaray Mine, Production Units 4 Through 9, March 1995*".

These plans were followed for the restoration programs as described below.

#### **4.3.3.1 Ore Zone Water Quality**

The progress of groundwater sweep and permeate injection was monitored in Production Units 1 through 3 by sampling and analyzing the groundwater on a weekly basis as well as on a treated volume basis, as follows:

- Weekly samples of the recovery stream composite were taken and analyzed for parameters such as bicarbonate, sulfate, chloride, conductivity, pH, and uranium. On a monthly basis, parameters such as sodium, calcium and ammonium were added to the weekly analysis. The samples were analyzed by COGEMA's on-site laboratory.
- Wells designated as restoration wells were sampled at the end of each pore volume displacement during the active restoration phases. Samples were analyzed by an outside commercial laboratory for the WDEQ Guideline 8 list of parameters. Each designated restoration well was previously utilized as a baseline water quality well.
- The designated restoration wells for Units 1 through 5 established in "*Section 5.1.1 of the Aquifer Restoration and Decommissioning Plan, Irigaray Mine, Units 1 Through 5, May 1991*" are: AP-4, BP-4, CP-10, DP-2, DI-4 (90), DI-27, DP-29, FP-5, FI-62, FI-67 (132), GI-76, GI-82, GP-9 and GI-134(GI-105). Locations of these wells are shown on Figure 4-1 of this report.

The progress of groundwater sweep and permeate injection was monitored in Production Units 4 through 9 in a similar fashion as Units 1 through 3, with some modification as follows:

- Weekly samples of the recovery stream composite were taken and analyzed for parameters such as bicarbonate, sulfate, chloride, conductivity, pH and uranium. Other parameters such as sodium, calcium, ammonium and TDS were added periodically to assess the progress of restoration. These samples were analyzed by COGEMA's on-site laboratory, or on occasion submitted to an outside commercial laboratory.
- The recovery stream composite was sampled at the end of each pore volume displacement of active restoration and analyzed for the WDEQ Guideline 8 list of parameters. These samples were analyzed by an outside commercial laboratory.
- Designated restoration wells were sampled at the end of each restoration phase (GWS, RO/permeate injection, recirculation) and analyzed for the WDEQ Guideline 8 list of parameters. These samples were analyzed by an

outside commercial laboratory. Each designated restoration well was previously utilized as a baseline water quality well. However, not all baseline water quality wells were used as designated restoration wells. The designated restoration wells were chosen from the available baseline wells to achieve good overall coverage of the wellfield and one designated restoration well per acre of wellfield.

- The designated restoration wells for Units 6 through 9 established in "*Section 5.1 of the Aquifer Restoration and Decommissioning Plan, Irigaray Mine, Units 4 Through 9, March 1995*" are: HP-87, HP-59 (50), HI-53, HI-57, HI-62, JP-26, JP-53, JP-57, JI-91, JP-63, KP-70, KI-128, KP-44, LI-51, LP-13, LP22, LP-43, and LP-63. Locations of these wells are shown on Figure 4-1 of this report. At the request of WDEQ, other wells in Units 6 through 9 with established baseline values were also used as designated restoration wells for sampling purposes. These wells were alternated into the sampling regime in place of other designated restoration wells to provide a higher degree of wellfield coverage. Wells used for this purpose are: GI-134, HI-50, HP-24, JI-84, JP-15, KP-29, KI-119, KP-45, KP-61, LI-91 and LP-24.

#### **4.3.3.2 Ore Zone Perimeter Monitor Wells**

The ore zone perimeter monitor wells were sampled monthly throughout the active restoration phases and quarterly thereafter. The specific well numbers are given in Table 4-4. Figure 2-1 shows the location of the monitor wells with respect to the wellfield. The samples were analyzed for chloride, conductivity and total alkalinity to determine if the wells had been affected by mining solutions. The monitoring results were reported in the Irigaray Mine Site Semi-Annual Reports. As demonstrated by the data submitted in those reports, the perimeter ore zone monitor wells were not affected by mining solutions during restoration operations and remained unaffected throughout the post-restoration period.

#### **4.3.3.3 Shallow Monitor Zone**

Initially, an overlying horizon known as the coal zone was designated as the shallow monitoring zone at Irigaray. Mining operations in Units 1 through 5 during the period of 1978 through 1981 caused lixiviant migrations into the coal zone via faulty injection well casings and improperly sealed exploration boreholes. Due to the inability to completely isolate the coal zone from mining operations, the coal zone was incorporated into the production zone for Units 1 through 9 via license amendments with both the USNRC and WDEQ. Another upper stratigraphic zone, called the Unit 1 Sand, was designated for shallow zone monitoring purposes.

The Unit 1 Sand monitor wells were sampled monthly throughout the active restoration phases and quarterly thereafter. The specific well numbers are given in Table 4-4. Figure 2-1 shows the location of the shallow monitor wells. The samples were analyzed

for chloride, conductivity and total alkalinity to determine if the wells had been affected by mining solutions. The monitoring results were reported in the Irigaray Mine Site Semi-Annual Reports.

Over the years of mining and restoration, several of the Unit 1 Sand monitor wells continued to show signs of residual lixiviant contamination caused by the earlier excursions. In 2003, one and a half years after the completion of active groundwater restoration, six of the shallow sand monitoring wells remained on excursion status. The WDEQ removed the six affected shallow sand monitor wells from excursion status (WDEQ/LQD letter dated July 29, 2003) because the excursion mitigation efforts effectively precluded further movement of the fluid from the production zone to the shallow sand and because the quality of the shallow sand water is still suitable for the same uses as before mining. Presently, none of the shallow sand monitor wells are on excursion status. Groundwater restoration operations are completed and the Unit 1 Sand water quality has stabilized.

#### **4.3.3.4 Deep Monitor Zone**

The deep zone monitor wells were sampled monthly throughout the active restoration phases and quarterly thereafter. The specific well numbers are given in Table 4-4. Figure 2-1 shows the location of the deep monitor wells. The samples were analyzed for chloride, conductivity and total alkalinity to determine if the wells had been affected by mining solutions. The monitoring results were reported in the Irigaray Mine Site Semi-Annual Reports.

With one exception, the deep zone monitor wells were not affected by mining solutions during restoration operations. Monitor well DM-10 in Unit 6 is located in an area where the production zone and the underlying monitor sand appear to be hydraulically connected. The well was declared on excursion status for more than a decade. In July 2003, the WDEQ removed DM-10 from excursion status (WDEQ/LQD letter dated July 29, 2003). This action was taken because the wellfield restoration effectively precluded further movement of fluid from the production zone to the deep sand and because the quality of the ground water in the deep sand is still suitable for the same uses as before mining. Presently, none of the deep sand monitor wells are on excursion status. Groundwater restoration operations have been completed and the deep-sand water quality has stabilized.

#### **4.3.4 Water Level Monitoring During Restoration**

The baseline piezometric surface of the Upper Irigaray Sandstone has been determined to be at or near 4,300 feet mean-sea-level (*Irigaray Mine, Application for In-Situ Permit to Mine, Revised February 1, 1982*). This level was established when the piezometric surfaces of individual wells within and around the Irigaray ore trend were measured during the establishment of baseline water quality conditions.

The water level of all monitor wells was observed routinely throughout the life of the operations. Water levels were taken prior to each monitor well sampling event. The water level results, along with piezometric surface maps of the ore, shallow and deep monitor zones, were presented annually in the Irigaray Mine Site Annual Reports submitted to WDEQ and NRC

The historical water level data of eight representative ore-zone wells is presented in Table 4-5. The eight perimeter monitor wells were selected for their locations in relation to the production units (see Figure 2-1). The data reflect how the piezometric surface of the ore zone aquifer was affected by the operational activities of mining and restoration.

A consumptive removal (bleed) stream was maintained throughout mining operations. The bleed stream typically ranged from 1% to 3% of the overall recovery flow. This had the effect of drawing down the piezometric water levels in the ore zone (UISS) from the baseline conditions throughout the life of mining. A higher bleed rate (up to 10%) was used on occasion in specific areas of the wellfield for corrective action purposes.

During active restoration, the piezometric surface of the ore zone (UISS) at the perimeter monitor ring was lowered as much as 115 feet in some wells. Drawdown was most pronounced during the groundwater sweep phase when up to four pore volumes were consumptively removed and disposed, with no re-injection. Bleed rates during the permeate injection phase were not as severe as groundwater sweep, and ranged from 10% to 30%.

Following the completion of active restoration in November 2001, the piezometric surface of the UISS has gradually been returning to its pre-mining level at or around 4,300 feet.

#### **4.4 RESTORATION RESULTS**

COGEMA has completed a substantial effort to restore the groundwater of the Irigaray wellfields to baseline conditions. The best practicable technology was applied to the restoration effort. The actual volume of groundwater treated greatly exceeded the volumes anticipated in the approved restoration plans. The beneficial results of the restoration efforts are indicated by the substantial reduction in ionic concentrations between the post-mining and the post-restoration sampling events, as discussed in the following sections.

##### **4.4.1 Post-Mining Water Quality**

The water quality of the ore zone after mining was established by sampling each of the designated restoration wells. The post-mining samples for Units 1 through 5 were obtained in May 1990. The post-mining samples for Units 6 through 9 were obtained in April 1995. The sampling dates differ because mining continued in Units 6 through 9

the analytical results from Production Units 1 through 9 is presented in Table 4-6. The post-mining analytical data for each well used to establish the mean are provided in Appendix A, Table A-2. Copies of the original laboratory analytical sheets for each sample are not included in this report due to the bulk of such information, but are available in COGEMA's corporate office in Mills, Wyoming.

The chemical alteration of the ore zone aquifer can be observed through comparison of the post-mining mean concentrations with the baseline concentrations. Twenty-two of the thirty-five analyte concentrations in the post-mining means exceeded the baseline range maximums. And, nineteen of these parameters did not meet Target Restoration Values (of the twenty-nine with established TRVs) as shown in Table 4-1. Based on that result, groundwater restoration was deemed necessary.

#### **4.4.2 Restoration Water Quality**

The water quality of the ore zone during the restoration process was evaluated after each restoration phase by sampling the designated restoration wells. The arithmetic means of the Post-GWS and Post-RO phase sampling events are presented in Table 4-6. Individual well data used for these means are provided in Appendix A, Tables A-3 and A-4 respectively. The recirculation phase was conducted in each production unit immediately following the RO phase. The designated restoration wells were also sampled at the completion of the recirculation phase. Because the stability phase starts when the recirculation phase is completed, the Post-Recirculation results are presented in Table 4-6 as the Round-1 Stability results. The individual well data used for the Round 1 results are provided in Appendix A, Table A-5. Again, copies of the original laboratory analytical sheets for each sample are not included in this report due to the bulk of such information, but are available in COGEMA's corporate office in Mills, Wyoming.

#### **4.4.3 Stabilization Monitoring Water Quality**

The post-restoration water quality stability was established by sampling each of the designated restoration wells four times over a nine-month period following active restoration (the stabilization samples). The arithmetic means of the four stability sampling events for Units 1 through 9 are presented in Table 4-6 as Round-1, Round-2, Round-3 and Round-4 Stability Means. Individual well data used for establishing these means are provided in Appendix A, Tables A-5 through A-8.

Due to the staggered completion dates of active restoration for each production unit, the stability sampling occurred over a prolonged period. As indicated in Table 4-3, the final stability sampling (Round-4) for Units 1 through 3 occurred when the stability monitoring period ended in August of 1993. The final stability samples (Round-4 of Unit 6) were collected nine years later in August of 2002. Although there is a significant spread in the timing of the sampling events, combining the data is justified by the restoration plan requirements and the necessity to maintain a consistency in approach. Further, it is

clear from the data that the water quality was in-fact stable over the nine-month monitoring periods following active restoration.

The ultimate success of the Irigaray restoration program is measured against the Target Restoration Values consisting of the Baseline Range for Units 1 through 9 along with the separately approved targets for ammonia, bicarbonate, chloride and uranium. All of the individual designated restoration well data obtained through the four rounds of stability sampling were combined to generate Rounds 1-4 Stability Mean values (see Table 4-6). Because the sample population size is four times that of any individual round, the Rounds 1-4 Stability Mean values have been chosen to represent the overall ore zone water quality at the end of restoration.

A comparison of the stabilization phase results to the Target Restoration Values is given in Table 4-7. Twenty-seven of the twenty-nine constituents with defined Target Restoration Values have been returned to acceptable concentrations. The two constituents that exceed the restoration targets are bicarbonate and manganese. A brief discussion on each of these constituents follows.

- **Bicarbonate,  $\text{HCO}_3$ :** Bicarbonate is the anionic component of the primary chemical added to the lixiviant during the mining process. The bicarbonate concentration at the end of mining (average of 1,343 mg/l) was almost ten times the baseline maximum concentration at the initiation of restoration. The target restoration value for bicarbonate is 295 mg/l. After the completion of restoration efforts, the mean stabilization bicarbonate concentration had been significantly reduced to 423 mg/l (a 69% reduction). The elevated bicarbonate concentration is directly reflected in the elevated alkalinity value, however, there is no established Target Restoration Value for alkalinity.

Neither the WDEQ nor the USEPA have set a maximum permissible concentration for bicarbonate in drinking waters. Further efforts to reduce the bicarbonate levels would not result in any significant benefit to the overall quality of the groundwater and the cost of the effort would be substantial.

- **Manganese, Mn:** The post-restoration stabilization concentration for manganese is 0.226 mg/l. The restoration program markedly lowered the manganese concentration from the post-mining average of 1.25 mg/l (a decrease of 82%). Both the baseline range (<0.005 to 0.19 mg/l) and the restoration result for manganese exceed the WDEQ and USEPA Class-1 domestic (drinking) use standard for manganese (0.05 mg/l). Because the ending manganese concentration of 0.226 mg/l exceeds the baseline range and the Class-1 standard, manganese is addressed as a constituent-of-interest in Section 5 and Appendix C of this report.

Some constituents were restored to meet the Target Restoration Values but remain at elevated concentrations that may exceed USEPA's maximum contaminant level or

WDEQ's Class I domestic use standard at isolated locations downgradient of the wellfield. Those constituents are noted below.

- **Total Dissolved Solids, TDS:** The concentration of TDS contained by the groundwater is an indication of the overall restoration success. The TDS of the groundwater within the ore zone was reduced by seventy-four percent during the restoration program but remained elevated primarily due to the residual bicarbonate concentration. The ending TDS value of 631 mg/l falls within the baseline range and therefore meets the Target Restoration Value. However, at 631 mg/l, the TDS value exceeds the WDEQ Class-1 use standard of 500 mg/l. It is noted that original concentrations also exceeded this regulatory standard for some wells. Because of this, TDS is addressed as a constituent-of-interest in the Section 5 and Appendix C of this report.
- **Uranium, U:** The post-restoration concentration of U meets the Target Restoration Value of 2.09 mg/l. Additionally, the uranium concentration meets the WDEQ Class-1 use standard of 5.0 mg/l. However, at a final wellfield concentration of 1.98 mg/l, uranium may exceed the USEPA regulatory standard (0.03 mg/l) at isolated locations downgradient of the wellfield. It is noted that original concentrations also exceeded this regulatory standard for some wells. Because of this, uranium is addressed as a constituent-of-interest in the Section 5 and Appendix C of this report.
- **Selenium, Se:** The post-restoration concentration of Se falls well within the restoration target of the baseline range (less than 0.001 to 0.416 mg/l). However, at a final wellfield concentration of 0.028 mg/l, Se potentially could exceed the WDEQ Class-1 use standard (0.01 mg/l) at isolated locations downgradient of the wellfield. It is noted that original concentrations also exceeded this regulatory standard for some wells. Because of this, Se is addressed as a constituent-of-interest in the Section 5 and Appendix C of this report.
- **Radium-226, Ra-226:** The post-restoration concentration of Ra-226 falls well within the restoration target of the baseline range (0.0 to 247.7 mg/l). However, at a final wellfield concentration of 125.4 pCi/l, the radium concentration may exceed the WDEQ and USEPA regulatory standard of 5.0 pCi/l at isolated locations downgradient of the wellfield. It is noted that original concentrations also exceeded this regulatory standard for some wells. Because of this, Ra-226 is addressed as a constituent-of-interest in the Section 5 and Appendix C of this report.

One issue that has been raised at other ISL facilities by State and NRC regulators is the validity of the stabilization monitoring data with regard to long-term trends. To evaluate this issue, the stability monitoring data previously discussed in Section 4.4.3 and

presented in Tables 4-6 and 4-7 were reviewed. Review of those data indicates the following:

Out of the total of 35 constituents analyzed, only three had increased concentrations over the nine-month stability monitoring period, none of which have a WDEQ Class-1 primary standard (comparing the Rounds 1-4 stability mean with the Round 1 stability mean). Of the three constituents, the increases are negligible for two (Na – 0.7% and conductivity – 1.4%). And, although a negligible increase in conductivity was seen, a corresponding increase in TDS was not observed. Concentrations of all other constituents have either stayed the same, or decreased, during the stability monitoring period.

The third constituent that showed increasing concentrations is manganese (Mn), which increased by 27.7%. However, this increase is expected in a reducing environment, and Mn has only a secondary aesthetics based-standard (USEPA), not a primary health-based regulatory standard. The observed Mn concentrations are not expected to impact the class of use in any way. Further, it is noted that, while Mn concentrations increased during Rounds 2 and 3 of stability monitoring, the concentration decreased in Round 4.

As expected in a reducing environment, concentrations of other key constituents (U, Se, and Ra-226) have decreased over the stability monitoring period. Se concentrations decreased by 28.2%; U and Ra-226 concentrations have decreased by 8.8 % and 12.0% respectively. In this regard, continuing increases in Mn should be viewed in a positive light, as they are an indicator of reducing conditions which are conducive to decreasing concentrations of Se, U, and Ra-226, all which have primary USEPA regulatory standards and WDEQ Class-1 standards, are decreasing.

#### **4.4.4 Summary and Conclusions**

##### **Summary**

COGEMA has expended significant effort to restore the groundwater quality within the Irigaray wellfield to baseline conditions. At the completion of the Irigaray groundwater restoration program, the ore zone aquifer has been restored to standards consistent with Best Practicable Technology (BPT) and NRC's ALARA (As Low As Reasonably Achievable) principle. In this regard, over 840 million gallons of water were processed over an 11.5-year period, and an average of 13.7 pore volumes were treated for the entire wellfield. Treatment volumes exceeded the amounts included in the approved treatment plan.

Significant beneficial results were realized through the application of BPT. Twenty-seven of the twenty-nine constituents with defined Target Restoration Values were restored to acceptable concentrations. The two constituents that exceeded the defined Target Restoration Values are bicarbonate and manganese. Bicarbonate does not

have a defined Class-1 use standard and has no potential impact on the future use of the aquifer. Manganese has a Class-1 use standard based on USEPA's secondary standard for aesthetics. However, slightly higher manganese levels are indicative of reducing conditions in the aquifer, which is a desirable condition for mitigating Se, U and Ra-226 concentrations. An assessment of the fate and transport of manganese, along with other constituents-of-interest, follows in Section 5 and Appendix C.

## **Conclusions**

Based on the restoration standards in Permit to Mine No. 478, as amended, COGEMA has achieved acceptable post-restoration water quality for the Irigaray wellfields, Production Units 1 through 9. For the one constituent, manganese, that exceeds its Target Restoration Value and its Class I standard, it is critical to consider that this standard is only a secondary standard and the resulting value is not expected to impact future use of the ground water. Further, the increasing manganese concentration is an indicator of reducing conditions, which is beneficial with regard to long-term water quality.

To further support restoration approval the potential impact of manganese concentrations, as well as concentrations of selenium, uranium, and radium-226 that potentially could exceed regulatory standards at isolated monitoring well locations downgradient of the wellfield (but within the permit boundary), has been fully evaluated through fate and transport modeling (Section 5.0 and Appendix C). The modeling results clearly demonstrate that concentrations at distances of 400 feet downgradient from the wellfield remain below WDEQ regulatory standards for all the constituents. Further, it is noted that in the downgradient direction, the permit boundary (where Class-1 standards would apply) is 1,400 to 2,200 feet from the wellfield. In addition, it is noted that efforts to further reduce manganese concentrations could result in increasing concentrations of U, Se, Ra-226, and TDS.

## **5.0 ASSESSMENT OF FUTURE GROUNDWATER QUALITY SUMMARY OF GROUNDWATER FLOW AND SOLUTE TRANSPORT MODEL**

### **5.1 MODEL OBJECTIVES AND STRATEGY**

A numerical groundwater flow and transport model was developed to evaluate the potential for future migration of constituents derived from the Irigaray uranium in-situ leach (ISL) operation in Johnson County, Wyoming. The site setting, geology, and hydrology were previously summarized in Section 3.0 and are presented in detail in Appendix B. The focus of the model is on reduction of dissolved constituent concentrations resulting predominately from advective flow and dispersion phenomena. Model results indicate that constituent concentrations will remain below WDEQ regulatory standards within 400 feet of the ISL wellfield.

The objective of this section is to provide a summary of the model development and results. A detailed discussion of the model, including assumptions, evaluation and results is provided in Appendix C.

As discussed previously in Section 4.0, recovery of uranium resulted in elevated groundwater concentrations for a limited number of constituents. Restoration of the aquifer has been ongoing since 1990. As discussed extensively in Section 4.0, the restoration process has significantly reduced constituent concentrations in groundwater. However, concentrations of some constituents remain above WDEQ regulatory standards within the boundary of the wellfield. A groundwater flow and transport model has been developed to assess fate and transport of residual constituents derived from the Irigaray ISL mine. The model was constructed using conservative and simplifying assumptions to address offsite migration under the influence of regional hydraulic gradients. The objective of the model was to demonstrate that residual concentrations will be below WDEQ regulatory standards at prescribed observation points located approximately 400 feet from the wellfield boundary.

The complex production and restoration history of the Irigaray ISL mine makes it impractical to attempt to replicate the hydraulic stresses that have been imposed on the UISS aquifer. Furthermore, the focus of this assessment is on the future migration potential of site-derived constituents without additional restoration activities. The model is used to evaluate continued migration under steady-state conditions, without pumping or injection. Therefore, the emphasis on the development of the model is to adequately represent steady-state advective flow within and across the production zone.

Many environmental studies attempt to demonstrate concentration reduction of inorganic constituents with the use of geochemical reaction models. While geochemical processes such as sorption and precipitation undoubtedly contribute significantly to the removal of contaminants from groundwater, the parameters required to develop defensible geochemical reaction models are often difficult to obtain. Many of the processes are dependent on redox conditions that are difficult to quantify or are based on equilibrium assumptions that may or may not exist.

The approach taken for this evaluation is to develop a model that is predominately dependent on advective transport for attenuation of constituents and minimizes reliance on geochemical reactions. The parameters required to simulate steady-state groundwater flow and advective transport include hydraulic conductivity, hydraulic gradient and effective porosity. Each of these parameters has been quantified for the Irigaray site and appropriate values are incorporated into the model. A dispersivity term is included in the model simulations based on the scale of the site and literature review.

A distribution coefficient ( $K_d$ ) was included in the model simulations for some constituents. For those simulations, the lowest reasonable  $K_d$  available from literature was used. It is noted that, while  $K_d$  values were used for applicable constituents, complete conservation of mass was assumed. Namely, application of the distribution coefficient retards transport, but no solute is removed from the system by geochemical processes.

Minimizing reliance on geochemical processes is extremely conservative and results in overprediction of constituent concentrations downgradient of the site. Uncertainty in model parameters was addressed with a sensitivity analysis.

The site geology and hydrology pertinent to the conceptual model for the simulations has been summarized in Section 3. Additional detail with regard to the site characteristics and the conceptual and associated numerical model is presented in Appendix B and C, respectively.

## **5.2 MODEL CODES**

The codes used to develop the model included the following

- MODFLOW: for simulation of the flow field (McDonald, 1996)
- MODPATH: for simulation of groundwater flowpaths (Pollack, 1994)
- MT3DMS: for simulation of transport of site-derived constituents (Zheng 1999)

The codes were selected because they are suitable for modeling diverse hydrologic conditions and are widely accepted within the scientific and regulatory community.

## **5.3 MODEL DEVELOPMENT**

The subject of the modeling study is the UISS aquifer system within and around the Irigaray ISL wellfield. The UISS aquifer is a 100 foot thick confined unit within the Wasatch Formation. The model grid encompasses approximately one square mile with dimensions of 7,250 feet by 4,800 feet. The model grid is centered over the Irigaray ISL Wellfield (Figure 5-1) and is rotated 15 degrees northwest. To be consistent with previous regulatory submittals, Figure 5-1 includes mine coordinates.

The model consists of 290 rows by 192 columns in 3 layers. A uniform cell dimension of 25 feet by 25 feet was used throughout the model domain. The central layer (Layer 2) represents the mineralized zone. Based on detailed site information and data from Harshman (1974), Layer 2 is assigned a uniform thickness of 21 feet. Layers 1 and 3 represent the bounding non-mineralized sand units above and below the mineralized zone. The thicknesses of Layers 1 and 3 are 39 and 40 feet, respectively. All three layers are simulated as distinct units, but there are no boundaries between the layers. A cross-sectional view of the model layers is provided in Figure 5-2.

Input parameters for the groundwater flow model included boundary conditions, hydraulic conductivity, bottom elevation, top elevation, storage coefficient and porosity of the UISS aquifer system. Input parameters for the transport model included initial concentrations, dispersivity and distribution coefficients. The values for these parameters were primarily derived from site-specific data. In some case literature derived values or best professional judgment were utilized. Discussion of the selection of parameters is provide in Appendix C and summarized in Table 5-1.

#### **5.4 CALIBRATION**

The flow field was calibrated to water level data collected on March 18, 2002. Results of the calibration simulation are shown in Figure 5-3. Results of the MODPATH particle tracking are also shown on the figure, representing flowpaths of groundwater migrating across the site. Twenty-four monitoring wells were used as calibration targets for the model. Model residuals at the calibration targets (the difference between observed and modeled values) are shown on the Figure 5-4. Table 5-2 summarizes the calibration target values and the calibration statistics. Overall, the model adequately reproduced the observed heads in the UISS aquifer. Additional discussion of the calibration and results is provided in Appendix C.

#### **5.5 VALIDATION**

It has been stated that the focus of the modeling effort is toward the replication of a steady-state flow system under natural regional hydraulic gradients. However, in order to provide validation of the model under known hydrologic stresses, the following simulation was developed.

Because few water level data are available that represent pre-mining and pre-restoration, the strategy employed was to simulate conditions near the end of the restoration period to determine if the aquifer system could recover to current conditions (the calibration simulation). Hydrologic stresses imposed on the UISS aquifer from June 2000 through March 2002 were simulated with a transient model. Details of the model inputs are provided in Appendix C. From June 2000 through November 2001, only Mine Units 6 and 7 were undergoing active restoration. From November 2001 through March 2002 there was no significant pumping activity within or near the ISL mine. During this period, water levels in the aquifer were returning to the natural

steady-state conditions that existed prior to mining. A comparison between the final head distribution of the transient simulation and the calibration simulations indicates they are very similar (Figure 5-5). The simulated response of the aquifer is similar to the actual recovery observed from field data.

## 5.6 SOLUTE TRANSPORT SIMULATIONS

The calibrated flow model was then coupled with the MT3DMS code to simulate migration of the following site-derived constituents/parameters: selenium, manganese, uranium, radium-226 and Total Dissolved Solids (TDS). For each transport simulation, the initial conditions included a uniform concentration of the constituent distributed across the footprint of the ISL wellfield within the mineralized zone layer (see Section 4 for additional discussion). Consistent with direction stated in the November, 2001, Clarification Paper (discussed in Section 2), the initial concentrations represent average values within the wellfield (see Section 4 for additional discussion).

All other portions of the model domain (e.g., Layers 1 and 3 within the wellfield, and all areas outside the wellfield) are simulated as having an initial concentration equal to background. The initial values used to represent the Layer 2 wellfield and background concentrations are summarized below.

<b>Constituent/Parameter</b>	<b>Initial Concentration (Layer 2 inside wellfield)</b>	<b>Background Concentration (Layers 1 &amp; 3 inside wellfield; area outside wellfield)</b>
Selenium	0.04 mg/L	0.0026 mg/L
Manganese	0.18 mg/L	0.0106 mg/L
Radium-226	139.9 pCi/L	0.9026 pCi/L
Uranium	2.1 mg/L	0.0165 mg/L
Total Dissolved Solids	650 mg/L	379 mg/L

Wellfield concentrations were based on 34 monitoring wells sampled during restoration operations (e.g., 1993 on the north end of the wellfield; 2001 [Round 1 stabilization] in Mine Units 6 and 7). Background concentrations were based on the arithmetic average (mean) of pre-mining data from 29 wells collected between 1977 and 1987. Based on additional sampling conducted since 2001, the average stability values are lower than those used in the modeling, except for manganese, which was slightly higher. The average concentrations for Rounds 1-4 were as follows: Se – 0.03 mg/l; Mn – 0.23 mg/l; TDS – 630 mg/l; U – 1.99 mg/l; Ra-226 – 134 pCi/l. Additional discussion regarding background water quality previously was provided in Section 4.0.

Dispersion was included in the transport simulations. Dispersion refers to the spreading of contaminants over a greater area than would be predicted solely from the average groundwater velocity vectors. Dispersion is scale dependent. Literature sources

generally indicate that dispersivity is from one to two orders of magnitude less than the distance a plume has migrated (Gelhar 1992).

