Prepared for:

UNITED NUCLEAR CORP.

Gallup, New Mexico

SUPPLEMENTAL FEASIBILITY STUDY

ZONE 3 HYDROSTRATIGRAPHIC UNIT

CHURCH ROCK

URANIUM MILL TAILING SITE

October 2004

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1.0 PROJECT BACKGROUND

This Supplemental Feasibility Study (SFS) for the Zone 3 hydrostratigraphic unit at the United Nuclear Church Rock Site (the Site) was conducted pursuant to a U.S. Environmental Protection Agency (USEPA) request dated March 10, 2004. The Site remedy as put forth in USEPA's 1989 Record of Decision includes pumping of impacted groundwater and its disposal of using on-site evaporation ponds. USEPA directed UNC to temporarily suspend Zone 3 pumping in November 2000, and this was reflected in the December 29, 2000 amendment to the Nuclear Regulatory Commission (NRC) Source Materials License. The existing remedial system was not adequately controlling the movement of seepage-impacted water.

The objective of the SFS is to develop conceptual alternatives and/or enhancements to the existing remedy that would better contain, and ideally withdraw, seepage-impacted groundwater.

The SFS was conducted in the phases as shown below following the conceptual development of alternatives, screening, testing, and detailed analysis as presented in the USEPA's "Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA (USEPA, 1989). Results from each phase were used as input into subsequent phases and analyses.

Phase 1 –Identification and Screening of Alternatives
Phase 2 – Detailed Hydraulic Analysis and Modeling of Alternatives for Further Screening
Phase 3 – Comparative Analysis and Development of Recommendations
Phase 4 – Pilot Study of Hydraulic Fracturing to Enhance Seepage Recovery Rates
Phase 5 – Detailed Analysis of Alternatives and Additional Modeling

A cross-functional team with experience in geology, hydrology, geochemistry, geotechnical engineering, and mine reclamation conducted the Phase 1 identification and screening of alternatives An initial list of alternatives was developed in June 2002. The alternatives identification process included screening of alternatives relative to effectiveness, public acceptance, time for completion, regulatory permitting requirements, and cost. Alternatives were screened using the Criterion Decision Plus (CDP) model relative to the criteria developed by UNC and MWH during the June 2002 creativity session. Based on this analysis, the following initial list of alternatives for evaluation was developed:

1. Monitored Natural Attenuation (MNA)

2. In-situ Geochemical Fixation

3. Tunnel (with optional side drifts)

4. Open Pit

5. Enhanced Well Field

6. Cut-off/Containment Wells

7. Large Diameter Vertical Well/Shaft with a Radial Horizontal Collection Fan (Ranney-type Well)

8. Directionally-drilled (horizontal) well

Based on the initial screening, natural attenuation and in-situ geochemical remediation (Alternatives 1 and 2) were dropped from further analysis for the reasons discussed below. Limited natural attenuation takes place at the site due to the reaction of the tailings seepage-impacted water with alkalinity in the aquifer, but this process has been insufficient to prevent further migration of the plume and, therefore, natural attenuation is not currently a solely acceptable remedy at the site.

The in-situ remedy, which would involve injection of alkalinity into the Zone 3 hydrostratigraphic unit, was dropped from further consideration due to the lack of reliability of this approach. Conceptually, this remedy would work by raising the pH of the system through the reaction of low pH groundwater with an alkaline source introduced via injection wells. Raising the pH would lower the solubility of dissolved constituents (such as metals and actinides) and these constituents would be precipitated as minerals. The effectiveness of this remedy would depend on introducing sufficient alkalinity to attenuate acidity within the impacted groundwater to the extent required to achieve circumneutral conditions and mineral precipitation. This would require introducing sufficient alkalinity through injection wells and effectively mixing the injected water with impacted groundwater. The effectiveness of this alternative is limited by hydraulic conditions within the Zone 3 hydrostratigraphic unit which would: 1) limit the effective radius of influence of the reactant introduced into the system due to the moderate permeability of the formation; and 2) result in fouling and blocking off of the aquifer due to the blockage of pore spaces by precipitated minerals. The ability of the in-situ remedy to prevent plume migration was considered to be poor because hydraulic and geochemical conditions in the aquifer would prevent the complete reaction of the plume with the chemical agent. Therefore, it was not carried forward in the SFS.

The Phase 2 hydraulic analysis and modeling of alternatives for further ranking was conducted by developing a conceptual hydrogeologic model for the site and using it to run MODFLOW simulations of each alternative. Results from this analysis are reported in Sections 2 and 3 of this SFS. The results of the hydraulic model were used in the Criterion Decision Plus (CDP) model to rank the alternatives. The CDP model allows the user to weight the relative importance of the criteria used to rank the alternatives and then combines them to produce a formal ranking. CDP also employs a probabilistic analysis that takes into account the relative uncertainty that exists with respect to assigning values to the criteria. Using the hydraulic analysis and CDP model, each alternative was ranked based on the criteria outlined below.

- Effectiveness: Ability of the alternative to effectively dewater the plume five years after implementation. Effectiveness is a combined measure of the effectiveness of the remedy with time, technical implementability, and a measure of the reduction in toxicity, mobility or volume through treatment.

- Cost: Only capital costs of each alternative need to be compared. Operations and Maintenance (O&M) costs are approximately the same for all alternatives because all require similar effort to operate, maintain, monitor, and report the activities at the Site.

- Environmental Impact: Environmental impacts associated with alternative.

- Regulatory Permitting: Amount of regulatory interaction and permitting required for alternative.

- Public Acceptance: Issues associated with alternative that may reduce its acceptance by the public.

The criteria embody the "effectiveness, implementability and cost criteria" contained in EPA's guidance with weighting and focus adjusted for conditions specific to Church Rock.

Phase 3 of the SFS involved reporting of results from the hydraulic analysis to UNC and development of recommendations. Prior to this meeting, the hydraulic model developed by MWH was peerreviewed by Dr. James Ewart at US Filter and deemed to be acceptable for the screening-level analysis.

An outcome from Phase 3 was to recommend a pilot study to evaluate enhancement of Alternatives 5 and 6 (Enhanced Well Field and Cut-off/Containment wells, respectively) using the hydraulic fracturing technique to enhance permeability and groundwater recovery. Alternative 3 (tunneling) was retained as the backup, if required. These studies were conducted in Phase 4 and results from the pilot study are provided in Section 4. Results from additional modeling conducted to evaluate data from the hydraulic fracturing studies are provided in Section 5. The detailed analysis of alternatives is provided in Section 6, and a summary of the SFS and recommendations for the modified remedy proposed as a result of the SFS process is provided in Section 7.

2.0 CONCEPTUAL HYDROGEOLOGIC MODEL

The location of the site is shown in Figure 1, *Site Location Map*, and the layout of seepage-impacted groundwater in Zone 3 is displayed in Figure 2, *Site Layout*. The hydraulic modeling for the alternatives was performed in 2002, and since then, there have been further studies (US Filter, 2004) that have better defined the leading edge of the plume. Although the plume configuration is different, the modeling results remain valid for the intended purpose, which was to choose the best method for improving the former remedy. The 2002 model can be used to compare the alternatives; however, if the model were eventually to be applied during the detailed design process, the model would be updated with the plume configuration that is most current. Therefore, Figure 2 depicts the plume boundary based on 2003 data as well as the plume configuration used during the 2002 model simulations.

The site stratigraphy is made up of the following units:

- Alluvium
- Dilco Coal Member of Crevasse Canyon Formation (Dilco Coal) (Kcdi)
- Upper Gallup Sandstone (Kg), comprised of
  - Zone 3 , upper sandstone (Kgu)
  - Zone 2, shale and coal
  - Zone 1, lower sandstone
- Mancos Shale (Km)

The Zone 3 hydrostratigraphic unit consists of the upper sandstone interval within the Gallup Sandstone. The area of interest for the proposed study is defined by the current saturation within the Zone 3 hydrostratigraphic unit and downgradient to the site boundary with the Navajo Reservation.

Prior to mining and milling, none of the stratigraphic units discussed above was saturated. Beginning in 1968, mine water was discharged to the Pipeline Arroyo, which partially saturated the alluvium and Zone 1 and Zone 3 hydrostratigraphic unit of the Gallup Sandstone. This water created an artificial hydrologic system referred to as the Artificial System. Tailings seepage also recharged the Artificial System. In general, the Dilco Coal, Zone 2 of the Gallup Formation and the Mancos Shale are low permeability units not capable of transmitting significant amounts of water. Discharge of mine water ceased in 1986 and discharge to the tailings impoundment ceased in 1982. The surface of the tailings basin is currently dry and capped to prevent infiltration of precipitation or escape of radon gas. Early studies concluded that the Artificial System would not migrate off-site and impact downgradient groundwater (Canonie, 1987).

A conceptual hydrogeologic model was developed to support the hydraulic analysis conducted as part of Phase 2 of the SFS and provide input to MODFLOW simulations. The first step in model development was to input stratigraphic information from well and boring logs into the Mine Site™ model. The Mine Site program is a three-dimensional model that can be used to simulate geologic systems and was used to develop structural maps for input to the groundwater flow simulation package.

Well log information was obtained from UNC in hard copy and manually entered into the model. Based on this information, the model was used to develop a series of geologic maps and cross-sections to illustrate the geologic setting of the site and the relationship of geologic units to water levels within the Artificial System.

Figure 3, *Surface Geology*, displays the surface geology of the site and relationship between these units and the tailings facility and other site features. The approximate extent of saturation within the alluvium is shown on this map, which indicates that the alluvium is saturated in the southwestern portion of the study area and to the north of the tailings disposal area. This map also displays the location of cross-sections discussed later in this section.

Figure 4, *Top of Zone 3 Unit Contours*, and Figure 5, *Bottom of Zone 3 Unit Contours*, display the orientation of the top and bottom surfaces for the Zone 3 sandstone, respectively. These maps indicate that the unit dips from south to north with an average slope of 0.04 and that the depth from the surface varies from partially exposed in the south to 100 feet below ground surface in northern portion of the study area. The thickness of the unit varies from 50 to 60 feet in the south to 85 feet in the north.

Figure 6, *Cross-Sections A and B*, displays the two cross-sections running approximately parallel to the dip of the Zone 3 hydrostratigraphic unit, along the western and eastern margins of the study area. These maps indicate that alluvium in the southwestern portion of the site (underlying and to the north of the tailings basin) is in direct contact with the Zone 3 hydrostratigraphic unit. As shown in Figure 3 and cross-section A, only a portion of the alluvium in this area is currently saturated. Cross-section B indicates that the alluvium in the southeast and north are separated from the Zone 3 hydrostratigraphic unit by a thick sequence of Dilco Coal and saturation is limited to the Zone 3 hydrostratigraphic unit in these areas.

A series of cross-sections (C through I) were developed to illustrate the extent of saturation within the alluvium relative to the Zone 3 -alluvial contact (Figures 7, 8 and 9). The locations of these cross-sections are presented on Figure 3. The cross sections indicate that a thick layer of alluvium (up to 100 feet) is in direct contact with the Zone 3 hydrostratigraphic unit in the central and western half of the site and pinches out to the east. A relatively thin section (generally 5 – 30 feet) of the alluvial layer is locally saturated to the west of the plume. The majority of the alluvium in contact with the Zone 3 hydrostratigraphic unit is unsaturated.

Potentiometric maps were developed using data from October 2001, January 2002, and April 2002. These data are presented in Figure 10, *Potentiometric Surface October 2001*, Figure 11, *Potentiometric Surface January 2002*, and Figure 12, *Potentiometric Surface April 2002*. These data indicate that the water surface slopes from south to north in the southern portion of the site and the gradient becomes slightly more northeasterly in the north part of the site. The magnitude of the gradient varies from approximately 0.038 in the south to 0.025 in the north, with a slightly flatter gradient of 0.018 in the central section of the site. The flatter gradients in the central and northern portions of the site reflect the impact of pumping, which has reduced the gradient to a value less than the dip of Zone 3 hydrostratigraphic unit.

Saturated thickness maps are displayed in Figure 13, *Saturated Thickness of the Zone 3 Unit - October 2001*, Figure 14, *Saturated Thickness of the Zone 3 Unit - January 2002*, and Figure 15, *Saturated Thickness of the Zone 3 Unit - April 2002*. These data indicate that saturated thickness increases from approximately 6 to 14 feet in the south to 20 to 40 feet in the central and northern part of the site.

The change in saturated thickness maps (Figure 16, *Change in Saturated Thickness – October 2001 to January 2002* and Figure 17, *Change in Saturated Thickness - January 2002 to April 2002*) indicate that on average saturated thickness decreased approximately 0.1 feet from October 2001 to January 2002 and from January 2002 to April 2002.

3.0 GROUNDWATER MODEL

3.1 MODELING APPROACH

The Phase 2 hydraulic analysis for the SFS was continued by developing a numeric groundwater flow model to evaluate the feasibility of significantly dewatering the Zone 3 hydrostratigraphic unit for the remedial alternatives retained after the Phase 1 screening. The groundwater flow model for the site was developed using MODFLOW (McDonald and Harbaugh, 1988), a three-dimensional, finite-difference groundwater flow model, developed by the United States Geological Survey. The input and output processing to MODFLOW were accomplished using the Visual MODFLOW v. 2.8.2 modeling package, which was developed by Waterloo Hydrogeologic Software. The modeling was performed in 2002, and since then there have been studies (US Filter, 2004) conducted that better define the leading edge of the plume as shown in Figure 2. Although the plume configuration is different, the modeling results remain valid for the intended purpose, which was to evaluate alternatives to improve the former remedy. The 2002 model can be used to compare the effectiveness of the alternatives; however, if the model were eventually to be applied during the detailed design process, the model would be updated with the most current plume configuration.

The model was developed to simulate groundwater flow conditions within the Zone 3 of the Gallup Sandstone (the artificial groundwater system). The active model domain is approximately 3000 feet by 4000 feet. The finite difference grid spacing is 10 feet by 10 feet in the vicinity of the seepage-impacted area, and increases to 40 ft by 40 ft toward the model boundaries. The model includes 290 rows, 270 columns and one layer.

The groundwater flow model was developed based on the current understanding of the hydrogeologic system including sources of groundwater inflow and outflow, aquifer stratigraphy and hydraulic properties, and groundwater flow boundaries. Each of these model components is discussed in the following sections.

3.2 BOUNDARY CONDITIONS

Aquifer boundaries were assigned based on regional topographic information and interpreted hydrogeologic conditions as follows:

- East-West Boundaries were specified as no-flow boundaries, parallel to the groundwater flow direction.
- North-South Boundaries - The north boundary was specified as a constant head (6800 ft), and serves as the natural discharge feature at the downgradient end of the system. The southern boundary was specified as a no-flow boundary. Sensitivity analyses indicated that the northern constant-head boundary was far enough from the area of interest that it did not impact model results.
- Bottom Boundary - The base of the Zone 3 hydrostratigraphic unit was specified as a no-flow boundary. The configuration of the surface was based on data from boring logs (see Figure 5).

3.3 INITIAL CONDITIONS

Initial conditions were based on the aquifer potentiometric surface data from April 2002 (Figure 12). Simulation of initial conditions was developed during the calibration process (see Section 3.5 for more discussion).

3.4 INPUT PARAMETERS

Data describing aquifer and hydrologic parameters were obtained from the following sources:

- Site-specific data including maps, well log data provided by UNC, well pumping and water level data (provided in spreadsheet format by UNC), and site reports (Canonie, 1987 and Earth Tech, 2002.
- Topographic maps and aerial photographs
- Based on this information, the following aquifer properties were assigned:
- Aquifer Thickness – The modeled aquifer saturated thickness varies spatially, based on the water table surface (which was modeled using April 2002 data – see discussion below) and the base of the Zone 3 unit. The base of the Zone 3 hydrostratigraphic unit was modeled using well log data provided by UNC.
- Aquifer Hydraulic Conductivity – Hydraulic conductivity was initially estimated based on previous reports (Canonie, 1987) (1×10^{-3} to 3.4×10^{-5} cm/s). Model calibration resulted in a conductivity of 5×10^{-4} cm/s.
- Recharge – Recharge was added in the southwest area of the model to simulate alluvial recharge to the Zone 3 hydrostratigraphic unit. A recharge rate of 2 in/year was selected as a result of the calibration process, which was reasonably similar to calculated Darcy fluxes over the recharge area.
- Specific Yield – A value of 0.15 was used for the unconfined storage term. This is within the range reported the 2002 Earth Tech pump tests. The value used in the model is at the high end of the range reported by Earth Tech, but is representative of this type of sandstone and values reported in the literature. A specific yield value toward the high end was used to avoid underpredicting the time needed for dewatering.

3.5 MODEL CALIBRATION

The following three sets of conditions were used to calibrate the model prior to simulating the effectiveness of the remedial alternatives.

- Aquifer head distribution presented in the 1987 Canonie report
- Aquifer head distribution from April 2002
- Change in aquifer head between October 2001, January 2002 and April 2002

Model calibration was accomplished by setting initial water levels to the 1987 potentiometric surface and running the model for 15 years to simulate drainage resulting in the April 2002 water levels. In addition, a check was performed to ensure that water-level changes in the final six-month period were on the order of those observed between October 2001 and April 2002. Water levels simulated for April 2002 were within one foot of observed values within the central part of the study area.

Figure 18, *Model Residuals,* displays the residuals from the calibration run. This figure shows that the heads from the simulation closely match April 2002 values in the central part of the site. The values in the southeastern portion of the site were less closely matched. This is most likely due to the limited saturated thickness in this part of the study area and could also be affected by changes in geologic and hydraulic properties not included in the model or measurement error.

In general, the model calibration process demonstrated that the model is capable of reproducing the drainage behavior of the Zone 3 hydrostratigraphic unit from 1987 to 2002. The residuals from comparing the 2002 predicted heads to actual values represent less than five percent of the total head change in the system.

Particle velocities were determined after the calibration process. These values ranged from 100 to 120 ft/year, which is consistent with field data from the site.

3.6 SENSITIVITY ANALYSIS

The model is sensitive to hydraulic conductivity values. Hydraulic conductivities were varied from 1 x 10^{-4} cm/s to 1 x 10^{-2} cm/s during model calibration. The higher values (i.e. 1 x 10^{-2} cm/s), resulted in model instabilities (non-convergence) and more rapid drainage then observed in the field. The lower hydraulic conductivity (1 x 10^{-4} cm/s) underestimated the rate of groundwater movement.

Water levels in the southern area of the model are sensitive to recharge rate. Recharge rates were varied from 0 in/yr to 4 in/yr. The higher rates resulted in excess water being added to the system. When recharge is removed from the system, aquifer heads in the southwestern area of the model drop rapidly and cells begin to dry up within a year. Heads in the vicinity of the facility begin to drop too rapidly (as compared with the case with continuing recharge) within three to five years.

A model simulation with pumping wells was conducted to determine the effect of varying specific yield on draw-down rates. The results indicated that pumping rates were lower with the lower specific yield (average 0.2 gallons per minute (gpm) per well compared to 0.14 gpm per well), but that the lower specific yield resulted in a larger fraction of the plume being extracted. However, the difference in fraction of plume extracted became smaller with time and at five years 57% of the plume was extracted (at Sy=0.15) verses 59% (at Sy=0.10), which is most likely due to the greater amount of head dissipation in the lower specific yield case.

The northern boundary condition was varied to determine the affect of its distance from the well field. The purpose of this analysis was to confirm that the boundary did not influence the simulations, especially as it relates to flow and well extraction rates. Simulating the boundary as a general head boundary (GHB) approximated the movement of this boundary to the north. This change from a constant head boundary to a general head boundary virtually relocated the boundary 1000 feet to the north of the previous location. The location of the boundary could not have been placed further north due to the dip of Zone 3 hydrostratigraphic unit, which causes the saturated thickness to decrease in this area. The results indicated that extraction rates and volumes were similar with the GHB compared to the base case. The volume of plume removed varied by less than five percent between to the cases. A slightly higher volume (57%) was removed in the base case verses 52% with the GHB.