The focus of this model is to predict solute concentrations over time at a distance of 400 feet from the wellfield. Parallel to the direction of groundwater flow the wellfield is approximately 500 to 600 feet wide. When the tail end of the plume has passed through the downgradient observation point, the total migration distance will be approximately 1,000 feet. Using the one to two orders of magnitude rule-of-thumb would provide a longitudinal dispersivity value of between 10 and 100. In modeling, greater dispersion will result in faster arrival times, but lower peak concentrations. Because the results of the Irigaray model will be compared against regulatory standards, the more conservative approach is to simulate values of dispersivity that will result in greater concentration peaks. The baseline dispersivity value used to simulate solute transport is 25 feet, on the lower end of the range previously discussed. Other values are evaluated in the sensitivity analysis.

Sorption was implemented in some of the solute transport simulations. Sorption refers to the mass transfer between the constituent dissolved in groundwater and the constituent sorbed on the porous medium. Equilibrium conditions are generally assumed to exist between the aqueous phase and the solid phase concentrations and the sorption reactions are fast enough relative to groundwater velocity to be treated as instantaneous. A linear sorption isotherm assumes that the sorbed concentration ( $C_s$ ) is directly proportional to the dissolved concentration ( $C$ ):

$$C_s = K_d C$$

where  $K_d$  is the distribution coefficient (L/kg).

The equilibrium controlled linear sorption isotherm is incorporated into the MT3DMS code through the use of a retardation factor, defined as:

$$R = 1 + p_b K_d / \phi$$

where  $p_b$  = bulk density  
 $\phi$  = effective porosity

It should be emphasized that the use of a  $K_d$  was done with full conservation of mass within the aquifer system. No solute is irreversibly removed via sorption or precipitation from the modeled system. The use of a  $K_d$  only serves to slow the velocity of solutes for which it is used. In simulations where  $K_d$ s were incorporated into the model, a value at the lower end of the reported range was used, as listed below.

Constituent	Range of Values	Source	Model Value L/kg
Selenium <sup>1</sup>	7 – 22	Aleni, 1991 Fio, 1991	0.1
Manganese	Not applicable	Not applicable	0
Uranium	0.4 – 10	Carlos, 2001 Johnson, 1994 U.S. DOE, 1996 U.S. NRC, 1990	0.5
Radium-226	5 – 6,700 10	Moody, 1982 U.S. NRC, 1980	5
TDS <sup>2</sup>	Not applicable	Not applicable	0

1 – For Se (IV). Limited sampling of ground-water at Irigaray has shown that Se(IV) is the predominant species.

2 - No Kd assigned because this is a composite parameter made of major anions and cations, each with different chemical properties, including Kds. Conservatively assumed no sorption of any of the constituents that comprise TDS.

Unless stated otherwise, reported concentrations from the transport simulations are for Layer 2 (the mineralized zone). This is conservative, as it represents the layer with the highest initial concentrations. Because of dispersion, concentrations in Layers 1 and 3 will eventually increase, but will remain at levels equal to or below those in Layer 2.

As discussed previously, the concentrations outside the wellfield were assigned background values. As such, the transport results indicate total concentrations that will be present outside the wellfield.

### 5.6.1 Transport Simulation Results

A series of model observation points were placed around the north and west (downgradient) sides of the wellfield at an approximate distance of 400 feet. The locations of the model observation points are in many cases coincident with actual monitoring wells, and the 400-foot distance is consistent with monitoring locations required under Permit to Mine No. 478. However, for ease of discussion and presentation of results the model monitoring points are identified as OP1 through OP9 going from north to south (Figure 5-6).

Results of the solute transport model simulations indicate that projected constituent concentrations will not exceed regulatory standards over a period of 300 years at any of the observation points located 400 feet from the wellfield. Results of the simulations for each of the constituents of concern are described below.

#### 5.6.1.1 Selenium

The selenium transport simulation was run for a period of 300 years. The initial concentration distribution within and outside the wellfield (0.04 and 0.0026 mg/l,

respectively) is shown on Figure 5-7. A dispersivity of 25 ft and a distribution coefficient of 0.1 L/Kg were used for the baseline selenium transport simulation. The modeled distribution of selenium at 24 years indicates minimal migration outside the wellfield (Figure 5-8). At 100 years the plume has reached some of the observation points, although at concentrations well below the WDEQ Class-1 standard of 0.01 mg/L (Figure 5-9). The modeled selenium distribution at 300 years shows the maximum concentration within the plume is below the regulatory standard (Figure 5-10). Plots of selenium concentration vs. time for the observation points show first arrival and peak concentrations for the selenium transport simulation (Figure 5-11). The first arrival of the plume occurs at OP3 at approximately 40 years. The maximum concentration occurs at OP5 approximately 290 years into the simulation with a value of nearly 0.008 mg/L. Figure 5-12 illustrates the migration of the plume relative to the wellfield boundary and observation point OP3. Figure 5-13 illustrates the vertical distribution of selenium over time at the location of OP3. Note that the selenium concentration is relatively uniform throughout the entire modeled aquifer by the time the plume has migrated 400 feet from the wellfield. Based on the results of the transport simulation, using a conservative value for both  $K_d$  and dispersivity, selenium will remain below the WDEQ Class-1 standard at a distance of 400 feet downgradient of the Irigaray ISL wellfield.

#### **5.6.1.2 Manganese**

The manganese transport simulation was also run for a period of 300 years using input concentrations of 0.18 and 0.0106 mg/l within and outside the wellfield, respectively. A dispersivity of 25 ft and a distribution coefficient of 0 L/Kg (no sorption) were used for the manganese transport simulation. The modeled distribution of manganese at 100 years shows that the concentration of the entire plume is below the WDEQ standard of 0.05 mg/L (Figure 5-14). Plots of manganese concentration vs. time shows no exceedance of the WDEQ Class-1 standard at any of the observation points (Figure 5-15). The first arrival of the plume occurs at OP3 at approximately 20 years. The maximum concentration occurs at OP5 approximately 170 years into the simulation with a value of 0.034 mg/L.

#### **5.6.1.3 Uranium**

The uranium concentrations used to represent the initial conditions (2.1 and 0.0165 mg/l, respectively), are below the WDEQ Class-1 standard of 5 mg/L. A dispersivity of 25 ft and a distribution coefficient of 0.5 L/Kg were used for the uranium transport simulation. At 300 years, the maximum uranium concentration within the entire plume is at least an order of magnitude lower than the standard (Figure 5-16). Plots of uranium concentration vs. time for the observation points show first arrival and peak concentrations for the uranium transport simulation (Figure 5-17). The first arrival of the plume occurs at OP3 between 125 and 150 years. The maximum concentration within the simulation occurs at OP3 at approximately 300 years with a value of 0.24 mg/L.

#### **5.6.1.4 Radium-226**

Initial radium-226 concentrations assigned were 139.9 and 0.903 pCi/l within and outside the wellfield, respectively. A dispersivity of 25 ft and a distribution coefficient of 5 L/Kg were used for the radium-226 transport simulation. Although the  $K_d$  used for the radium-226 transport simulation is a conservative value, it is higher than the  $K_d$ s used for any of the other constituents/parameters (however, use of this value is supported in NRC documents). Consequently, the migration rate of the radium-226 plume is much slower than for the other constituents. The transport simulation for radium-226 was run for 1,000 years in order to determine first arrivals of the plume at the observation points (Figure 5-18). Plots of radium-226 concentration vs. time for the observation points show first arrivals for the radium-226 transport simulation (Figure 5-19). The first arrival of the plume occurs at OP3 between 400 and 500 years. At 1,000 years the maximum concentration for the observation points occurs at OP3 at less than 2.2 pCi/L, well below the WDEQ Class-1 standard of 5 pCi/L.

#### **5.6.1.5 TDS**

Initial TDS concentrations used in the model were 650 mg/l (inside Layer 2 in the wellfield) and 379 mg/l (all other model areas). As previously stated, TDS is a composite parameter, comprised of numerous cations and anions, each with different sorption coefficients. To project TDS values, it was conservatively assumed that no sorption of TDS would occur along the groundwater flowpath. The dispersivity used in the transport simulation was 25 feet. The modeled TDS distribution at 100 years indicates that the TDS plume has reached several of the observation points but at concentrations well below the WDEQ Class-1 standard of 500 mg/L (Figure 5-20). Plots of TDS concentration vs. time for the observation points show that TDS never exceeds 420 mg/L for the duration of the simulation (Figure 5-21), even though the initial background concentration outside the wellfield was 379 mg/l.

### **5.7 SENSITIVITY ANALYSES**

An analysis was performed to evaluate the sensitivity of specific model parameters on simulated concentrations at the model observation points. Because of the large number of simulations required to perform the sensitivity analysis on all key model parameters, the analysis was limited to a single constituent. A review of the baseline transport simulations previously conducted indicated that selenium came the closest to exceeding a specific regulatory standard. Therefore, selenium was selected as the constituent to evaluate with the sensitivity analysis. The sensitivity analyses were performed by changing a single parameter for each simulation. All other parameters were the same as those used in the baseline selenium transport simulation. The following model parameters were included in the analysis.

- Hydraulic Conductivity/ Hydraulic Gradient
- Horizontal to Vertical Hydraulic Conductivity Ratio

- Porosity
- Mineralized Zone Thickness
- Dispersivity
- Distribution Coefficient

### **5.7.1 Hydraulic Conductivity/Hydraulic Gradient**

For the baseline simulation, the hydraulic conductivity values of the mineralized zone (Layer 2), and non-mineralized zones (Layers 1 and 3) were assigned as 0.5 ft/d, and 1.0 ft/d, respectively. For the sensitivity analysis, the hydraulic conductivity of Layer 2 was simulated as 0.25 ft/d and 1.0 ft/d. An additional simulation was run where the hydraulic conductivity of the mineralized and non-mineralized zones were switched (Layer 2 was 1.0 ft/d and Layers 1 and 3 were 0.5 ft/d). The results of the simulations for observation point OP3 are shown in Figure 5-22. The concentration vs. time plots indicate that the hydraulic conductivity strongly effects the initial arrival of the site-derived constituent at the observation point but has minimal impact on the peak concentration. The results are consistent with the groundwater flow equation in that hydraulic conductivity is directly proportional to groundwater velocity. Note that for all simulations, the maximum concentration remains below the WDEQ Class-1 standard for selenium.

As with hydraulic conductivity, hydraulic gradient is directly proportional to groundwater velocity. Therefore, the model response to increases or decreases in hydraulic gradient (with respect to groundwater velocity and solute transport) will be similar to the response to changes in hydraulic conductivity. However, significantly changing the hydraulic gradient in the model will result in (1) a poor match to the observed water levels used as calibration targets and (2) a groundwater flow system that is not consistent with available data. Therefore, a sensitivity analysis was not directly performed for this parameter. In the case of hydraulic conductivity, increasing the parameter by a factor of two resulted in an increase in the maximum concentration by approximately 5 percent. The response of the model to a similar change in hydraulic gradient would be of the same magnitude, although it is unlikely the hydraulic gradient would vary to that degree under steady-state, non-pumping conditions.

### **5.7.2 Horizontal to Vertical Hydraulic Conductivity Ratio**

The baseline simulation utilized a horizontal to vertical hydraulic conductivity ratio ( $K_h/K_v$ ) of 10. The sensitivity analysis included simulations with the  $K_h/K_v$  of 5, 7.5, 20 and 30. The horizontal hydraulic conductivity was 0.5 ft/d for each of the simulations but the vertical hydraulic conductivity was modified to achieve the desired  $K_h/K_v$ . Results of the simulations indicate no impacts to either arrival times or peak concentrations as shown in the plot for observation point OP3 (Figure 5-23). The lack of sensitivity to this parameter is because the model is constructed to simulate steady-state horizontal flow without vertical gradients. Vertical movement of the solute is controlled predominately by the dispersion term, which is also included in the sensitivity analysis.

### **5.7.3 Porosity**

The porosity values used in the baseline simulation were 0.25 for Layer 2 and 0.29 for Layers 1 and 3. Simulations were run with a Layer 2 porosity of 0.20 and 0.30. Results of the simulations indicate that as the porosity increases, the peak concentration rises as shown in the concentration vs. time plots of observation point OP3 (Figure 5-24). The arrival of the peak concentration is also delayed as the porosity is increased. Both of these occurrences are expected. Increasing the porosity decreases the groundwater velocity and increases the total initial dissolved mass of contaminant in the model. For the simulation with porosity of 0.30, the maximum selenium concentration increases by less than 10 percent over the baseline simulation and is still less than the regulatory standard.

### **5.7.4 Mineralized Zone Thickness**

To account for flare (historically less than 10 percent), for the baseline simulations, the mineralized zone thickness was 21 feet. The average mineralized zone thickness was actually lower at 18 feet (see Section 3 for additional information). Using the higher value is a conservative assumption because it provides for a greater initial contaminant load in the model. The sensitivity analysis for the mineralized zone thickness substantiates this conservatism. Simulations were run using a mineralized zone thickness of 15 feet, 18 feet, 24 feet and 27 feet. As shown in the concentration vs. time plots for the observation point OP3, the maximum selenium concentration increases as the mineralized zone thickness is increased (Figure 5-25). However, the WDEQ Class-1 standard for selenium of 0.01 mg/L is not exceeded during any of the simulations.

### **5.7.5 Dispersivity**

The baseline simulation was run with a dispersivity of 25 feet. Additional simulations performed for the sensitivity analysis included values of 10, 20, 30 and 50 feet. Results of the sensitivity analyses are shown in the concentration vs. time plots for the observation point OP3 (Figure 5-26). As dispersivity increases, the maximum concentration in the mineralized zone decreases. This reflects the increased dispersion of solute into the sand units above and below the mineralized zone as the plume moves away from the wellfield. For the dispersivity simulation of 10 feet, the maximum concentration at OP3 approaches the WDEQ Class-1 standard of 0.01 mg/L. However, this value represents the concentration only within the mineralized zone. The mineralized zone is one fifth of the total thickness of the modeled aquifer. Plots of the average weighted concentration of the entire modeled aquifer for the dispersivity simulations of 10, 25 and 50 feet show much lower sensitivity to this parameter (Figure 5-27).

### **5.7.6 Distribution Coefficient**

A  $K_d$  of 0.1 was used for the baseline selenium transport simulations.  $K_d$  values of 0 (no sorption), 0.05, 0.2 and 0.5 L/kg were evaluated in the sensitivity analysis. The concentration vs. time plots of selenium at observation point OP3 indicate that the value of  $K_d$  has minimal impact on the peak concentrations but strongly effects the migration rate of the plume (Figure 5-28). Increasing the  $K_d$  effectively "retards" solute transport. However, because advective dispersion is the primary transport mechanism, and mass is conserved (e.g., no geochemical sorption or irreversible precipitation occurs), peak concentrations are not significantly affected.

### **5.8 MODELING SUMMARY/CONCLUSIONS**

A numerical groundwater flow and solute transport model was developed to evaluate future migration of selected groundwater constituents at the Irigaray ISL uranium mine. The model is designed to represent post-restoration, steady-state conditions of groundwater flow within the UISS aquifer of the Wasatch Formation. The modeling effort focused on advective and dispersive flow components, minimizing the reliance on geochemical processes for attenuation. The model was constructed with 3 layers, corresponding to the mineralized zone and the overlying and underlying sand units of the UISS. All layers were simulated as distinct units. Vertical flow was permitted between layers, but the upper and lower boundaries were simulated as not flow boundaries. Thus, the UISS unit (Layers 1-3) was treated as a confined aquifer. The model simulations were run for a minimum period of 300 years. As discussed in Section 5.6, the concentrations outside the wellfield were assigned background values. As such, the transport results indicate the total concentrations that will result from migration of constituents from the wellfield.

Results of the modeling indicate that residual concentrations of selenium, manganese, uranium, radium-226 and TDS will be below WDEQ Class-1 regulatory limits at the observation points 400 feet from the wellfield (Table 5-3). Concentrations of those constituents would be even lower at the permit boundary where Class-1 standards would apply. Sensitivity analyses performed on model parameters determined that hydraulic conductivity and distribution coefficient strongly impacted the rate of transport but had minimal impact on peak concentrations. Dispersivity had the greatest impact on constituent concentrations within the mineralized zone. However, the weighted average constituent concentration within the UISS (all three model layers) was similar for simulations over a range of dispersivities.

## 6.0 SUMMARY AND CONCLUSIONS

### 6.1 Summary

During the period from 1990 to 2002, COGEMA expended significant effort to restore the groundwater quality within the Irigaray wellfield. Restoration efforts have significantly improved water quality for all indicator parameters. At the completion of the Irigaray groundwater restoration program, the ore zone aquifer has been restored to standards consistent with BPT and the ALARA principle. In this regard, over 840 million gallons of water were processed over an 11.5-year period, with a minimum of 9.5 pore volumes displaced (PVD) and treated in each wellfield. On average for the entire wellfield, 13.7 PVDs were treated.

Significant beneficial results were realized through the application of BPT. Based on the restoration standards in Permit to Mine No. 478, as amended, COGEMA has achieved targeted post-restoration water quality for 27 of 29 constituents with defined restoration target values (RTVs). Of the two constituents that did not meet the RTVs, (bicarbonate and manganese), bicarbonate does not have defined EPA or WDEQ Class-1 use standards. The slight increase of this constituent over baseline will not impact any future use of the aquifer. The only other constituent exceeding its RTV is manganese. Manganese has only a secondary standard based on aesthetics and the restored concentration is not expected to impact any future use of the groundwater.

Stability monitoring has been completed and the stability results demonstrate the validity of the data with regard to long-term trends. Out of the total of 35 constituents analyzed, only three had concentrations that increased during the stability monitoring period (sodium, conductivity and manganese). Of these, manganese is the only constituent that has a WDEQ Class 1 standard (EPA-based on aesthetics). Concentrations of manganese increased during stability monitoring, while concentrations of other more important key constituents (U, Se, and Ra-226, all which have Class-1 WDEQ standards) decreased. These variations are expected in a reducing environment, and suggest that the overall impacts to the aquifer will continue to decrease over time and distance from the wellfield. The remaining constituents (sodium and conductivity) have no WDEQ Class-1 primary standards or EPA standards. Concentrations of all other constituents have either stayed the same, or decreased, during the stability monitoring period.

The potential impact of manganese concentrations, as well as concentrations of selenium, uranium, and radium-226 that potentially could exceed regulatory standards at isolated locations downgradient of the wellfield (but within the permit area) have been fully evaluated through fate and transport modeling. To address uncertainty with regard to hydrogeologic parameters, numerous sensitivity transport analyses were conducted.

The transport model assumed complete conservation of mass. Based on reducing conditions indicated by field parameters (redox potential of -50 to -150 mv), it is apparent that significant geochemical alteration/mass removal will likely occur,

especially with regard to selenium, uranium, and radium-226. This is consistent with the low historical concentrations of these constituents observed in the monitoring wells downgradient of the wellfield. As such, the modeling results as presented, are very conservative.

## **6.2 Conclusions**

The results of the final water quality during stability monitoring demonstrate that the Irigaray wellfield has been successfully restored using best practicable technology. Although all constituents were not restored to background concentrations, or to Class I standards in the case of manganese, the groundwater was clearly returned to a quality of use that is equal to or better than, and consistent with the uses for which the water was suitable prior to the operation (Class IV or V). Further restoration at this site is not deemed justifiable in terms of the technical practicability or economic reasonableness of reducing the chemical concentrations any further. Current conditions are likely to result in continued concentration decreases for primary constituents of concern.

The modeling results clearly demonstrate that remaining concentrations at distances of 400 feet downgradient from the wellfield are below WDEQ regulatory standards for all the constituents. Further, it is noted that in the downgradient direction, the permit boundary (where Class-1 standards would apply) is 1,400 to 2,600 feet from the wellfield. In this regard, the residual constituent concentrations are not expected to have any impact at the permit (aquifer exemption) boundary. Based on the restoration work conducted and discussed herein, COGEMA considers that restoration consistent with Permit No. 478 has been completed, and requests that restoration approval be granted.

Table 4-1 Target Restoration Values

PARAMETER (mg/l)	BASELINE RANGE <sup>a</sup> (Table 6.1, Permit 478)	WYOMING GROUNDWATER CLASS STANDARDS <sup>b</sup>		TARGET RESTORATION VALUES <sup>c</sup>
		DOMESTIC	LIVESTOCK	
Ammonia (NH <sub>4</sub> as N)	<0.5	0.5 (as NH <sub>3</sub> )		50
Arsenic (As)	<0.01 - 0.105	0.05	0.2	Baseline
Barium (Ba)	<0.01 - 0.08	1		Baseline
Bicarbonate (HCO <sub>3</sub> )	14.2 - 133.6			295
Boron (B)	<0.01 - 0.225	0.75	5	Baseline
Cadmium (Cd)	<0.002 - 0.006	0.01	0.05	Baseline
Calcium (Ca)	1.6 - 27.1			Baseline
Chloride (Cl)	7.8 - 15.1	250	2000	56
Chromium (Cr)	<0.002 - 0.024	0.05	0.05	Baseline
Copper (Cu)	<0.005 - 0.051	1	0.5	Baseline
Fluoride (F)	0.2 - 0.68	1.4 - 2.4		Baseline
Iron (Fe)	0.02 - 6.88	0.3		Baseline
Lead (Pb)	<0.002 - 0.014	0.05	0.1	Baseline
Magnesium (Mg)	<0.1 - 7.1			Baseline
Manganese (Mn)	<0.005 - 0.058	0.05		Baseline
Mercury (Hg)	<0.0002	0.002	0.00005	Baseline
Molybdenum (Mo)	<0.02 - 0.05			Baseline
Nickel (Ni)	<0.2			Baseline
Nitrate (NO <sub>2</sub> +NO <sub>3</sub> )	0.2 - 1.0	10		Baseline
Potassium (K)	1.4 - 5.3			Baseline
Selenium (Se)	<0.01 - 0.322	0.01	0.05	Baseline
Sodium (Na)	99.7 - 164.0			Baseline
Sulfate (SO <sub>4</sub> )	140 - 300	250	3000	Baseline
Total Dissolved Solids (TDS)	271 - 555	500	5000	Baseline
Uranium (U)	0.01 - 18.6	5	5	2.09 <sup>d</sup>
Vanadium (V)	<0.05 - 0.55		0.1	Baseline
Zinc (Zn)	<0.02 - 0.17	5	25	Baseline
pH (units)	8.0 - 10.4	6.5 - 9.0	6.5 - 8.5	Baseline
Radium-226 (Ra-226) (pCi/l)	2.5 - 210	5	5	Baseline

<sup>a</sup> Ranges were compiled using average baseline data from production zone wells located in Production Units 1 through 6 and E-Field. (Average baseline = average results from three baseline samples per well). The wells are: AP-3, AP-4, AP-10, DI-4, DI-12, DI-21, DI-27, EI-15, EI-16, EI-17, EI-18, EI-34, EI-54, EI-68, FI-60, FI-62, FI-64, FI-66, FI-67, GI-76, GI-82, GI-105, HI-57, HI-62, HP-59, HP-87 and GI-122. It was noted that baseline ranges may change as mining progresses. This table is taken from Table 6.1 out of Permit to Mine No. 478, A-2, January 5, 1996 (Update Document).

<sup>b</sup> Taken from Wyoming Department of Environmental Quality, Water Quality Rules and Regulations, Chapter VIII, Table 1; April 9, 1980.

<sup>c</sup> Taken from the original Table R1-1 and Table 6.1 (Permit to Mine 478, A-2). The target restoration value for NH<sub>4</sub> applies only to Units 1 through 5 where ammonium bicarbonate lixiviant was used. Target values for bicarbonate, chloride and uranium are based upon the final 360-day E Field stabilization values (mean plus 2 standard deviations).

<sup>d</sup> It is noted in Table 6.1 (Permit to Mine 478, A-2) that the target value for uranium may have to be adjusted as necessary as restoration proceeds, however in no case should the value be greater than 5 mg/l (Class of Use). This is assuming that the Class of Use for the ore zone is Class I Domestic, which is not the case.

Table 4-2 Comparison of Baseline Ranges, Units 1-9 and Units 1-6

	UNITS 1-9			UNITS 1-6*			Do Maximums Agree?
	NUMBER OF SAMPLES	BASELINE MINIMUM	BASELINE MAXIMUM	NUMBER OF SAMPLES	BASELINE MINIMUM	BASELINE MAXIMUM	
<b>Major Ions mg/l:</b>							
Ca	200	1.6	33.6	81	1.6	27.1	No
Mg	200	0.02	9.0	81	< 0.1	7.1	No
Na	200	95	280	81	99.7	164	No
K	200	0.4	17.5	81	1.4	5.3	No
CO3	200	0	96.0				
HCO3	200	5	144	81	14.2	133.6	No
SO4	200	136	624	81	140	300	No
Cl	199	5.3	15.1	81	7.8	15.1	YES
NH4	200	< 0.05	1.88	81		< 0.5	No
NO2 (N)	188	< 0.01	1.0				
NO3 (N)	65	< 0.2	1.0	81	0.20	1.00	YES
F	197	0.11	0.68	81	0.20	0.68	YES
SiO2	197	3.2	17.2				
TDS	200	308	1054	81	271	555	No
Cond. (umho/cm)	200	490	1465				
Alk. (as CaCO3)	200	30.9	232				
pH (units)	200	6.6	11.0	81	8	10.4	No
<b>Trace Metals mg/l:</b>							
Al	115	< 0.05	4.25				
As	197	< 0.001	0.105	81	< 0.01	0.105	YES
Ba	167	< 0.01	0.12	81	< 0.01	0.08	No
B	167	< 0.01	0.225	81	< 0.01	0.225	YES
Cd	167	< 0.002	0.013	81	< 0.002	0.006	No
Cr	167	< 0.002	0.063	81	< 0.002	0.024	No
Cu	167	< 0.002	0.04	81	< 0.005	0.051	No
Fe	197	0.02	11.8	81	0.02	6.88	No
Pb	167	< 0.002	< 0.05	81	< 0.002	0.014	No
Mn	167	< 0.005	0.19	81	< 0.005	0.058	No
Hg	167	< 0.0002	< 0.001	81		< 0.0002	YES
Mo	167	< 0.02	< 0.10	81	< 0.02	0.05	YES
Ni	167	< 0.01	< 0.20	81		< 0.2	YES
Se	193	< 0.001	0.416	81	< 0.01	0.322	No
V	167	< 0.05	0.55	81	< 0.05	0.55	YES
Zn	167	< 0.01	0.20	81	< 0.02	0.17	No
<b>Radiometric pCi/l:</b>							
U (mg/l)	197	< 0.0003	18.6	81	0.01	18.6	YES
Ra 226	194	0	247.7	81	2.5	210	No

\*Units 1-6 data are taken from Table 6.1 of Permit to Mine No. 478

Notes: 1 - Units 1-9 data does not include E-field baseline wells, Units 1-6 does.

2 - Units 1-9 data includes AP-5 and DP-7, wells not included with Units 1-6.

3 - Units 1-9 data includes JP-15 and other Units 7-9 baseline wells, not included in Table 6.1.

4 - Units 1-9 data compiled from all 46 baseline wells contained in Appendix 1 of this report.

Table 4-3 Total Volumes Processed and Key Operational Dates

**Irigaray Mine Restoration Groundwater Recovery Volumes**

AREA	GWS		RO		RECIRCULATION		TOTAL	
	KGAL	PV	KGAL	PV	KGAL	PV	KGAL	PV
PU 1-3	49,012	4.2	154,611	13.2	12,595	1.1	216,218	18.4
PU 4-5	34,407	3.4	97,470	9.5	10,490	1.0	142,367	13.9
PU 6	18,467	1.4	95,461	7.1	13,066	1.0	126,994	9.5
PU 7	21,387	1.6	154,729	11.7	13,256	1.0	189,372	14.3
PU 8	6,296	1.4	44,825	10.2	3,731	0.9	54,852	12.5
PU 9	14,333	1.7	91,375	10.7	4,664	0.5	110,372	13.0
Total	143,902		638,471		57,803		840,175	
Average		2.3		10.4		0.9		13.7

**Irigaray Mine Phase History**

AREA	PROD START	PROD END	GWS START	GWS END	RO START	RO END	RECIRC END	STAB END
PU 1-3	01-Oct-78	12-Jun-89	30-May-90	28-Apr-91	29-Apr-91	22-Oct-92	30-Nov-92	02-Sep-93
PU 4-5	01-Nov-79	12-Jun-89	10-Jun-91	03-Oct-95	04-Oct-95	16-Aug-98	29-Sep-98	16-Jul-99
PU 6	09-Jun-88	28-Nov-94	01-Jan-96	20-Aug-98	20-Jul-00	11-Oct-01	15-Nov-01	13-Aug-02
PU 7	01-Jan-88	28-Nov-94	15-Apr-95	27-Sep-97	11-Feb-00	12-Jul-01	30-Aug-01	05-Jun-02
PU 8	29-Feb-88	28-Nov-94	15-Apr-95	19-Sep-97	01-Mar-99	29-Jun-00	31-Aug-00	06-Jun-01
PU 9	22-Mar-88	28-Nov-94	15-Apr-95	20-Sep-97	18-Nov-98	26-Apr-00	25-May-00	25-Jan-01

Table 4-4 Irigaray Mine Monitor Wells

**PERIMETER ORE ZONE**

Well No.	Location	Well No.	Location
M2	Unit 2	M27	Unit 7
M4	Unit 2	M28	Unit 8
M7	Unit 1	M29	Unit 8
M10	Unit 4	M30	Unit 9
M17	Unit 1	M31	Unit 9
M18	Unit 1	M32	Unit 9
M19	Unit 3	M33	Unit 9
M23	Unit 5	T31	Unit 1
M24	Unit 6	RS27	Unit 5
M25	Unit 6	16-151	Unit 9
M26	Unit 7		

**SHALLOW SAND**

Well No.	Location	Well No.	Location
SSM2	Unit 1	SSM19	Unit 8
SSM3	Unit 2	SSM34	Unit 9
SSM4	Unit 2	SSM35	Unit 9
SSM5	Unit 3	SSM36	Unit 9
SSM6	Unit 4	SSM37	Unit 7
SSM7	Unit 5	SSM38	Unit 7
SSM8	Unit 5	SSM39	Unit 7
SSM9	Unit 6	SSM40	Unit 8
SSM10	Unit 6	SSM41	Unit 4
SSM11	Unit 6	SSM42	Unit 3
SSM18	Unit 8	SSM43	Unit 1

**DEEP SAND**

Well No.	Location	Well No.	Location
DM1	Unit 1	DM14	Unit 8
DM2	Unit 1	DM15	Unit 9
DM3	Unit 2	DM16	Unit 9
DM4	Unit 4	DM17	Unit 5
DM5	Unit 2	DM18	Unit 4
DM9	Unit 5	DM19	Unit 3
DM10	Unit 6	DM20	Unit 3
DM11	Unit 7	DM21	Unit 7
DM13	Unit 8	DM22	Unit 6

Table 4-5 Historic Water Level Data

WELL No. M10	
Date	Piezometric Elevation (ft - msl)
Baseline (estimate)	4,300.0
Jun-79	4,258.2
Jun-80	4,284.7
Jun-81	4,282.3
Jun-82	4,288.5
Jun-83	4,293.8
Jun-84	4,295.2
Jun-85	4,292.0
Jun-86	4,302.4
Jun-87	4,301.6
Jun-88	4,269.2
Jun-89	4,278.3
Jun-90	4,266.7
Jun-91	4,211.6
Jun-92	4,202.0
Jun-93	4,238.1
Jun-94	4,281.0
Jun-95	4,241.0
Jun-96	4,247.0
Jun-97	4,259.0
Jun-98	4,258.6
Jun-99	4,278.1
May-00	4,259.2
May-01	4,266.3
May-02	4,292.1
Jun-03	4,295.9
Dec-03	4,301.9
Minimum	4,202.0
Maximum	4,302.4
Difference	100.40

WELL No. M17	
Date	Piezometric Elevation (ft - msl)
Baseline (estimate)	4,300.0
Jun-79	4,279.0
Jun-80	4,291.6
Jun-81	4,291.4
Jun-82	4,287.1
Jun-83	4,298.2
Jun-84	4,300.2
Jun-85	4,297.9
Jun-86	4,304.3
Jun-87	4,303.5
Jun-88	4,284.4
Jun-89	4,285.9
Jun-90	4,281.6
Jun-91	4,242.8
Jun-92	4,220.8
Jun-93	4,260.7
Jun-94	4,287.6
Jun-95	4,266.8
Jun-96	4,258.8
Jun-97	4,271.4
Jun-98	4,266.1
May-99	4,276.3
May-00	4,267.2
May-01	4,276.3
May-02	4,297.6
Jun-03	4,304.1
Dec-03	4,305.0
Minimum	4,220.8
Maximum	4,305.0
Difference	84.20

WELL No. M18	
Date	Piezometric Elevation (ft - msl)
Baseline (estimate)	4,300.0
Jun-79	4,285.1
Jun-80	4,300.3
Jun-81	4,296.3
Jun-82	4,297.0
Jun-83	4,307.0
Jun-84	4,306.0
Jun-85	4,304.0
Jun-86	4,306.0
Jun-87	4,306.0
Jun-88	4,289.0
Jun-89	4,290.9
Jun-90	4,286.2
Jun-91	4,245.8
Jun-92	4,224.1
Jun-93	4,267.4
Jun-94	4,293.4
Jun-95	4,266.3
Jun-96	4,264.8
Jun-97	4,280.6
Jun-98	4,277.8
May-99	4,284.2
May-00	4,276.7
May-01	4,278.5
May-02	4,303.2
Jun-03	4,309.8
Dec-03	4,309.8
Minimum	4,224.1
Maximum	4,309.8
Difference	85.70

WELL No. M19	
Date	Piezometric Elevation (ft - msl)
Baseline (estimate)	4,300.0
Jun-79	4,279.2
Jun-80	4,297.1
Jun-81	4,293.6
Jun-82	4,300.0
Jun-83	4,307.0
Jun-84	4,306.0
Jun-85	4,304.0
Jun-86	4,306.0
Jun-87	4,306.0
Jun-88	4,281.8
Jun-89	4,286.1
Jun-90	4,285.2
Jun-91	4,236.8
Jun-92	4,218.3
Jun-93	4,257.6
Jun-94	4,290.3
Jun-95	4,247.1
Jun-96	4,257.0
Jun-97	4,276.8
Jun-98	4,269.4
Jun-99	4,279.9
May-00	4,272.0
May-01	4,271.1
May-02	4,303.7
Jun-03	4,311.0
Dec-03	4,311.5
Minimum	4,218.3
Maximum	4,311.5
Difference	93.20

Table 4-5 Historic Water Level Data

WELL No. M26	
Date	Piezometric Elevation (ft - msl)
Baseline: '79-'87	4,301.8
Nov-87	4,300.5
Jun-88	4,284.0
Jun-89	4,292.2
Jun-90	4,294.4
Jun-91	4,248.8
Jun-92	4,239.8
Jun-93	4,263.3
Jun-94	4,273.6
Jun-95	4,198.4
Jun-96	4,237.4
Jun-97	4,292.0
Jun-98	4,275.5
Jun-99	4,263.0
Jun-00	4,247.5
May-01	4,260.7
May-02	4,305.3
Jun-03	4,313.0
Dec-03	4,313.3
Minimum	4,198.4
Maximum	4,313.3
Difference	114.90

WELL No. M27	
Date	Piezometric Elevation (ft - msl)
Baseline: '79-'87	4,302.3
Nov-87	4,292.3
Jun-88	4,284.3
Jun-89	4,284.7
Jun-90	4,286.8
Jun-91	4,236.7
Jun-92	4,226.5
Jun-93	4,250.6
Jun-94	4,260.2
Jun-95	4,200.5
Jun-96	4,222.3
Jun-97	4,263.7
Jun-98	4,267.9
Jun-99	4,251.7
Jun-00	4,239.3
May-01	4,247.8
Jun-02	4,301.9
Jun-03	4,309.6
Dec-03	4,310.4
Minimum	4,200.5
Maximum	4,310.4
Difference	109.90

WELL No. M32	
Date	Piezometric Elevation (ft - msl)
Baseline: '79-'87	4,319.7
Mar-88	4,307.8
Jun-88	4,321.1
Jun-89	4,302.9
Jun-90	4,314.9
Jun-91	4,284.3
Jun-92	4,271.9
Jun-93	4,287.9
Jun-94	4,307.1
Jun-95	4,247.1
Jun-96	4,257.4
Jun-97	4,289.8
Jun-98	4,297.0
Jun-99	4,271.8
Jun-00	4,274.2
May-01	4,283.9
May-02	4,314.5
Jun-03	4,323.3
Dec-03	4,324.1
Minimum	4,247.1
Maximum	4,324.1
Difference	77.00

WELL No. M33	
Date	Piezometric Elevation (ft - msl)
Baseline: '79-'87	4,311.8
Mar-88	4,309.9
Jun-88	4,312.3
Jun-89	4,298.9
Jun-90	4,306.0
Jun-91	4,271.6
Jun-92	4,258.6
Jun-93	4,274.3
Jun-94	4,287.6
Jun-95	4,222.1
Jun-96	4,238.8
Jun-97	4,273.8
Jun-98	4,286.2
Jun-99	4,247.2
Jun-00	4,253.1
May-01	4,267.0
May-02	4,308.1
Jun-03	4,317.5
Dec-03	4,317.8
Minimum	4,222.1
Maximum	4,317.8
Difference	95.70

Table 4-6 Restoration Water Quality Results

	Unit 1-9 Baseline Range		Post-Mining Mean	Restoration Post-GWS Mean	Post-RO Mean	Round - 1 Stability Mean	Round - 2 Stability Mean	Round - 3 Stability Mean	Round - 4 Stability Mean	Round 1-4 Stability Mean
	Minimum n=65-200	Maximum n=65-200								
Sample Population	n=65-200	n=65-200	n = 32	n = 32	n = 35	n = 33	n = 31	n = 33	n = 33	n = 130
<b>Major Ions mg/l:</b>										
Ca	1.6	33.6	199.2	124.9	23.1	29.0	28.2	29.5	28.8	28.9
Mg	0.02	9.0	45.7	31.3	5.5	7.0	7.3	7.0	7.0	7.1
Na	95	280	627	450.9	151.2	186.7	188.2	191.7	185.6	188.1
K	0.4	17.5	9	6.9	2.6	2.9	2.7	3.3	2.9	2.9
CO <sub>3</sub>	0	96.0	2	1.6	0.8	0.9	0.7	0.9	0.8	0.8
HCO <sub>3</sub>	5	144	1343	1036.1	359.0	424.7	431.5	427.7	409.0	423.1
SO <sub>4</sub>	136	624	639	409.6	103.0	133.9	135.4	133.4	132.0	133.6
Cl	5.3	15.1	277	175.2	32.3	43.3	43.1	43.1	39.4	42.2
NH <sub>4</sub>	< 0.05	1.88	23	14.9	5.8	10.0	8.3	8.0	8.5	8.7
NO <sub>2</sub> (N)	< 0.1	1.0	1	0.9	0.2	0.1	0.1	0.1	0.1	0.1
NO <sub>3</sub> (N)	< 0.2	1.0	2	1.0	0.3	0.1	0.1	0.1	0.1	0.1
F	0.11	0.68	1	0.8	0.1	0.1	0.1	0.2	0.1	0.1
SiO <sub>2</sub>	3.2	17.2	12	7.3	4.8	5.4	5.0	5.0	5.0	5.1
TDS	308	1054	2451	1771.8	517.7	642.6	636.5	620.7	625.9	631.3
Cond. (umho/cm)	490	1465	3795	2733.5	876.0	1066.0	1082.1	1080.0	1093.8	1080.5
Alk. (as CaCO <sub>3</sub> )	30.9	232	1101	836.0	295.1	351.0	354.0	351.0	344.5	350.1
pH (units)	6.6	11.0	7.1	7.4	8.0	7.88	7.90	7.87	7.76	7.85
<b>Trace Metals mg/l:</b>										
Al	< 0.05	4.25	1.037	1.041	0.100	0.100	0.100	0.100	0.102	0.101
As	< 0.001	0.105	0.641	0.255	0.003	0.004	0.005	0.005	0.005	0.004
Ba	< 0.01	0.12	1.067	0.824	0.094	0.092	0.091	0.088	0.095	0.091
B	< 0.01	0.225	0.442	0.939	0.089	0.090	0.088	0.088	0.088	0.088
Cd	< 0.002	0.013	0.979	0.975	0.004	0.004	0.004	0.004	0.004	0.004
Cr	< 0.002	0.063	1.018	0.919	0.040	0.039	0.038	0.039	0.039	0.039
Cu	< 0.002	0.04	0.828	0.829	0.010	0.010	0.010	0.011	0.010	0.010
Fe	0.02	11.80	1.098	1.686	0.058	0.118	0.107	0.072	0.113	0.102
Pb	< 0.002	0.050	1.018	1.009	0.039	0.038	0.037	0.038	0.039	0.038
Mn	< 0.005	0.190	1.249	0.622	0.113	0.177	0.227	0.287	0.215	0.226
Hg	< 0.0002	0.001	0.971	0.971	0.001	0.001	0.001	0.001	0.001	0.001
Mo	< 0.02	0.1	1.067	1.056	0.086	0.086	0.085	0.085	0.069	0.081
Ni	< 0.01	0.2	1.018	1.018	0.050	0.050	0.050	0.050	0.050	0.050
Se	< 0.001	0.416	0.247	0.173	0.065	0.039	0.026	0.028	0.019	0.028
V	< 0.05	0.55	1.067	1.058	0.089	0.088	0.087	0.088	0.088	0.088
Zn	< 0.01	0.200	0.065	0.949	0.016	0.011	0.010	0.010	0.010	0.010
<b>Radiometric pCi/l:</b>										
U (mg/l)	< 0.0003	18.6	7.411	6.235	1.561	2.169	1.952	1.968	1.826	1.979
Ra 226	0	247.7	200.5	225.1	63.4	142.5	99.3	127.5	130.7	125.4
Ra 226+/-			4.9	5.1	2.4	4.1	3.3	3.9	4.4	3.9

\*Notes:

1 - One PV of Recirculation was conducted between the RO Phase and the first round of Stabilization sampling.

2 - Wells used to establish Unit 1-9 baseline are provided in Appendix 1.

Table 4-7 Restoration Results Compared with Target Restoration Values, Units 1-9

	Round 1 Stability Mean	Round 2 Stability Mean	Round 3 Stability Mean	Round 4 Stability Mean	Rounds 1-4 Stability Mean*	Target Restoration Value	Baseline Range PU-1-9		Rounds 1-4 Stability Mean Within Target Value?
							Minimum	Maximum	
<b>Major Ions mg/l:</b>									
Ca	29.0	28.2	29.5	28.8	28.9	BL Range	1.6	33.6	Yes
Mg	7.0	7.3	7.0	7.0	7.1	BL Range	0.02	9.0	Yes
Na	186.7	188.2	191.7	185.6	188.1	BL Range	95	280	Yes
K	2.9	2.7	3.3	2.9	2.9	BL Range	0.4	17.5	Yes
CO <sub>3</sub>	< 0.9	< 0.7	< 0.9	< 0.8	< 0.8		0	96	
HCO <sub>3</sub>	424.7	431.5	427.7	409.0	423.1	295	5	144	No
SO <sub>4</sub>	133.9	135.4	133.4	132.0	133.6	BL Range	136	624	Yes
Cl	43.3	43.1	43.1	39.4	42.2	56	5.3	15.1	Yes
NH <sub>4</sub>	10.0	8.3	8.0	8.5	8.7	50	<0.05	1.88	Yes
NO <sub>2</sub> + NO <sub>3</sub> (N)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	BL Range	<0.01	1.0	Yes
NO <sub>3</sub> (N)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1		<0.01	1.0	
F	< 0.1	< 0.1	< 0.2	< 0.1	< 0.1	BL Range	0.11	0.68	Yes
SiO <sub>2</sub>	5.4	5.0	5.0	5.0	5.1		3.2	17.2	
TDS	642.6	636.5	620.7	625.9	631.3	BL Range	308	1054	Yes
Cond. (umho/cm)	1066.0	1082.1	1080.0	1093.8	1080.5		490	1465	
Alk. (as CaCO <sub>3</sub> )	351.0	354.0	351.0	344.5	350.1		30.9	232	
pH (units)	7.88	7.90	7.87	7.76	7.85	BL Range	6.6	11.0	Yes
<b>Trace Metals mg/l:</b>									
Al	< 0.100	< 0.100	< 0.100	< 0.102	< 0.101		<0.05	4.25	
As	< 0.004	< 0.005	< 0.005	< 0.005	< 0.004	BL Range	<0.001	0.105	Yes
Ba	< 0.092	< 0.091	< 0.088	< 0.095	< 0.091	BL Range	<0.01	0.12	Yes
B	< 0.090	< 0.088	< 0.088	< 0.088	< 0.088	BL Range	<0.01	0.225	Yes
Cd	< 0.004	< 0.004	< 0.004	< 0.004	< 0.004	BL Range	<0.002	0.013	Yes
Cr	< 0.039	< 0.038	< 0.039	< 0.039	< 0.039	BL Range	<0.002	0.063	Yes
Cu	< 0.010	< 0.010	< 0.011	< 0.010	< 0.010	BL Range	<0.002	0.04	Yes
Fe	< 0.118	< 0.107	< 0.072	< 0.113	< 0.102	BL Range	0.02	11.80	Yes
Pb	< 0.038	< 0.037	< 0.038	< 0.039	< 0.038	BL Range	<0.002	<0.05	Yes
Mn	0.177	0.227	0.287	0.215	0.226	BL Range	<0.005	0.190	No
Hg	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	BL Range	<0.0002	<0.001	Yes
Mo	< 0.086	< 0.085	< 0.085	< 0.069	< 0.081	BL Range	<0.02	<0.10	Yes
Ni	< 0.050	< 0.050	< 0.050	< 0.050	< 0.050	BL Range	<0.01	<0.2	Yes
Se	< 0.039	< 0.026	< 0.028	< 0.019	< 0.028	BL Range	<0.001	0.416	Yes
V	< 0.088	< 0.087	< 0.088	< 0.088	< 0.088	BL Range	<0.05	0.55	Yes
Zn	< 0.011	< 0.010	< 0.010	< 0.010	< 0.010	BL Range	<0.01	0.20	Yes
<b>Radiometric pCi/l:</b>									
U (mg/l)	2.169	1.952	1.968	1.826	1.979	2.09	<0.01	18.6	Yes
Ra 226	142.5	99.3	127.5	130.7	125.4	BL Range	2.5	247.7	Yes
Ra 226+/-	4.1	3.3	3.9	4.4	3.9				

Note: Bold values exceed Target Restoration Values.

\*All stability samples included in Round 1-4 mean value (n=130 samples).

Table 5-1-Input Parameters for the Irigaray Groundwater Flow Model

Parameter	Value	Units
<b>Model Dimensions</b>		
South to North	7250	feet
West to East	4800	feet
Rotation	15 degrees clockwise	
<b>Tie-in Coordinates (from bottom lefthand corner)</b>		
x =	818,418.00	feet
y =	1,170,647.00	feet
<b>Layer Thickness</b>		
Layer 1-Non Mining Zone	39	feet
Layer 2-Mining Zone	21	feet
Layer 3-Non Mining Zone	40	feet
<b>Cell dimensions</b>		
Size	25' x 25' (uniform)	
Top Elevation Layer 1(south end)	4190	ft amsl
Top Elevation Layer 1 (north end)	4180	ft amsl
Bottom Elevation Layer 3 (south end)	4090	ft amsl
Bottom Elevation Layer 3 (north end)	4080	ft amsl
<b>Boundaries</b>		
South end-Constant Head	4315	ft amsl
North end	4280-4295	ft amsl
East and west sides; top and bottom	4280-4315	ft amsl
<b>Recharge (Confined Aquifer)</b>		
	0	feet/d
<b>Hydraulic Conductivity</b>		
Layers 1 and 3-Non Mining Zones	1	ft/d
Layer 2-Mining Zone	0.50	ft/d
<b>Porosity</b>		
Layers 1 and 3-Non Mining Zones	25.0	percent
Layer 2-Mining Zone	29.0	percent
<b>Storativity</b>		
	$2 \times 10^{-4}$	
<b>Calibration Targets (see Table 5-2)</b>		Water levels measured at monitor wells in March 2002

Table 5-2. Calibration Targets, Residuals and Statistics for the Irigaray Groundwater Flow Model

Calibration Target	Observed Head (ft)	Computed Head (ft)	Residual (ft)
M1	4295.8	4295.50	0.30
T3	4294.4	4294.19	0.21
M4	4299.9	4298.79	1.11
M12	4302.5	4302.40	0.10
M15	4296.9	4297.06	-0.16
M19	4300.3	4300.39	-0.09
M24	4304.0	4303.71	0.29
T39	4300.2	4300.12	0.08
M29	4303.6	4302.84	0.76
M30	4309.4	4309.18	0.22
M31	4305.7	4306.09	-0.39
M32	4311.8	4311.56	0.24
T51	4305.4	4305.42	-0.02
T8	4295.2	4294.18	1.02
T12	4290.5	4292.28	-1.78
T24	4295.8	4294.41	1.39
T25	4292.4	4293.23	-0.83
T36	4297.7	4298.79	-1.09
M10	4292.5	4293.74	-1.24
M25	4296.4	4297.51	-1.11
M28	4305.9	4306.61	-0.71
DI40	4294.2	4295.64	-1.44
RS26	4296.3	4295.80	0.50
RS27	4296.8	4295.47	1.33

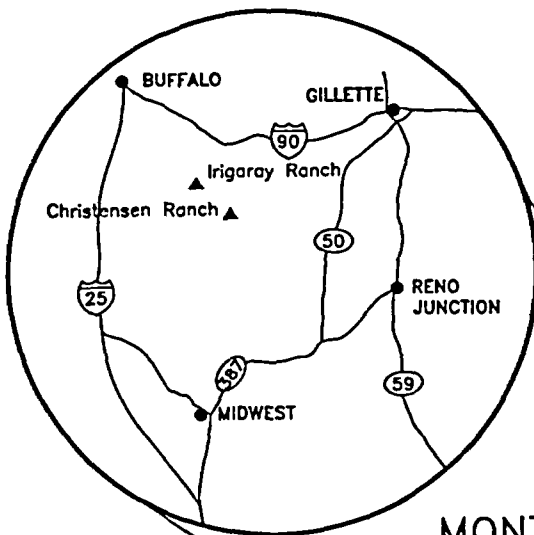
Residual is calculated by subtracting the computed head from the observed head

Statistical Parameter	Value (feet)
Residual Mean	-0.06
Residual Standard Deviation	0.86
Sum of Squares	17.71
Absolute Residual Mean	0.68
Minimum Residual	-1.78
Maximum Residual	1.39
Head Range	21.3
Standard Deviation/Head Range	0.04

Table Summary of Model Input Concentrations and Maximum Simulated Concentrations vs. WDEQ Class-1 Standards

	Selenium (mg/l)	Manganese (mg/l)	Uranium (mg/l)	Radium (pCi/l)	TDS (mg/l)
Initial Model Concentration inside Wellfield	0.04	0.18	2.1	139.9	650
Initial Model Concentration outside Wellfield	0.0026	0.0106	0.0165	0.9026	379
Maximum Total Simulated Concentration <sup>1</sup>	0.008	0.034	0.24	2.2	420
WDEQ Class 1 Regulatory Standard	0.01	0.05	5.0	5.0	500

1 - Maximum level at any observation point 400 feet downgradient of the wellfield (base case conditions)



MONTANA

NORTH  
DAKOTA

SOUTH  
DAKOTA

POWDER RIVER  
BASIN

IDAHO

WYOMING

CASPER

NEBRASKA

ROCK SPRINGS

LARAMIE

CHEYENNE

UTAH

COLORADO

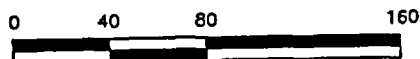


COGEMA Mining Inc.