3.7 SUMMARY OF CALIBRATION AND PARAMETER SELECTION PROCESS

Parameters were selected based on existing hydrologic data and refined during the calibration process. The calibration process resulted in the model successfully predicting drainage from 1987 to 2002 with an average particle velocity (seepage velocity) of 100 to 120 feet per year. These data are consistent with field observations and provide an indication that the model is successfully simulating site conditions. Based on the calibration results, the model precision is adequate for the intended purposes of this study which are: 1) comparison of remedial alternatives; 2) providing estimates of dewatering capability over time; and 3) providing information for cost estimates for each dewatering alternative. Values of 5 x 10^{-4} cm/s and 0.15 were used for hydraulic conductivity, and specific yield, respectively, during evaluation of the remedial alternatives, unless stated otherwise. Following completion of the set-up and calibration process, each alternative was simulated using the calibrated model to determine its effectiveness in dewatering the Zone 3 hydrostratigraphic unit over a three to five year period. Selected alternatives were analyzed over an additional five year period for a total of ten years.

3.8 MODEL RESULTS

Each of the alternatives was simulated in the model based on the descriptions provided below. Note that Alternatives 1 and 2 were eliminated in the Phase 1 screening process and not simulated in the model.

In addition, a two-dimensional (horizontal) transient flow model (MODFLOW) was used to evaluate the potential for dewatering the alluvium and preventing recharge to the Zone 3 aquifer. The results of the model (see section 3.8.4) show that it is technically feasible to dewater the alluvial aquifer by installing dewatering wells in the saturated alluvium, and that dewatering can be effectively accomplished in one year. Simulations of each alternative were conducted for two cases; the first which assumed that the alluvium is not dewatered and therefore contributes recharge to Zone 3, and the second, which assumed that the alluvium has been dewatered prior to implementing the alternative.

Alternative 3 Tunnel (with optional side drifts)

The objective of this alternative is to mine a tunnel at the base of the Zone 3 hydrostratigraphic unit along the western boundary of the contaminant plume and drain the plume. The dip of the Zone 3 hydrostratigraphic unit in the plume footprint is to the northwest (see Figure 5), which constrains the placement of the tunnel. The preliminary design calls for a 10- by 10-foot tunnel, which collars in the Upper Gallup Sandstone. The tunnel will be installed on an aggressive decline of 12% to reach the target depth of approximately 175 feet at the base of the Zone 3 hydrostratigraphic unit in the shortest practical distance. The total length of the tunnel would be approximately 4400 feet. Six optional side drifts were also included that trend to the southeast and are approximately 500 feet in length.

Alternative 4 Open Pit

The objective of this alternative is to excavate an open pit to the base of the Zone 3 hydrostratigraphic unit and draw water into the base of the pit for in-situ evaporation, augmented by pumping to the evaporation system as necessary. At an overall slope angle of 45 degrees, approximately 500,000 cubic yards of mining will be required, exposing approximately, 10,000 to 15,000 square feet of area for evaporation at the bottom.

Alternative 5 Enhanced Well Field

The objective of this alternative is to install additional conventional pumping wells to the base of the Zone 3 hydrostratigraphic unit to enhance the extraction capacity of the existing well field. The depth of the wells will be approximately 175 to 190 feet and approximately 70 wells are anticipated on 200 foot centers. The extracted water will be routed to existing evaporation basins. An additional scenario, which increased the density of the well field (140 wells on approximately 100 foot centers) was also evaluated.

Alternative 6 Cut-off/Containment Wells

This alternative provides a different objective when it is compared to Alternatives 3-5. The purpose of this alternative is to capture the plume as it moves downgradient through a series of cut-off wells. This option allows for the plume to be contained and prevents offsite migration like Alternatives 3-5; however, the option does not dewater or drain the plume.

The final configuration includes two rows of cut-off wells with a total of 32 wells. Alternative 6 is included because of the uncertainty of being able to fully dewater the seepage-impacted groundwater. It provides for containing the seepage-impacted groundwater as an alternative to dewatering, but is inherently less preferable than dewatering because of the required long-term O&M.

<u>Alternative 7 Large Diameter Vertical Well/Shaft with a Radial Horizontal Collection Fan</u>

The objective of this alternative is to install one to three large diameter vertical wells or shafts (8 to 10 feet in diameter) to the base of the Zone 3 hydrostratigraphic unit and drill a radial fan of small diameter horizontal holes at the base of the shaft to collect impacted water. The depth of the shaft would be approximately 175 to 190 feet with a radial array of six or more, 2 to 4 inch-diameter horizontal holes. Following construction, the shaft will be equipped with a pump to extract the impacted water. The extracted water will then be routed to existing evaporation basins.

<u>Alternative 8 Directionally-drilled (horizontal) well</u>

The objective of this alternative is to install a 12-inch diameter directionally controlled drill hole at the base of the Zone 3 hydrostratigraphic unit along the western boundary of the contaminant plume and drain the plume downgradient into the drill hole by passive flow. The length of the hole is estimated at 4000 feet and will require stainless steel casing to resist corrosion in low pH conditions. Following installation, the casing will be perforated and converted to a pumping well to extract the impacted water. The extracted water will then be routed to existing evaporation basins.

3.8.1 Results from Modeling

As a first step, a simple semi-analytical, one-dimensional flow model was developed to evaluate the potential to drain the Zone 3 hydrostratigraphic unit under a simple, hypothetical scenario. This simulation was used to determine if it is practical to dewater the aquifer given some simple assumptions (i.e. a series of fully penetrating drains and no recharge). The first figure (Figure 19) illustrates the effect of eliminating recharge from the system and allowing the unit to drain naturally downslope, which shows that the system becomes unsaturated in the upper (southern) portion of the flow system. The next figures (Figures 20 – 23) display the affect of one, two, three and five fully-penetrating drains installed perpendicular to the flow direction. Two conclusions can be reached based on these results: 1) a very aggressive dewatering scenario will be required to have a significant impact on water levels; and 2) eliminating recharge will be necessary to dewater the aquifer. Based on these data, the full numeric model was developed to further analyze the remedial alternatives.

The next step in the analysis was to evaluate each of the proposed alternatives using the MODFLOW model. Each of these alternatives was simulated for a period of at least five years and the results are displayed below in Tables 1 and 2, *Groundwater Modeling Results With Recharge and Groundwater Modeling Results Without Recharge.* Selected options (i.e. the well field with and without recharge) were simulated for a period of ten years. Drawdowns predicted by each simulation are shown in Figures 24 through 58, and described briefly below:

<u>Alternative 3 Tunnel (with optional side drifts) (Figures 24 – 29)</u>

Model results indicate that drawdown would occur rapidly along the axis of the tunnel and in an elliptical shape away from the tunnel (Figure 24). After five years, the radius of influence would increase to cover an area approximately 3000 by 2000 feet and intersect much of the plume. A considerable amount of water would be extracted (5.5 million cubic feet over five years); however this volume would capture only 33% of the plume due to the spatial design of the tunnel system. Additional side drifts would provide similar extraction volumes and increase plume capture to 41% at five years as a result of more directed coverage into the plume area (Figure 29).

TABLE 1
GROUNDWATER FLOW – MODEL RESULTS WITH RECHARGE

Alternative	EXTRACTION RATE (Ft^3/d x 1,000)				Total Volume Extracted (MFt^3)			Percent of Plume Volume Extracted		
	10 Days	3 Years	5 Years	10 Years	3 Years	5 Years	10 Years	3 Years	5 Years	10 Years
3A Tunnel	19.1	2.0	1.7	--	4.1	5.5	--	28	33	--
3B Tunnel (with Drifts)	21.0	2.0	1.6	--	4.4	5.8	--	35	41	--
4 Open Pit	3.7	0.81	0.71	--	1.2	1.8	--	8	12	--
5A Well field (70 Wells) (pump 6 ft above Zone 3 base)	6.0	2.2	1.4	--	3.8	5.1	--	34	47	--
5B Well field (70 Wells) (pump 3 ft above Zone 3 base)	7.4	2.7	1.7	0.84	4.6	6.2	8.4	42	57	67
5C Well field (Sy = 0.10) (pump 3 ft above Zone 3 base)	7.3	2.0	1.3	--	3.9	5.1	--	50	59	--
5E Well field (GHB Boundary) (pump 3 ft above Zone 3 base)	7.6	2.7	1.9	--	4.7	6.3	--	43	52	--
5F Well field (140 Wells) (pump 3 ft above Zone 3 base)	16.0	2.8	1.9	1.30	6.7	8.4	11.2	60	66	71
6 Cut-off/Containment Well	1.47	0.70	0.56	--	1.0	1.5	--	--	--	--
7 One Ranney-type Well	0.91	0.53	0.48	--	0.68	1.0	--	5	10	--
8 Horizontal Well	14.3	1.8	1.4	--	3.6	4.7	--	26	31	--

Notes:
1. Initial volume of water in the model within the plume footprint = 5.24 million cubic ft (39.2 million gallons)
2. Extraction rates and volumes are from MODFLOW output, and include all water extracted from the system, from inside and outside the plume area.
3. Percent of plume volume extracted is based on change in saturated thickness within the plume area (assuming 15 percent specific yield (Sy), except where noted).

TABLE 2
GROUNDWATER FLOW – MODEL RESULTS WITHOUT RECHARGE

Alternative	EXTRACTION RATE (Ft^3/d x 1,000)				Total Volume Extracted (MFt^3)			Percent of Plume Volume Extracted		
	10 Days	3 Years	5 Years	10 Years	3 Years	5 Years	10 Years	3 Years	5 Years	10 Years
3 Tunnel (No Recharge)	19.1	1.8	1.2	--	3.9	5.1	--	38	49	--
4 Open Pit (No Recharge)	3.6	0.8	0.68	--	1.2	1.8	--	20	33	--
5D Well field (70 wells) (No Recharge)	7.4	2.3	1.4	0.46	4.4	5.7	7.3	52	66	83
5G Well field (140 wells) (No Recharge)	16.6	2.3	1.2	0.40	6.5	7.7	9.2	69	79	89
7A One Ranney-type Well (No Recharge)	5.9	.93	0.76	0.45	1.5	2.2	3.3	23	36	63
7B Two Ranney-type Wells (No Recharge)	13.8	1.5	1.1	0.54	3.1	4.0	5.5	38	52	76
7C Three Ranney-type Wells (No Recharge)	18.0	1.7	1.1	0.54	3.7	4.7	6.1	46	59	79
8 Horizontal Well (No Recharge)	14.3	1.5	1.0	--	3.4	4.3	--	36	47	--

Notes:
1. Initial volume of water in the model within the plume footprint = 5.24 million cubic ft (39.2 million gallons)
2. Extraction rates and volumes are from MODFLOW output, and include all water extracted from the system, from inside and outside the plume area.
3. Percent of plume volume extracted is based on change in saturated thickness within the plume area (assuming 15 percent specific yield (Sy), except where noted).

When alluvial recharge is removed from the system, the percentage of the plume captured after five years increased to 49% without the optional side drifts. The model was not run for the optional side drifts without recharge scenario; however, based on the results of the tunnel (no side drifts) without recharge, it is expected that the percent of the plume captured after five years would increase to greater than 50%.

Alternative 4 Open Pit (Figures 30 – 32)

Drawdown would also occur rapidly from the open pit, extending in a circular cone of depression radiating from the pit (Figure 30). However, even after five years the radius of influence would be relatively small (less than 1000 feet) compared to the other alternatives (Figure 32), and significantly less water would be extracted (1.8 million cubic feet, representing only 12% of the plume) using this remedial alternative as compared to the other alternatives. However, if alluvial recharge is removed from the system, 33% of the plume is captured after five years with the same total volume extracted of 1.8 million cubic feet.

Alternative 5 Enhanced Well Field (Figures 33 – 51)

The well field was designed using 70 wells spaced on approximately 200 foot centers. Simulations were run varying model parameters such as the depth of the well pumps above the base of the Zone 3 hydrostratigraphic unit, the specific yield (Sy), including and removing recharge from the system and varying the distance (head) of the northern boundary. With the well pumps set at three feet above the Zone 3 hydrostratigraphic unit, assuming a Sy of 0.15 and allowing recharge, a total of 6.2 million cubic feet of water (57% of the plume) would be removed in five years (Alternative 5B). The radius of influence would extend over a surface area of approximately 3500 by 2250 feet and drawdown would vary from two to 18 feet (Figure 38). Model simulations extending this system an additional five years (total of 10 years) would not appreciably alter the extent of the capture zone (Figure 39); however the volume of water extracted would increase to 8.4 million cubic feet (representing 67% of the plume).

Varying the Sy of the aquifer to 0.10 (Alternative 5C) slightly reduced the extent of the drawdown area (Figures 40 - 42) and reduced the total extracted water volume; however the plume capture was increased slightly to 59% at five years. Removing recharge from the simulations (Alternative 5D) vastly increased the size of the pumping influence (Figures 43 - 46) and increased plume capture to 66% and 83% over five and ten years, respectively. Increasing the distance between the northern boundary and the well field slightly reduced the size of the drawdown area in the northern part of the site (Alternative 5E - Figures 47). The boundary change reduced the volume of the plume extracted after five years from 57% to 52%.

When the density of the well field was increased to 140 wells with recharge (Alternative 5F), the size of the drawdown area increased (Figures 48 and 49) and the volume extracted was greater in years three and five when compared to the 70 well design. The percentage of the plume volume extracted in three years was 60% for the 140 well design and 42% for the 70 well design. However, in 10 years the difference between the percentages was only 4% (67% for 70 wells and 71% for 140 wells). Without recharge (Alternative 5G - Figures 50 – 51), the 140 well scenario resulted in 79% and 89% of the plume extracted at five and ten years, respectively versus 66 and 83% percent for the 70 well configuration.

Alternative 6 Cut-off/Containment Wells (Figure 52)

Several iterations of the cut-off well scenario were simulated to determine the spacing required to achieve containment. The wells were positioned to prevent the plume from migrating past the property boundary to the north. This remedial alternative does not attempt to dewater the plume in the Zone 3 hydrostratigraphic unit. The chosen configuration included two rows of wells offset by

50 feet. The first line of wells includes 21 wells on 50 foot centers located in the north-central portion of the site. The second line of 11 wells (100-ft spacing) was placed 50 ft north of the original line. This configuration of 32 wells effectively achieved containment, however complete capture of all particles was not achieved. The extraction rate after five years had decreased to 560 cubic feet per day and the volume extracted was 1.5 million cubic feet. The model simulation and particle pathways are shown on Figure 52.

Alternative 7 Large Diameter Vertical Well/Shaft with a Radial Horizontal Collection Fan (Ranney-type Well) (Figures 53-61)

Similar to the pit remedy, the Ranney-type well would provide rapid drawdown with a very narrow radius of influence of less than 1000 feet over 5 years (Figure 55). The total extraction volume would be approximately 1.0 million cubic feet, representing only 10% of the plume. As with the open pit alternative, the removal of recharge significantly increased the amount of plume removal (36% of plume removed and 2.2 million cubic feet extracted). Multiple Ranney-type wells (Alternatives 7B and 7C) were also evaluated with recharged removed. After five years, two Ranney-type wells removed 52% of the plume and 4.0 million cubic feet extracted (Figure 58). For the three Ranney-type wells, 59% of the plume was extracted after five years with 4.7 million cubic feet extracted (Figure 61). The additional wells increased the amount of drawdown in the vicinity of the wells to greater than 20 feet compared to approximately 10 feet of drawdown with only one well. The multiple well scenarios also increased the radius of influence to several thousand feet over 5 years.

Alternative 8 Directionally-drilled (horizontal) well (Figures 62-64)

The pattern and extent of the drawdown influence of the horizontal well would be similar to the tunnel alternative. Drawdown would occur rapidly along the axis of the well and in an elliptical shape away from the well (Figure 62). After 5 years, a total of 4.7 million cubic feet would be extracted, capturing only 31% of the plume due to inadequate spatial coverage of the system (Figure 64). With the removal of recharge, the percentage of the plume captured increased to 47% and the total extracted volume slightly decreased to 4.3 million cubic feet.

3.8.2 Summary

The well field alternatives predicted the highest percentage of dewatering of the plume over the five year period. The 70 well design was predicted to remove 57% to 59% of the plume in five years (with alluvial recharge – Scenarios 5B and 5C) and 66% of the plume in five years without recharge (Scenario 5D). The extracted plume volume was 66% after five years for the 140 well design (Scenario 5F) with recharge and 79% without recharge (Scenario 5G). At ten years, the well field was predicted to remove 67% of the plume (with recharge) and 83% of the plume (without recharge) for the 70 well design and 71% and 89%, respectively, for the 140 well design (with and without recharge).

Total system pumping rates for the 70 well scenario with alluvial recharge are predicted to decrease exponentially with time from approximately 38 gpm at ten days, to 14 gpm at three years, to nine gpm at five years, and four gpm at ten years, due to decreasing hydraulic head within the Zone 3 hydrostratigraphic unit. This equates to pumping rates of 0.55 to 0.06 gpm per well over the ten year simulation period. The same exponential decline would occur with the 140 well design (approximately 83 gpm at ten days to seven gpm at ten years). Without alluvial recharge, the model predicts system pumping rates to decrease at a similar rate from approximately 86 gpm to two gpm. These pumping rates were predicted using the MODFLOW Drain Package during the hydraulic modeling of Alternative 5.

Particle velocities between the seepage-impacted area and the wellfield were determined after five and ten years of well pumping with and without recharge for the 70 well simulation. These values indicated that seepage velocities were reduced from an average of 120 ft/year prior to pumping to 70 ft/year (with recharge) and 65 ft/year (without recharge) due to the decrease in hydraulic gradient. Seepage velocities towards the wells did not change significantly between five and ten years indicating that head changes were not appreciable during this time. However, the 70 and 140 well designs will capture 83% and 89% of the seepage impacted water after 10 years without recharge.

3.8.3 Unsaturated Modeling Results

A simple one-dimensional saturated/unsaturated drainage model was developed to determine potential effects of unsaturated flow (i.e. delayed yield) on the performance of the alternatives. The model was developed using the SEEP/W software. The model domain consisted of a 10 meter column with the initial water table at the top of the column. The base of the column was set as a free drainage boundary (i.e. head equals zero) and the column was allowed to drain starting at time equals zero.

Two water retention curves were used in the analysis. The first curve is based on uniform fine sand and the second is based on a more heterogeneous fine sand. The second curve is more representative of heterogeneous fine sand with fine-grained, silt-sized particles. Data for both curves were default curves provided by the SEEP/W model based on the soil description, and they bracket the range of properties for the alluvium. Both water retention type curves are similar and can be used to approximate the delayed yield of the Zone 3 unit. The saturated hydraulic conductivity was set at 5.00×10^{-4} cm/s for both curves, consistent with the MODFLOW model simulations. Complete water retention curves and model results are provided in Appendix A, *Unsaturated Model Parameters*.

As indicated by the model results, the uniform fine sand (first curve) was approximately 50 percent drained in one year. The next 25 percent of the water volume then drained over the next year (for a total of two years). However, the final 20 to 25 percent of the water volume took several years (up to 15) to complete drainage. Compared to the uniform sand, the heterogeneous fine sand (second curve) maintains a higher water content throughout drainage, but drains relatively faster. This material was approximately 50 percent drained in 2 days, and 75% drained in 48 days. Similarly, the final 20 to 25 percent of the water volume took several years (up to 15) to complete drainage; however, the final water content of the heterogeneous fine sand was higher than for the uniform fine sand.

The results from the unsaturated model indicate that unsaturated flow in the Zone 3 hydrostratigraphic unit could result in delayed drainage of the saturated zone (especially the last 20 to 25 percent of the water). These data indicate that under a reasonable best case, several years of delayed drainage could exist during dewatering of the system.

3.8.4 Dewatering Analysis for the Alluvium

To further assess the feasibility for dewatering the alluvial aquifer, a two-dimensional (horizontal) transient flow analysis was developed using the finite-difference groundwater flow model, MODFLOW. The results of the model are considered preliminary and will be subject to revision following completion of a well installation and pump testing program, focussed on the alluvial aquifer, scheduled for the end of 2004 or the beginning of 2005. This field program will provide additional information on alluvium geometry, groundwater levels, and an estimate of in-situ hydraulic conductivity.

Details of the conceptual evaluation and model configuration are described in Appendix B, *Alluvial Aquifer Dewatering Analysis*. For this model, the aquifer material was assumed to be homogeneous and isotropic, with a hydraulic conductivity of 2×10^{-3} cm/sec (U.S. Filter, 2004) and a specific yield of 0.20. Based on the conceptual model, dewatering wells (or drains) were simulated in the northeast portion of the saturated alluvium, along the axis of the alluvial trough where saturated thickness is currently greatest. Transient flow simulations were performed to evaluate alluvial aquifer dewatering. Based on the model simulations, the alluvial aquifer would be significantly dewatered in one year, leakage to the Z3 unit would cease after three years, and nearly complete dewatering would be achieved after five years. The initial pumping rate under this scenario would be approximately 50 gpm, and would decrease to approximately 12 gpm over three years according to results from the MODFLOW Drain Package.