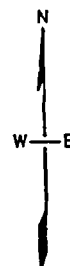
FIGURE 1-1

IRIGARAY MINE  
SITE LOCATION MAP

LEGEND

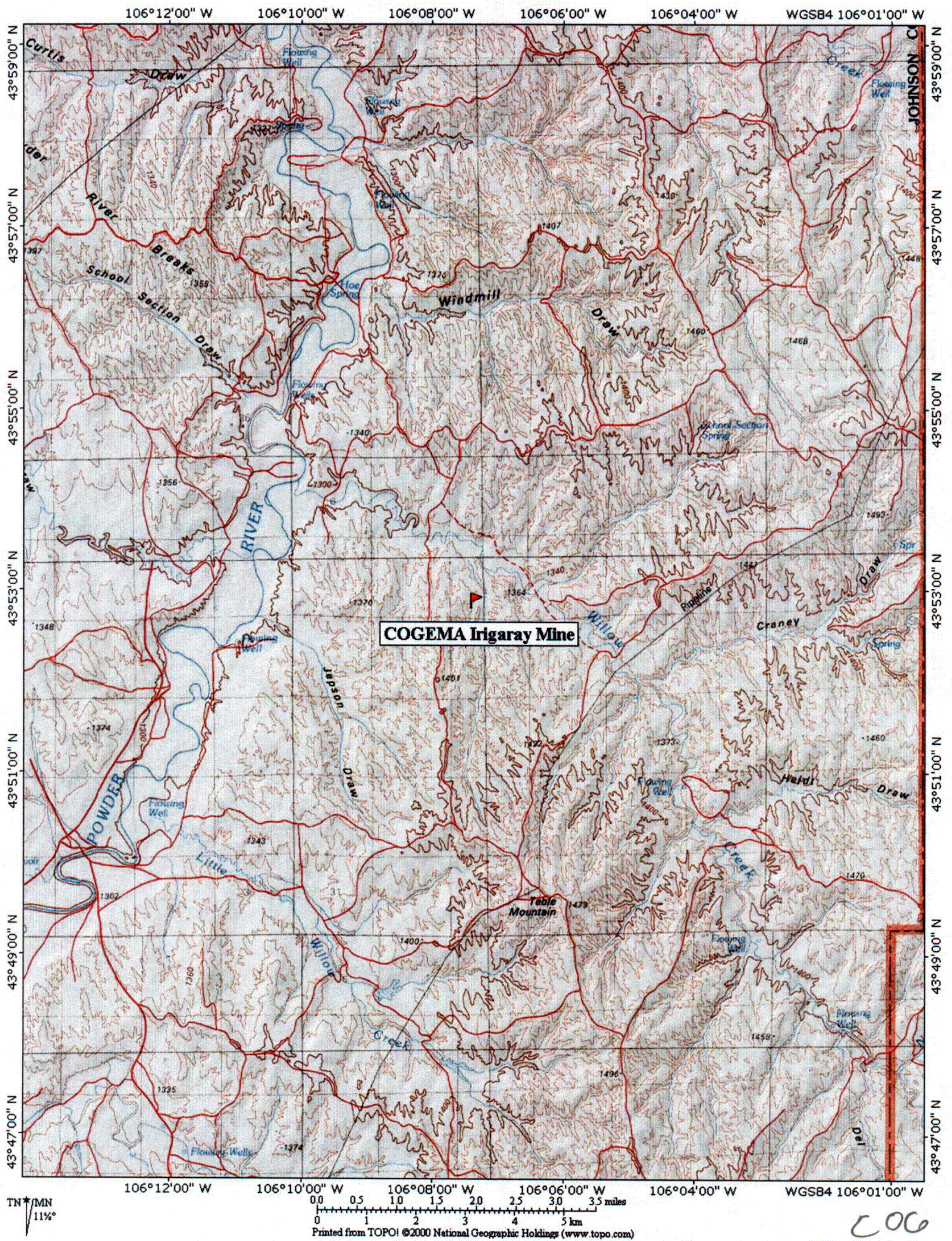


SCALE IN FEET 1" ~ 80 MILES

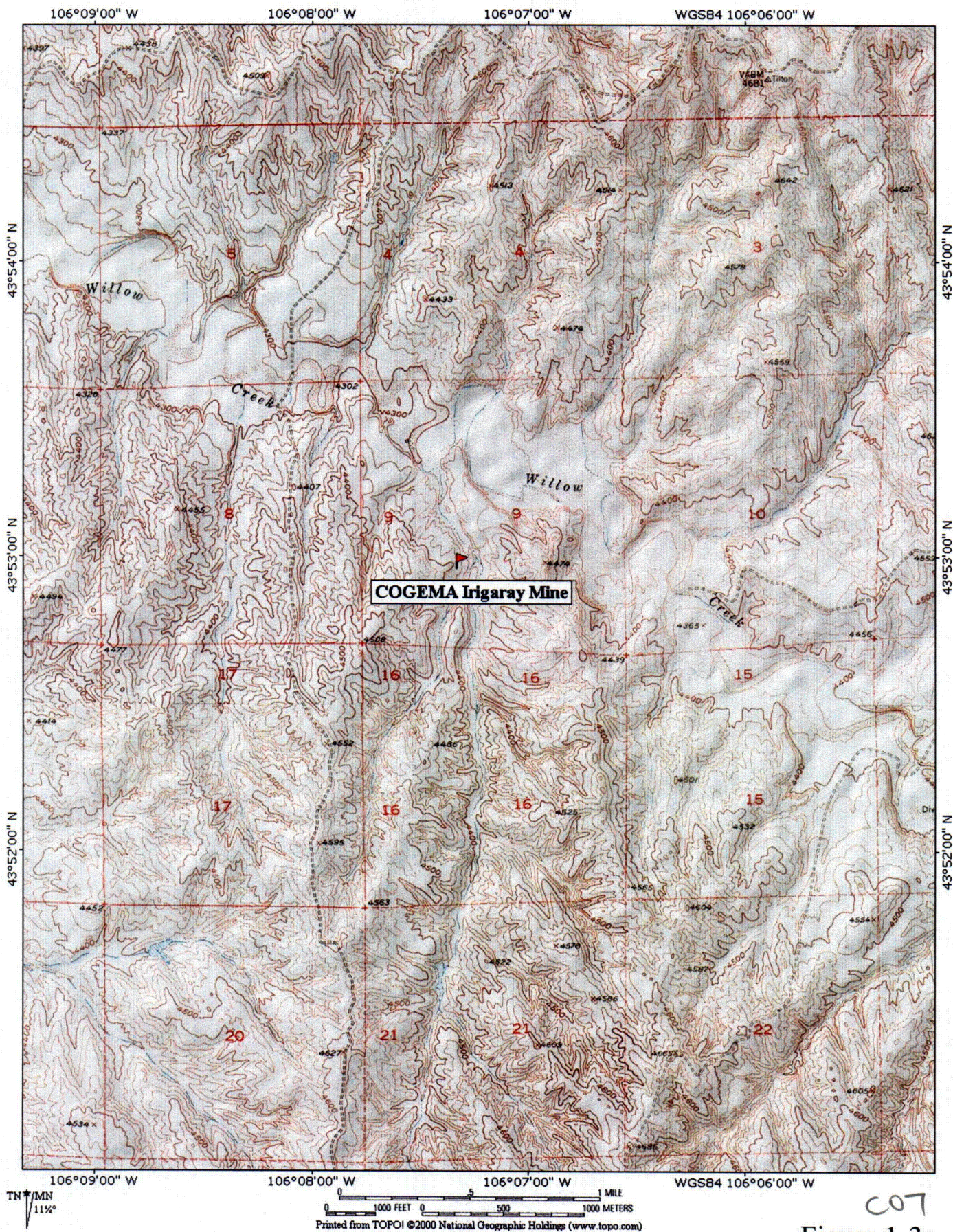


PROJECT: CMI-IR1	DATE: SEPTEMBER 2002
DWG: IR1Fig1-1.dwg	BY: HPD   CHECKED: KRS

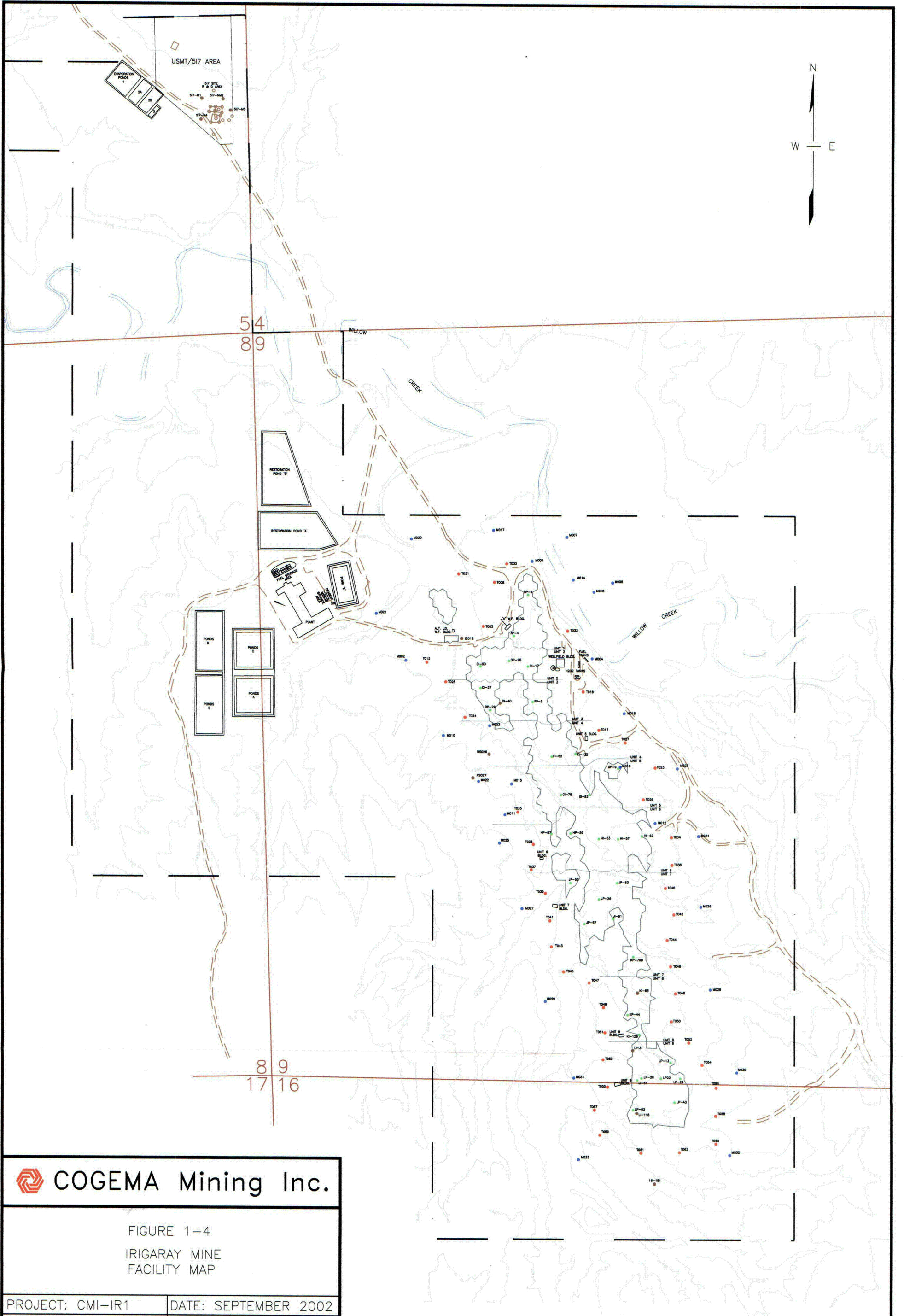
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COG  
Figure 1-2



CO7  
Figure 1-3



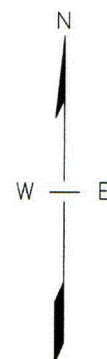
 **COGEMA Mining Inc.**

FIGURE 1-4  
IRIGARAY MINE  
FACILITY MAP

PROJECT: CMI-IR1	DATE: SEPTEMBER 2002
DWG: SiteMap.dwg	BY: HPD CHECKED: KRS

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0 325 650 1300  
SCALE IN FEET, 1" = 650'



## LEGEND

- T008 ORE ZONE TREND WELLS
- M001 PERIMETER ORE ZONE MONITORING WELLS
- SSM19 SHALLOW SAND MONITORING WELL
- DM014 DEEP SAND MONITORING WELL

0 175 350 700  
SCALE IN FEET, 1" = 350'

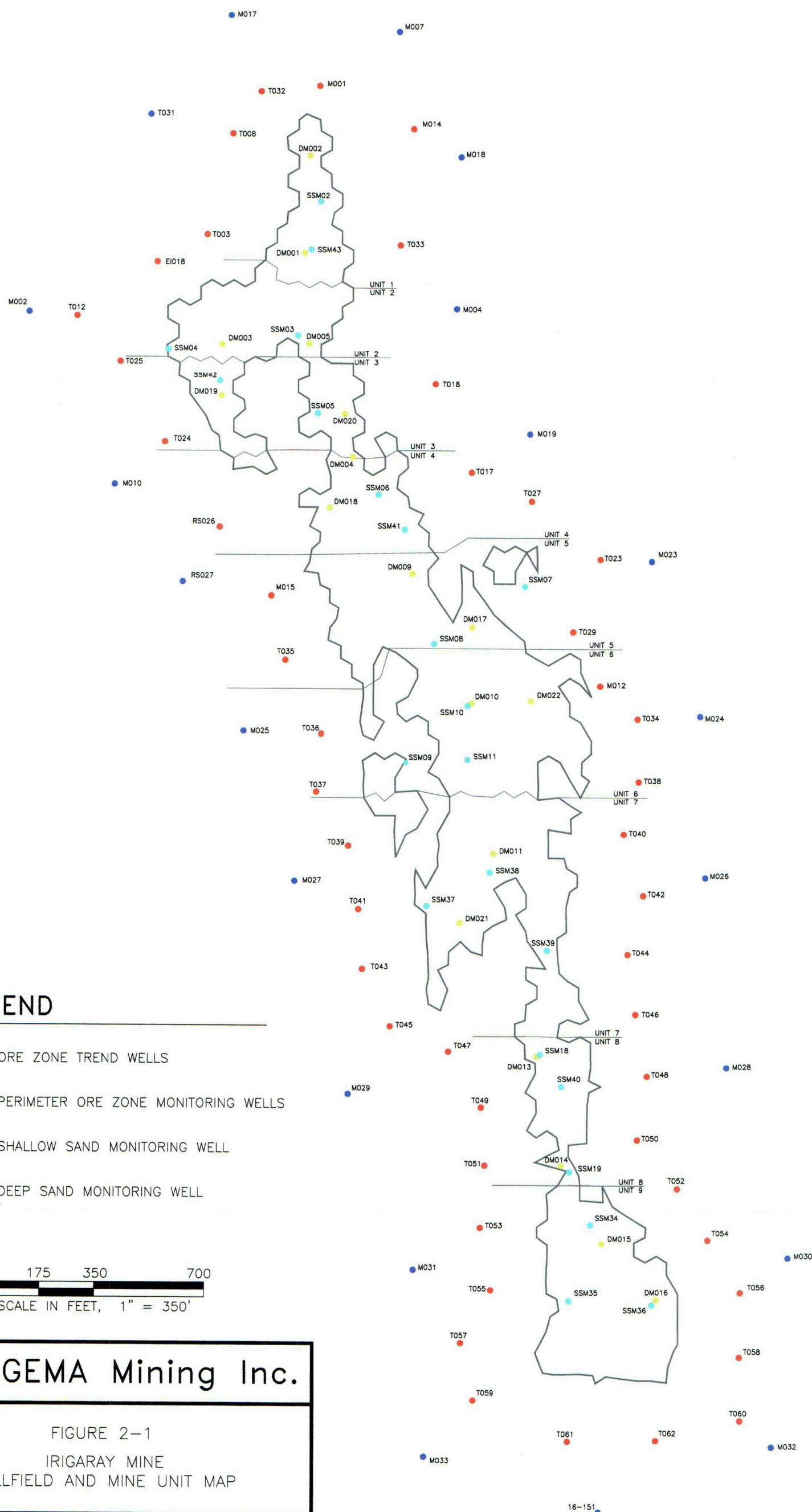


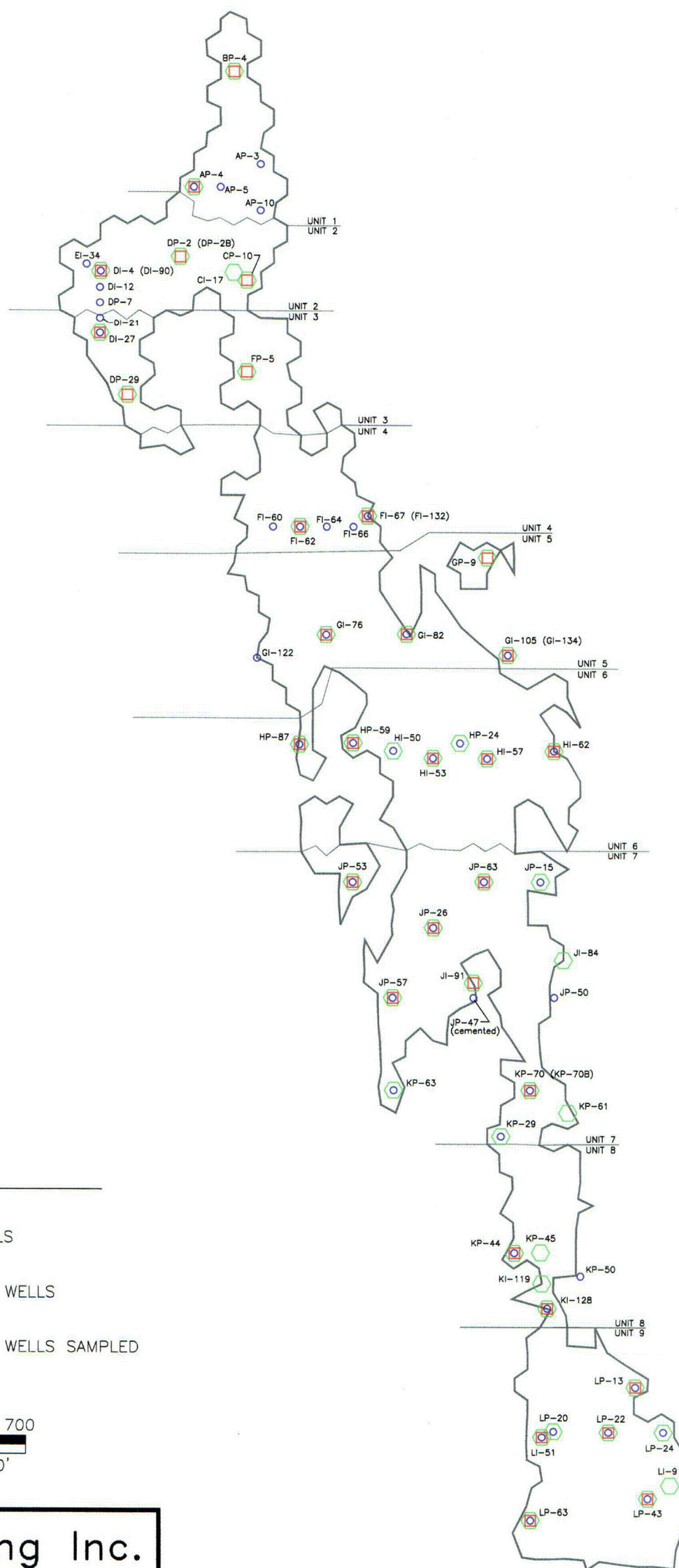
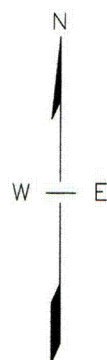
**COGEMA Mining Inc.**

FIGURE 2-1  
IRIGARAY MINE  
WELLFIELD AND MINE UNIT MAP




PROJECT: CMI-IR1	DATE: SEPTEMBER 2003
DWG: SiteMap.dwg	BY: HPD CHECKED: KRS

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## LEGEND

-  KI-128 ORE ZONE BASELINE WELLS
-  KI-128 DESIGNATED RESTORATION WELLS
-  KI-128 DESIGNATED RESTORATION WELLS SAMPLED

0 175 350 700  
SCALE IN FEET, 1" = 350'

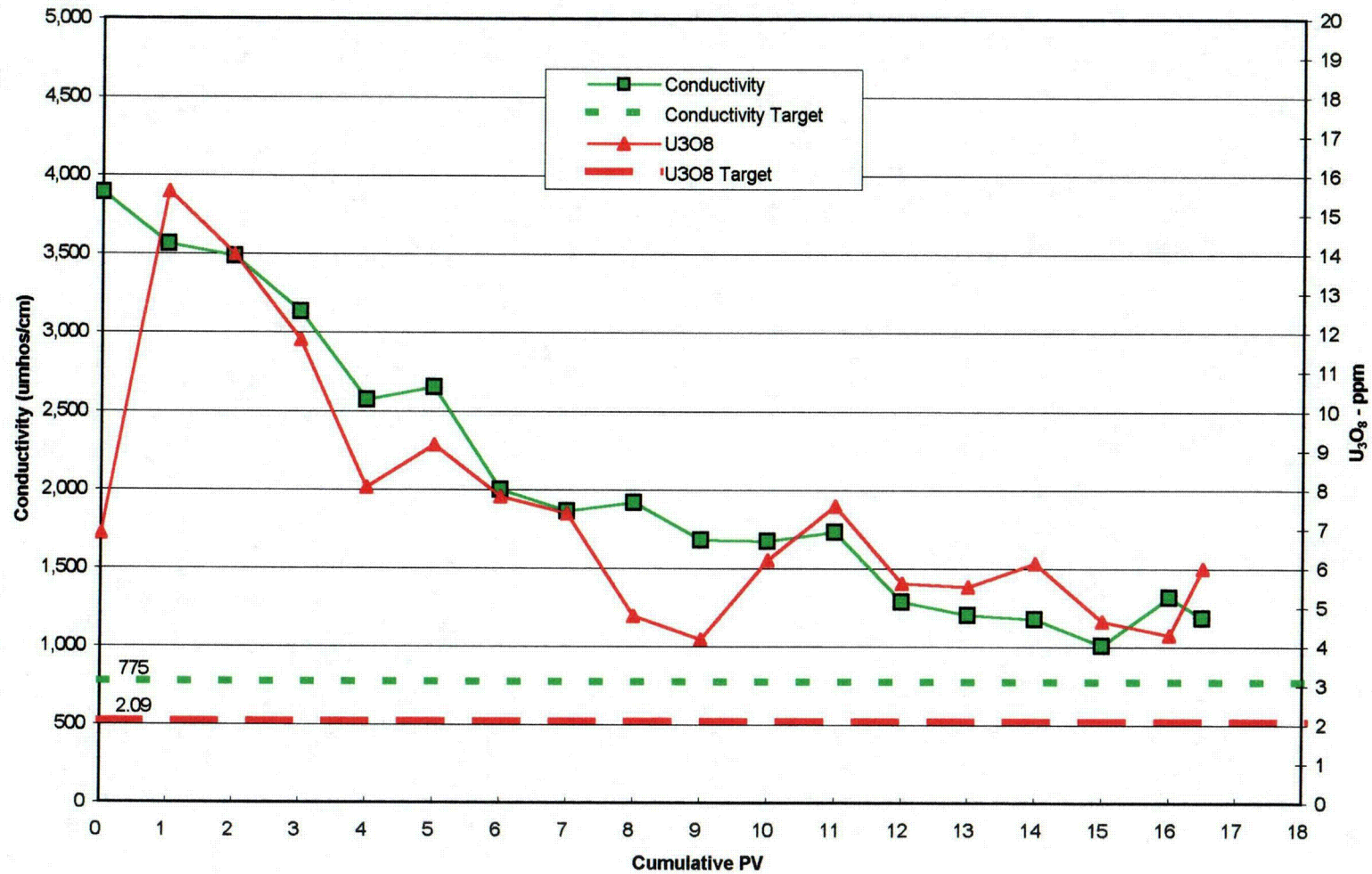
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FIGURE 4-1  
IRIGARAY MINE  
DESIGNATED RESTORATION/SAMPLED WELLS

PROJECT: CMI-IR1	DATE: SEPTEMBER 2003
DWG: SiteMap.dwg	BY: HPD CHECKED: KRS

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**FIGURE 4-2**  
**CONDUCTIVITY AND URANIUM TRENDS**  
**PRODUCTION UNITS 1 THROUGH 3, GWS AND RO PHASES**  
**(BASELINE WELL AVERAGES)**



C11

FIGURE 4-3  
CONDUCTIVITY AND URANIUM TRENDS  
PRODUCTION UNITS 4 AND 5, RO PHASE  
(MONTHLY RECOVERY WELL AVERAGES)

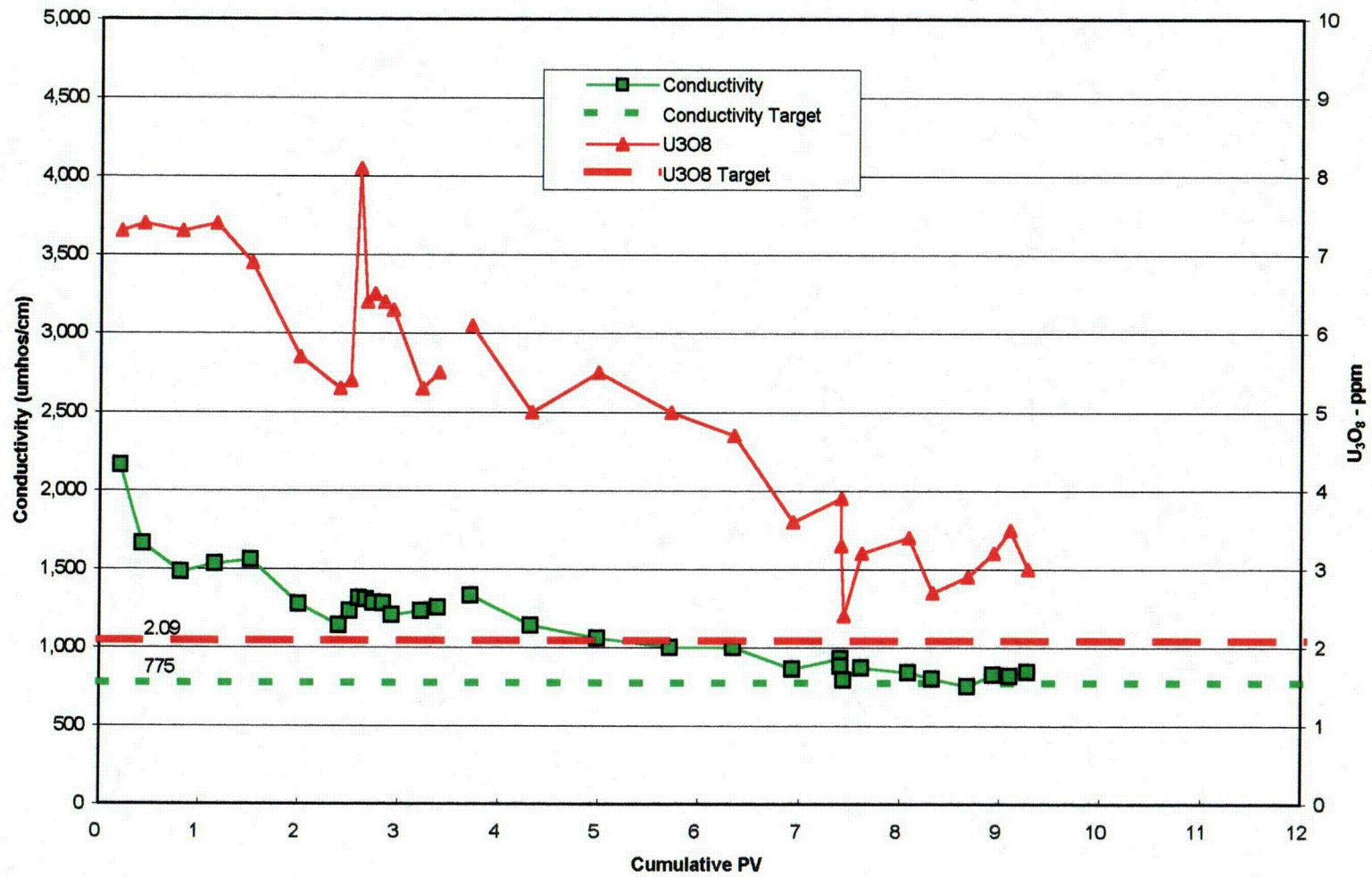


FIGURE 4-4  
CONDUCTIVITY AND URANIUM TRENDS  
PRODUCTION UNIT 6, RO PHASE  
(MONTHLY RECOVERY WELL AVERAGES)

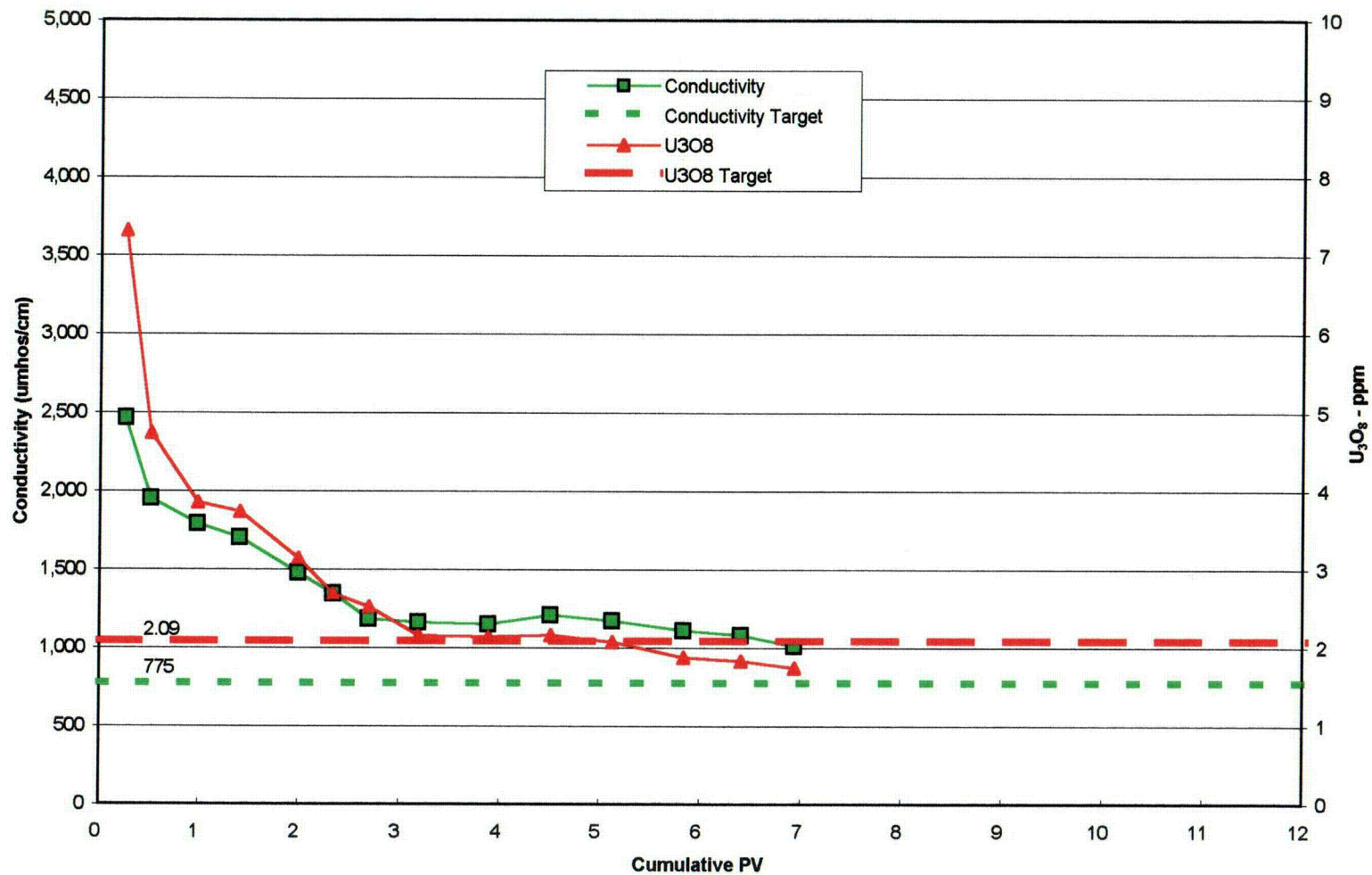


FIGURE 4-6  
CONDUCTIVITY AND URANIUM TRENDS  
PRODUCTION UNIT 8, RO PHASE  
(MONTHLY RECOVERY WELL AVERAGES)

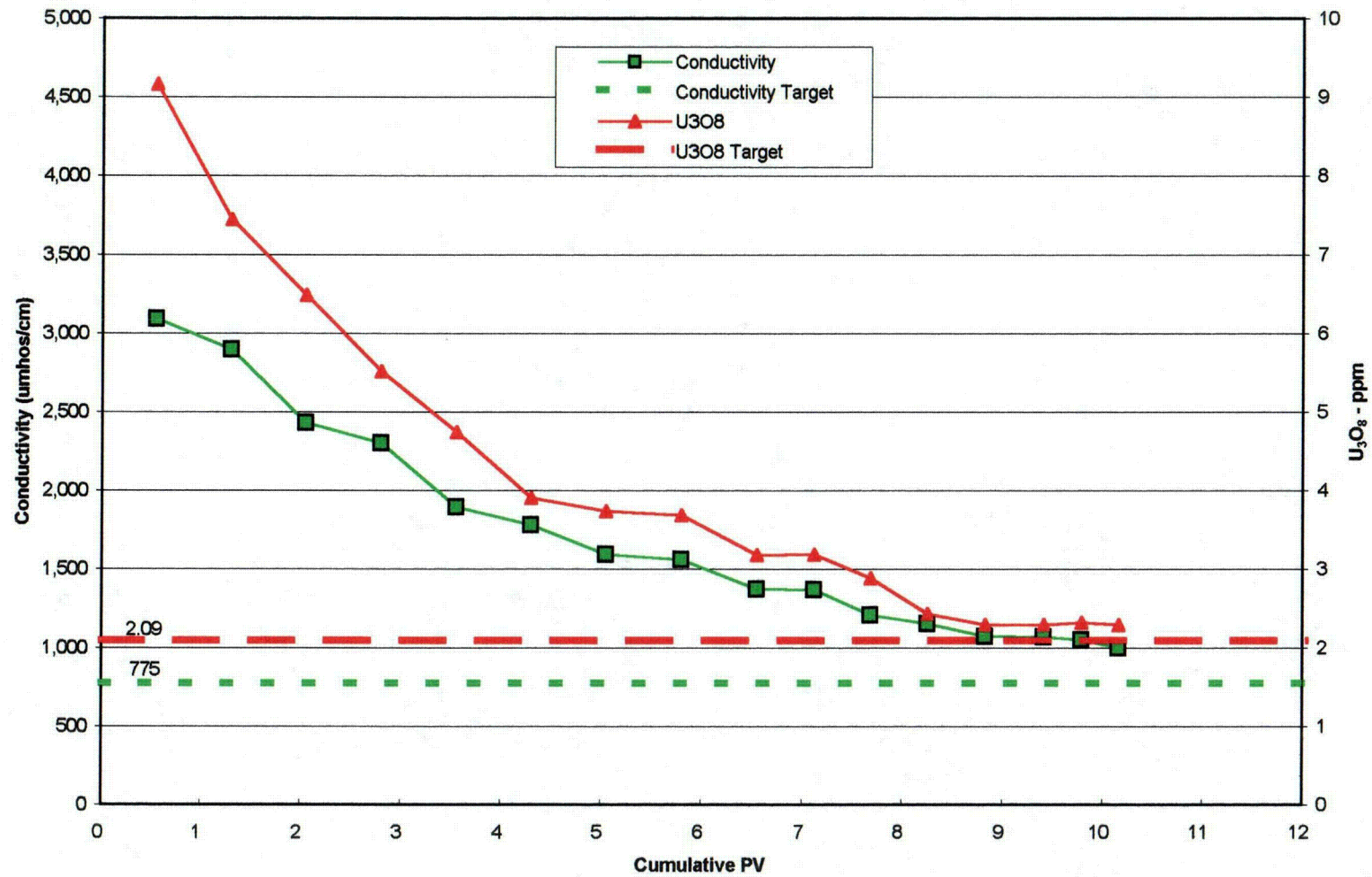
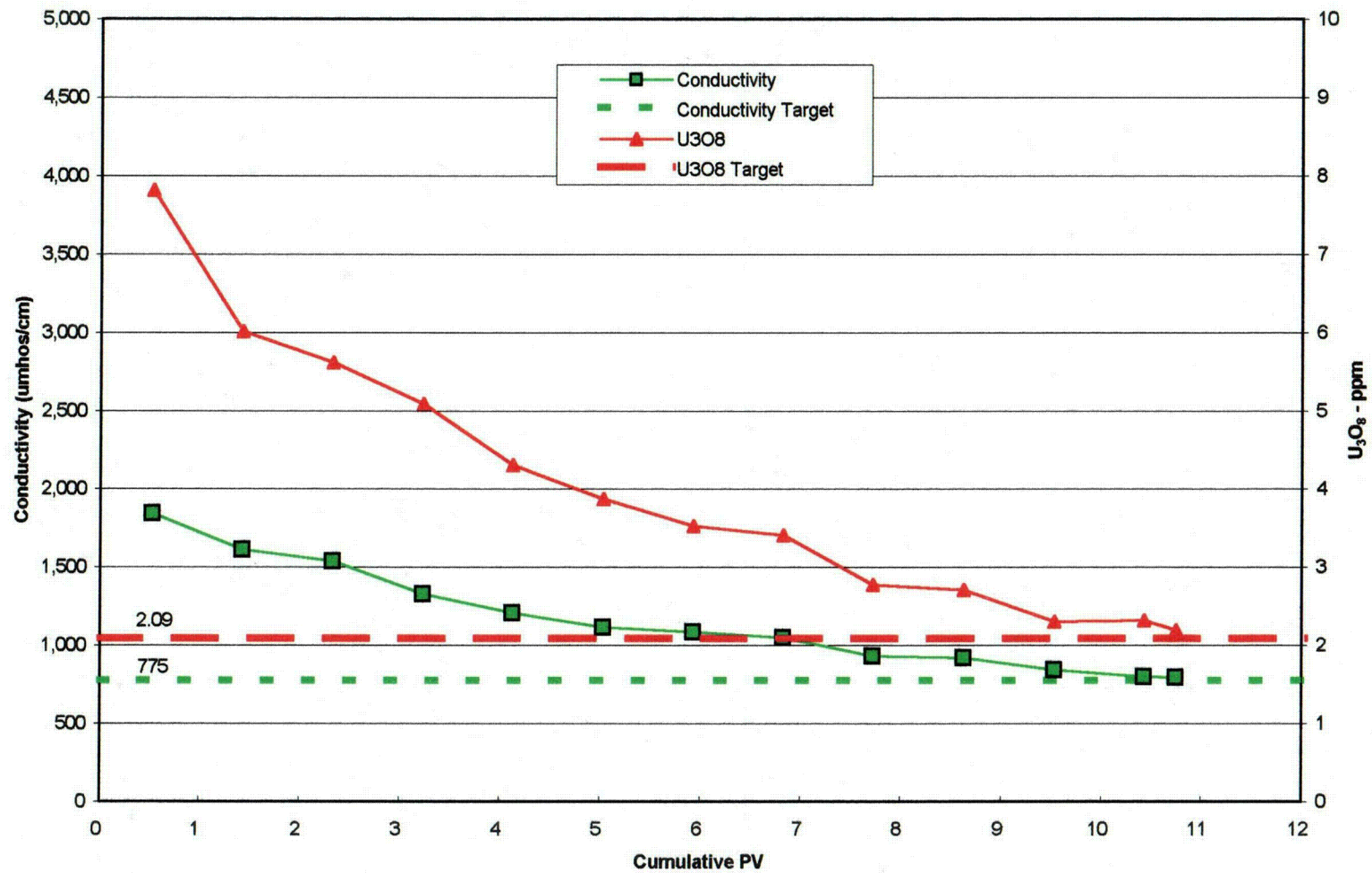


FIGURE 4-7  
CONDUCTIVITY AND URANIUM TRENDS  
PRODUCTION UNIT 9, RO PHASE  
(MONTHLY RECOVERY WELL AVERAGES)



1177500

1175000

1172500

817500

820000

822500

**LEGEND**

Model Grid Rotation Is 15 Degrees Northwest

**BOUNDARY CONDITIONS** CONSTANT HEAD BOUNDARY GENERAL HEAD BOUNDARY**IRIGARAY  
ISL WELLFIELD****COGEMA MINING, INC.  
IRIGARAY MINE**

FIGURE 5-1  
MODEL DOMAIN, GRID AND BOUNDARY CONDITIONS  
IRIGARAY ISL WELLFIELD

PROJECT: CMI/IRIGARAY

DATE: MAY 2002

DWG: COGEMAFIG5-1.SRF

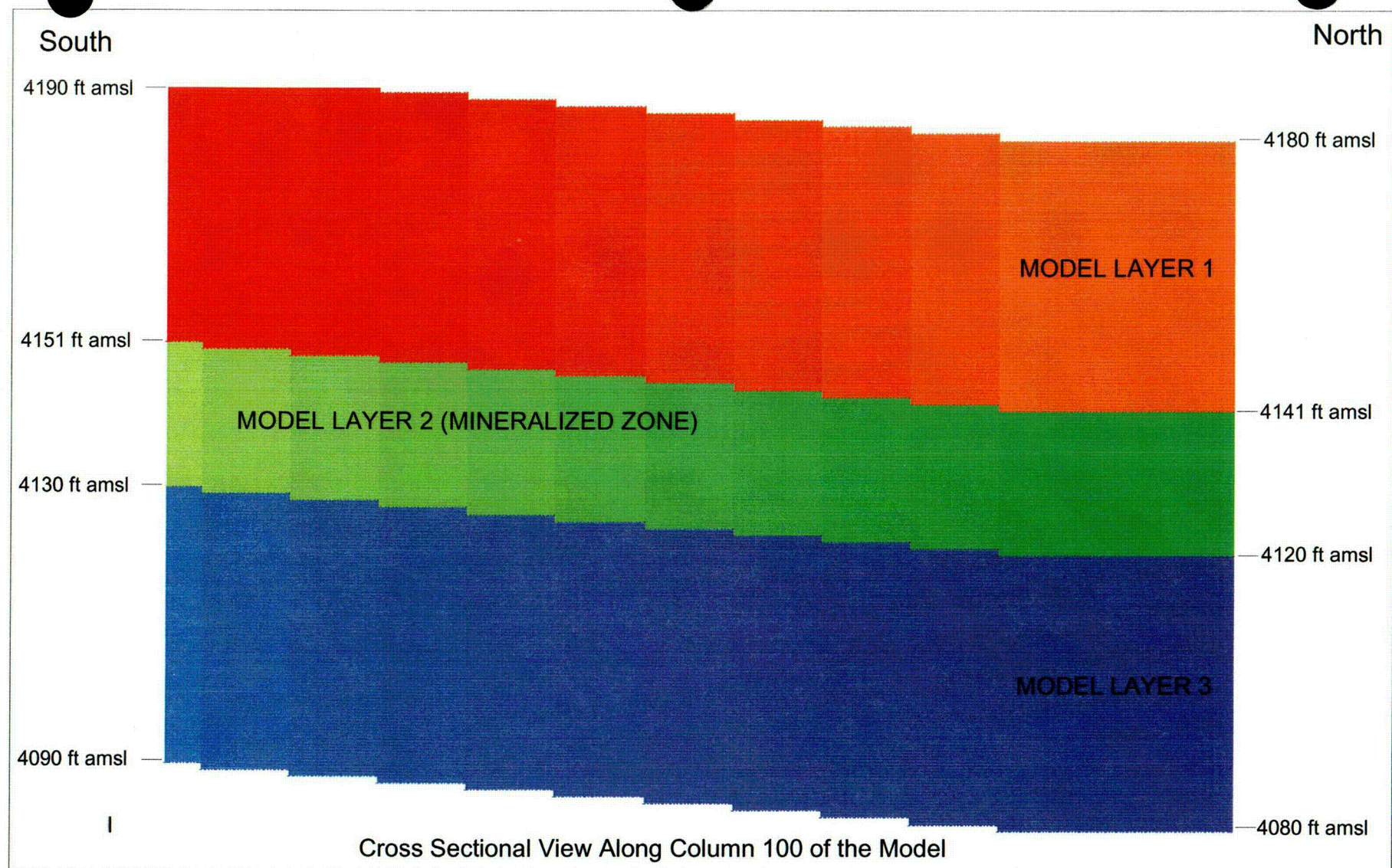
BY: EPL

CHECKED: HPD

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C17



**COGEMA MINING, INC.  
IRIGARAY MINE**

**FIGURE 5-2  
CROSS SECTIONAL VIEW - MODEL LAYERS  
IRIGARAY GROUNDWATER FLOW MODEL**

PROJECT: CMI/IRIGARAY

DATE: MAY 2002

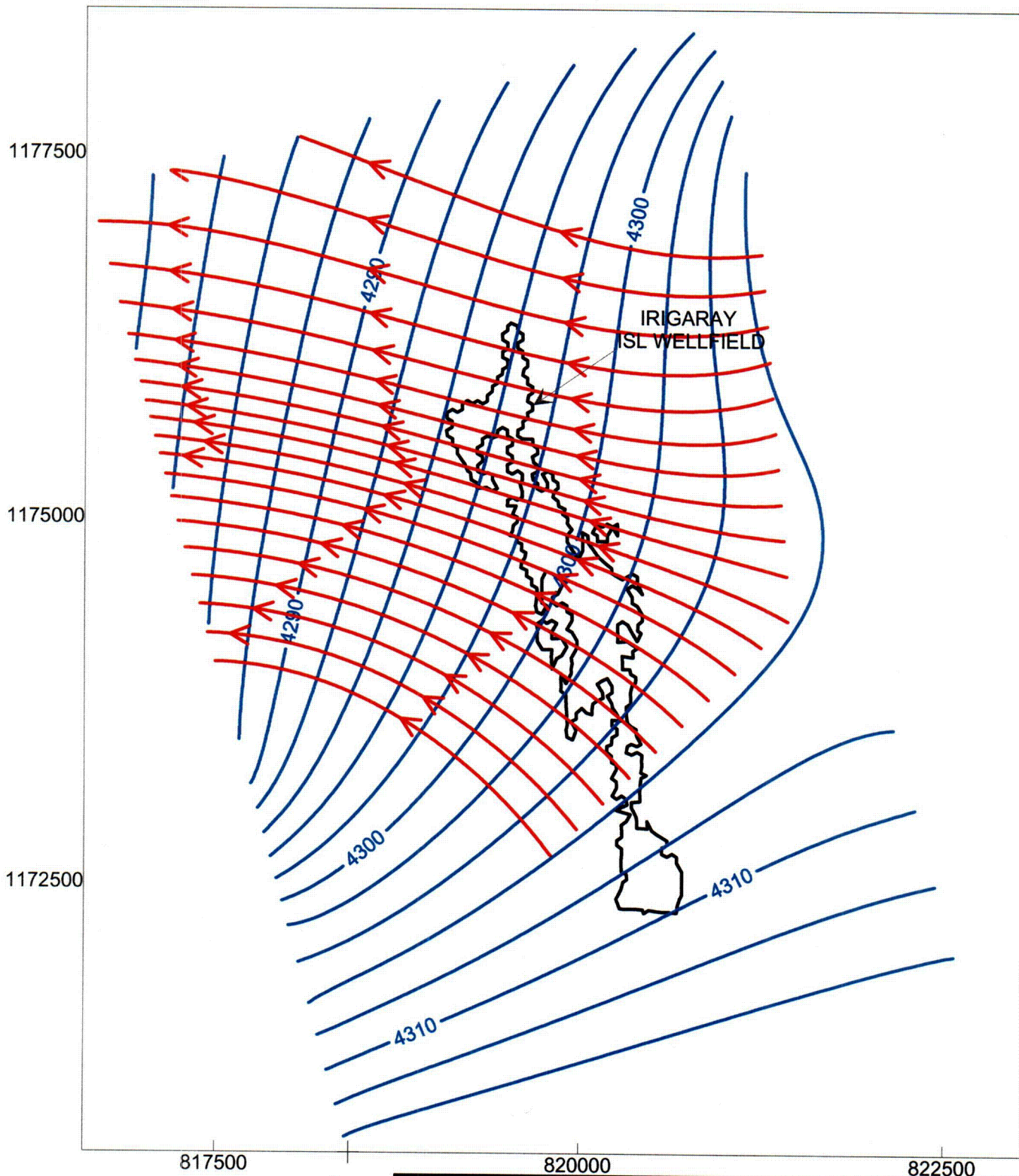
DWG: COGEMAFIG5-2r.srf

BY: EPL CHECKED: HPD

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C18



# **LEGEND**



SCALE IN FEET 1" = 1000'  
CONTOUR INTERVAL = 2 feet

**4310** Potentiometric Surface  
(feet above mean sea level)

Groundwater Flowpath



## **COGEMA MINING, INC. IRIGARAY MINE**

**FIGURE 5-3  
SIMULATED HEAD DISTRIBUTION AND GROUNDWATER FLOWPATHS  
IRIGARAY ISL WELLFIELD**

PROJECT: CMI/IRIGARAY  
DWG: COGEMAFIG5-3.SRF

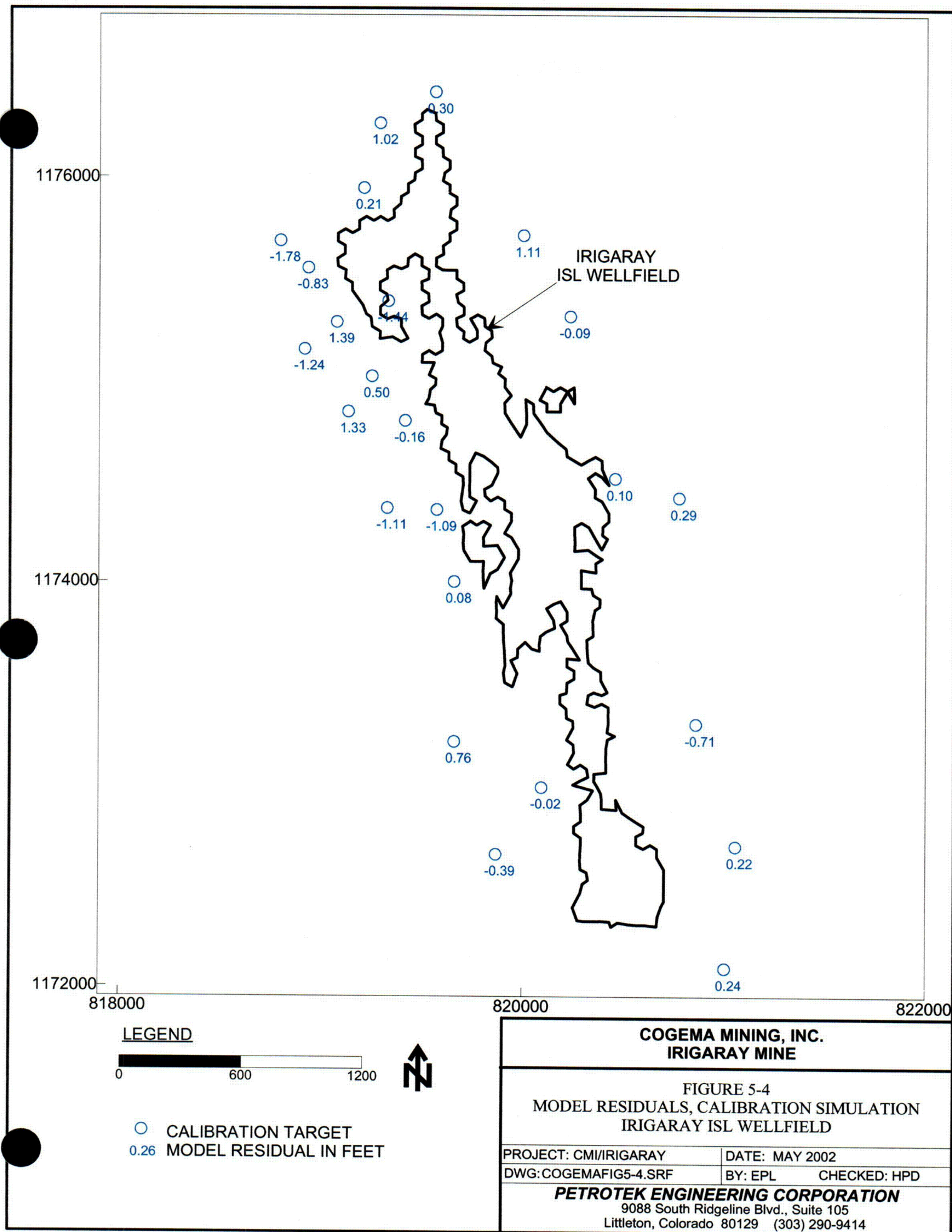
DATE: MAY 2002

BY: EPL

CHECKED: HPD

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1177500

1175000

1172500

817500

820000

822500

IRIGARAY  
SL WELLFIELD**LEGEND**

0 500 1000

SCALE IN FEET 1" = 1000'

CONTOUR INTERVAL = 2 feet

-4310- Potentiometric Surface  
Calibration Simulation (ft amsl)-4310- Potentiometric Surface  
Validation Simulation (ft amsl)**COGEMA MINING, INC.  
IRIGARAY MINE****FIGURE 5-5  
COMPARISON OF HEAD DISTRIBUTION FOR  
CALIBRATION AND VALIDATION SIMULATIONS**

PROJECT: CMI/IRIGARAY

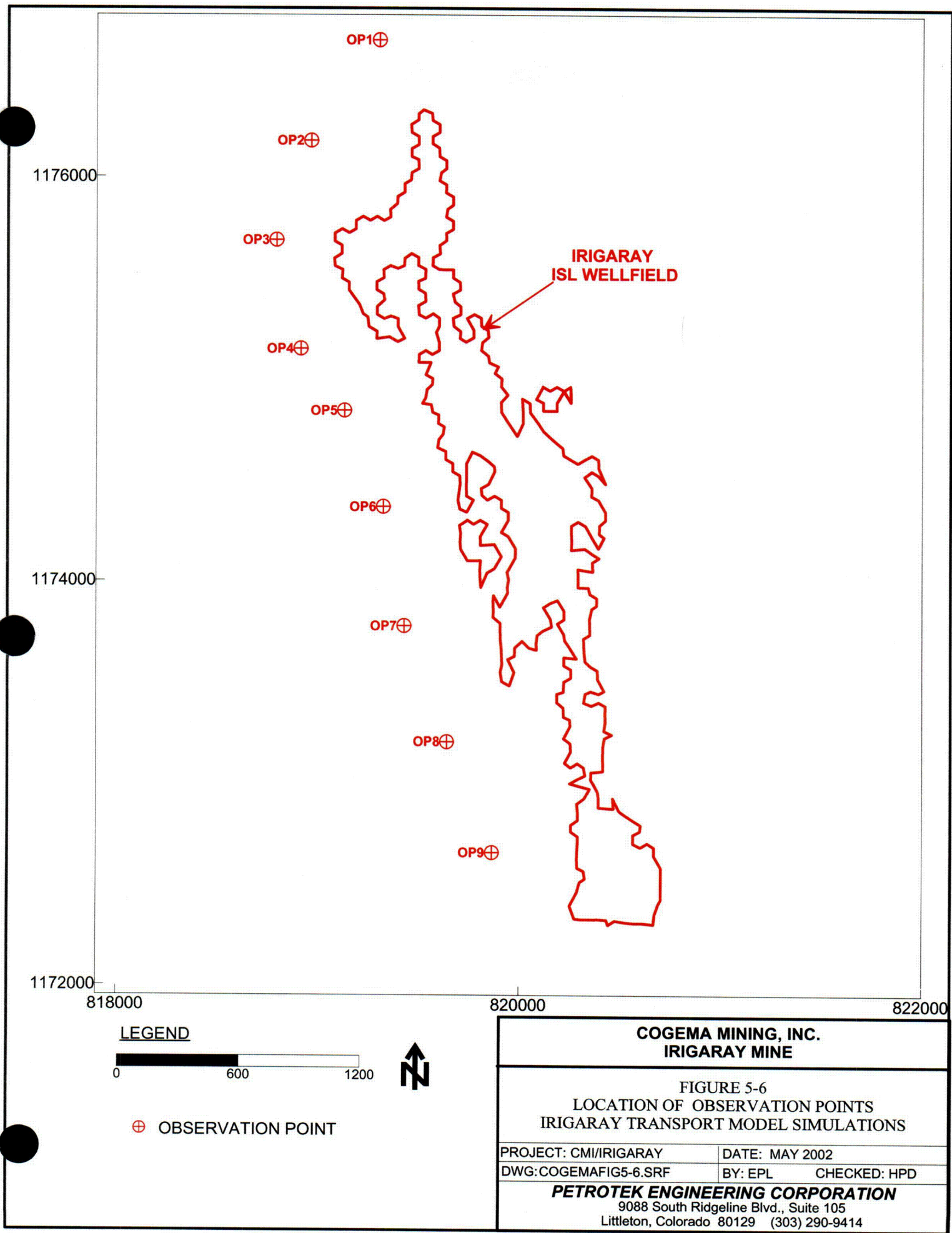
DATE: MAY 2002

DWG: COGEMAFIG5-5.SRF

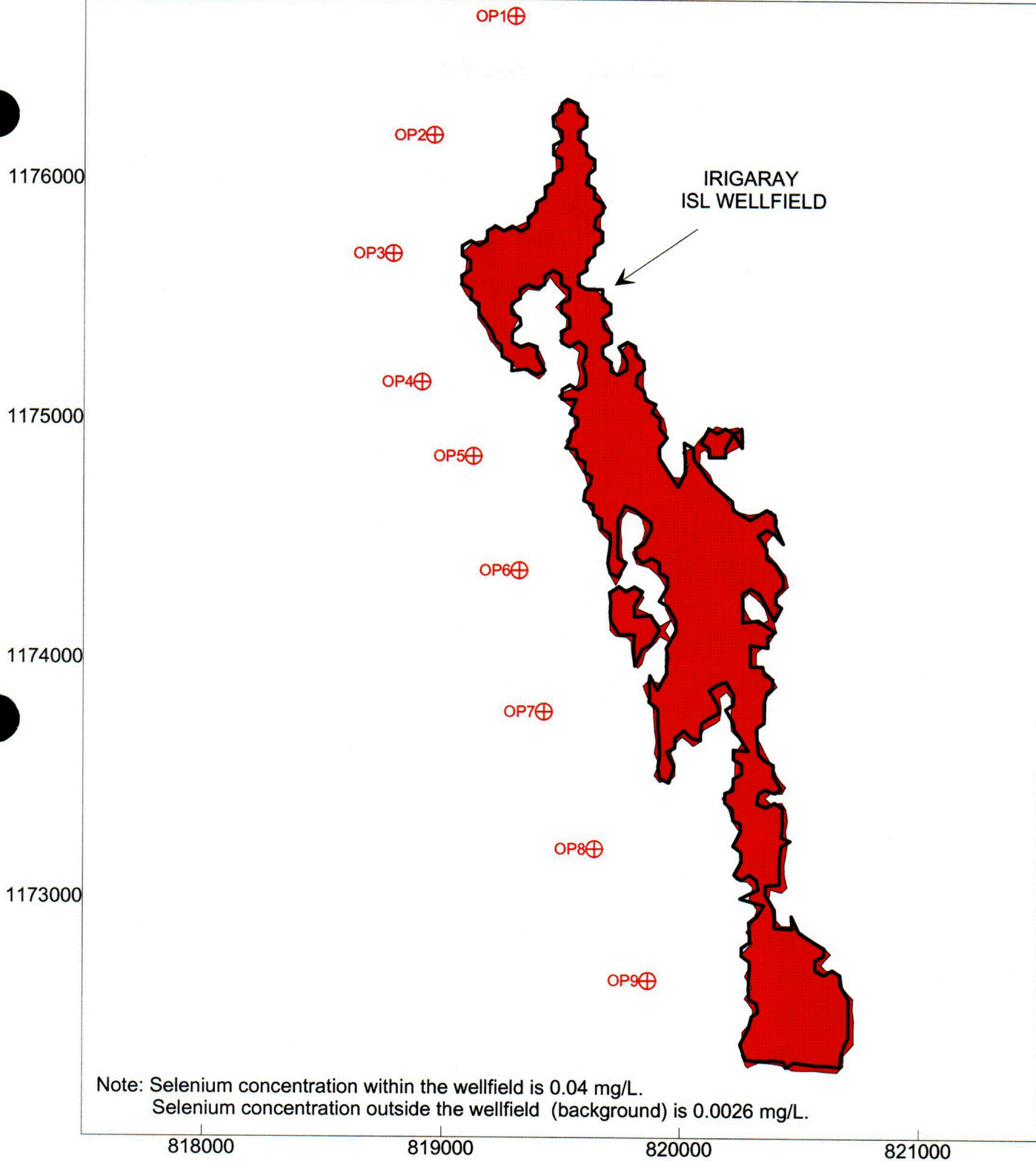
BY: EPL

CHECKED: HPD

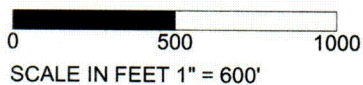
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C22



# **LEGEND**



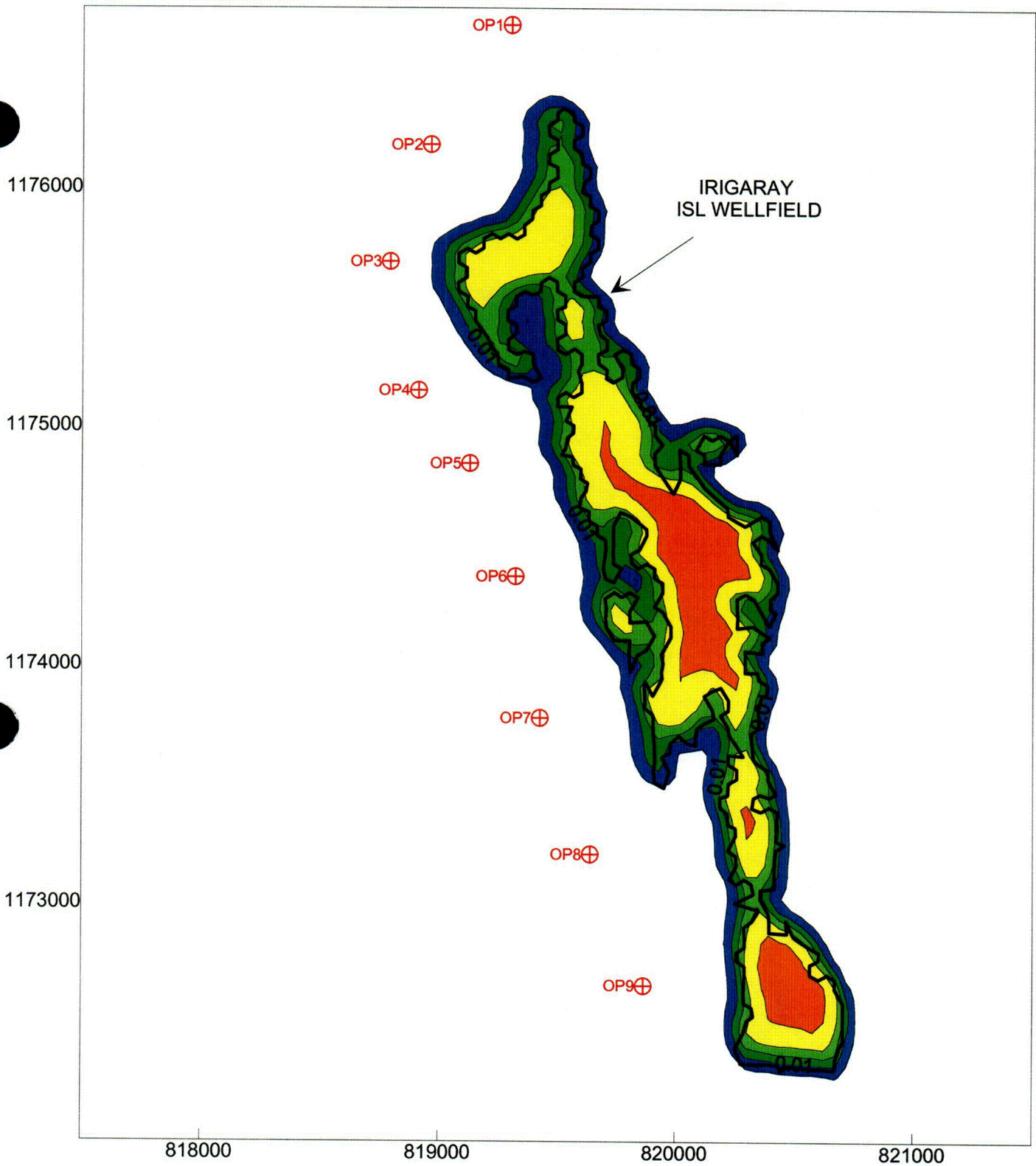
⊕ Observation point for simulated concentrations  
(400 feet from wellfield)



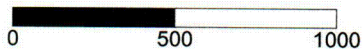
**COGEMA MINING, INC.**  
**IRIGARAY MINE**

**FIGURE 5-7**  
**INITIAL SELENIUM DISTRIBUTION**  
**IRIGARAY ISL WELLFIELD**

PROJECT: CMI/IRIGARAY	DATE: MAY 2002
DWG: COGEMAFIG5-7r.SRF	BY: EPL CHECKED: HPD
<b>PETROTEK ENGINEERING CORPORATION</b>	
9088 South Ridgeline Blvd., Suite 105 Littleton, Colorado 80129 (303) 290-9414	