These results show that it is technically feasible to dewater the alluvial aquifer by installing dewatering wells in the northeast portion of the saturated alluvium, along the axis of the alluvial trough, and that significant dewatering can be accomplished in one year. Furthermore, based on the estimated flow rate of 50 gpm (approximately 26.3 million gallons per year) from the alluvium during the first year, the current evaporation/evaporation pond system could accommodate this discharge, precluding the necessity of a discharge permit. The evaporation capacity at the site is discussed further in Section 3.8.5.

As indicated by the previous modeling results, dewatering of the alluvium is a critical component of any dewatering plan for the Zone 3 hydrostratigraphic unit and also is more effective, in terms of the time required, then extracting water from the Zone 3 hydrostratigraphic unit due its higher permeability and specific yield.

3.8.5 Analysis of Evaporation Capacity

Water produced by the groundwater extraction methods described above would be managed using the existing evaporation system at the site. This evaporation system includes two lined evaporation ponds on the tailings impoundment and a spray evaporation system located to the south of the reclaimed tailings impoundment. A spray bar system is also included with the evaporation ponds to enhance evaporation from the ponds.

Capacity of each of the five-acre evaporation ponds is 6.4 million gallons for total capacity of 12.8 million gallons (Larry Bush, personal communication). The operational history of the evaporation system indicates that twenty million gallons of fluid can be evaporated between the evaporation ponds and the spray system during a normal year.

At this time the evaporation ponds are essentially empty with only minimal water being maintained in the ponds to protect the liner integrity. By using the storage capacity of the ponds and the evaporative capacity of the system, the total water management capacity available for the first year of groundwater extraction would be thirty-two million gallons with twenty million gallons of evaporative capacity in subsequent years.

Average pan evaporation for the area (Gallup, New Mexico) is 61.0 inches per year (New Mexico Climate Center website, http://weather.nmsu.edu). Using 10 acres of surface area for evaporation and a pan evaporation coefficient of 0.9, results in an annual evaporation of approximately 15 million gallons per year. This is consistent with the operational evaporation data for the site.

The above water balance calculations indicate that the existing system has sufficient capacity to manage all of the water produced by the most aggressive option (well field with recharge), which would produce approximately 10 million gallons per year over the first three years.

4.0 PILOT STUDY

4.1 BACKGROUND

One problem with conventional pumping wells in the former Zone 3 pumping system had been the declining well yields that always occurred within a few years of active pumping. Part of this decline was attributed to the decreasing saturated thickness. To overcome the effect of declining water levels on well performance, lines of extraction wells were moved in succession northwestward toward areas of greater saturated thickness. By the time of EPA's 5- year review in 1998, it was understood that this arrangement was not accomplishing the remedial objectives and resulted in the advance of the seepage-impacted groundwater. UNC therefore considered a modification of Alternatives 5 and 6 to include a recommendation to conduct a pilot study using the hydraulic fracturing technique to improve permeability and groundwater recovery for Alternatives 5 and 6. The results from the pilot study are provided in this section and were conducted as Phase 4 of the SFS.

Hydraulic fracturing is a technology that has been used to increase production in water supply wells as well as enhanced containment and capture in environmental extraction wells. Hydraulic fracturing is induced by pumping fluids such as water into the formation at a rate faster than the fluids can flow into the rock. Fluid pressure builds up and the formation fractures along a plane perpendicular to the minimum compressive stress in the formation matrix. The fracture apertures are maintained by filling the fractures with proppant such as sand to hold the fracture faces apart.

The pilot study consisted of several tasks to evaluate the hydraulic fracturing in the Zone 3 hydrostratigraphic unit. UNC in conjunction with MACTEC Engineering and Consulting, Inc. (MACTEC), Halliburton Energy Services (Halliburton) and others implemented borehole geophysical imaging, saturated zone testing, fracture diagnostics, and hydraulic fracturing in an area 300 feet northwest of the plume boundary. Detailed methods and results from the pilot study are reported in the Final Report Hydraulic Fracturing Pilot Test Results and Preliminary Full Scale Design (MACTEC, 2003) and are briefly summarized in this section to support the development of the SFS. The geophysical imaging, aquifer tests, and fracture diagnostics evaluated the effectiveness of the hydraulic fracturing. The hydraulic fracturing was performed in one borehole under perforated casing and open hole conditions.

UNC installed pilot test well HF-3 and observation well CHHF-2 into the Zone 3 hydrostratigraphic unit. Pilot test well, HF-3, was installed using a 8 ¾ inch bit to a depth of approximately 5 feet above the anticipated base of the Zone 3 hydrostratigraphic unit. The well was then set and cemented with 7 inch J rated casing (20 pound). After the cement had cured, the boring was drilled to approximately 1 foot above the base of the Zone 3 hydrostratigraphic unit. This depth allowed the total depth of HF-3 to be a close as possible to the base of the Zone 3 hydrostratigraphic unit without encountering underlying coal beds. It was thought that encountering the coal may cause the induced fractures to preferentially propagate through the coal seam instead of the Zone 3 hydrostratigraphic unit (MACTEC, 2003). Observation well CHHF-2 was installed approximately 20 feet from HF-3.

After installing wells, HF-3 and CHHF-2, a series of baseline observations were measured. Borehole geophysical imaging was performed to observe natural fractures prior to the hydraulic fracturing. Two saturated zone tests, a long-term pumping test and a falling head test, were conducted in the pilot test well using CHHF-2 as an observation well. The pumping test allowed for quantitative evaluation of transmissivity and storativity of natural conditions. After the draw-down and falling head tests, CHHF-2 was sealed with cement to avoid interference during hydraulic fracturing operations in HF-3. These wells are shown on Figure 2.

Prior to the start of hydraulic fracturing operations, an array of 32 surface tilt meters was installed to monitor the growth and coverage of the induced hydraulic fractures. A falling head test was performed on the open hole portion of the well prior to hydraulic fracturing. Stage 1 of the hydraulic fracturing operation was conducted in HF-3 in the open hole portion near the base of the Zone 3 hydrostratigraphic unit. After this hydraulic fracturing operation, a falling head test was performed to qualitatively evaluate the test. Significant improvements were noted and Stage 2 of the pilot test was performed. Stage 2 was conducted in a perforated portion of the casing in HF-3 over an interval from 148.5 to 150.5. Well MWHF-3, was installed after the hydraulic fracturing operations to act as an observation well for a pump test after completion of operations. The pre- and post-test observation wells and pilot test well are identified on Figure 2. After completion of operations, geophysical imaging was performed in the bottom portion of HF-3 and the new observation boring, MWHF-3 to observe induced fractures. The method and results of the hydraulic fracturing, borehole imaging, aquifer tests and fracture diagnostics are described in more detail in the following sections.

4.2 HYDRAULIC FRACTURING

Halliburton implemented two stages of hydraulic fracturing in the pilot test well, HF-3. Stage 1 was conducted in the uncased or open hole portion of HF-3 at depths of 161 to 166 feet. A total of 27,431 gallons of water were pumped into the interval at a rate of 36.4 barrels per minute (bpm). The average pressure was 225 pounds per square inch (psi) and the amount of sand used as proppant was 25,254 pounds (lbs). During Stage 1 in the open-hole a discernable break was noted at a pressure of 709 psi.

Stage 2 of the hydraulic fracturing occurred in a cased and perforated portion of the HF-3. After the completion of Stage 1, a composite plug was set by wireline in the 7 inch casing at an approximate depth of 155 to 158 feet to isolate the open hole portion of the well from the cased portion. After the plug was set, the casing was perforated at a density of 4 shots per foot over an interval from 148.5 to 150.5 feet. A total of 33,984 gallons of water were pumped into the interval at a rate of 32.6 bpm. The average pressure was 2,982 psi and the amount of sand used as proppant was 24,995 lbs. Multiple breaks were noted during Stage 2, however, at pressures greater than in Stage 1.

4.3 BOREHOLE GEOPHYSICAL IMAGING

Borehole geophysical imaging (DOPTV) was performed in HF-3 to observe the strike, dip, frequency and aperture of fractures in the open hole portion prior to and after hydraulic fracturing. DOPTV logging prior to the fracturing revealed no discernable natural fractures in the uncased interval (approximately 161 to 166 feet). After hydraulic fracturing operations were completed, a large, relatively horizontal, open fracture at 164.1 feet with an aperture of 2 inches was logged in HF-3. Geophysical imaging in CHHF-2 was attempted prior to the tests, however, residual bentonite in the hole reduced visibility. This well was cemented prior to the start of hydraulic fracturing operation so imaging was not performed after the tests. However, MWHF-3 was logged with DOPTV after the fracturing was completed and ten fractures were noted. Since there was no baseline log for comparison, direct conclusion could not be made as to whether the fractures were natural or induced. However, it is believed that some of the fractures appeared to be induced based on their fresh appearance and the fact that proppant may have been visible in some of the fractures (MACTEC, 2003).

4.4 SATURATED ZONE TESTING

Pumping tests were used to obtain hydraulic parameters such as hydraulic conductivity, transmissivity and storativity from Zone 3 hydrostratigraphic unit prior to and after the hydraulic fracturing operations. While the pump tests quantified the hydraulic parameters, a succession of falling head tests allowed for a qualitative evaluation of hydraulic conductivity throughout the operations.

4.4.1 Pre Pump Test - Prior to Hydraulic Fracturing

Prior to the aquifer tests, water levels were monitored in existing monitoring wells using pressure transducers. These data allowed for correction of pump test observations due to barometric pressure and temperature changes. A step drawdown test was conducted in HF-3 in order to determine the initial pumping rate for the pump test. Based on evaluation of the step test, an initial rate of 0.8 gpm was selected for the pumping test with a drawdown objective of approximately 50 to 60 percent of the saturated thickness. The saturated thickness in the area of the pilot test was approximately 41 feet. The pump test continued for a total of 1500 minutes. Water levels were monitored in HF-3 and CHHF-2, using data logging, pressure transducers and manual measurements during the test for a period of 300 minutes after pumping had ceased.

Review of the measured (raw) time-drawdown data for CHHF-2 indicated that the water level rose during the pumping test to a level that was above the pre-test static level. This was a result of diurnal fluctuations in water levels due to changes in daily air temperature and barometric pressure. Baseline water level data from existing monitoring wells was used to correct the pump test data for these fluctuations. The drawdown data from HF-3 was also corrected to account for well efficiency. Well efficiency was calculated to be approximately three percent (MACTEC, 2003).

Once the data were corrected, transmissivity was calculated using the Cooper-Jacob time drawdown and distance drawdown methods. The storage coefficient was calculated using both the time drawdown and distance drawdown data. Hydraulic conductivity was calculated using the values for transmissivity and an aquifer thickness of 41 ft. The calculated storage coefficient using time drawdown data was 0.085 compared to 0.029 using the distance drawdown data. The time drawdown data estimated a hydraulic conductivity raging between 2.88 and 5.31 ft/day (cm/s). The hydraulic conductivity from the distance drawdown data was 2.93 ft/day (cm/s).

4.4.2 Post Pump Test – After Hydraulic Fracturing

After completion of the hydraulic fracturing, observation well MWHF-3 was installed 20 feet away from HF-3. A pumping rate of 0.8 gpm was again used for the post-fracturing pump test. As in the first pump test, water levels were corrected for diurnal fluctuation due to barometric pressure and temperature. Drawdown observations were collected for 1500 minutes followed by the recovery period. After drawdown and recovery, HF-3 was pumped at 2.0 gpm and 5.25 gpm for 60 minutes each to evaluate the well's maximum pumping rate.

The total drawdown in HF-3 after 1500 minutes of pumping at a rate of 0.8 gpm was only 0.54 feet compared to a pre-fracturing pumping test total drawdown of 21.97 feet. The storage coefficient using the time drawdown data was 0.03 whereas it was 0.002 using the distance drawdown data. The hydraulic conductivity using the time drawdown data ranged between 4.45 and 6.28 ft/day (cm/s). The distance drawdown data estimated a hydraulic conductivity of 10.07 ft/day (cm/s).

Following the completion of the pumping test, the pumping rate was increased to 2 and 5.25 gpm to evaluate, the well's ability to sustain greater yields. The pumping rate of 5 gpm was projected to cause a total drawdown in the pumping well of approximately 3 feet after 1000 minutes.

4.4.3 Falling Head Tests

Falling head tests were performed in HF-3 at various stages prior to and during the pilot test to qualitatively evaluate the hydraulic conductivity of the Zone 3 hydrostratigraphic unit. To complete falling head tests, the pumping well was filled with water to the top of the casing and the water level was measured with a depth sounding probe for at least 90 minutes.

Prior to the hydraulic fracturing operations, well HF-3 was filled to the top of the casing with water and the water level declined to approximately 110 feet below the top of casing over a period of 240 minutes. After Stage 1 of fracturing in the open hole portion of HF-3, water was pumped into HF-3 at a rate of 170 gpm, in order to perform the falling head test. The well could not be filled at this pumping rate, and the test was started with a water level at approximately 80 feet below the top of casing. The water level declined to a level of approximately 110 feet below the top of casing in 90 minutes.

After Stage 1 operations, the open hole interval of HF-3 was isolated with a wireline plug and the casing was perforated. A falling head test was performed and only a very small decline in water level was observed. After completion of Stage 2 operations, introduction of water at pumping rate of approximately 170 gpm resulted in an initial water level of approximately 41 feet below the top of casing. The falling head test indicated the water level declined to approximately 110 feet below the top of casing within 90 minutes. These results were interpreted to indicate that both fracturing events had significantly enhanced the hydraulic conductivity of the Zone 3 hydrostratigraphic unit around HF-3 (MACTEC, 2003).

4.5 FRACTURE DIAGNOSTICS

An array of tilt meters was installed to evaluate the geometry and growth of the induced fractures. The surface tilt meter data were collected during both stages, cased and open-hole, of the hydraulic fracturing. Results from Stage 1 indicated that a horizontal fracture was created with no detected vertical component. The resulting fracture was centered slightly southwest of HF-3 at an approximate depth of 164 feet from the surface and was essentially circular in shape with a radius of 35 to 45 feet. The horizontal fracture dipped to the north approximately 12 degrees (MACTEC, 2003).

Analysis of the Stage 2 tilt meter data indicated that a horizontal fracture was created with no vertical component early in the fracture operations. However, 16 minutes into the operation of Stage 2, the induced hydraulic fracture propagated vertically approximately 50 feet. The fracture continued to propagate horizontally after it reached a height of 50 feet. The center of growth was approximately 15 feet southwest of HF-3. The resulting fracture was centered at an approximate depth of 100 feet from the surface and was essentially oval in shape with a radius of approximately 100 feet. The horizontal fracture dipped to the west approximately 18 degrees after the vertical jump. No vertical component was detected by the tilt meter array at any time during the hydraulic fracturing operations, suggesting that some high conductivity conduit (either man-made, or natural) was encountered by the propagating fracture, allowing the fracture to move to another level without causing deformation in the vertical direction (MACTEC, 2003). The fracture diagnostics contractor believed that the "jump" to a shallower depth during Stage 2 may have been the result when the fracture intersected the observation well CHHF-2 that was cemented prior to the pilot test. The observation well may not have been properly sealed before the test and when the induced fracture encountered the well, the fracture propagated up a weakness or channel in the cement to an unconsolidated formation at a shallower depth, and then continued horizontally through the zone. The higher treating pressures associated with Stage 2 may have also contributed to the "jump".

4.6 PILOT TEST CONCLUSIONS

The results of the pilot hydraulic fracturing test indicate that hydraulic fracturing is feasible in the Zone 3 hydrostratigraphic unit with resultant increases in the hydraulic conductivity (MACTEC, 2003). The open borehole method appeared to be more effective than hydraulic fracturing within the perforated casing. In the open hole portion of the casing, the geophysical imaging and tilt meter data revealed a large, relatively horizontal, open fracture with an aperture of approximately two inches. The horizontal fracture was created with no detected vertical component. The hydraulic fracturing in the perforated casing also produced multiple breaks. However significantly higher pressures were required to produce the breaks compared to Stage 1. Results from the pre- and post- aquifer tests indicated that an improvement in several hydraulic characteristics of the aquifer including increased well efficiency, hydraulic conductivity, maximum yield of HF-3 and size of the cone of depression (MACTEC, 2003).

5.0 ADDITIONAL MODELING

Based on the hydraulic fracturing pilot test results, Alternative 5, enhanced well field, was reevaluated with the MODFLOW model. The hydraulic conductivity in the area of the well field was revised by a factor of two from 5 x 10^{-4} cm/s to 1 x 10^{-3} cm/s based on the results of the MACTEC (2003) hydraulic fracturing study. The objective of this alternative was to install additional conventional pumping wells to the base of the Zone 3 hydrostratigraphic unit to enhance the extraction capacity of the existing well field. The well field was designed using 70 wells spaced on approximately 200 foot centers and 140 wells spaced on approximately 100 foot centers. For Alternatives 5H and 5J, the alluvium provided a source of recharge to the Zone 3 hydrostratigraphic unit. For Alternatives 5I and 5K, it was assumed that the alluvium would be dewatered prior to implementation of this alternative and recharge to the system was removed from the model. The pumps in the wells were set to three feet above the base of the Zone 3 hydrostratigraphic unit and the specific yield was assumed to be 0.15 for all alternatives. Results of modeling with the enhanced hydraulic conductivity as well as a comparison to previous model results are shown on Table 3, *Additional Model Results*.

Alternative 5H (Figures 65-66) simulates the 70 well scenario with revised hydraulic conductivity and alluvial recharge. After five years, the percent of plume captured increased from 57% (Alternative 5B) to 61% (Alternative 5H) as a result of the hydraulic fracturing. After 10 years, the relative difference of plume captured between the well field with and without hydraulic fracturing was only 1% (67% for Alternative 5B and 68% for Alternative 5H).

Alternative 5I (Figures 67-68) simulates the 70 well scenario with the revised hydraulic conductivity, no recharge. After five years, the percent of plume captured increased from 66% (Alternative 5D) to 76% (Alternative 5I) as a result of hydraulic fracturing. Model simulations extending this system an additional five years (total of 10 years) would increase the relative percent of impacted water removed to 91%. This is 8% percent greater than the 10 year simulation at the lower hydraulic conductivity (83% of the plume extracted for Alternative 5D).

The results of the 140 well field scenario (Figures 69-70) with revised hydraulic conductivity and alluvial recharge (Alternative 5J) showed an increase in the percentage of plume captured after five years (72% for Alternative 5J compared to 66% for Alternative 5F). After 10 years, the relative difference of plume captured between the 140 well field options with and without hydraulic fracturing was 5% (71% for Alternative 5F and 76% for Alternative 5J).

The revised hydraulic conductivity of the Zone 3 hydrostratigraphic unit also enhanced the recovery of impacted groundwater for the 140 well field alternative with no recharge (Alternative 5K) (Figures 71-72). After five years, the percent of plume volume extracted increased from 79% to 85% with the revised permeability and it increased 5% after 10 years (89% for 140 wells without fracturing and 94% for 140 with fracturing).

The size of the drawdown area increased for the 140 well design and the volume extracted was greater in all years when compared to the 70 well design with and without alluvial recharge. The percentage of the plume volume extracted in five years was 85% for the 140 well design and 76% for the 70 well design (Alternative 5I) using the revised hydraulic conductivity value and no recharge. In 10 years the relative difference was 3% for revised hydraulic conductivity simulations (91% for 70 wells and 94% for 140 wells). The 70 well design and the 140 design are essentially the same 10 years after implementation with both designs achieving a goal of 90% of the plume captured.

TABLE 3
GROUNDWATER FLOW – ADDITIONAL MODEL RESULTS

Alternative	EXTRACTION RATE (Ft^3/d x 1,000)				Total Volume Extracted (MFt^3)			Percent of Plume Volume Extracted		
	10 Days	3 Years	5 Years	10 Years	3 Years	5 Years	10 Years	3 Years	5 Years	10 Years
5B Well field (70 Wells) (With Recharge)	7.4	2.7	1.7	0.84	4.6	6.2	8.4	42	57	67
5D Well field (70 wells) (No Recharge)	7.4	2.3	1.4	0.46	4.4	5.7	7.3	52	66	83
5H Well field (70 wells) (With Recharge, Increase K)	8.1	2.7	1.8	1.10	5.0	6.5	9.0	51	61	68
5I Well field (70 Wells) (No Recharge, Increase K)	8.1	2.4	1.3	0.41	4.7	6.0	7.5	61	76	91
5F Well field (140 Wells) (With Recharge)	16.0	2.8	1.9	1.30	6.7	8.4	11.2	60	66	71
5G Well field (140 wells) (No Recharge)	16.6	2.3	1.2	0.40	6.5	7.7	9.2	69	79	89
5J Well field (140 wells) (With Recharge, Increase K)	17.5	2.9	1.9	1.20	7.1	8.8	11.6	66	72	76
5K Well field (140 wells) (No Recharge, Increase K)	17.5	2.4	1.2	0.36	6.8	8.1	9.7	75	85	94

Notes:
1. Initial volume of water in the model within the plume footprint = 5.24 million cubic ft (39.2 million gallons)
2. Extraction rates and volumes are from MODFLOW output, and include all water extracted from the system, from inside and outside the plume area.
3. Percent of plume volume extracted is based on change in saturated thickness within the plume area (assuming 15 percent specific yield (Sy), except where noted).

6.0 ALTERNATIVES ANALYSIS

6.1 INTRODUCTION

Remedial alternatives that were retained after screening alternatives (Alternatives 3-8) for the Zone 3 hydrostratigraphic unit were subject to detailed analysis, as described in this section. The affects of hydraulic fracturing were included for Alternative 5, enhanced well field, as discussed in Section 5.0 and it was assumed that recharge from the Southwest Alluvium was reduced or diminished for all retained alternatives.

Detailed analysis consisted of analyzing the alternatives with respect to the established criteria using a decision analysis software package, Criterion Decision Plus (CDP). This software facilitated the decision-making process by utilizing a methodical approach to alternatives evaluation using the following process.

- Identification of the goal or objective
- Identification of the alternatives being considered to meet the goal
- Identification of the factors or criteria important in satisfying the goal
- Determination of the relative importance of the criteria
- Quantitative rating of the alternatives for each of the criteria

Once these steps are completed, results of the model were analyzed. The model calculated a score for each of the alternatives based on the quantitative rating given for the criteria and its relative importance to the objective. The overall scores of each alternative were ranked to determine the preferred alternative and provide comparison amongst alternatives considered in the model.

6.2 EVALUATION CRITERIA

The criteria developed by the UNC and MWH working group during a creativity session are consistent with EPA criteria and include the following:

- Effectiveness
- Cost
- Environmental Impact
- Regulatory Permitting
- Public Acceptance

These criteria are described below:

Effectiveness: This criterion assesses the effectiveness and performance of the alternative by measuring the volume of the plume extracted after five years. This criterion incorporates a time component by evaluating the alternative after a certain period of time; therefore, time was not considered independently in this analysis. The effectiveness criterion encompasses the relative level of protection to human health and the environment that each alternative will achieve. This assessment also evaluates the statutory preference for selecting a remedial alternative that permanently and significantly reduces toxicity, mobility or volume of the plume and includes consideration for failure modes and technical implementability.

Cost: This criterion evaluates the capital cost of each alternative. Direct capital costs include construction, equipment, land and site development, buildings and services, relation expenses and disposal.

Indirect capital costs could include engineering expenses, license or permit fees, start-up and contingency allowances. The cost comparison is based on the recognition that the ongoing operations, maintenance, monitoring, and reporting for the various alternatives would be roughly the same; therefore, O&M costs did not have to be included.

Environmental Impact: This criterion includes consideration for unintended environmental consequences of the alternatives.

Regulatory Permitting: This criterion evaluates the relative extent of permitting required for each alternative and how difficult such permits may be to acquire.

Public Acceptance: This assessment evaluates issues associated with the alternative that may reduce its acceptance by the community.

6.3 MODEL INPUTS AND ASSUMPTIONS

The alternatives were compared according to the above criteria. Each criterion was represented in the CDP model by assigning a weight value on a scale of 0 to 100, with 100 being associated with criteria that are strongly affected by a remedy modification and 0 being associated with criteria that are unaffected by a remedy modification. Criteria such as environmental impact, regulatory permitting and public acceptance were considered to be important for ranking each alternative; however the issues associated with these criteria were more generally similar across the range of alternatives than were the issues associated with effectiveness and cost (see Appendix D, Table D-1). Thus, the advantages and disadvantages between alternatives were not particularly sensitive to these criteria, and so they were assigned less weight. The assigned weights used for the evaluation are shown in Table 4, *Weight Assignment Criteria,* below.

TABLE 4
WEIGHT ASSIGNMENT CRITERIA

Criteria	Assigned Weight
Effectiveness	100
Cost	80
Environmental Impact	40
Regulatory Permitting	40
Public Acceptance	20

A capital cost estimate was prepared for each alternative to compare relative costs. The capital cost comparison was made assuming that the ongoing operations and maintenance for the various alternatives will be roughly the same.

A summary of the capital costs is present in Table 5, *Cost Summary*, with back-up calculations and assumptions presented in Appendix C, *Cost Evaluation Data.*

TABLE 5
COST SUMMARY

Alternative	Capital Cost
3. Tunnel	$6,353,750
4. Open Pit	$2,362,470
5I. Enhanced Well field (70 wells)	$1,484,050
5K. Enhanced Well field (140 wells)	$2,790,050
6. Cut-off/Containment Wells	$694,150
7. Large Diameter Well (Cost per Ranney-type Well)	$2,029,750
8. Directional Drilling (Horizontal Well)	$2,004,750

Based on the information shown in Appendix C, the enhanced well field (70 wells) with hydraulic fracturing sub-option will be the most economical alternative for dewatering the Zone 3 hydrostratigraphic unit (approximately $1,484,050). The cut-off well with hydraulic fracturing sub-option was the cheapest alternative; however, this alternative does not dewater the Zone 3 hydrostratigraphic unit. The open pit, directional drilling and large diameter well had similar costs (approximately 2.0 to 2.4 million dollars for the open pit and directional drilling and 2.0 to 6.0 million dollars for the one to three Ranney-type wells), while the tunnel was the most expensive alternative at $6.4 million.

The quantitative ratings of each alternative for each criterion used in the alternative's evaluation are presented in the Table 6, *Quantitative Rating Criteria,* below.

TABLE 6
QUANTATIVE RATING CRITERIA

Criteria	Scale	3 Tunnel	4 Pit	5I Well Field - 70	5K Well Field - 140	6 Cut-off Wells	7 Large Diameter Wells 1	2	3	8 Directional Drilling
Effectiveness	0 - 100	49	33	76	85	0	36	52	59	10
Cost	0 - 100	97.7	36.3	22.8	42.9	10.7	31.2	62.4	93.7	30.8
Environmental Impact	0 - 100	100	60	100	100	100	100	100	100	100
Regulatory Permitting	0 - 100	60	60	100	100	100	80	80	80	100
Public	0 - 100	100	80	100	100	100	100	100	100	100

Cost ratings are based on actual estimates for each alternative normalized to a scale of 0 to 100, where each scale unit represents $65,000. Effectiveness ratings are based on modeling results. Effectiveness ratings represent the percentage of the plume volume extracted after five years assuming that the alluvium is dewatered, which is indicative of whether plume containment to support license transfer could be achieved within five years of implementation. The effectiveness value of Alternative 8, Directional (horizontal) drilling was reduced from 47 (percentage of plume volume extracted after five years) to 10 due to fact that failure of this horizontal well would be irreversible. Environmental Impact and regulatory permitting criteria are more subjective criteria that are assigned a relative rating on a scale of 0 to 100. These are described qualitatively in Appendix D, Table D-1.

6.4 MODEL RESULTS

The overall score of an alternative is was calculated based on the combination of its rating for each of the criteria and the relative importance of the criteria to the decision. Specific inputs, results, and analysis of the CDP evaluation are presented in Appendix D, *Criterion Decision Analysis.* The CDP decision score results rank the enhanced well field design (70 wells – Alternative 5I) as the preferred alternative, and the enhanced well field design (140 wells – Alternative 5K) was ranked closely behind with the second highest score. All the other alternatives scored significantly lower than the well field options, with the pit and tunnel receiving the lowest scores. The CDP results from highest to lowest rankings were as follows; enhanced well field (70), enhanced well field (140), one large diameter well, two large diameters wells, cut-off/containment wells, directional (horizontal) drilling, three large diameter wells, pit, and tunnel.

Although the 70 well option is less effective than the 140 well option, its significantly lower cost (almost half) makes it the highest-ranking alternative. This is based on the relative weighting assigned for cost and effectiveness, which indicates that a 1% increase in effectiveness has equal value to over $80,000 (i.e. establishes a willingness to pay over $800,000 for each 10% percent of plume volume extracted after five years).

Even though the 140 well option is able to manage 9% more of the plume volume than the 70 well option, it costs an additional $1.3 million. Due to the level of savings, the 70 well option provides an acceptable trade-off worth the lower performance level and is an overall better option than the 140 well option. It should be noted that after 10 years, both the 70 and 140 well field options have essentially the same performance with greater than 90% of the plume removed.

7.0 SUMMARY AND RECOMMENDATIONS

The CDP decision score results rank Alternative 5, the enhanced well field (70 wells – Alternative 5I) as the preferred alternative. The enhanced well field design (140 wells – Alternative 5K) was ranked closely behind with the second highest score. All the other alternatives scored significantly lower than the well field options, with the pit and tunnel receiving the lowest scores. Although there is a nine percent difference in the volume of plume captured after five years between the enhanced 70 and 140 well options, that difference is not significant after 10 years with both options achieving greater than 90 percent removal.

The hydraulic modeling results show that for any of the alternatives to be effective, with the exception of Alternative 6, Cut-off/Containment wells, the recharge from the Southwest Alluvium to Zone 3 must be reduced or eliminated. Thus a component of all the retained alternatives is the partial dewatering in the vicinity of its contact with the Zone 3 hydrostratigraphic unit. A groundwater flow model was developed to evaluate the potential for dewatering the alluvium and preventing recharge to the Zone 3 aquifer. The results of the model show that it is technically feasible to dewater the alluvial aquifer by installing dewatering wells in the saturated alluvium, and that significant dewatering can be accomplished in one year. Furthermore, based on the estimated flow rate of 50 gpm (approximately 26.3 million gallons per year) from the alluvium during the first year, the evaporation/evaporation pond system on site could accommodate this discharge, precluding the necessity of a discharge permit.

Although Alternative 6 does not dewater the Zone 3 hydrostratigraphic unit and ranked the fourth highest in the CDP, it is recommended that this alternative be implemented. The implementation of this alternative would allow for data collection to determine the extent to which a full-scale dewatering (Alternative 5I) of the seepage-impacted water will be feasible while controlling potential down gradient migration of the plume. Information collected during the development of Alternative 6 will allow optimization of the enhanced well field alternative. Based on the hydrogeologic model of Alternative 5I, an enhanced well field with hydraulic fracturing may be able to capture at least 90 percent of the plume after 10 years of implementation and could be implemented following development of Alternative 6, if necessary.

8.0 REFERENCES

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Earth Tech, 2002. Letter Report – Results of Zone 3 Aquifer Test. May 22, 2002.

MACTEC Engineering and Consulting, Inc., 2003. Final Report Hydraulic Fracturing Pilot Test Results and Preliminary Full Scale Design - United Nuclear Church Rock Facility, Gallup, New Mexico. December 23, 2003.

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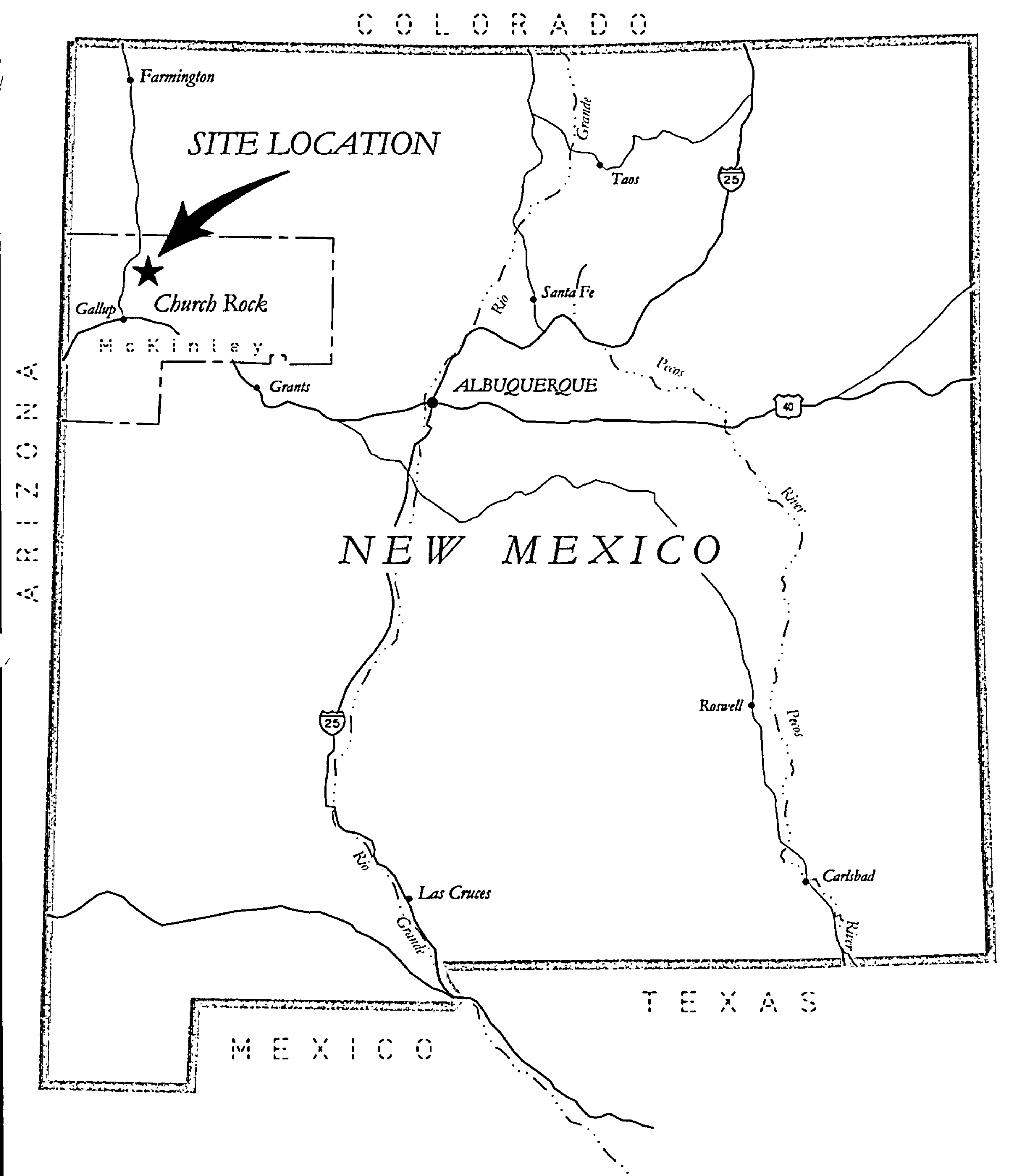
FIGURES



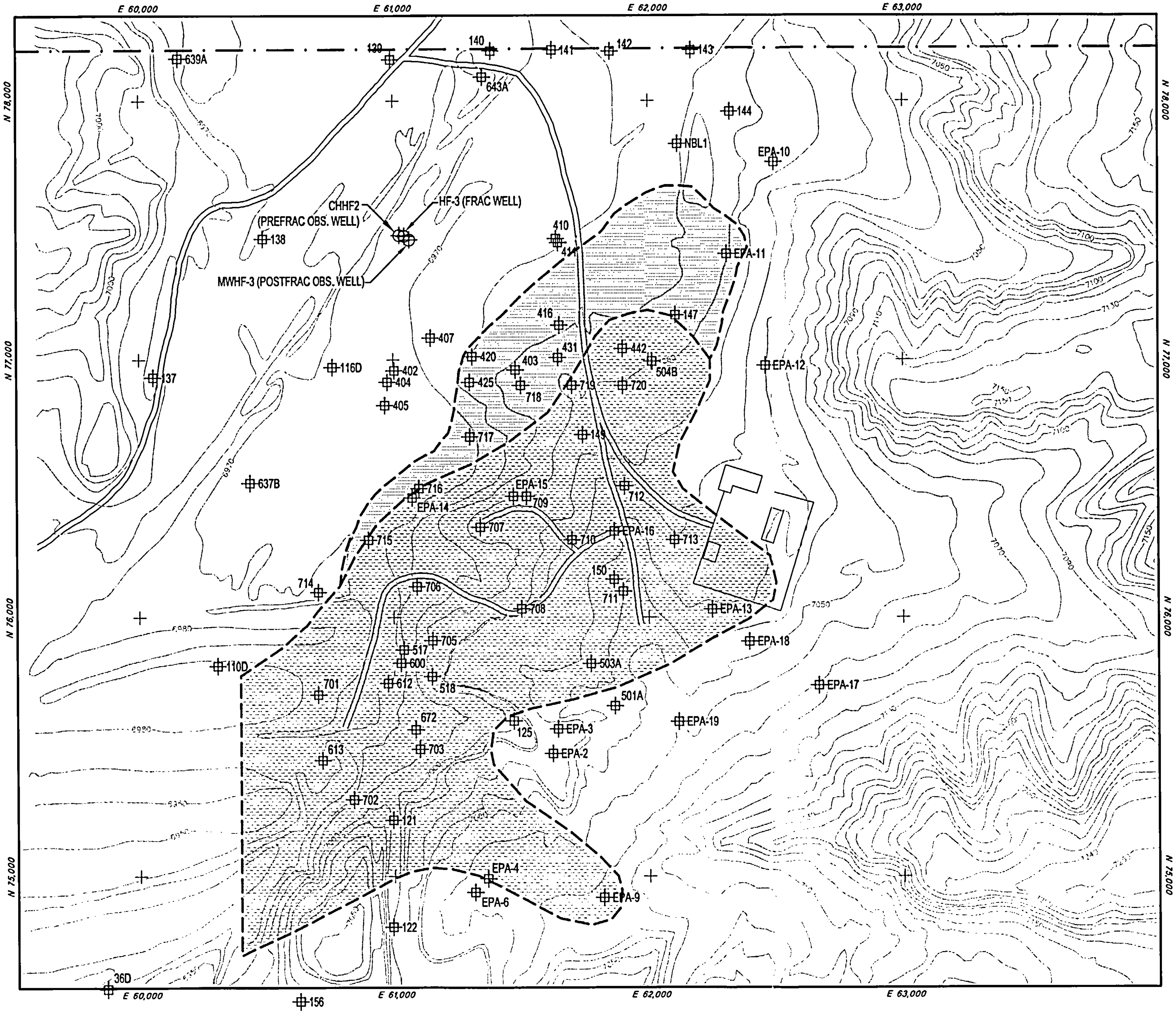
REV No	REVISIONS	REV DATE	DESIGN BY	DRAWN BY	REVIEWED AND SIGNED BY
1	Final FFS	10/04	P.Anderson	K.Conrath	P.Anderson
0	Draft FFS	4/04	P.Anderson	D.Gallery	P.Anderson

MWH

PROJECT No.: 5030087
AutoCAD FILE: ChurchRck Genloc
SCALE: N/A
FIGURE No: 1

UNITED NUCLEAR CORPORATION
Hydraulic Evaluation of Remedial Alternatives

SITE LOCATION MAP



LEGEND

143 DRILLHOLE LOCATION

HF-3 WELL LOCATION

NAVAJO INDIAN RESERVATION BOUNDARY

2002 MODELING PLUME BOUNDARY

2003 PLUME BOUNDARY

NOTE: EXTENSION OF THE APPROXIMATE PLUME BOUNDARY BASED ON STUDIES CONDUCTED IN 2003

N

SCALE

200' 0 200' 400'

CONTOUR INTERVAL 10 FT.