# **LEGEND**



SCALE IN FEET 1" = 600'  
CONTOUR INTERVAL = 0.005 mg/L

⊕ Observation point for simulated concentrations  
(400 feet from wellfield)



Se (mg/L)



**COGEMA MINING, INC.  
IRIGARAY MINE**

**FIGURE 5-8  
SELENIUM DISTRIBUTION AT 24 YEARS  
IRIGARAY ISL WELLFIELD**

PROJECT: CMI/IRIGARAY

DATE: MAY 2002

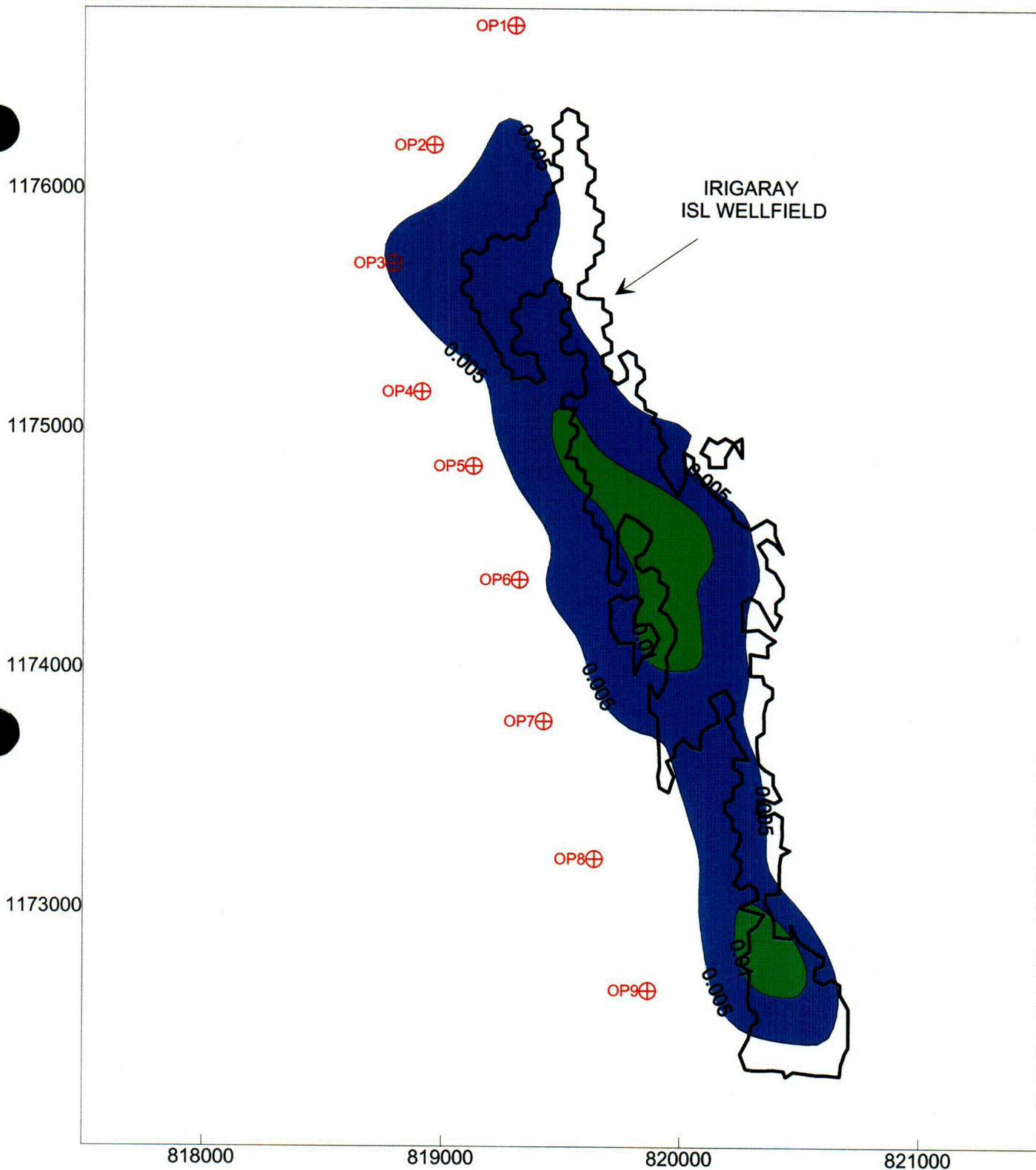
DWG: COGEMAFIG5-8r.SRF

BY: EPL

CHECKED: HPD

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Littleton, Colorado 80129 (303) 290-9414



# **LEGEND**

0 500 1000

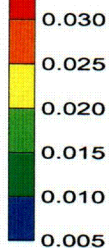
SCALE IN FEET 1" = 600'

CONTOUR INTERVAL = 0.005 mg/L

⊕ Observation point for simulated concentrations  
(400 feet from wellfield)



Se (mg/L)



**COGEMA MINING, INC.**  
**IRIGARAY MINE**

**FIGURE 5-9**  
**SELENIUM DISTRIBUTION AT 100 YEARS**  
**IRIGARAY ISL WELLFIELD**

PROJECT: CMI/IRIGARAY

DATE: MAY 2002

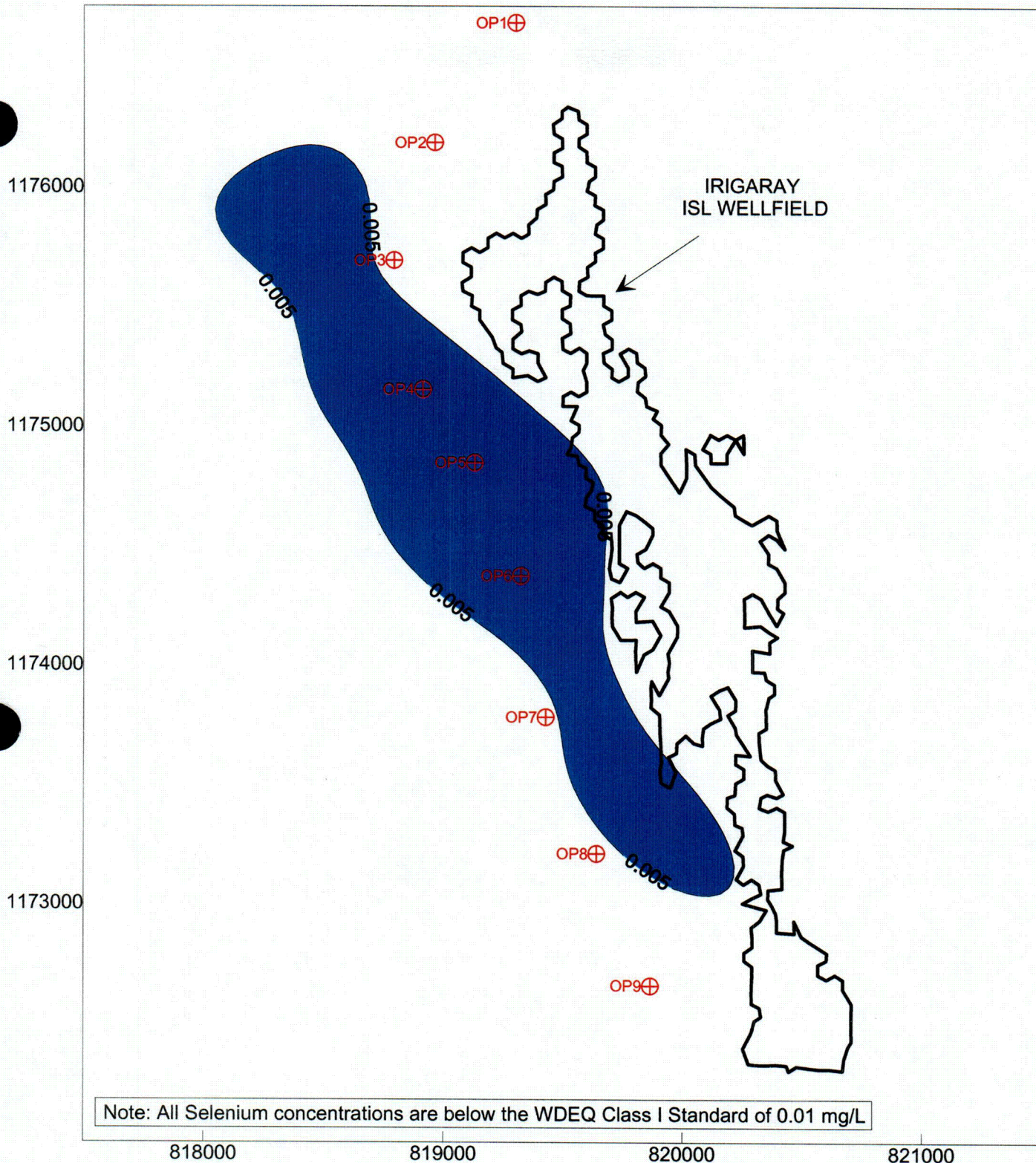
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BY: EPL

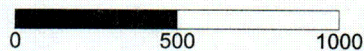
CHECKED: HPD

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# **LEGEND**



SCALE IN FEET 1" = 600'  
CONTOUR INTERVAL = 0.005 mg/L

⊕ Observation point for simulated concentrations  
(400 feet from wellfield)



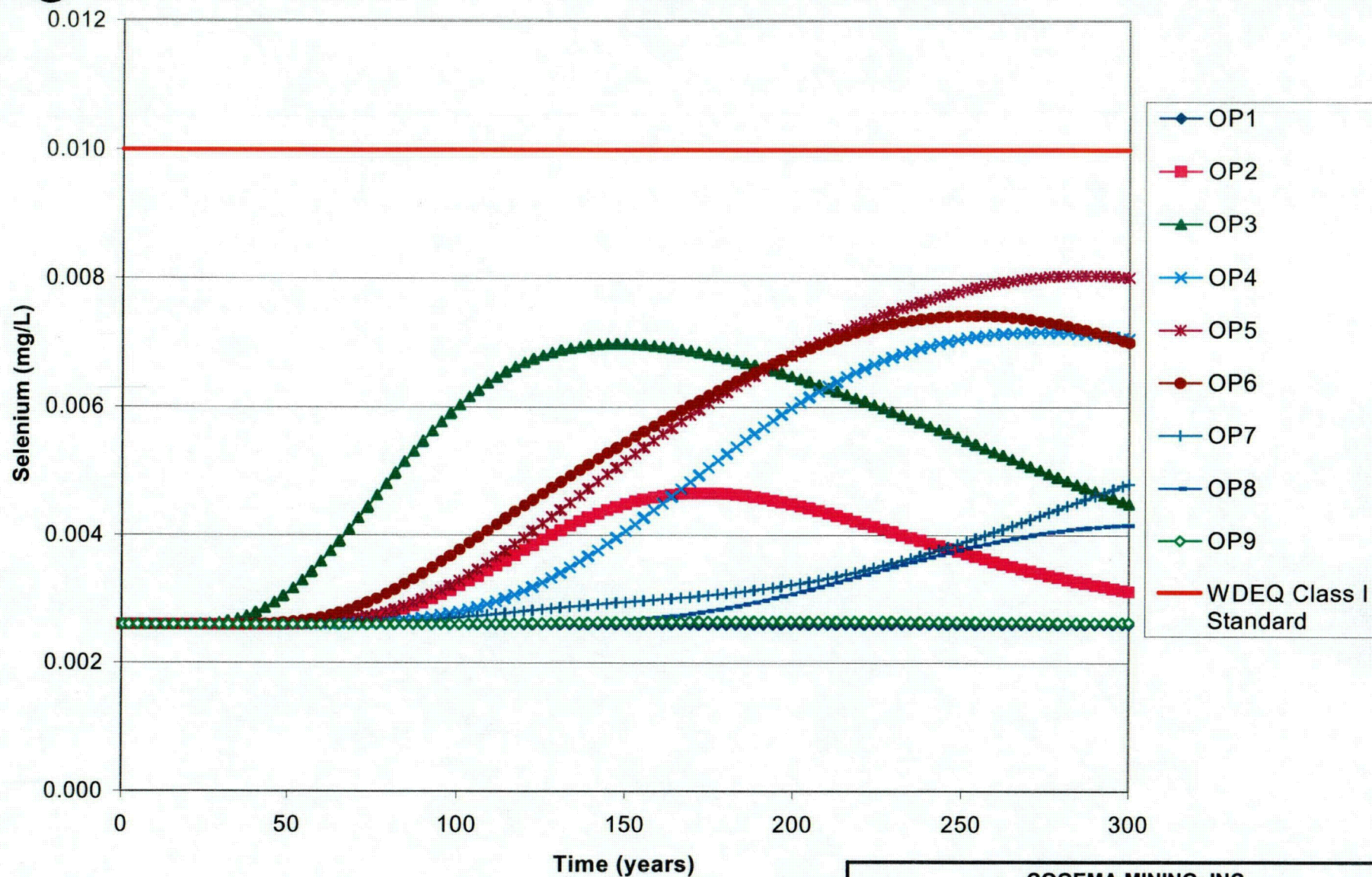
Se (mg/L)



## **COGEMA MINING, INC. IRIGARAY MINE**

**FIGURE 5-10  
SELENIUM DISTRIBUTION AT 300 YEARS  
IRIGARAY ISL WELLFIELD**

PROJECT: CMI/IRIGARAY	DATE: MAY 2002
DWG: COGEMAFIGC5-10r.SRF	BY: EPL CHECKED: HPD
<b>PETROTEK ENGINEERING CORPORATION</b>	
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**COGEMA MINING, INC.  
IRIGARAY MINE**

**FIGURE 5-11**  
**MODELED SELENIUM CONCENTRATION vs TIME**  
**AT OBSERVATION POINTS 400 FEET FROM WELLFIELD**

PROJECT: CMI/IRIGARAY

DATE: MAY 2002

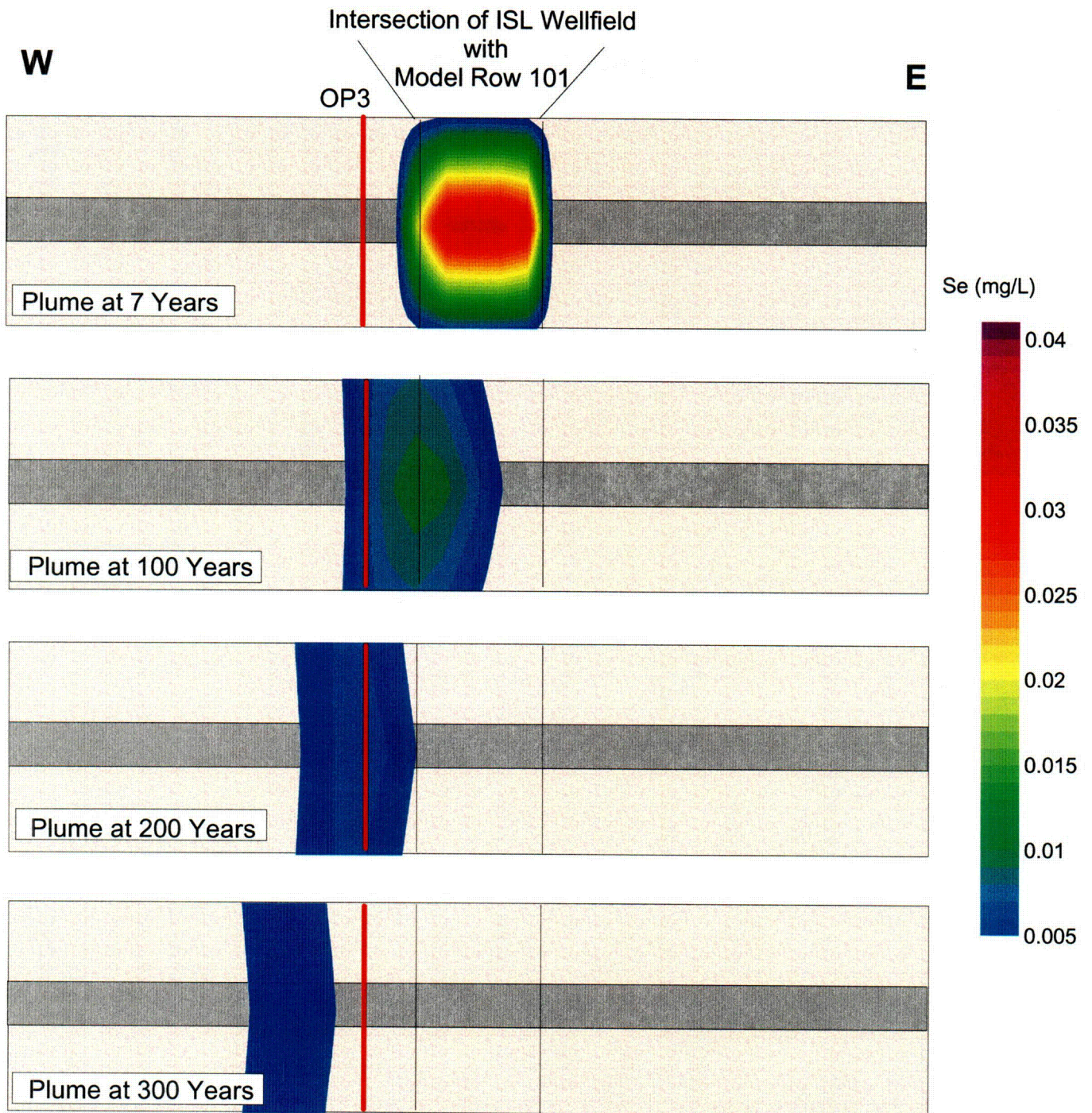
DWG: COGEMAFIG5-11r.srf

BY: EPL

CHECKED: HPD

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# **LEGEND**

Cross Section Represents Row 101 of the Model, Passing through OP3

CONCENTRATION CONTOUR INTERVAL = 0.001 mg/L

HORIZONTAL SCALE 1" = 735'

VERTICAL SCALE 1" = 73.5'

MINERALIZED ZONE

NON-MINERALIZED ZONE

## **COGEMA MINING, INC. IRIGARAY MINE**

FIGURE 5-12  
SIMULATED MIGRATION OF THE SELENIUM PLUME  
IRIGARAY ISL WELLFIELD

PROJECT: CMI/IRIGARAY

DATE: MAY 2002

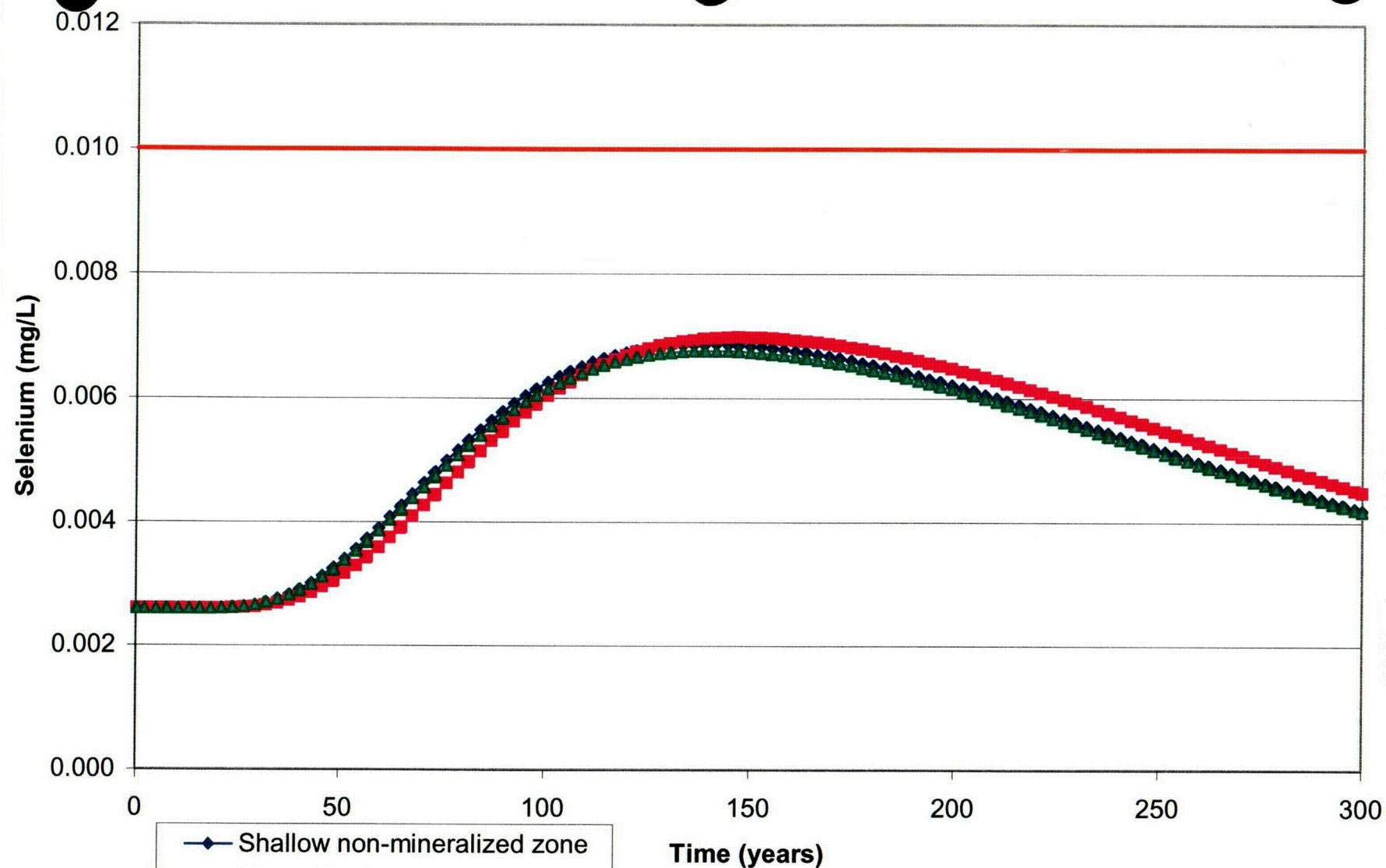
DWG: COGEMAFIG512r.SRF

BY: EPL

CHECKED: HPD

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**COGEMA MINING, INC.  
IRIGARAY MINE**

**FIGURE 5-13  
VERTICAL SELENIUM DISTRIBUTION  
AT OBSERVATION POINT OP3**

PROJECT: CMI/IRIGARAY

DATE: MAY 2002

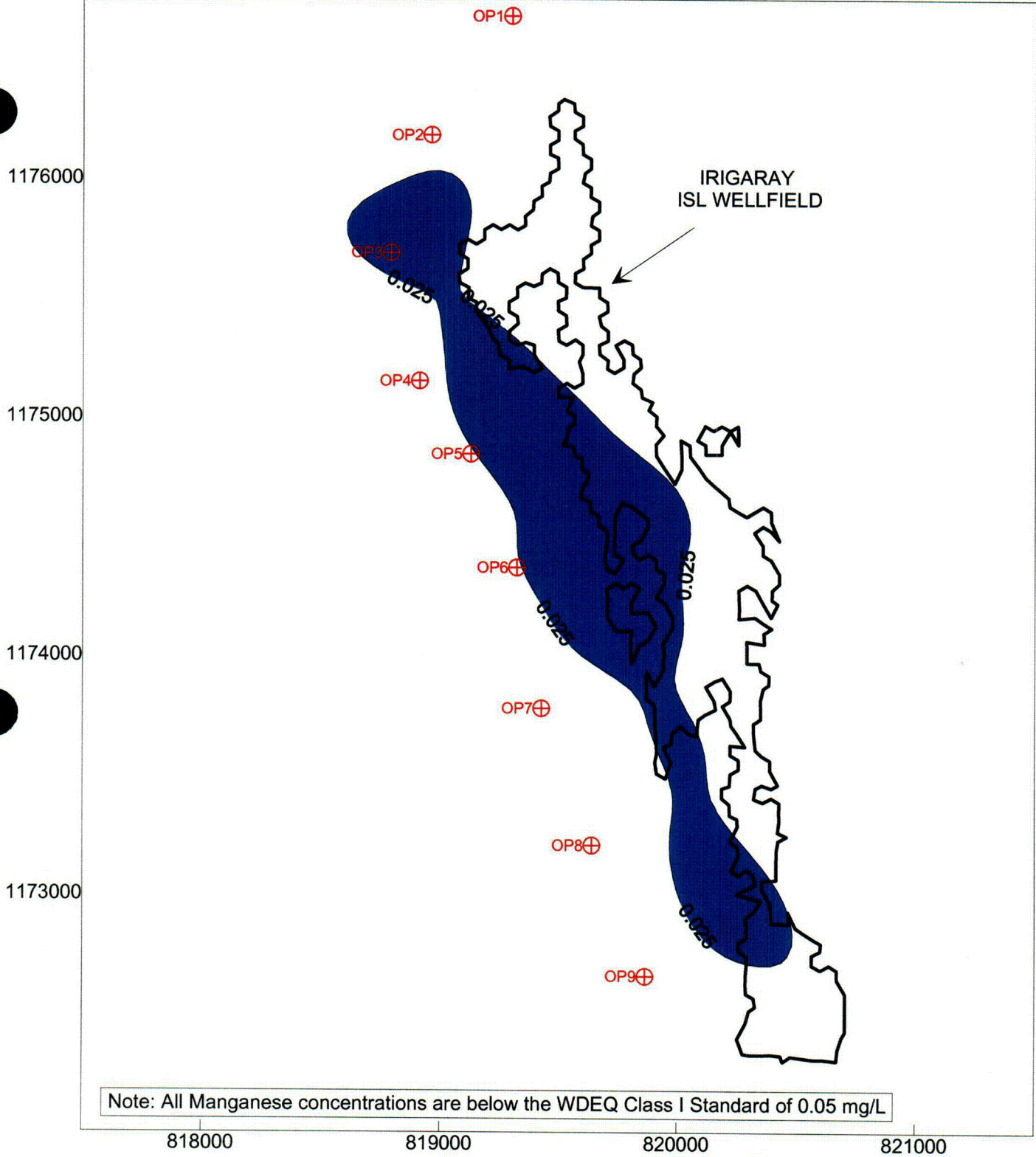
DWG: COGEMAFIG5-13r.srf

BY: EPL

CHECKED: HPD

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# **LEGEND**

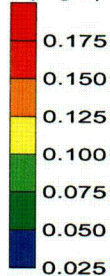


SCALE IN FEET 1" = 600'  
CONTOUR INTERVAL = 0.025 mg/L

⊕ Observation point for simulated concentrations  
(400 feet from wellfield)



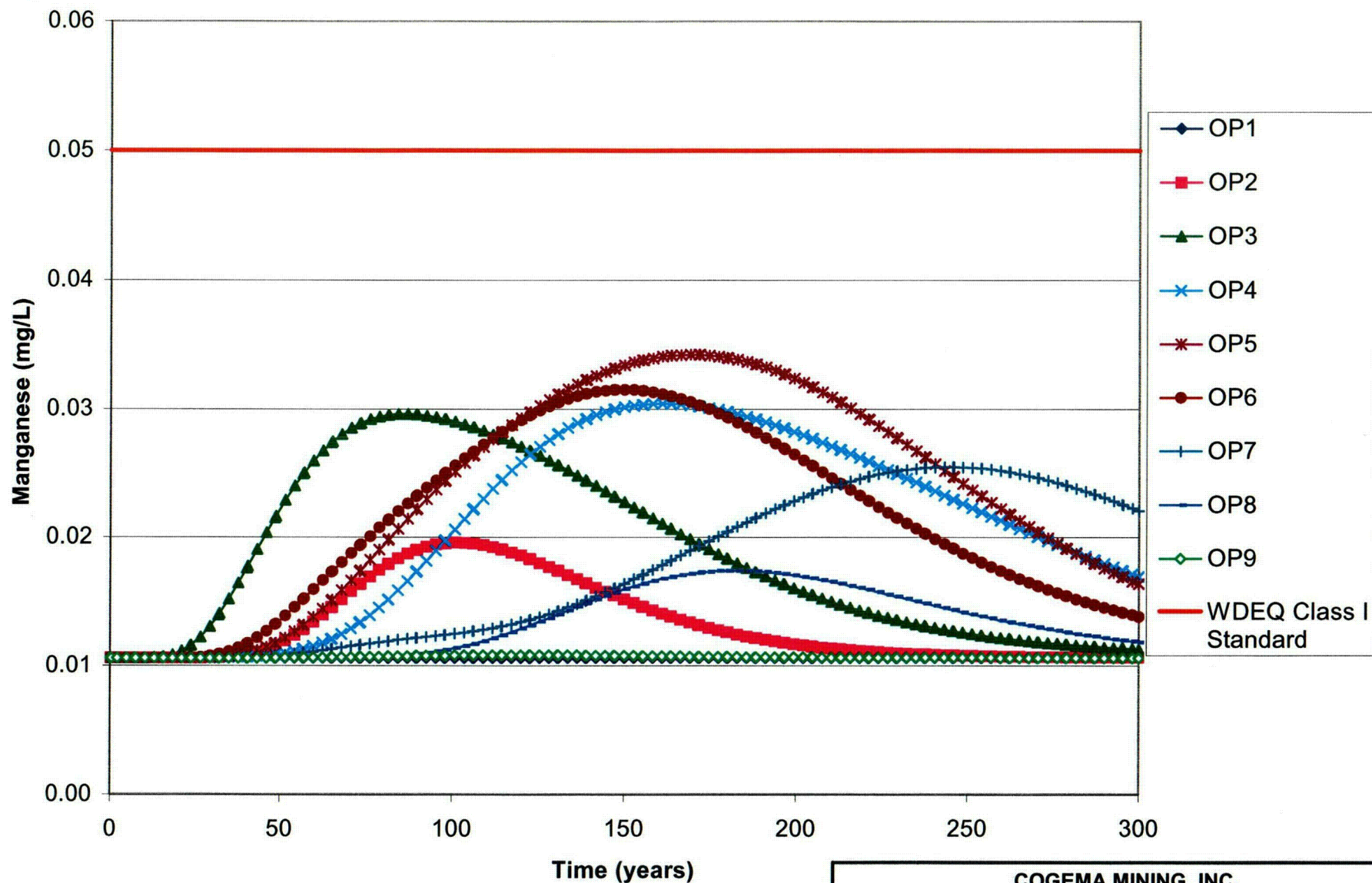
Mn (mg/L)