REV. No.	REVISIONS	DATE	DESIGN BY	DRAWN BY	REVIEWED AND SIGNED BY
2	Final FFS	10/04	P.Anderson	K.Conrath	P.Anderson
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UNITED NUCLEAR CORPORATION

PROJECT: *Hydraulic Evaluation of Remedial Alternatives*

DRAWING TITLE: *SITE LAYOUT*

MWH

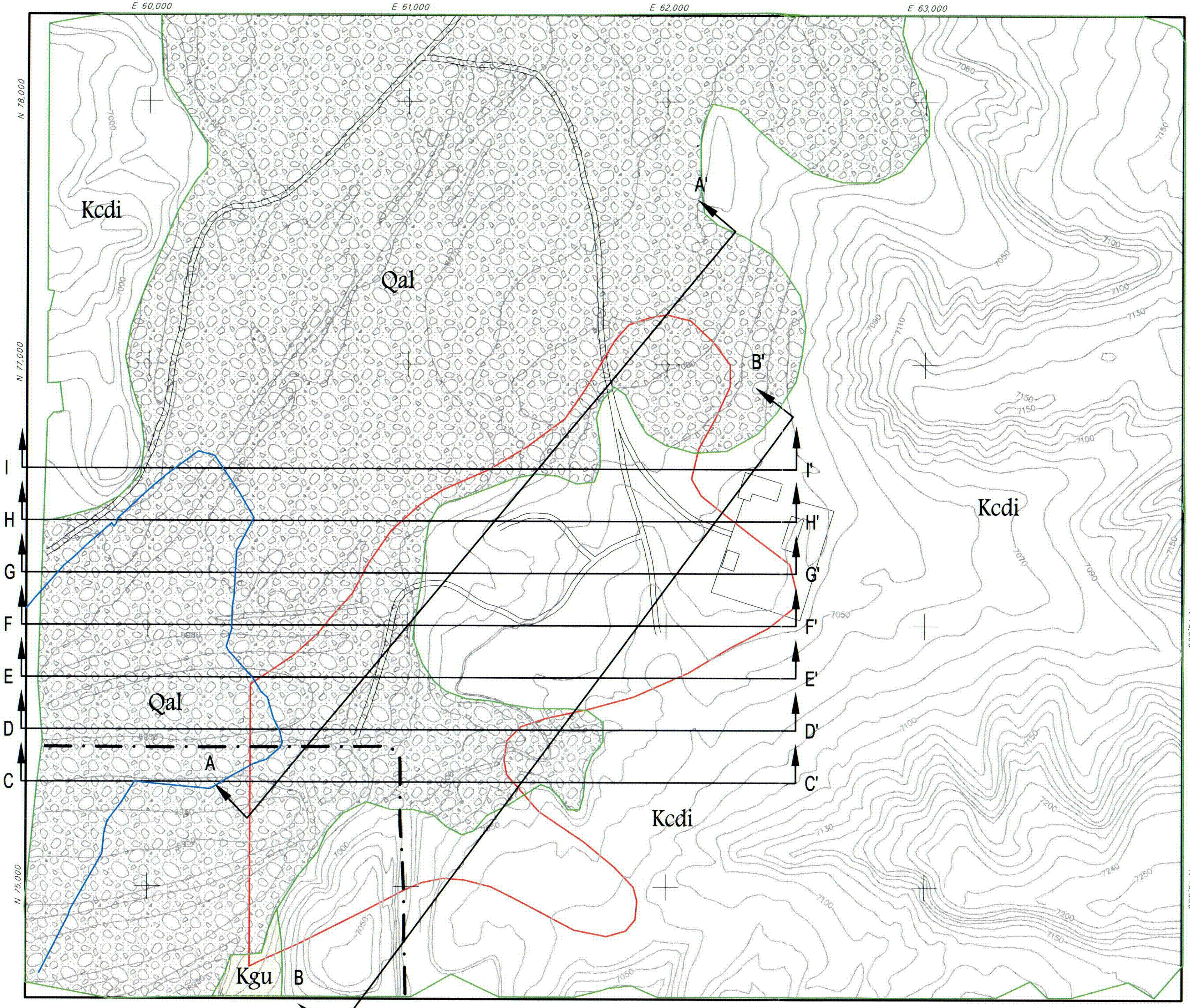
Sheet 1 Of 1 Sheets

SCALE: As Shown

FIGURE No. 2

PROJECT NUMBER: 1020087.011801

AutoCAD FILE: Site Layout.



LEGEND

- APPROXIMATE ALLUVIUM SATURATION BOUNDARY
- APPROXIMATE PLUME BOUNDARY
- GEOLOGIC CONTACTS
- TAILINGS IMPOUNDMENT BOUNDARY
- Qal - ALLUVIUM
- Kcdi - DILCO COAL
- Kgu - ZONE 3 OF UPPER GALLUP SANDSTONE (Z3)
- CROSS SECTION LOCATION

N

SCALE

200' 0 200' 400'

CONTOUR INTERVAL 10 FT.

REV. No.	REVISIONS	DATE	DESIGN BY	DRAWN BY	REVIEWED AND SIGNED BY
1	Final FFS	10/04	P.Anderson	K.Conrath	P.Anderson
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PROJECT: ***Hydraulic Evaluation of Remedial Alternatives***

DRAWING TITLE: ***SURFACE GEOLOGY***

MWH

Sheet 1 Of 1 Sheets

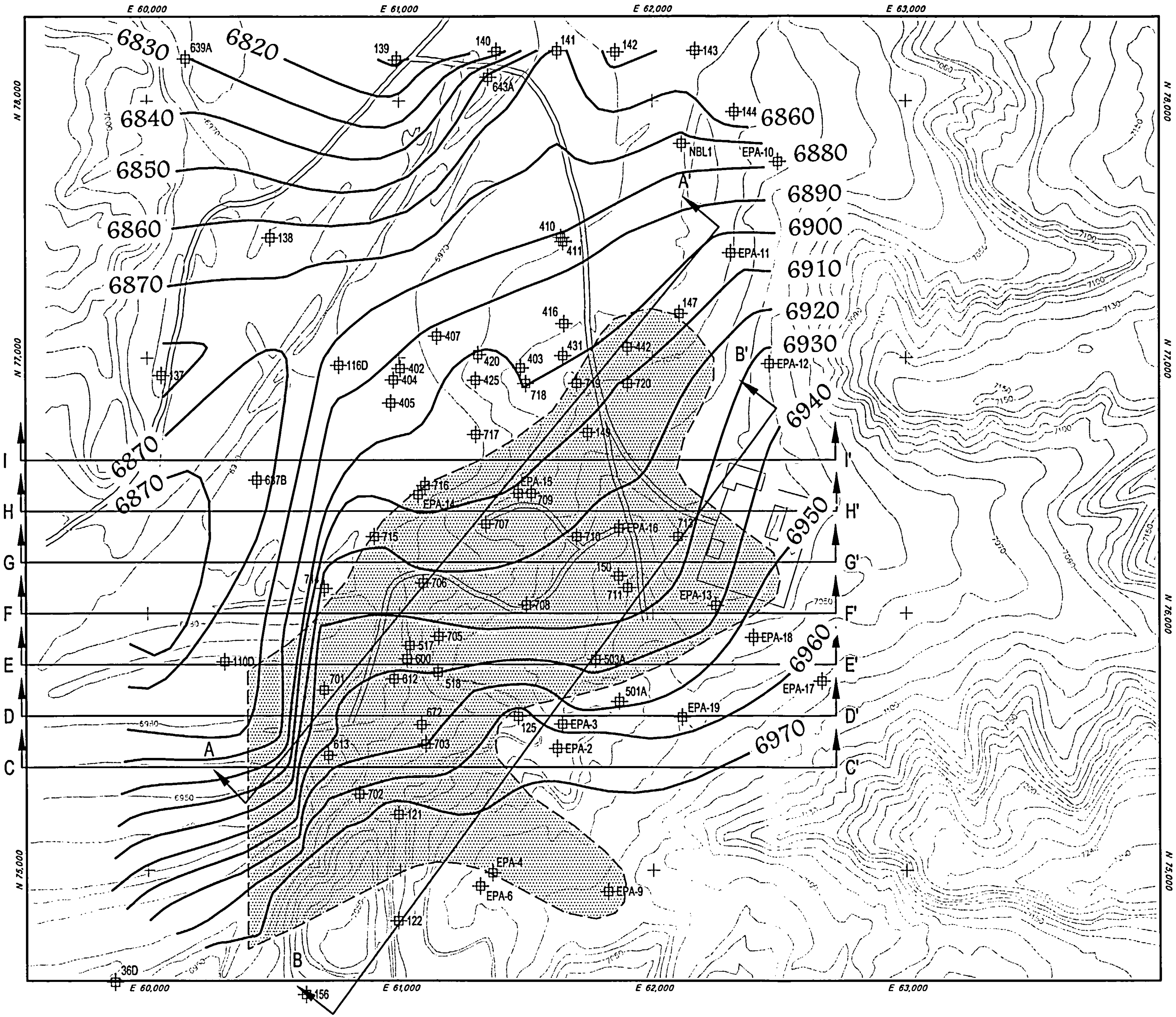
SCALE: 1"=400'

FIGURE No. 3

AutoCAD FILE: Contacts Base.dwg

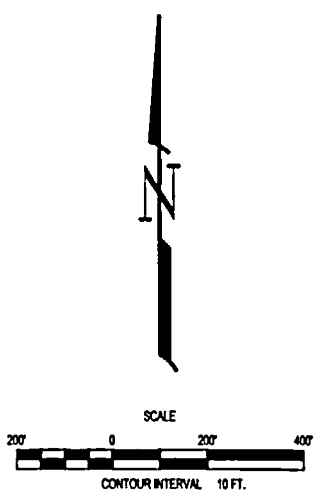
PROJECT NUMBER: 5030087.011801

co1



LEGEND

- APPROXIMATE PLUME BOUNDARY
- 6860 GEOLOGIC STRUCTURE CONTOURS (Elevation in feet AMSL)
- 143 DRILLHOLE LOCATION
- CROSS SECTION LOCATION



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PROJECT: *Hydraulic Evaluation of Remedial Alternatives*

DRAWING TITLE: *TOP OF ZONE 3 UNIT CONTOURS*

MWH

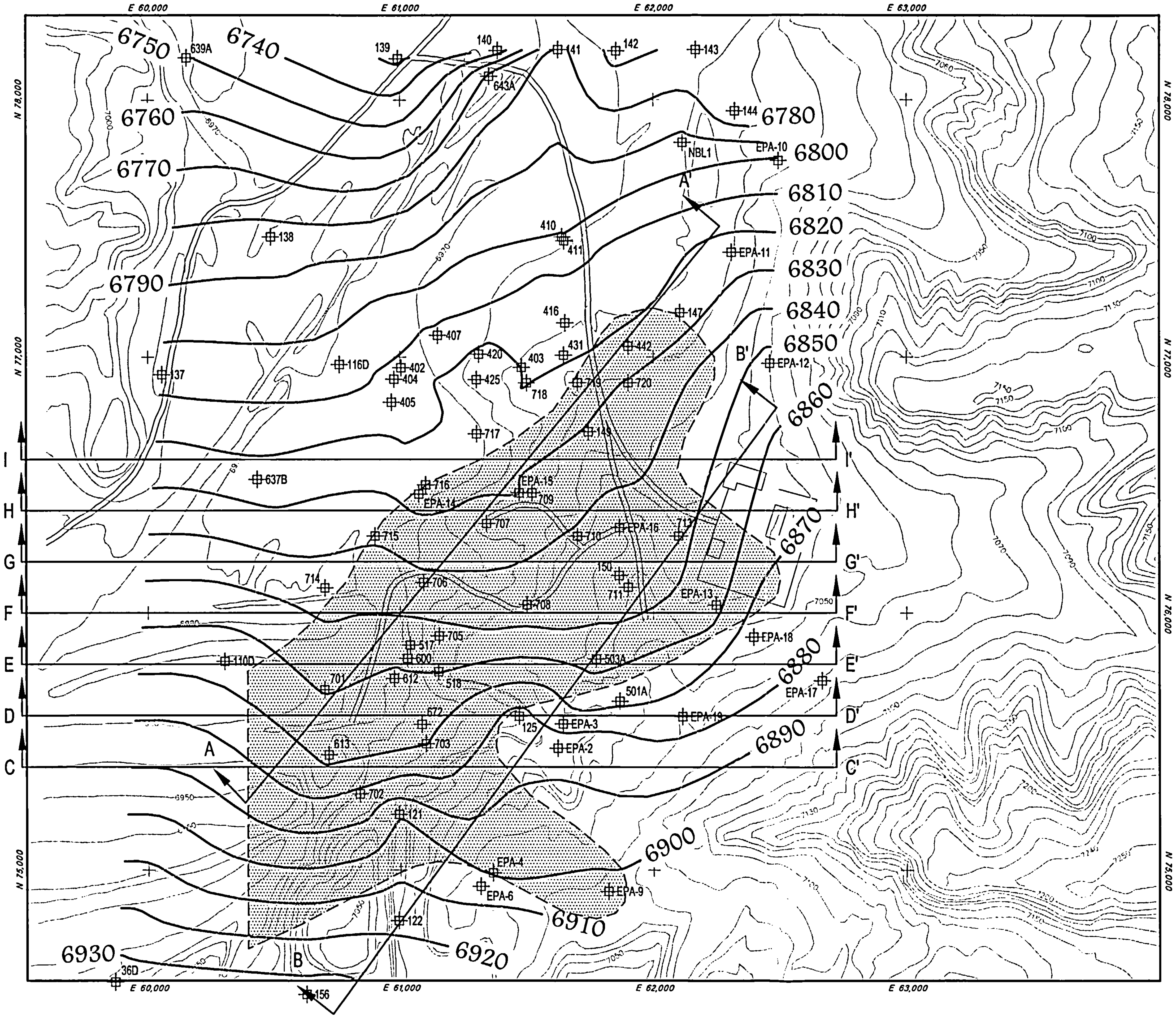
Sheet 1 Of 1 Sheets

SCALE: As Shown

FIGURE No. 4

AutoCAD FILE: Top Z3.dwg

PROJECT NUMBER: 5030087.011801



LEGEND

APPROXIMATE PLUME BOUNDARY

6800 GEOLOGIC STRUCTURE CONTOURS (Elevation in feet AMSL)

143 DRILLHOLE LOCATION

CROSS SECTION LOCATION

SCALE

200' 0 200' 400'

CONTOUR INTERVAL 10 FT.

REV. No.	REVISIONS	DATE	DESIGN BY	DRAWN BY	REVIEWED AND SIGNED BY
2	Final FFS	10/04	P.Anderson	K.Conrath	P.Anderson
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UNITED NUCLEAR CORPORATION

PROJECT:
Hydraulic Evaluation of Remedial Alternatives

DRAWING TITLE:
BOTTOM OF ZONE 3 UNIT CONTOURS

MWH

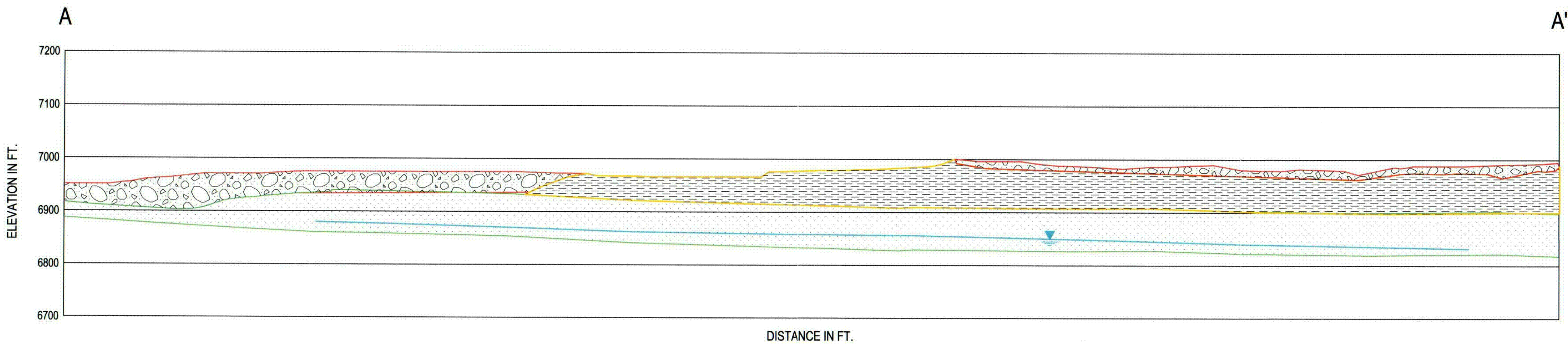
Sheet 1 Of 1 Sheets

SCALE: As Shown

FIGURE No. 5

AutoCAD FILE: Bott Z3.dwg

PROJECT NUMBER: 5020087.011801



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VERTICAL SCALE
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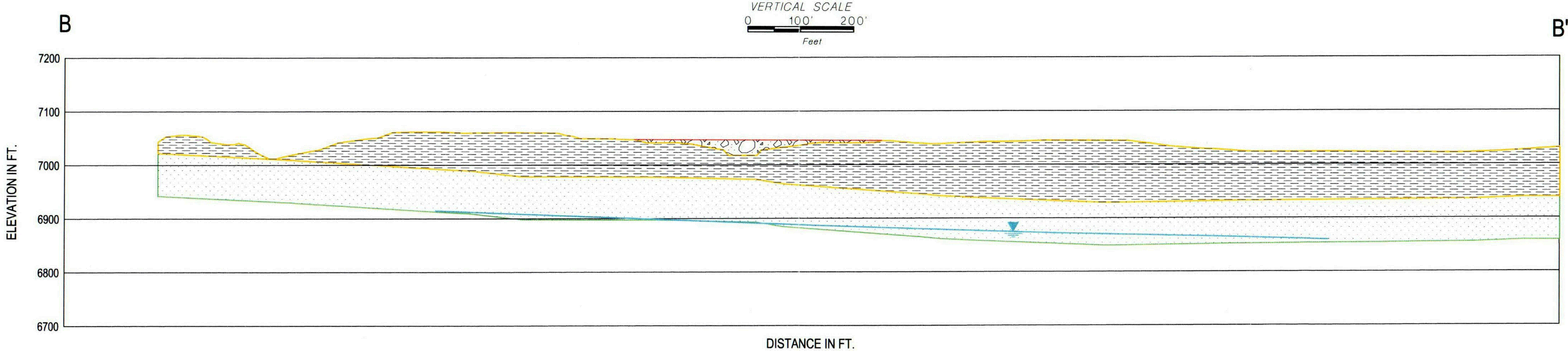
Feet



HORIZONTAL SCALE
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VERTICAL SCALE
0 100' 200'
Feet

LEGEND

- Qal - ALLUVIUM
- Kgu - ZONE 3 OF UPPER GALLUP SANDSTONE (Z3)
- Kcdi - DILCO COAL
- PIEZOMETRIC SURFACE APRIL 2002
  (Surface not extrapolated beyond extent of data)

REV. No.	REVISIONS	DATE	DESIGN BY	DRAWN BY	REVIEWED AND SIGNED BY
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PROJECT: **Hydraulic Evaluation of Remedial Alternatives**

DRAWING TITLE: **CROSS SECTIONS A & B**

MWH

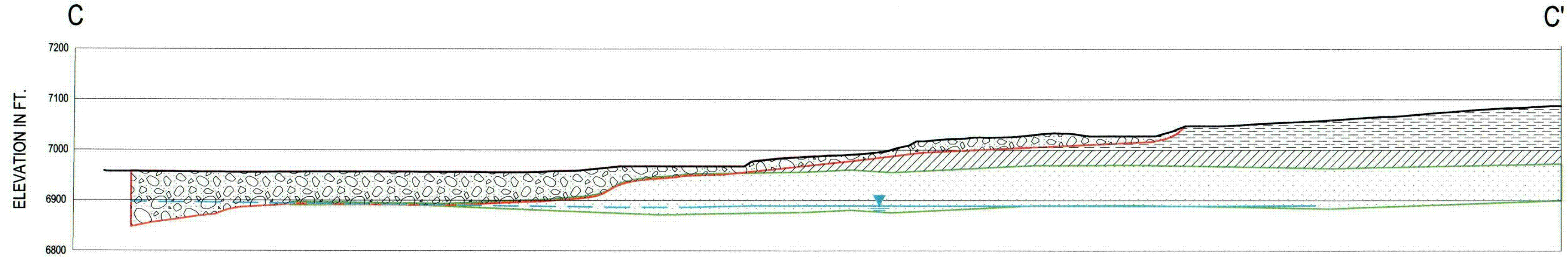
Sheet 1 Of 1 Sheets

SCALE: 1"=200'

FIGURE No. 6

AutoCAD FILE: Secs A and B   PROJECT NUMBER: 5030087.011801

C02



DISTANCE IN FT.

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VERTICAL SCALE
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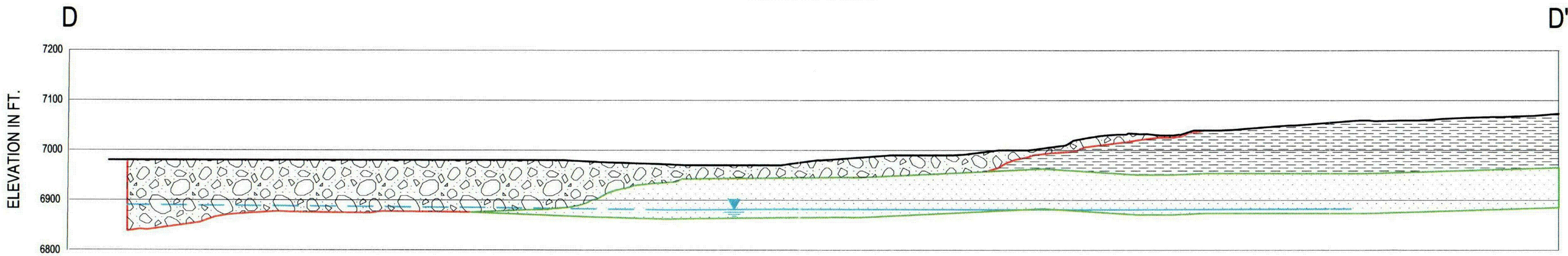

DISTANCE IN FT.

HORIZONTAL SCALE
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VERTICAL SCALE
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LEGEND

- Qal - ALLUVIUM
- Kgu - ZONE 3 OF UPPER GALLUP SANDSTONE (Z3)
- Kcdi - DILCO COAL
- PIEZOMETRIC SURFACE APRIL 2002 *(Surface not extrapolated beyond extent of data)*
- PIEZOMETRIC SURFACE 2002 *(Extrapolated)*
- TOPOGRAPHIC SURFACE

REV. No.	REVISIONS	DATE	DESIGN BY	DRAWN BY	REVIEWED AND SIGNED BY
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PROJECT: **Hydraulic Evaluation of Remedial Alternatives**

DRAWING TITLE: **CROSS SECTIONS C & D**

MWH

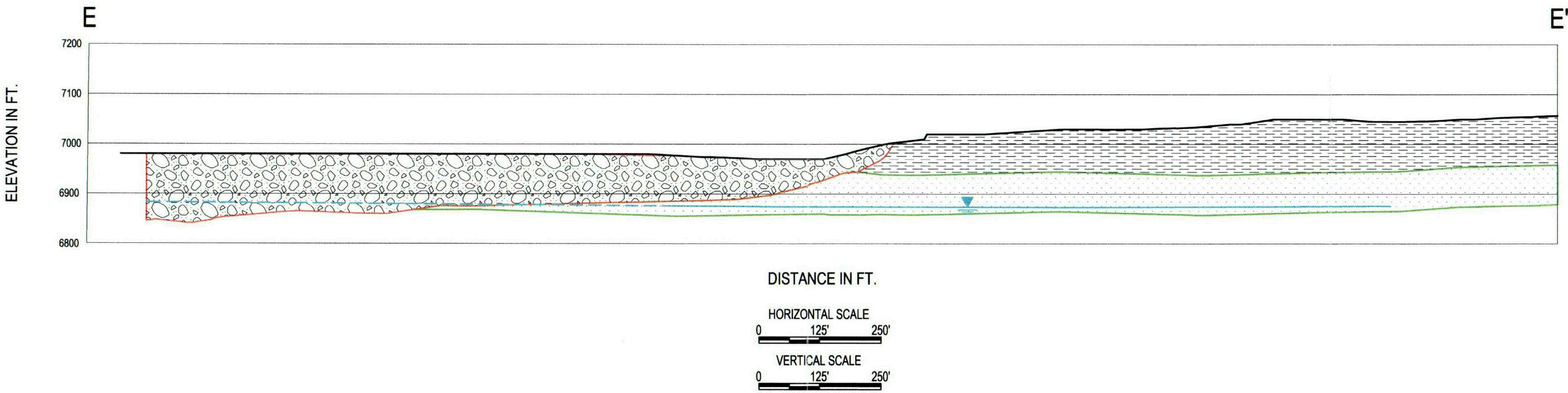
Sheet 1 Of 3 Sheets

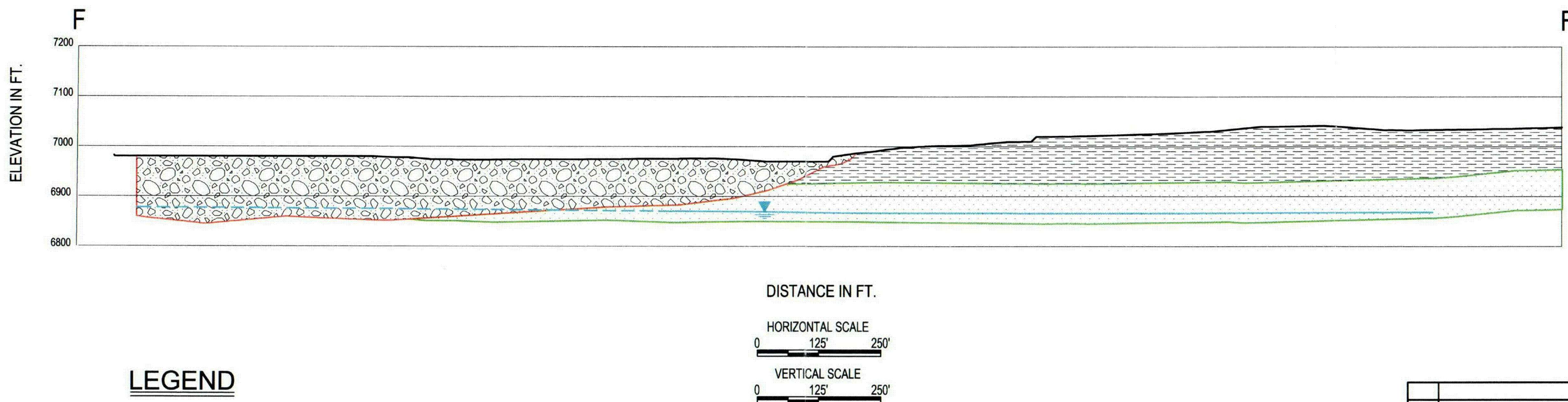
SCALE: 1"=250'

FIGURE No. 7

AutoCAD FILE: North Sections [illegible]1.dwg PROJECT NUMBER: 5030087.011801

C03





LEGEND

- Qal - ALLUVIUM
- Kgu - ZONE 3 OF UPPER GALLUP SANDSTONE (Z3)
- Kcdi - DILCO COAL
- PIEZOMETRIC SURFACE APRIL 2002 *(Surface not extrapolated beyond extent of data)*
- PIEZOMETRIC SURFACE 2002 *(Extrapolated)*
- TOPOGRAPHIC SURFACE

REV. No.	REVISIONS	DATE	DESIGN BY	DRAWN BY	REVIEWED AND SIGNED BY
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0	Draft FFS	4/04	J.Pennington	D.Gallery	D.Ellerbroek

UNITED NUCLEAR CORPORATION

PROJECT:
Hydraulic Evaluation of Remedial Alternatives

DRAWING TITLE:
CROSS SECTIONS E & F

MWH

Sheet 2 Of 3 Sheets

SCALE: 1"=250'

FIGURE No. 8

AutoCAD FILE: North Sections Sh2.dwg PROJECT NUMBER: 50300087.011801

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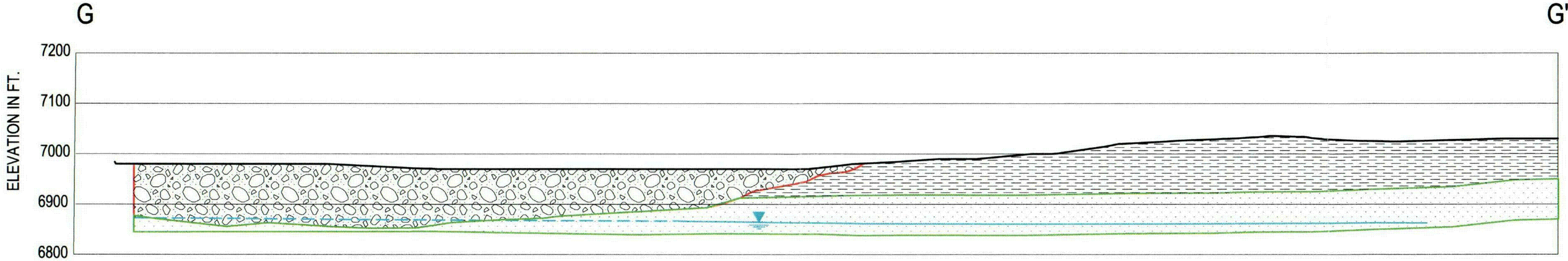

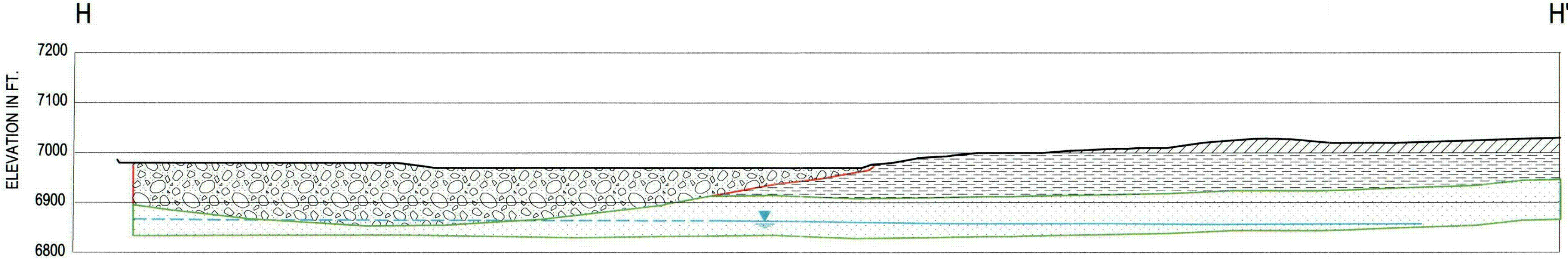

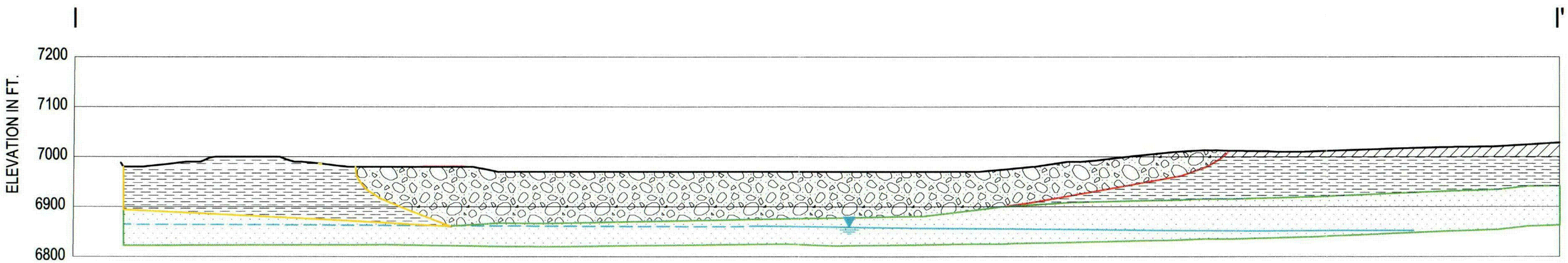

LEGEND

- Qal - ALLUVIUM
- Kgu - ZONE 3 OF UPPER GALLUP SANDSTONE (Z3)
- Kcdi - DILCO COAL
- PIEZOMETRIC SURFACE APRIL 2002 *(Surface not extrapolated beyond extent of data)*
- PIEZOMETRIC SURFACE 2002 *(Extrapolated)*
- TOPOGRAPHIC SURFACE

HORIZONTAL SCALE
0 125' 250'

VERTICAL SCALE
0 125' 250'
Feet

REV. No.	REVISIONS	DATE	DESIGN BY	DRAWN BY	REVIEWED AND SIGNED BY
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UNITED NUCLEAR CORPORATION

PROJECT:
Hydraulic Evaluation of Remedial Alternatives

DRAWING TITLE:
CROSS SECTIONS G, H & I

MWH

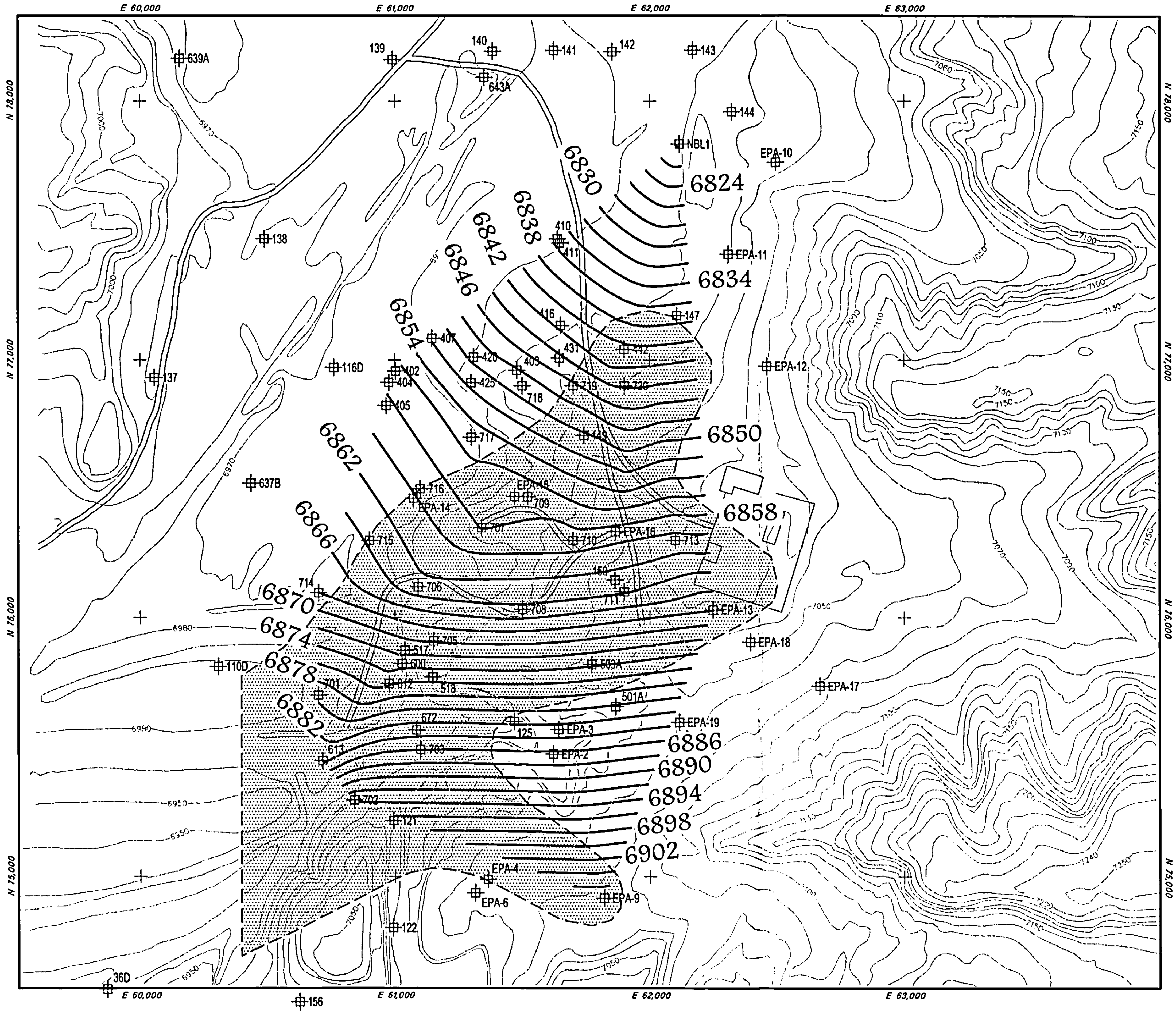
Sheet 3 Of 3 Sheets

SCALE: 1"=250'

FIGURE No. 9

AutoCAD FILE: North_Sections_SH3.dwg PROJECT NUMBER: 5030087.011801

C05



LEGEND

APPROXIMATE PLUME BOUNDARY

POTENTIOMETRIC CONTOURS *(Elevation in feet AMSL)*

143 DRILLHOLE LOCATION

SCALE

200' 0 200' 400'

CONTOUR INTERVAL 10 FT.

REV. No.	REVISIONS	DATE	DESIGN BY	DRAWN BY	REVIEWED AND SIGNED BY
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0	Draft FFS	4/04	J.Pennington	D.Gallery	J.Pennington

UNITED NUCLEAR CORPORATION

PROJECT: ***Hydraulic Evaluation of Remedial Alternatives***

DRAWING TITLE: ***POTENTIOMETRIC SURFACE JANUARY 2002***

MWH

Sheet 1 Of 1 Sheets

SCALE: As Shown

FIGURE No. 11

PROJECT NUMBER: 5030087.01601

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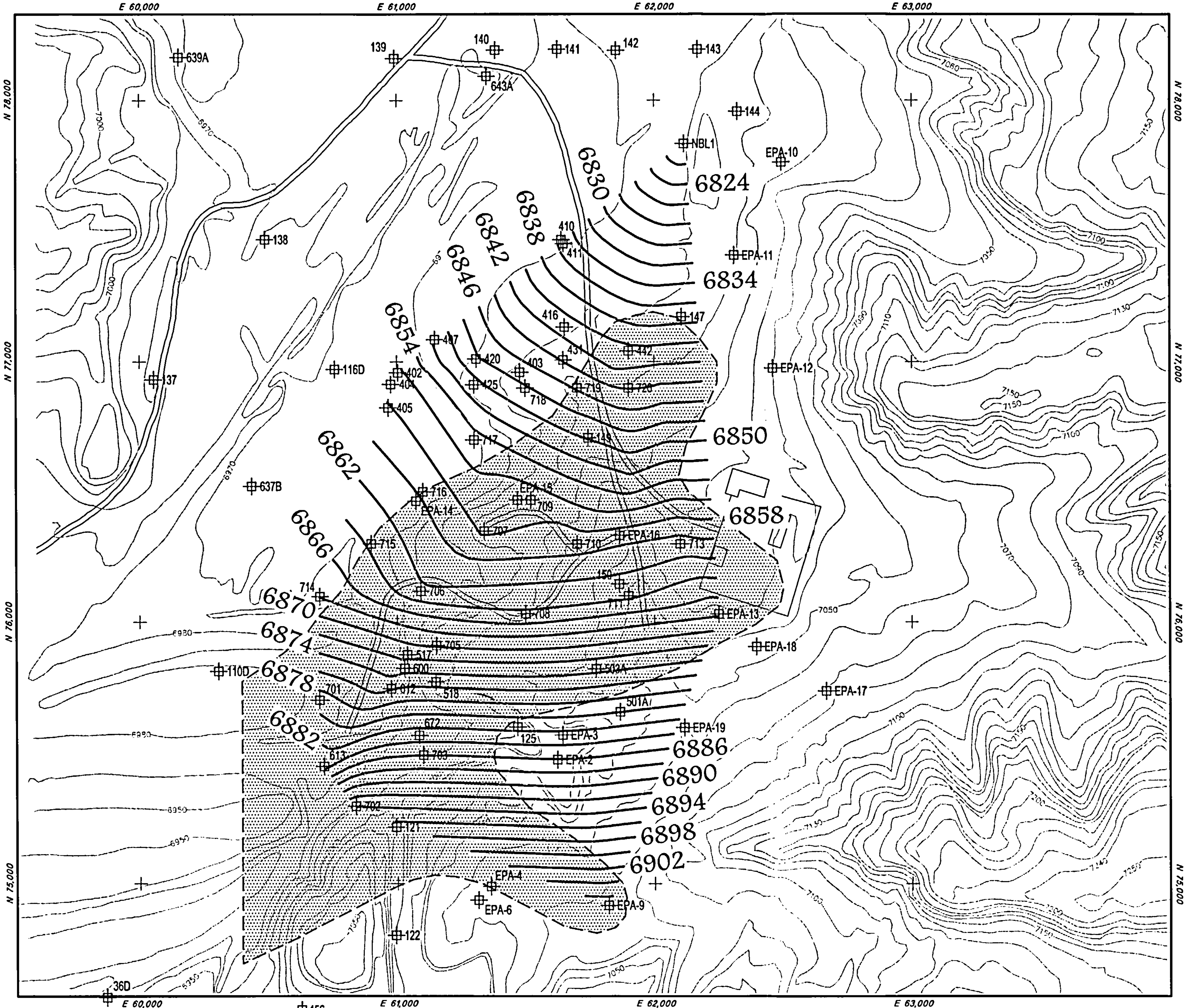


LEGEND

APPROXIMATE PLUME BOUNDARY

POTENTIOMETRIC CONTOURS *(Elevation in feet AMSL)*

143 DRILLHOLE LOCATION

SCALE

200' 0 200' 400'

CONTOUR INTERVAL 10 FT.