## **COGEMA MINING, INC. IRIGARAY MINE**

**FIGURE 5-14  
MANGANESE DISTRIBUTION AT 100 YEARS  
IRIGARAY ISL WELLFIELD**

PROJECT: CMI/IRIGARAY	DATE: MAY 2002
DWG: COGEMAFIG5-14r.SRF	BY: EPL CHECKED: HPD
<b>PETROTEK ENGINEERING CORPORATION</b>	
9088 South Ridgeline Blvd., Suite 105 Littleton, Colorado 80129 (303) 290-9414	



LOCATION OF OBSERVATION POINTS SHOWN ON FIGURE 5-6

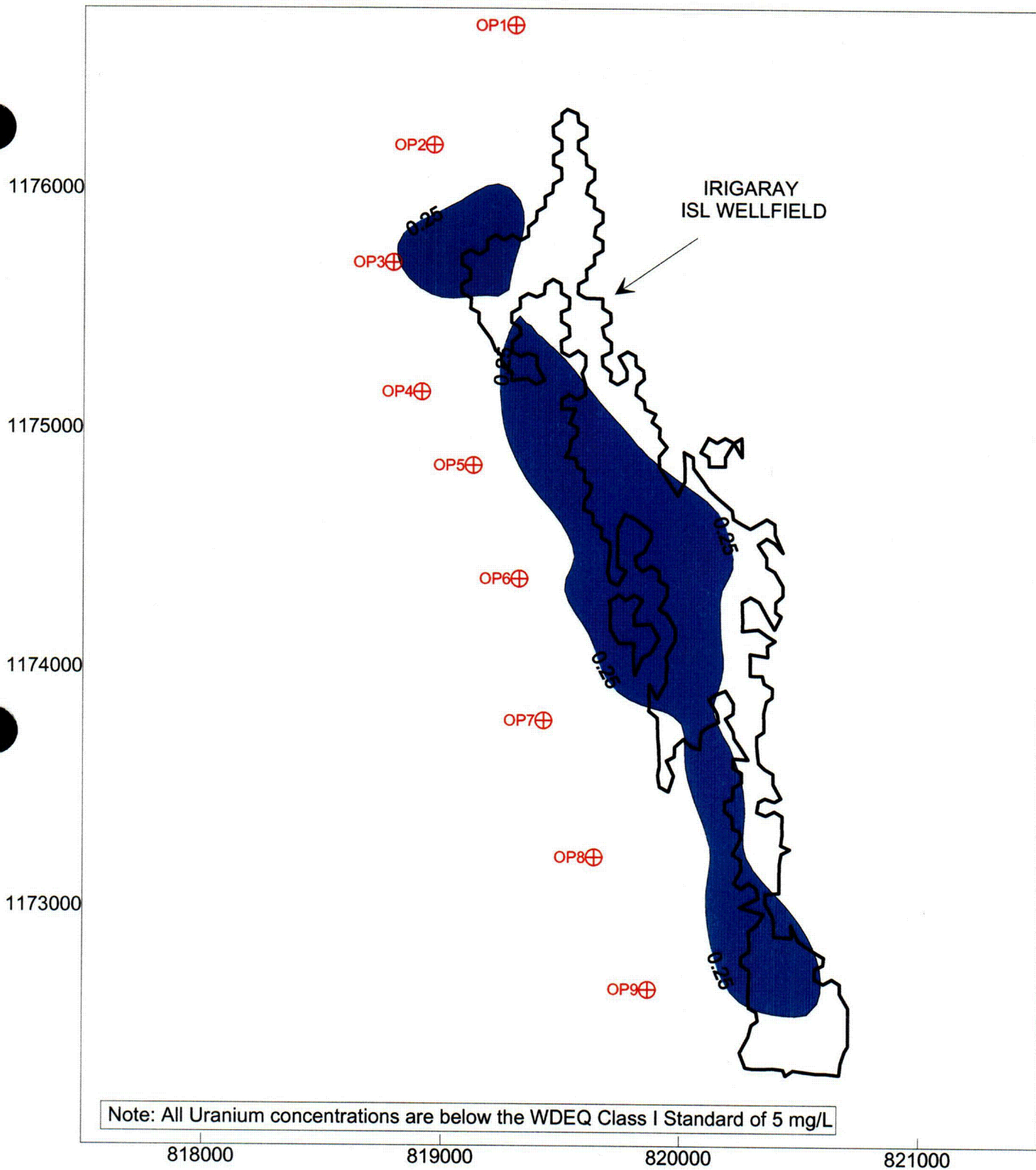
**COGEMA MINING, INC.  
IRIGARAY MINE**

**FIGURE 5-15**  
MODELED MANGANESE CONCENTRATION vs TIME  
AT OBSERVATION POINTS 400 FEET FROM WELLFIELD

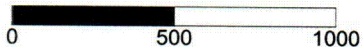
PROJECT: CMI/IRIGARAY	DATE: MAY 2002
DWG: COGEMAFIG5-15r.srf	BY: EPL CHECKED: HPD

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# **LEGEND**



SCALE IN FEET 1" = 600'

CONTOUR INTERVAL = 0.25 mg/L

⊕ Observation point for simulated concentrations (400 feet from wellfield)



U (mg/L)



## **COGEMA MINING, INC. IRIGARAY MINE**

**FIGURE 5-16  
URANIUM DISTRIBUTION AT 300 YEARS  
IRIGARAY ISL WELLFIELD**

PROJECT: CMI/IRIGARAY

DATE: MAY 2002

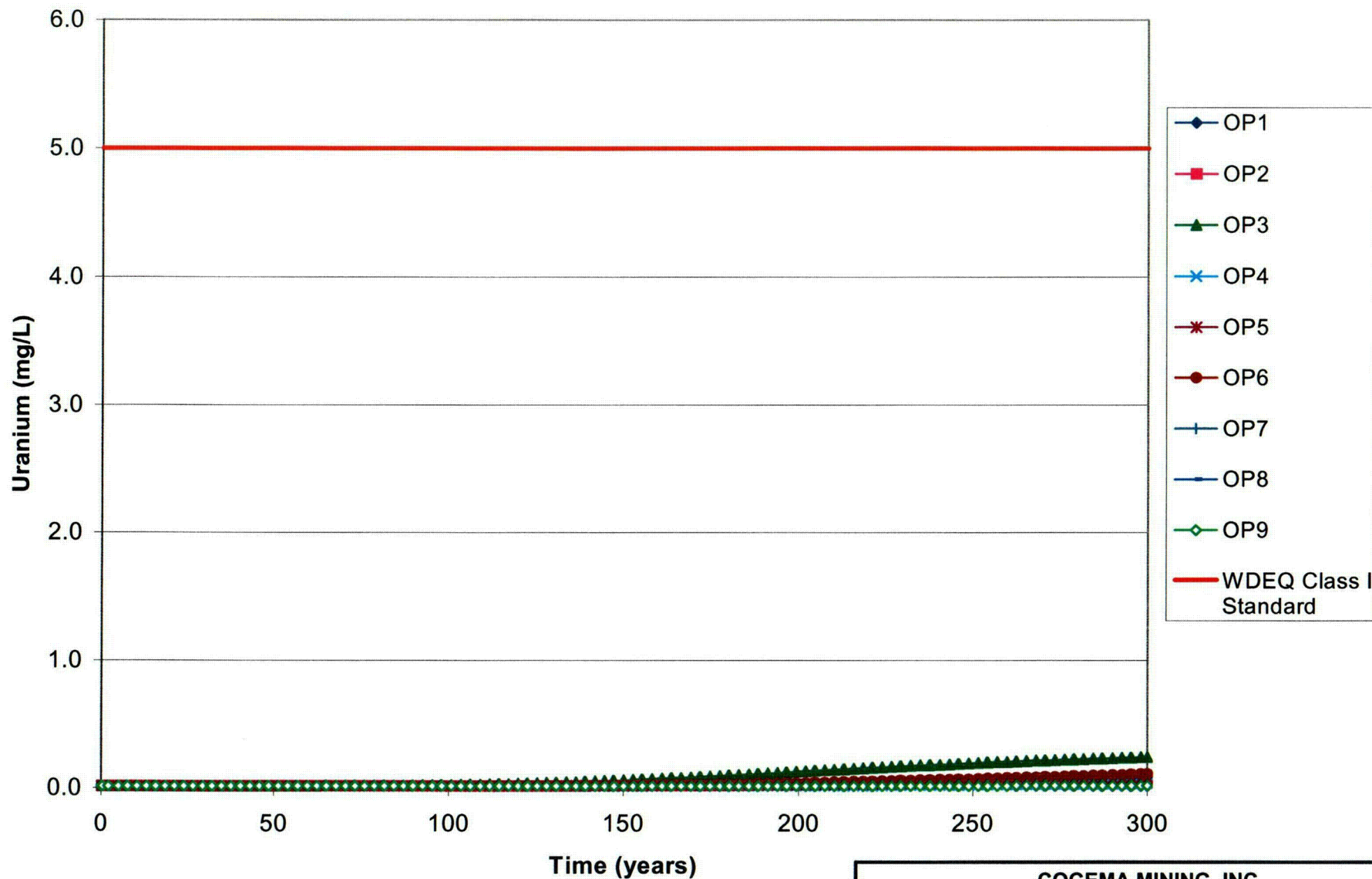
DWG: COGEMAFIG5-16r.SRF

BY: EPL

CHECKED: HPD

## **PETROTEK ENGINEERING CORPORATION**

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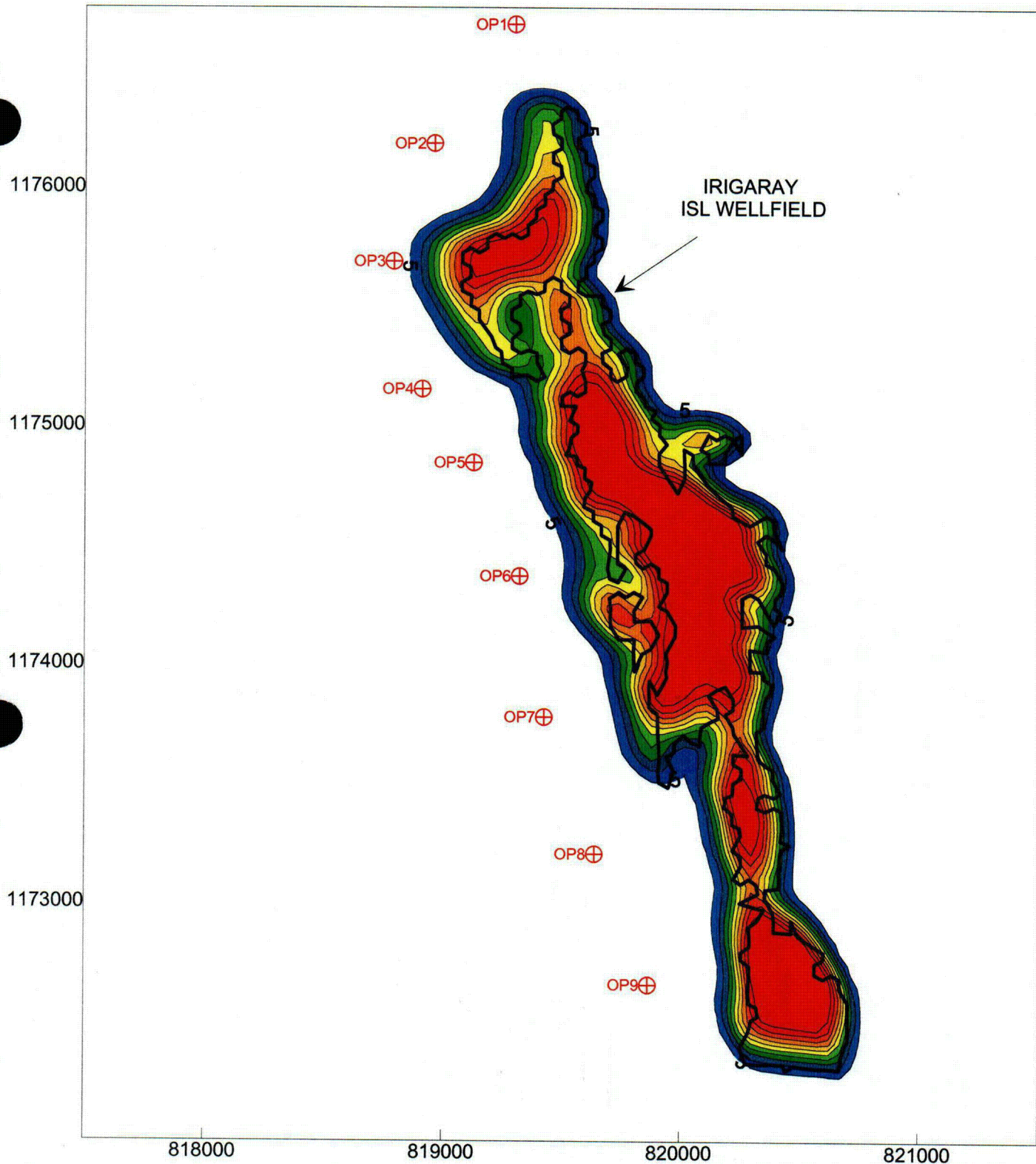
LOCATION OF OBSERVATION POINTS SHOWN ON FIGURE 5-6

**COGEMA MINING, INC.  
IRIGARAY MINE**

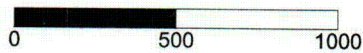
**FIGURE 5-17  
MODELED URANIUM CONCENTRATION vs TIME  
AT OBSERVATION POINTS 400 FEET FROM WELLFIELD**

PROJECT: CMI/IRIGARAY	DATE: MAY 2002
DWG: COGEMAFIG5-17r.srf	BY: EPL      CHECKED: HPD

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# **LEGEND**

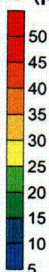


SCALE IN FEET 1" = 600'

CONTOUR INTERVAL = 5 pCi/L

⊕ Observation point for simulated concentrations  
(400 feet from wellfield)

Ra-226 (pCi/L)



## **COGEMA MINING, INC. IRIGARAY MINE**

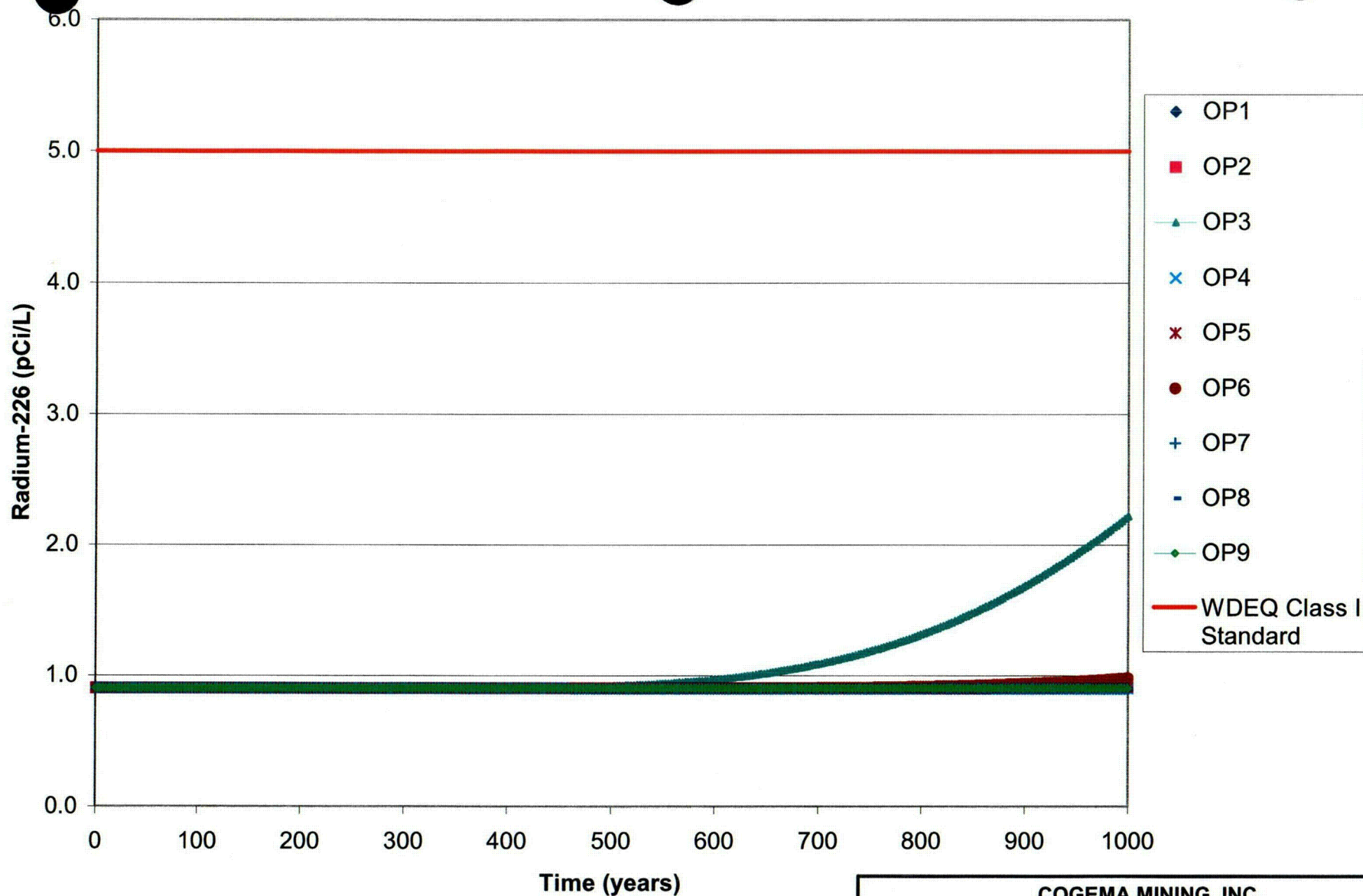
**FIGURE 5-18  
RADIUM-226 DISTRIBUTION AT 1000 YEARS  
IRIGARAY ISL WELLFIELD**

PROJECT: CMI/IRIGARAY DATE: MAY 2002

DWG: COGEMAFIG5-18r.SRF BY: EPL CHECKED: HPD

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LOCATION OF OBSERVATION POINTS SHOWN ON FIGURE 5-6

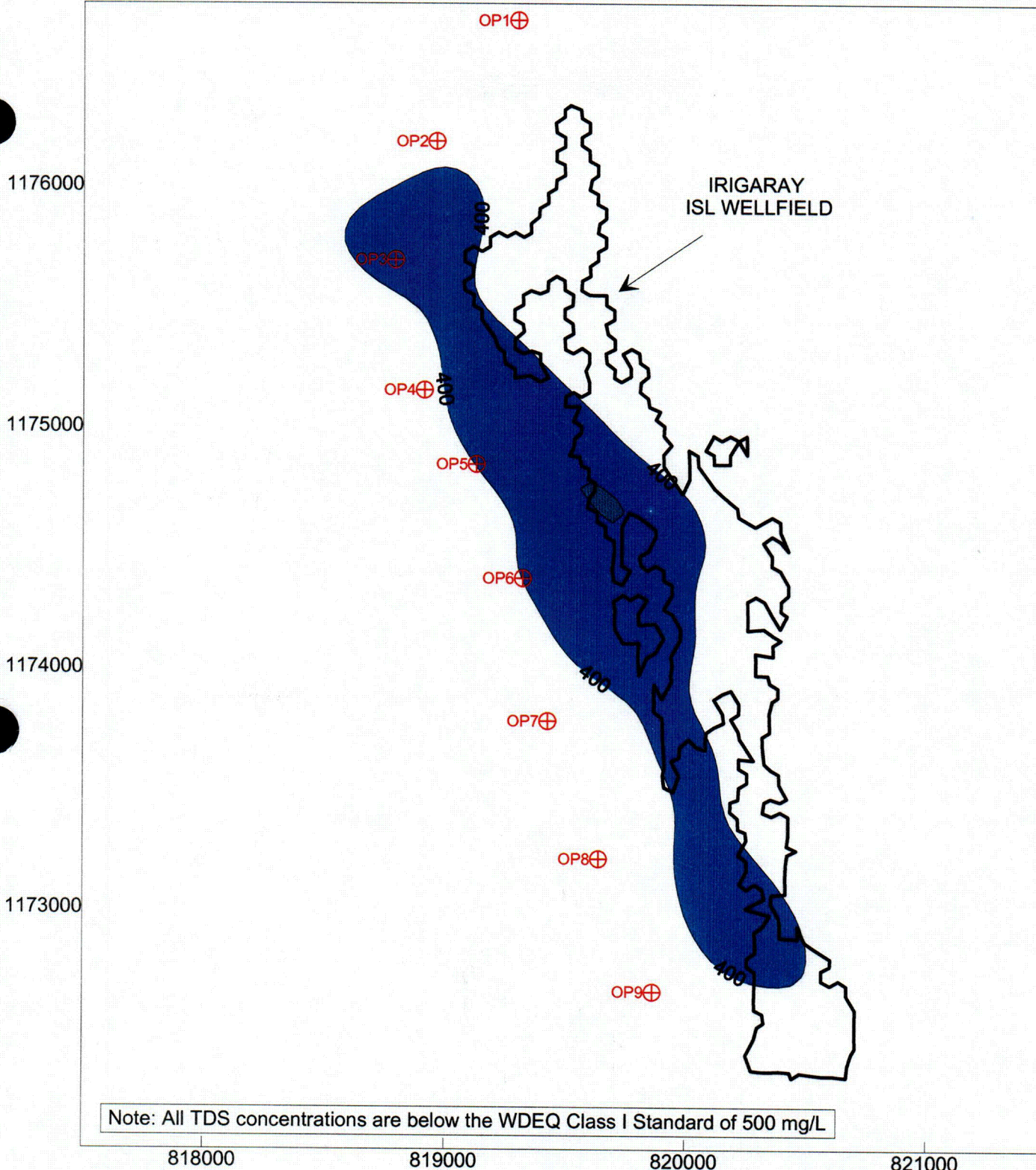
**COGEMA MINING, INC.  
IRIGARAY MINE**

**FIGURE 5-19  
MODELED RADIUM-226 CONCENTRATION vs TIME  
AT OBSERVATION POINTS 400 FEET FROM WELLFIELD**

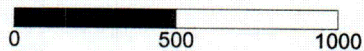
PROJECT: CMI/IRIGARAY	DATE: MAY 2002
DWG: COGEMAFIG5-19r.srf	BY: EPL CHECKED: HPD

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**LEGEND**

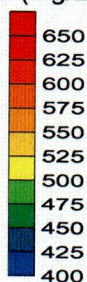


SCALE IN FEET 1" = 600'

CONTOUR INTERVAL = 25 mg/L

⊕ Observation point for simulated concentrations  
(400 feet from wellfield)

TDS (mg/L)



**COGEMA MINING, INC.  
IRIGARAY MINE**

**FIGURE 5-20  
TOTAL DISSOLVED SOLIDS DISTRIBUTION AT 100 YEARS  
IRIGARAY ISL WELLFIELD**

PROJECT: CMI/IRIGARAY

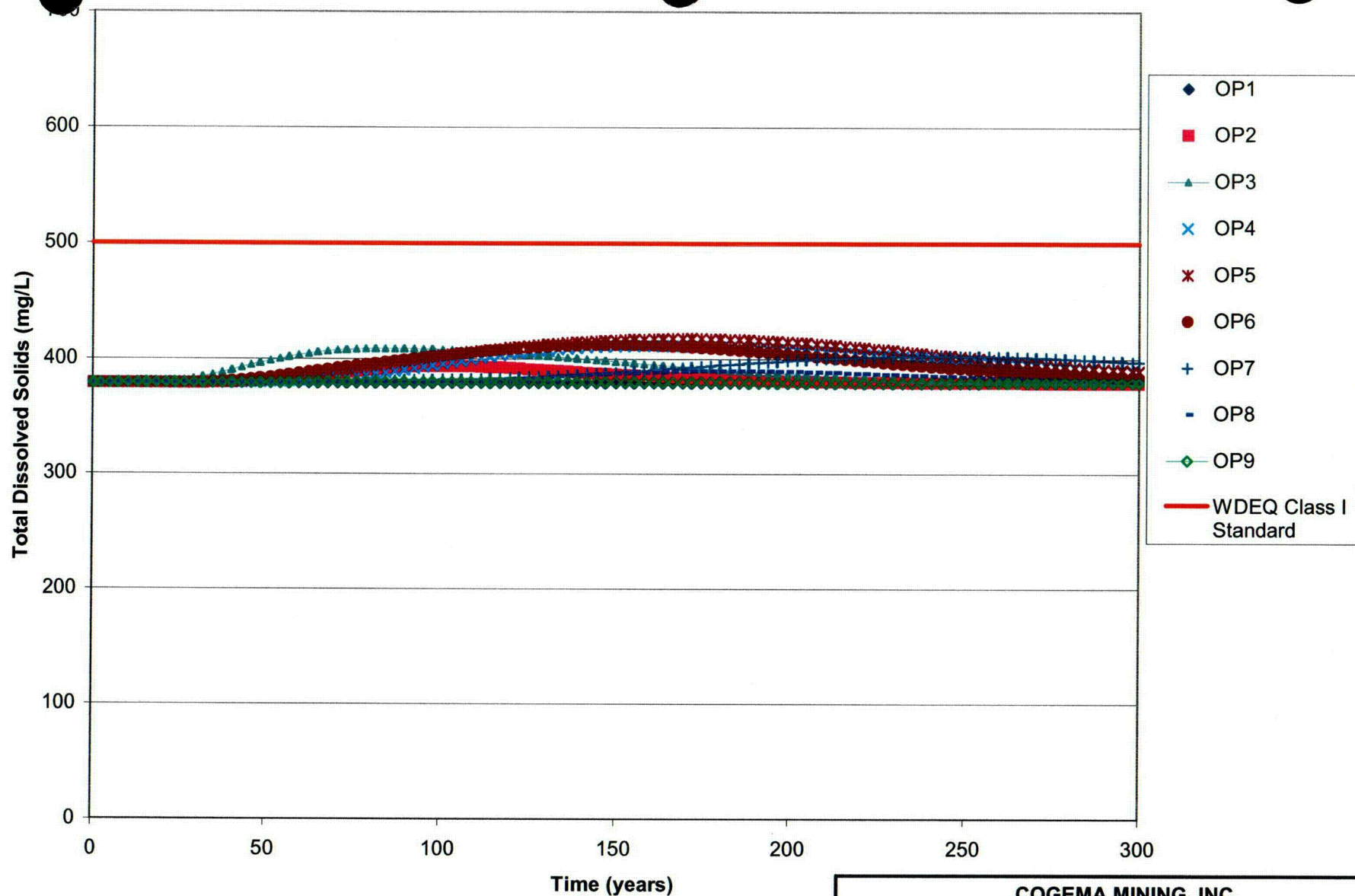
DATE: MAY 2002

DWG: COGEMAFIG5-20r.SRF

BY: EPL CHECKED: HPD

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LOCATION OF OBSERVATION POINTS SHOWN ON FIGURE 5-6

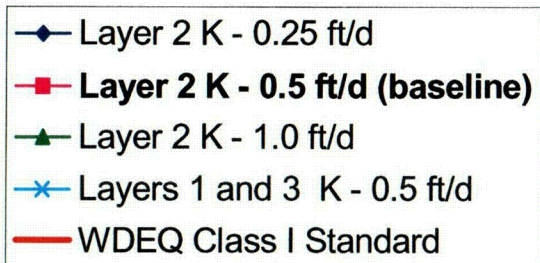
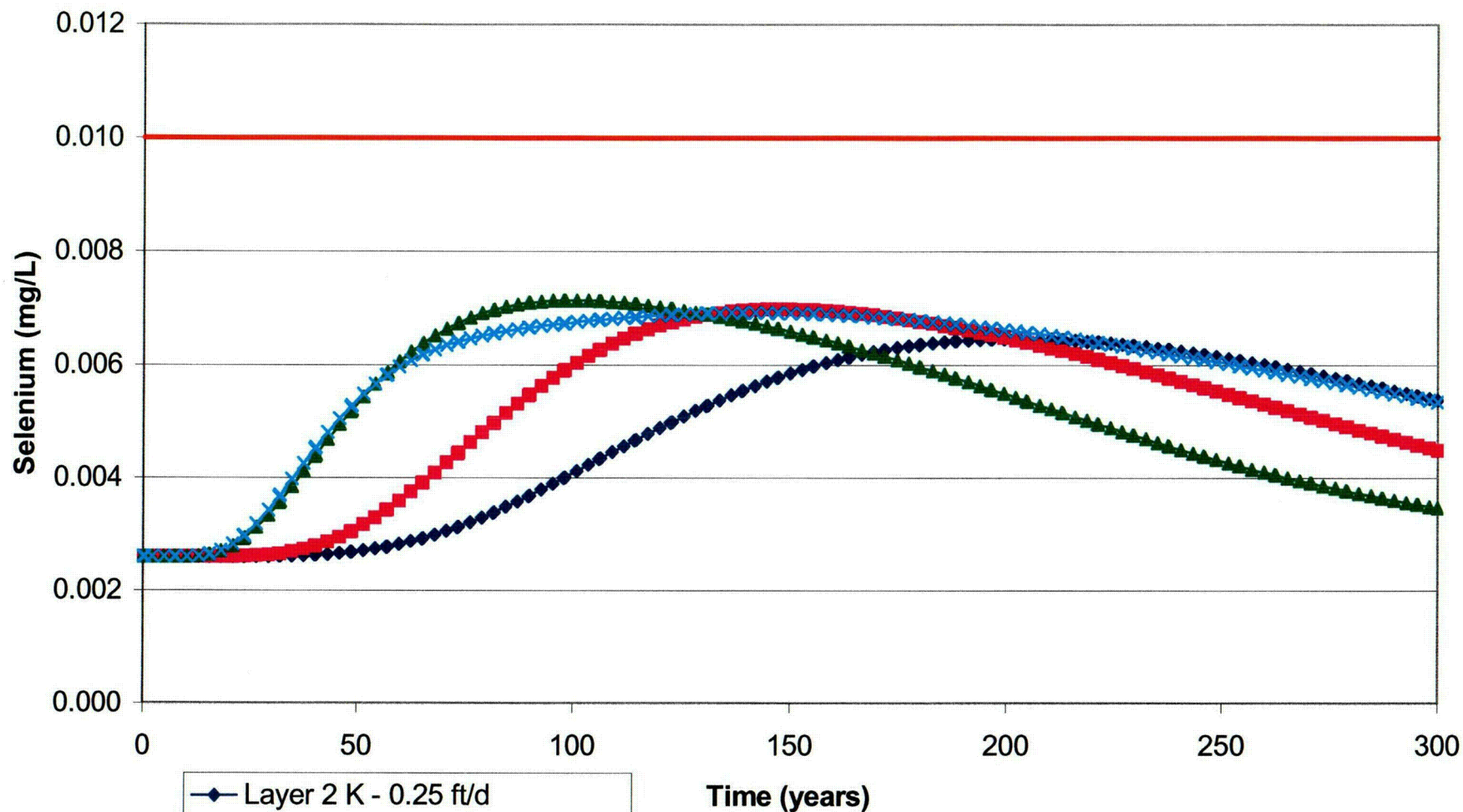
**COGEMA MINING, INC.  
IRIGARAY MINE**