REV. No.	REVISIONS	DATE	DESIGN BY	DRAWN BY	REVIEWED AND SIGNED BY
1	Final FFS	10/04	P.Anderson	K.Conrath	P.Anderson
0	Draft FFS	4/04	J.Pennington	D.Gallery	J.Pennington

UNITED NUCLEAR CORPORATION

PROJECT:
Hydraulic Evaluation of Remedial Alternatives

DRAWING TITLE:
POTENTIOMETRIC SURFACE APRIL 2002

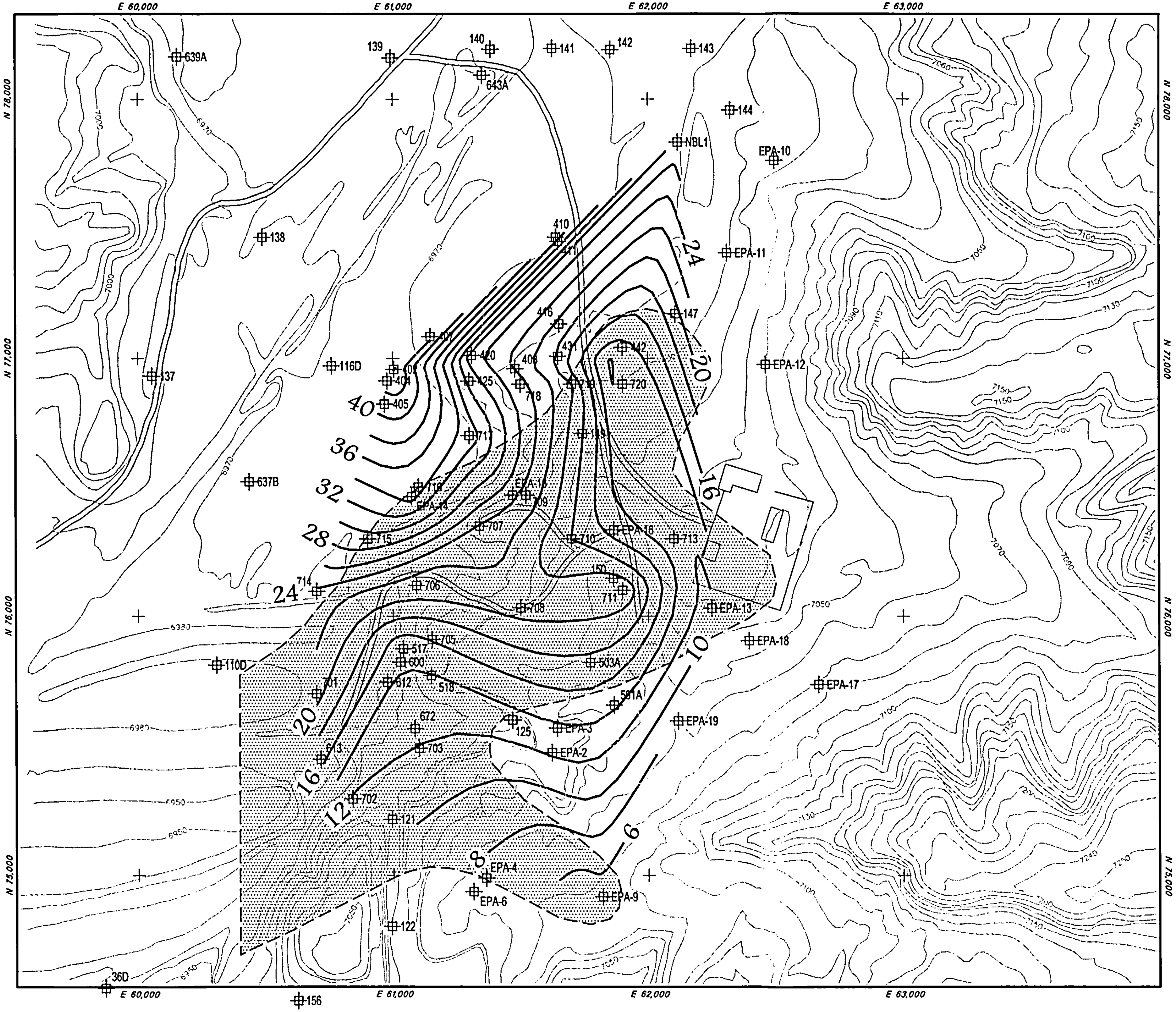
MWH

Sheet 1 Of 1 Sheets

SCALE: *As Shown*

FIGURE No. 12

AutoCAD FILE: Pot Surf Apr02.dwg PROJECT NUMBER: 5030087.011801



LEGEND

APPROXIMATE PLUME BOUNDARY
SATURATION THICKNESS CONTOURS (ft)
143 DRILLHOLE LOCATION

SCALE
CONTOUR INTERVAL 10 FT.

REV. No.	REVISIONS	DATE	DESIGN BY	DRAWN BY	REVIEWED AND SIGNED BY
1	Final FFS	10/04	P.Anderson	K.Cowreth	P.Anderson
0	Draft FFS	6/04	J.Pennington	D.Gallery	J.Pennington

UNITED NUCLEAR CORPORATION

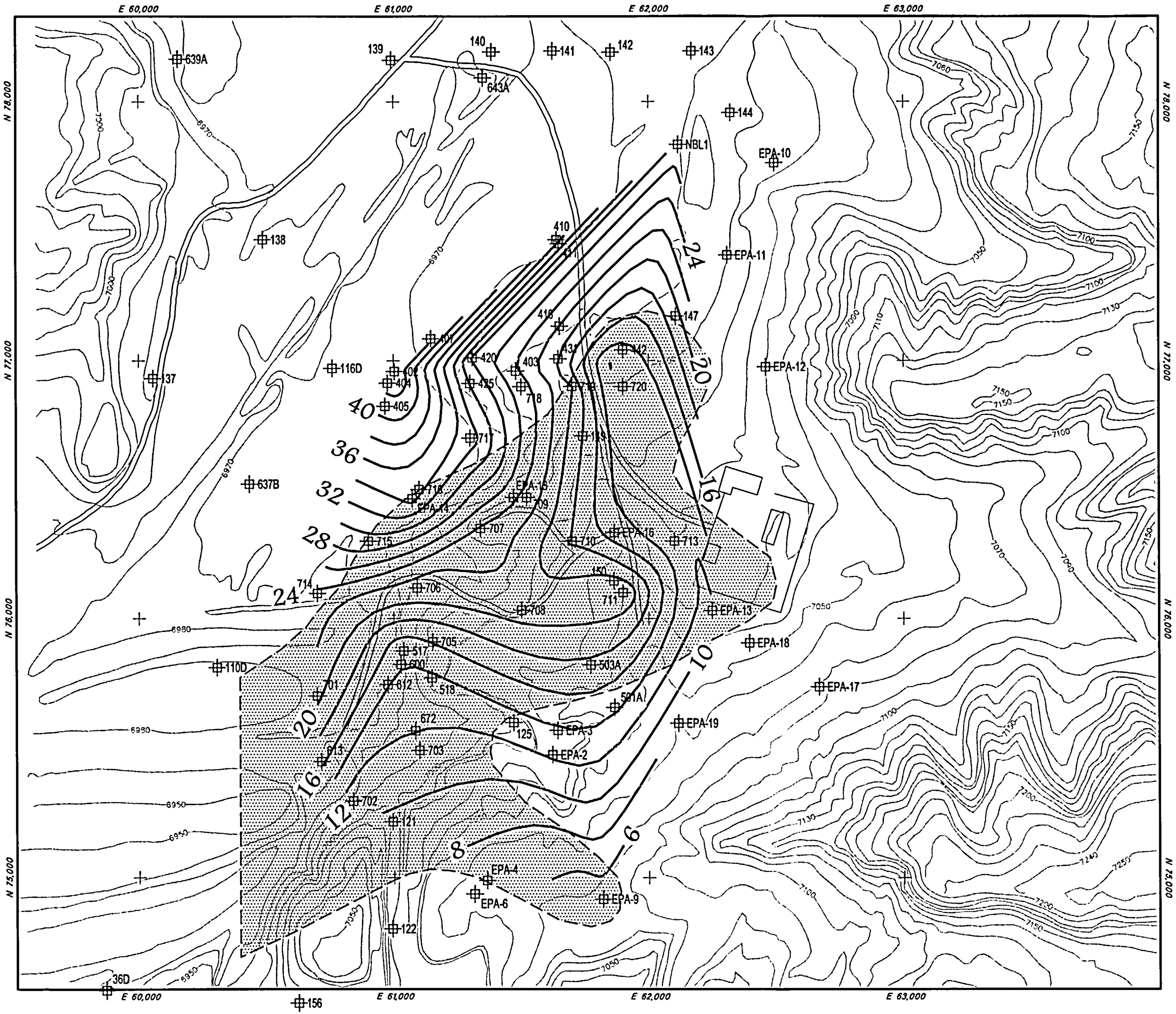
PROJECT:
Hydraulic Evaluation of Remedial Alternatives

DRAWING TITLE:
SATURATED THICKNESS OF ZONE 3 UNIT - OCTOBER 2001

MWH

Sheet 1 Of 1 Sheets
SCALE: As Shown
DRAWING No. 13

PROJECT NUMBER: 5030087.011801
AutoCAD FILE: Sat Oct01.dwg



LEGEND

APPROXIMATE PLUME BOUNDARY
SATURATION THICKNESS CONTOURS (ft)
143 DRILLHOLE LOCATION

REV. No.	REVISIONS	DATE	DESIGN BY	DRAWN BY	REVIEWED AND SIGNED BY
1	Final FFS	10/04	P.Anderson	K.Conrath	P.Anderson
0	Draft FFS	4/04	J.Pennington	D.Gallery	J.Pennington

UNITED NUCLEAR CORPORATION

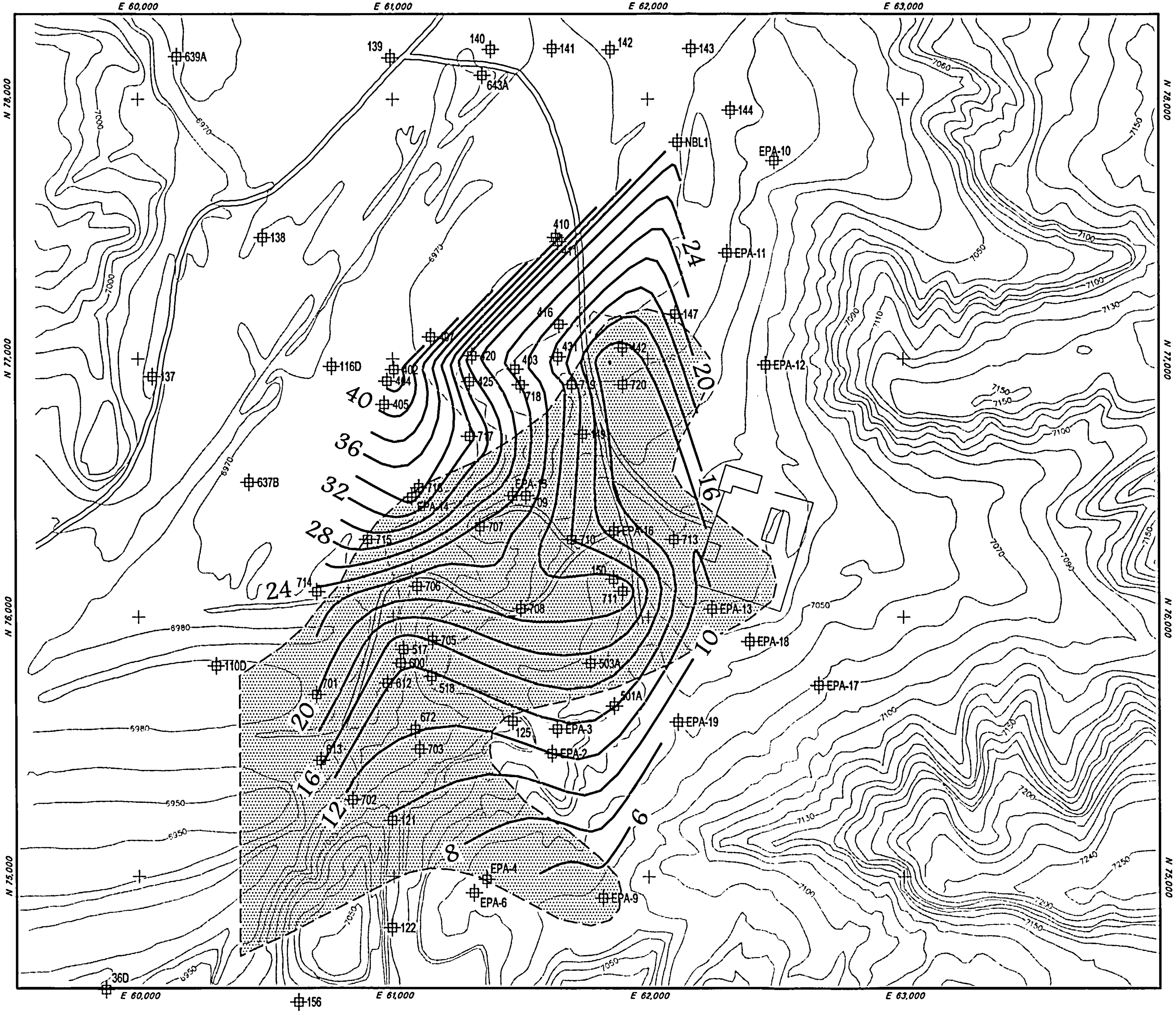
PROJECT:
Hydraulic Evaluation of Remedial Alternatives

DRAWING TITLE:
SATURATED THICKNESS OF ZONE 3 UNIT- JANUARY 2002

MWH

Sheet 1 Of 1 Sheets
SCALE: As Shown
FIGURE No. 14

AutoCAD FILE: Sat Jan02.dwg PROJECT NUMBER: 5030087.011801



LEGEND

- APPROXIMATE PLUME BOUNDARY
- SATURATION THICKNESS CONTOURS
- 143 DRILLHOLE LOCATION

N

SCALE

200' 0 200' 400'

CONTOUR INTERVAL 10 FT.

REV. No.	REVISIONS	DATE	DESIGN BY	DRAWN BY	REVIEWED AND SIGNED BY
1	Final FFS	10/04	P.Anderson	K.Conrath	P.Anderson
0	Draft FFS	4/04	J.Pennington	D.Gallery	J.Pennington

UNITED NUCLEAR CORPORATION

PROJECT:
Hydraulic Evaluation of Remedial Alternatives

DRAWING TITLE:
SATURATED THICKNESS OF ZONE 3 UNIT - APRIL 2002

MWH

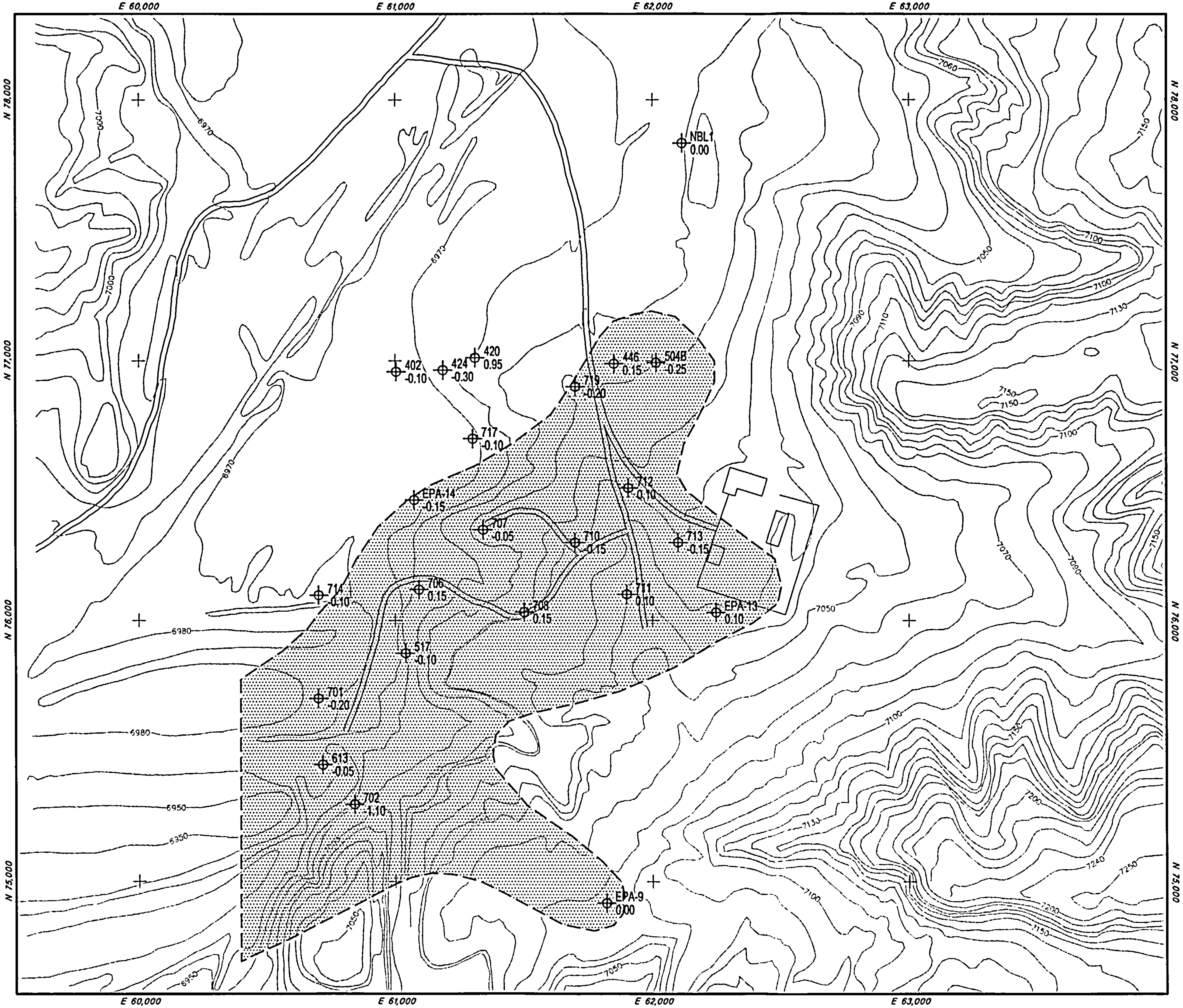
Sheet 1 Of 1 Sheets

SCALE: As Shown

FIGURE No. 15

AutoCAD FILE: Sat_Apr02.dwg

PROJECT NUMBER: 5020087.01601



LEGEND

APPROXIMATE PLUME BOUNDARY

NBL1 0.00 MONITORING LOCATION *(with Change in feet of Saturation Thickness from Monitoring Well)*

SCALE

200' 0 200' 400'

CONTOUR INTERVAL 10 FT.