**FIGURE 5-21**  
**MODELED TDS CONCENTRATION vs TIME**  
**AT OBSERVATION POINTS 400 FEET FROM WELLFIELD**

PROJECT: CMI/IRIGARAY	DATE: MAY 2002
DWG: COGEMAFIG5-21r.srf	BY: EPL CHECKED: HPD

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**FIGURE 5-22  
SENSITIVITY ANALYSIS-HYDRAULIC CONDUCTIVITY  
SELENIUM AT OBSERVATION POINT OP3**

PROJECT: CMI/IRIGARAY

DATE: JUNE 2002

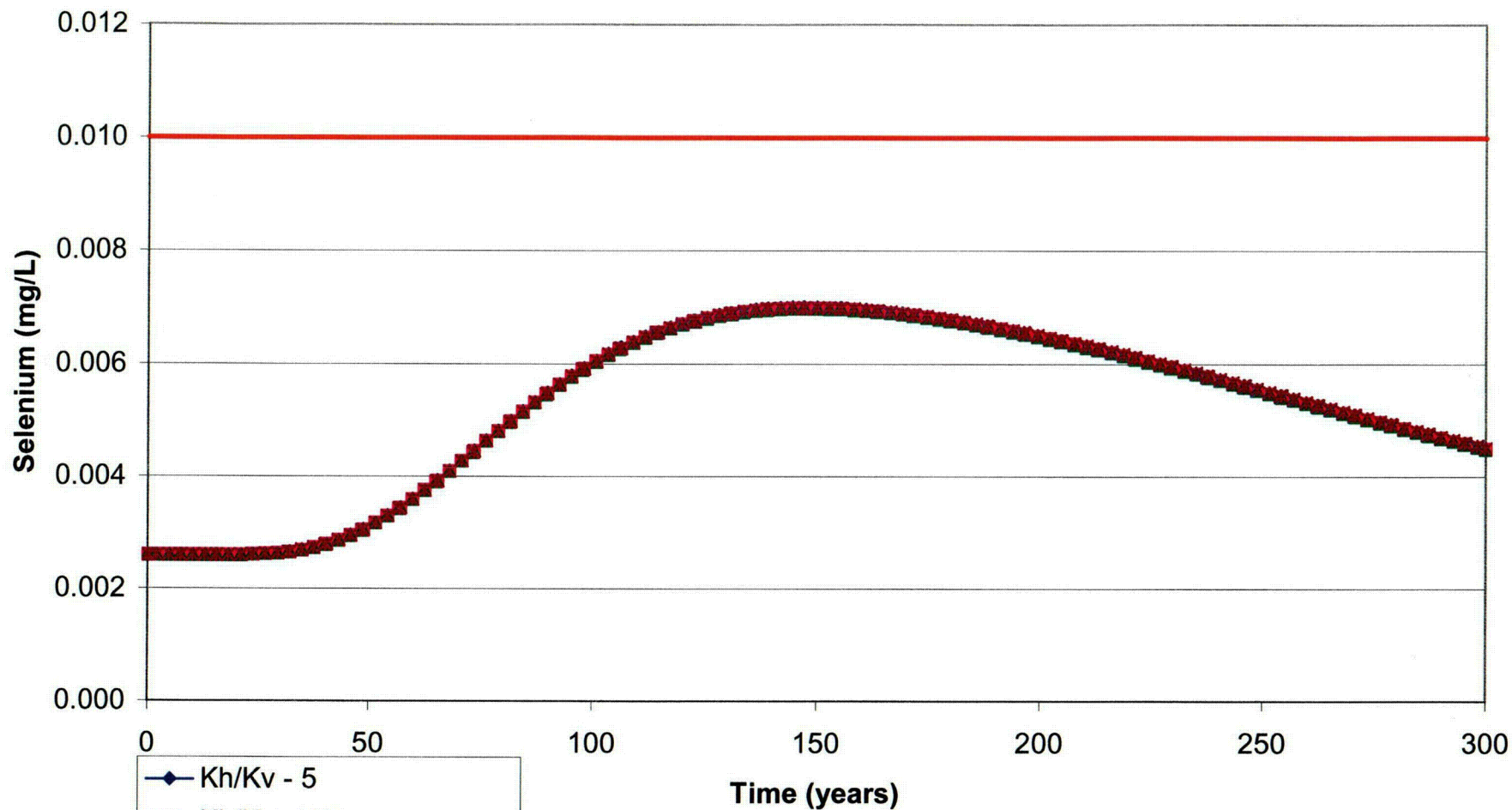
DWG: COGEMAFIG5-22r.srf

BY: EPL

CHECKED: HPD

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- ◆ Kh/Kv - 5
- Kh/Kv - 7.5
- ▲ Kh/Kv - 10 (baseline)
- ✕ Kh/Kv - 20
- \* Kh/Kv - 30
- WDEQ Class I Standard

**COGEMA MINING, INC.  
IRIGARAY MINE**

FIGURE 5-23  
SENSITIVITY ANALYSIS-HORIZONTAL/VERTICAL HYDRAULIC CONDUCTIVITY RATIO  
SELENIUM AT OBSERVATION POINT OP3

PROJECT: CMI/IRIGARAY  
DWG: COGEMAFIG5-23.srf

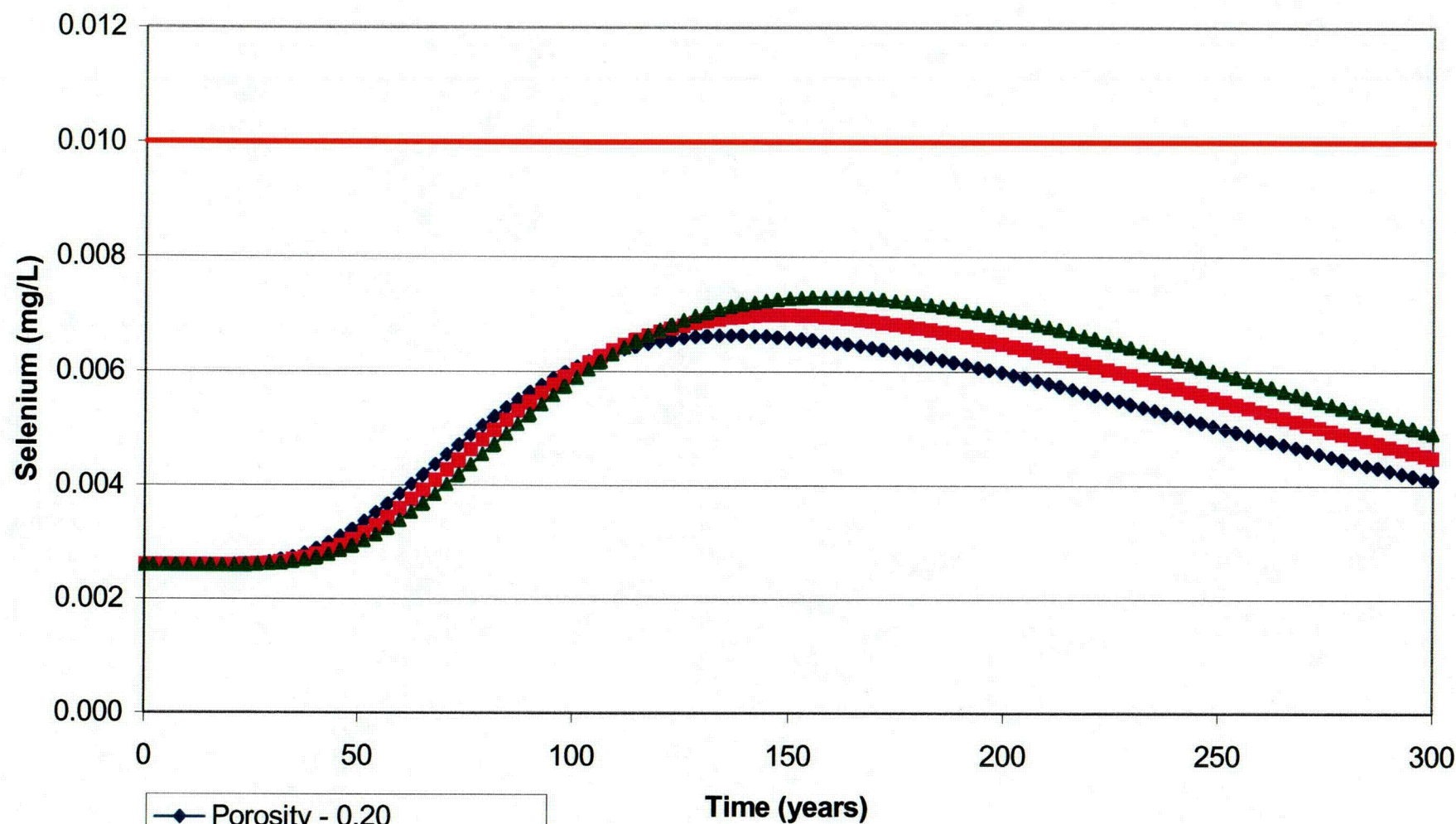
DATE: JUNE 2002

BY: EPL

CHECKED: HPD

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◆ Porosity - 0.20  
 ■ Porosity - 0.25 (baseline)  
 ▲ Porosity - 0.30  
 — WDEQ Class I Standard

**COGEMA MINING, INC.  
IRIGARAY MINE**

**FIGURE 5-24  
SENSITIVITY ANALYSIS-POROSITY (LAYER 2)  
SELENIUM AT OBSERVATION POINT OP3**

PROJECT: CMI/IRIGARAY

DATE: JUNE 2002

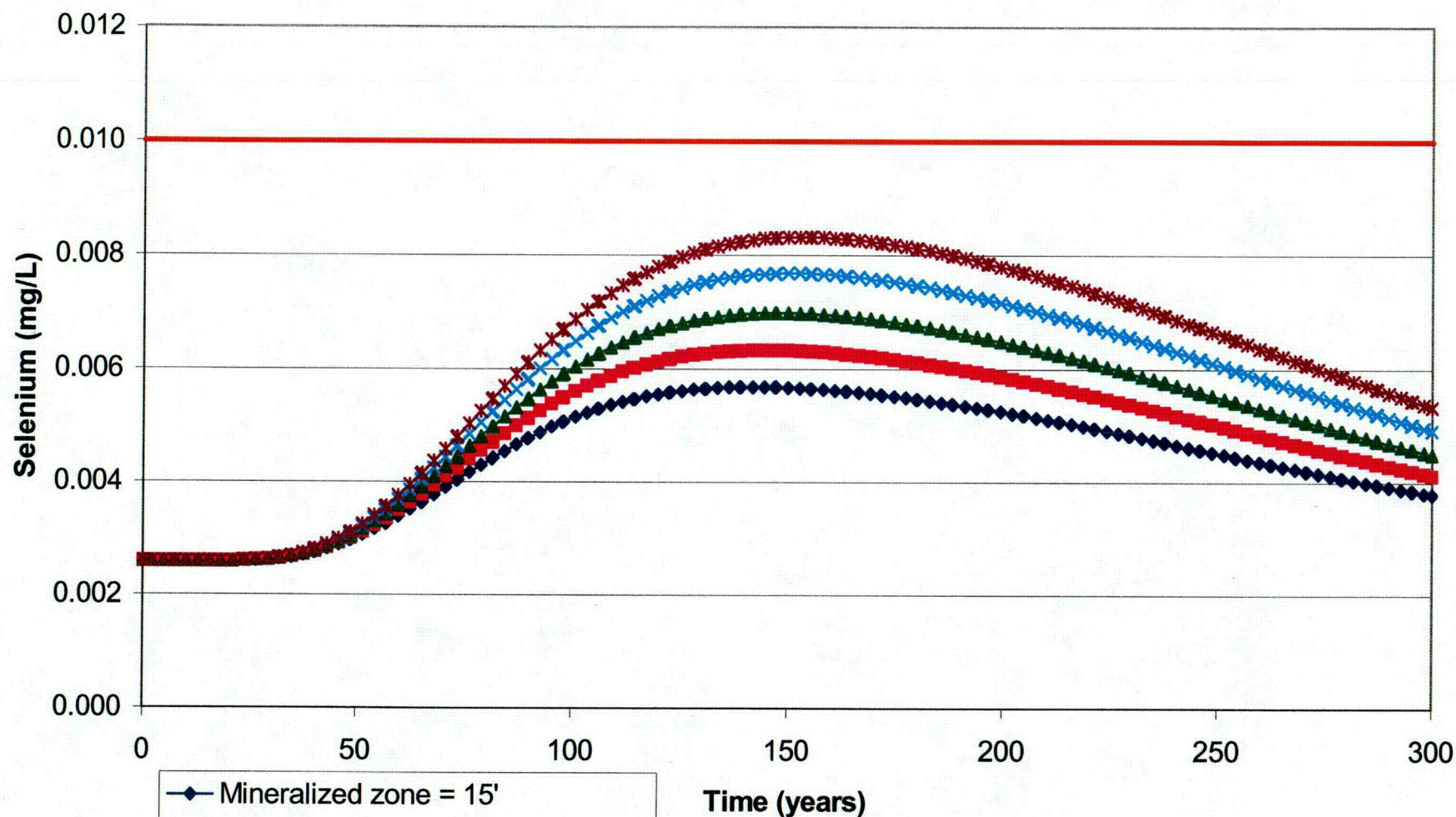
DWG: COGEMAFIG5-24.srf

BY: EPL

CHECKED: HPD

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- ◆ Mineralized zone = 15'
- Mineralized zone = 18'
- ▲ Mineralized zone = 21' (baseline)
- ✕ Mineralized zone = 24'
- \* Mineralized zone = 27'
- WDEQ Class I Standard

**COGEMA MINING, INC.  
IRIGARAY MINE**

**FIGURE 5-25**  
SENSITIVITY ANALYSIS-MINERALIZED ZONE THICKNESS  
SELENIUM AT OBSERVATION POINT OP3

PROJECT: CMI/IRIGARAY

DATE: MAY 2002

DWG: COGEMAFIG5-25r.srf

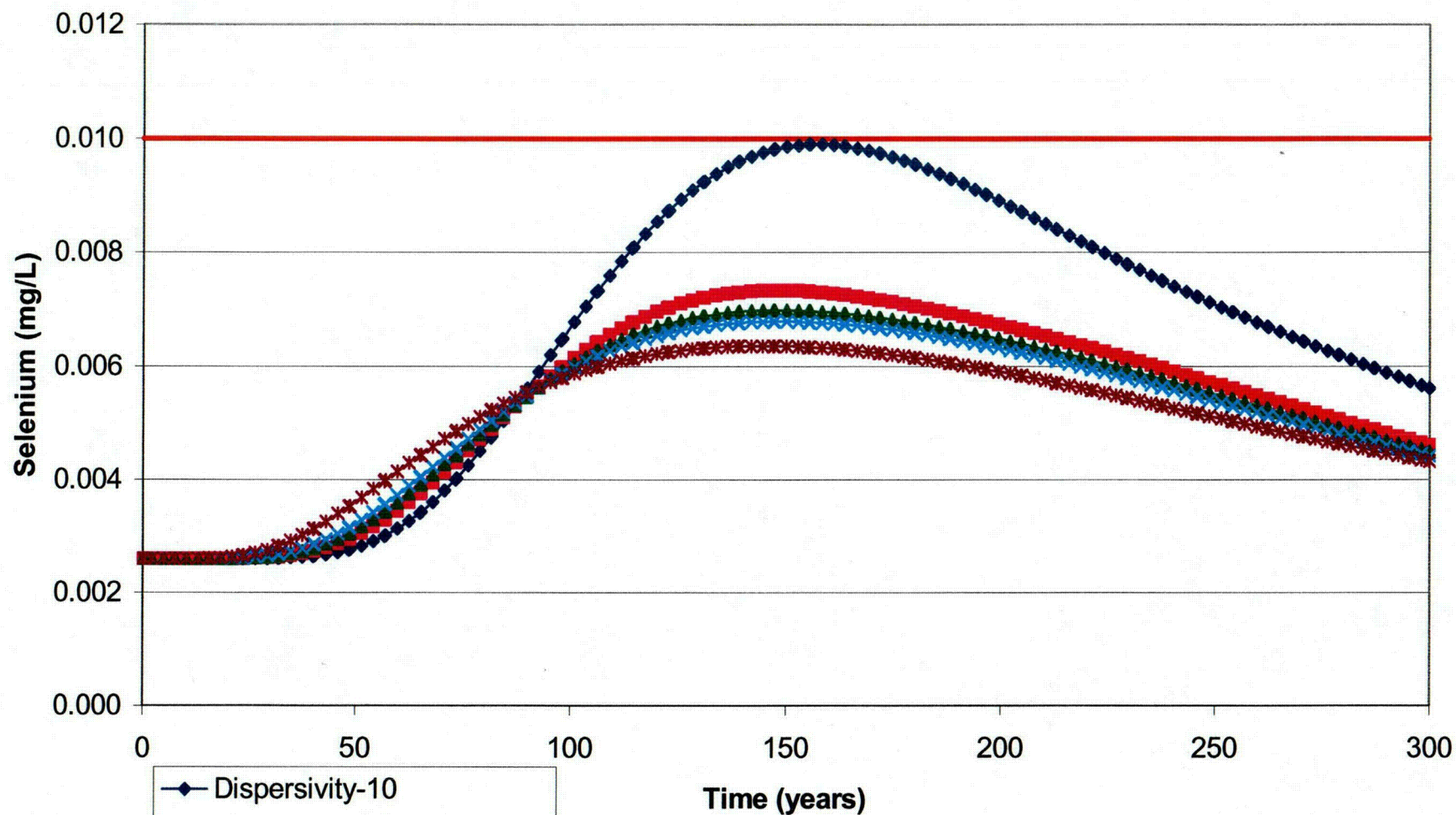
BY: EPL

CHECKED: HPD

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41



- ◆ Dispersivity-10
- Dispersivity-20
- ▲ Dispersivity-25 (baseline)
- ✧ Dispersivity-30
- ✱ Dispersivity-50
- WDEQ Class I Standard

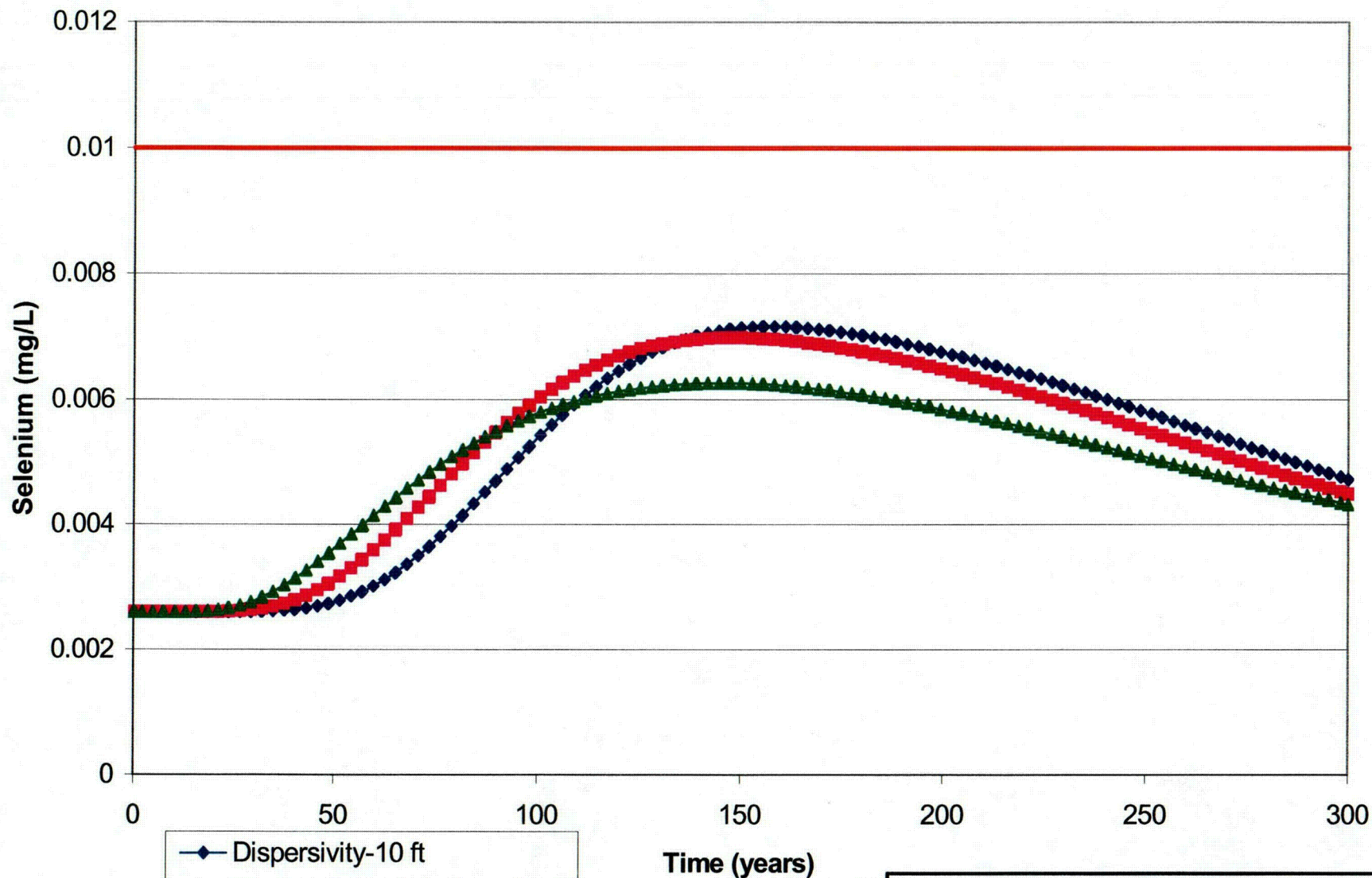
**COGEMA MINING, INC.  
IRIGARAY MINE**

**FIGURE 5-26  
SENSITIVITY ANALYSIS-DISPERSIVITY  
SELENIUM AT OBSERVATION POINT OP3**

PROJECT: CMI/IRIGARAY  
DWG: COGEMAFIG5-26r.srf

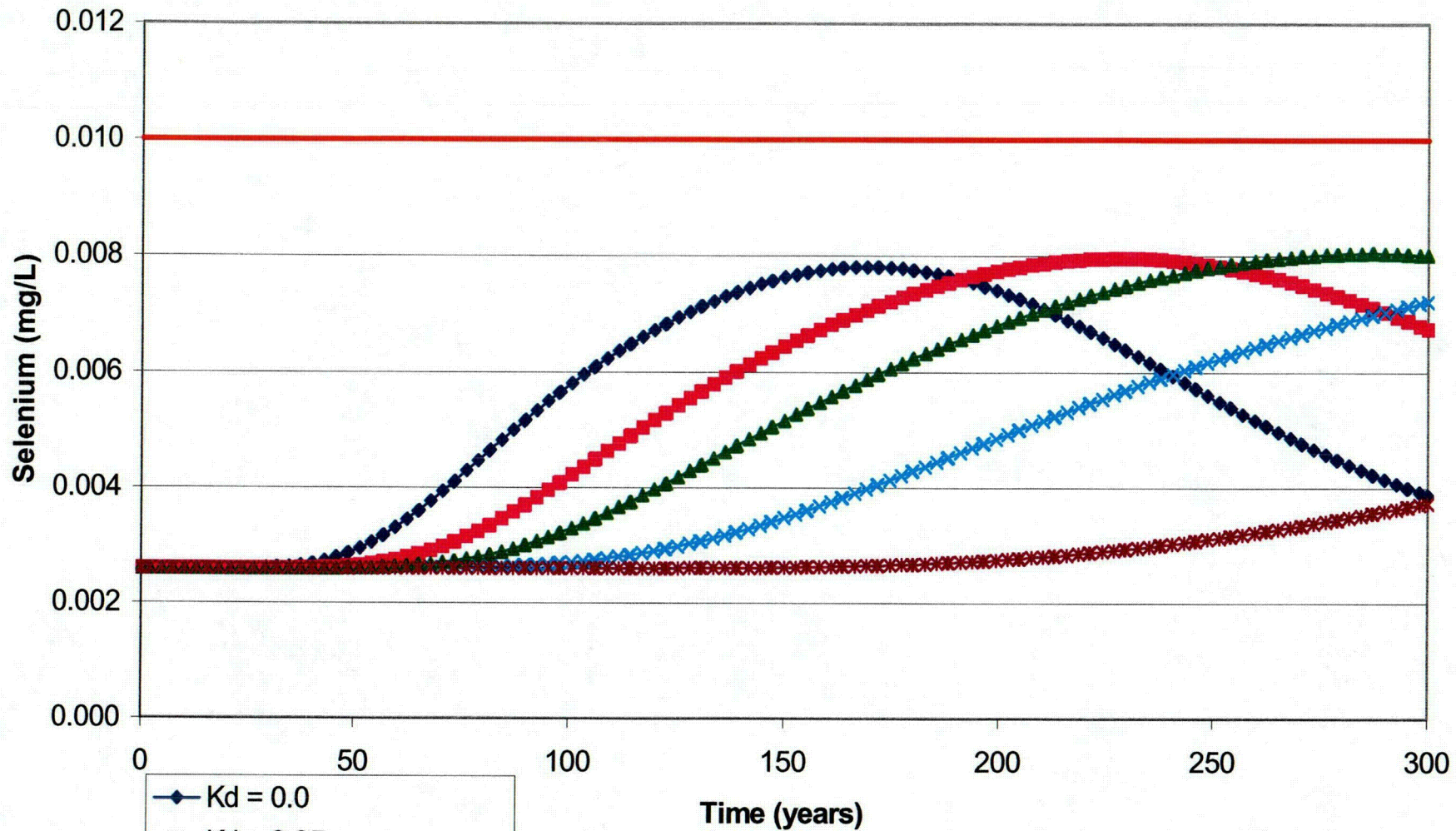
DATE: MAY 2002  
BY: EPL CHECKED: HPD

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- ◆ Dispersivity-10 ft
- Dispersivity-25 ft (baseline)
- ▲ Dispersivity-50 ft
- WDEQ Class I Standard

<b>COGEMA MINING, INC.</b>		
<b>IRIGARAY MINE</b>		
FIGURE 5-27		
SENSITIVITY OF DISPERSIVITY ON AVERAGE (WEIGHTED) SELENIUM CONCENTRATION		
MODELED AQUIFER AT OBSERVATION POINT OP3		
PROJECT: CMI/IRIGARAY	DATE: MAY 2002	
DWG: COGEMAFIG5-27r.srf	BY: EPL	CHECKED: HPD
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**COGEMA MINING, INC.  
IRIGARAY MINE**

**FIGURE 5-28  
SENSITIVITY ANALYSIS-DISTRIBUTION COEFFICIENT (Kd)  
SELENIUM AT OBSERVATION POINT OP3**

PROJECT: CMI/IRIGARAY  
DWG: COGEMAFIG5-28r.srf

DATE: MAY 2002  
BY: EPL  
CHECKED: HPD

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C44