1	Final FFS	10/04	P.Anderson	K.Conrath	P.Anderson
0	Draft FFS	4/04	J.Pennington	D.Gallery	J.Pennington
REV. No.	REVISIONS	DATE	DESIGN BY	DRAWN BY	REVIEWED AND SIGNED BY

UNITED NUCLEAR CORPORATION

PROJECT:
Hydraulic Evaluation of Remedial Alternatives

DRAWING TITLE:
CHANGE IN SATURATED THICKNESS OCTOBER 2001 TO JANUARY 2002

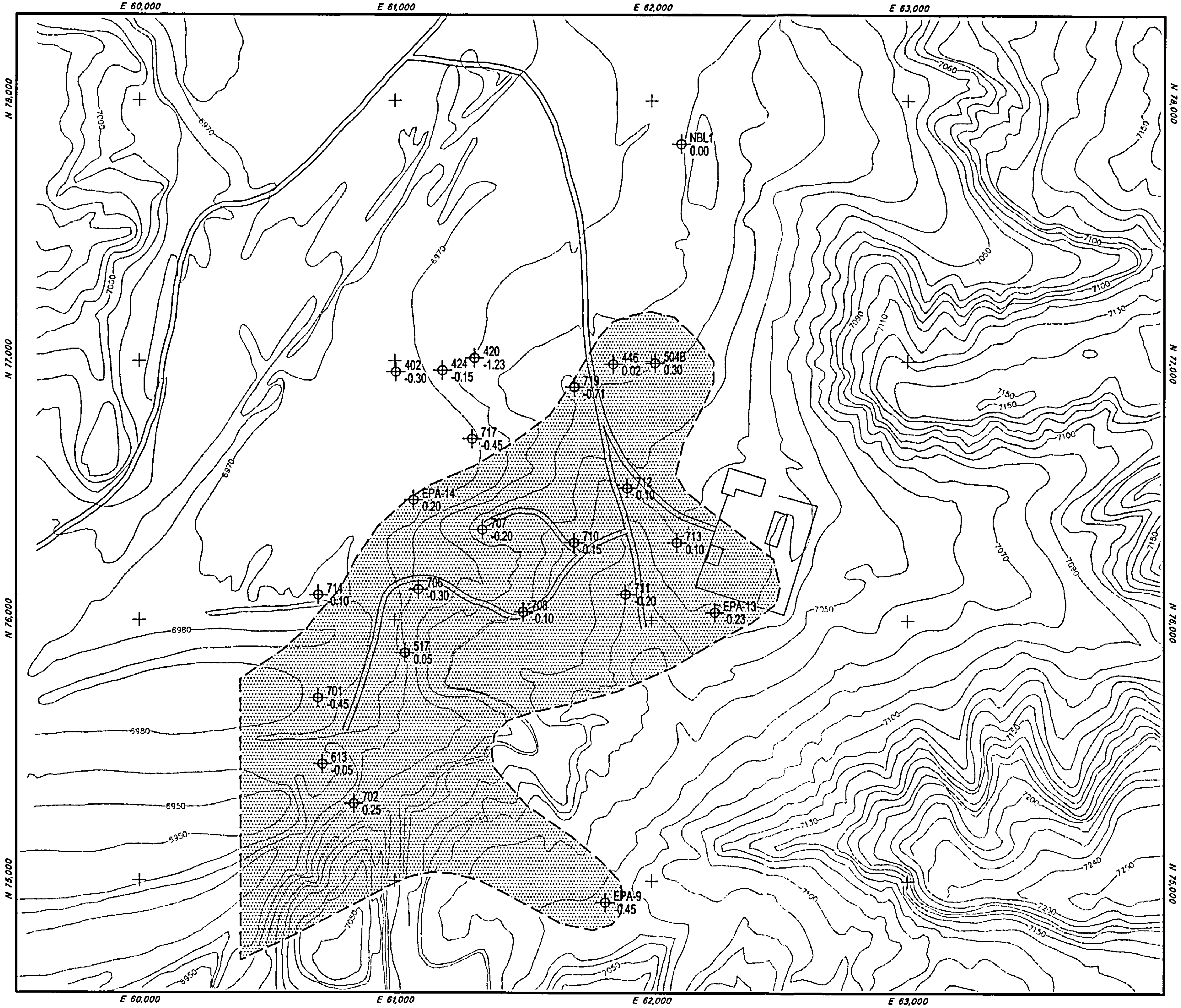
MWH

Sheet 1 Of 1 Sheets

SCALE: As Shown

FIGURE No. 16

AutoCAD FILE: CHNG SAT OCt-Jan02 PROJECT NUMBER: 3020087.011601



LEGEND

APPROXIMATE PLUME BOUNDARY

NBL1 0.00 MONITORING WELL LOCATION (with Change in Feet of Saturation Thickness from Monitoring Well)

SCALE 200' 0 200' 400'

CONTOUR INTERVAL 10 FT.

REV. No.	REVISIONS	DATE	DESIGN BY	DRAWN BY	REVIEWED AND SIGNED BY
1	Final FFS	10/04	P.Andersen	K.Conrath	P.Andersen
0	Draft FFS	4/04	J.Pennington	D.Gallery	J.Pennington

UNITED NUCLEAR CORPORATION

PROJECT: Hydraulic Evaluation of Remedial Alternatives

DRAWING TITLE: CHANGE IN SATURATED THICKNESS JANUARY 2002 TO APRIL 2002

MWH

Sheet 1 Of 1 Sheets

SCALE: As Shown

FIGURE No. 17

AutoCAD FILE: CHNG SAT JANvA.dwg PROJECT NUMBER: 5030087.01801

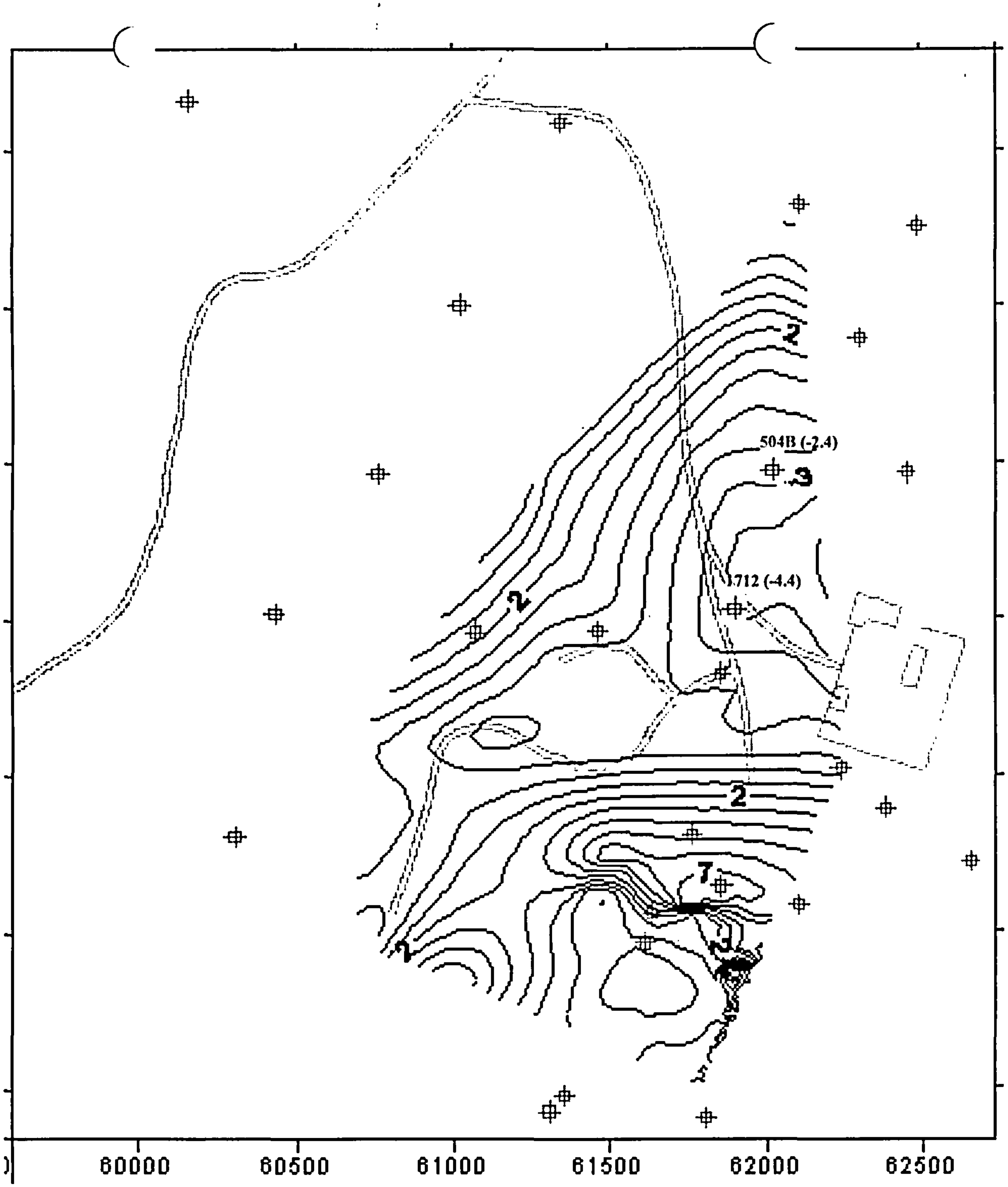
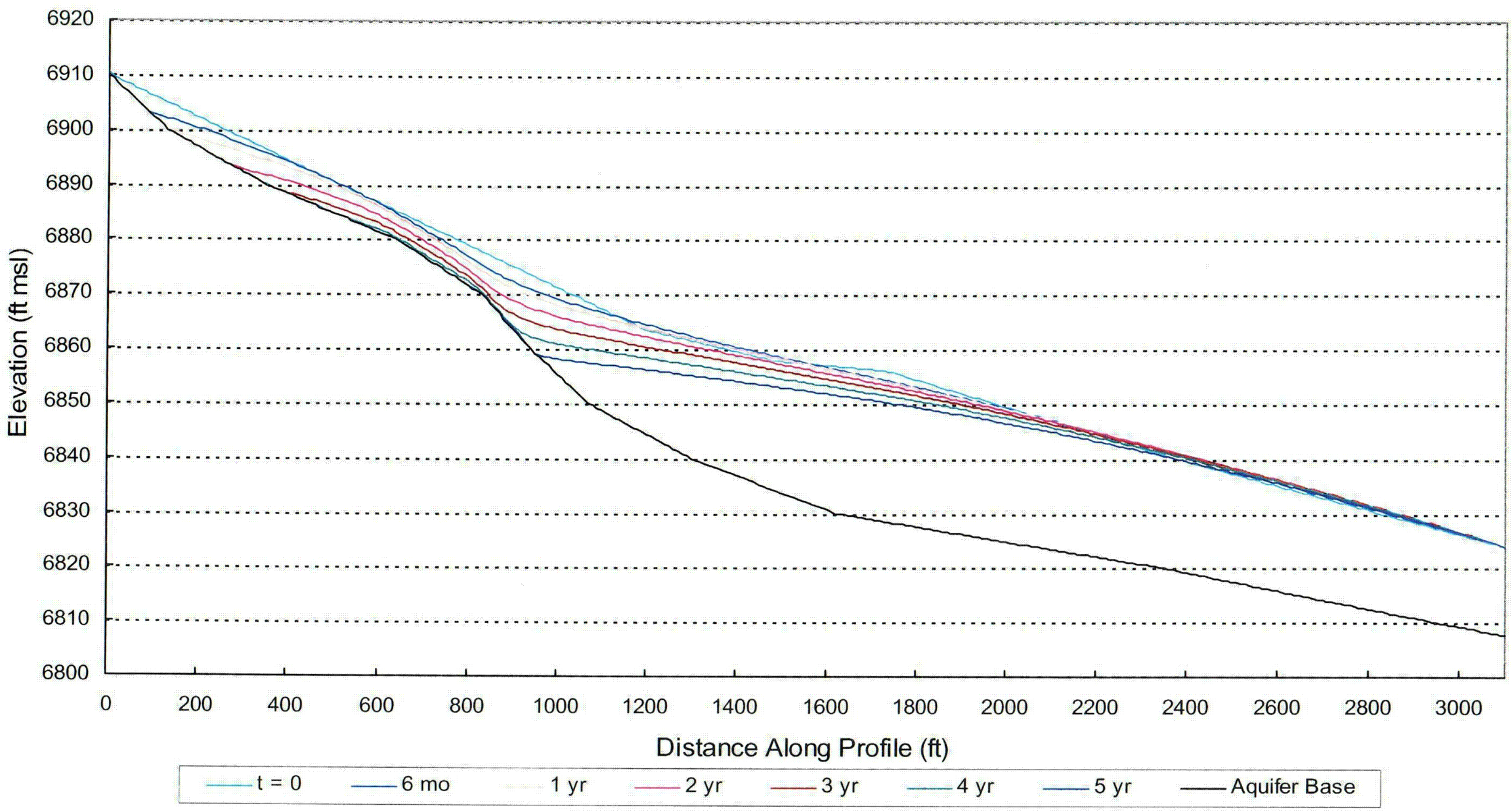


Figure 18
Model Residuals
Observed Heads
Minus Simulated
Initial Heads

April 2002

Figure 19

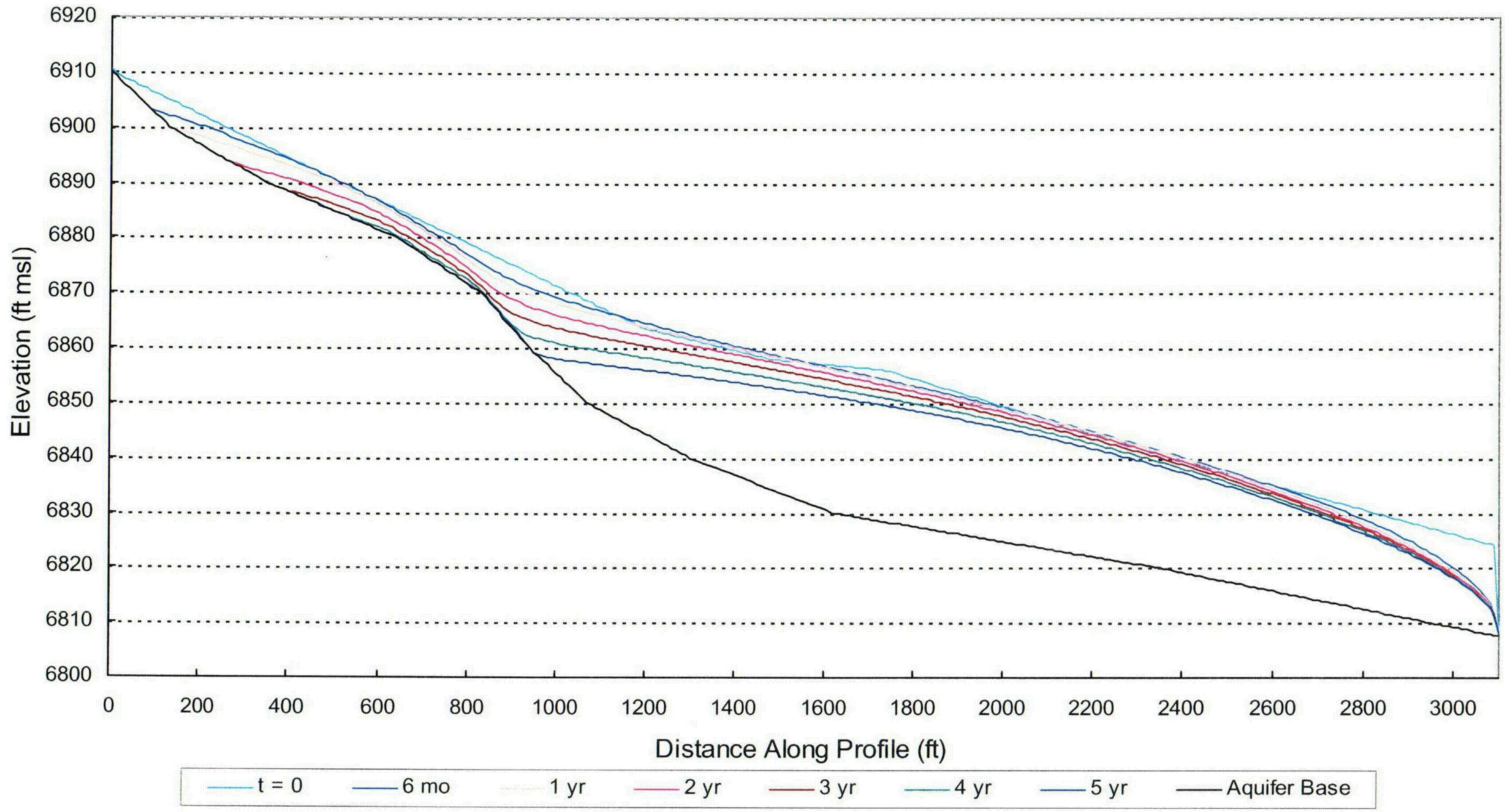
Zone 3 Hydrostratigraphic Unit Drainage - Natural Drainage



C06

Figure 20

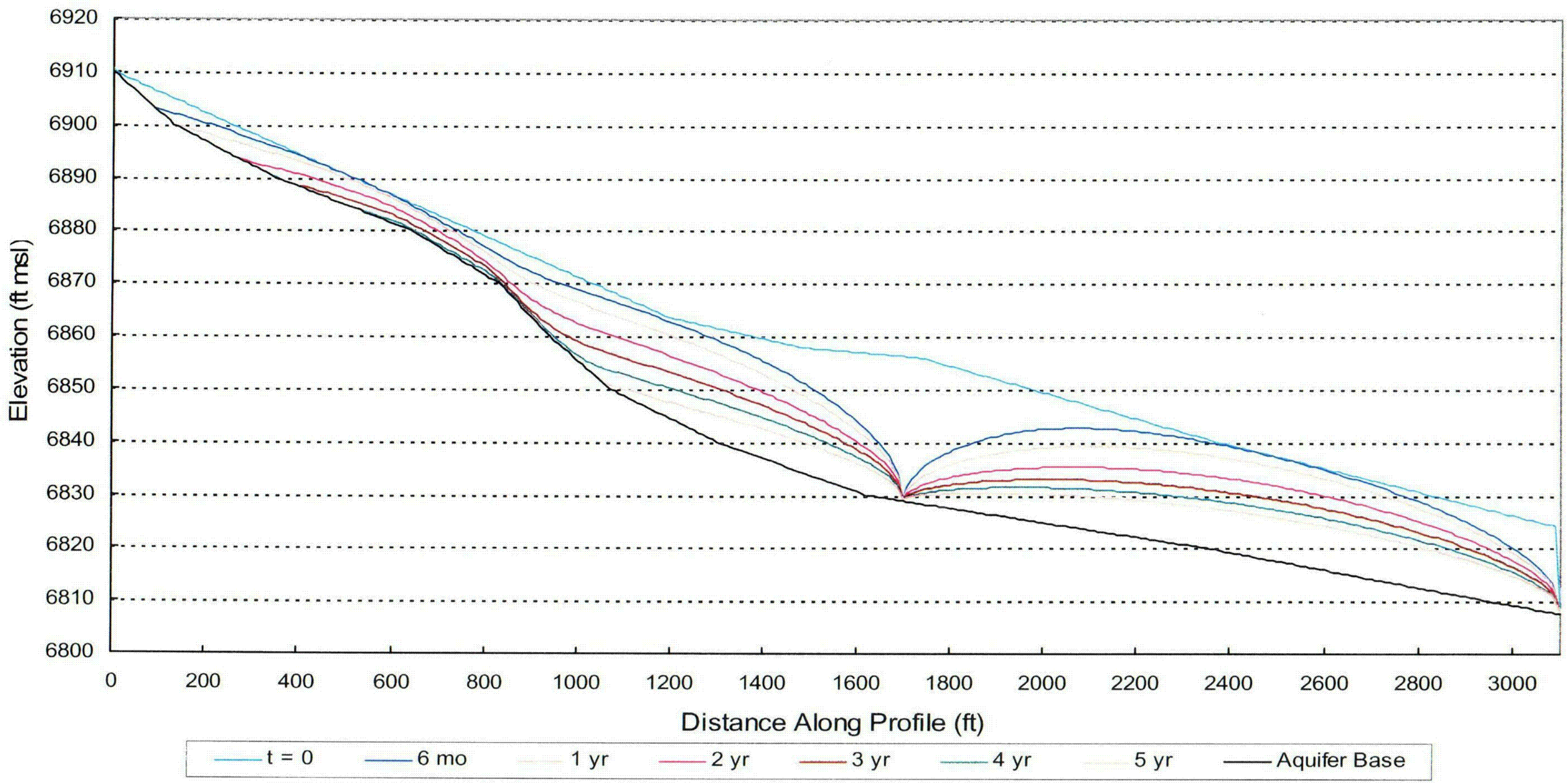
Zone 3 Hydrostratigraphic Unit Drainage - One Artificial Drain



C07

Figure 21

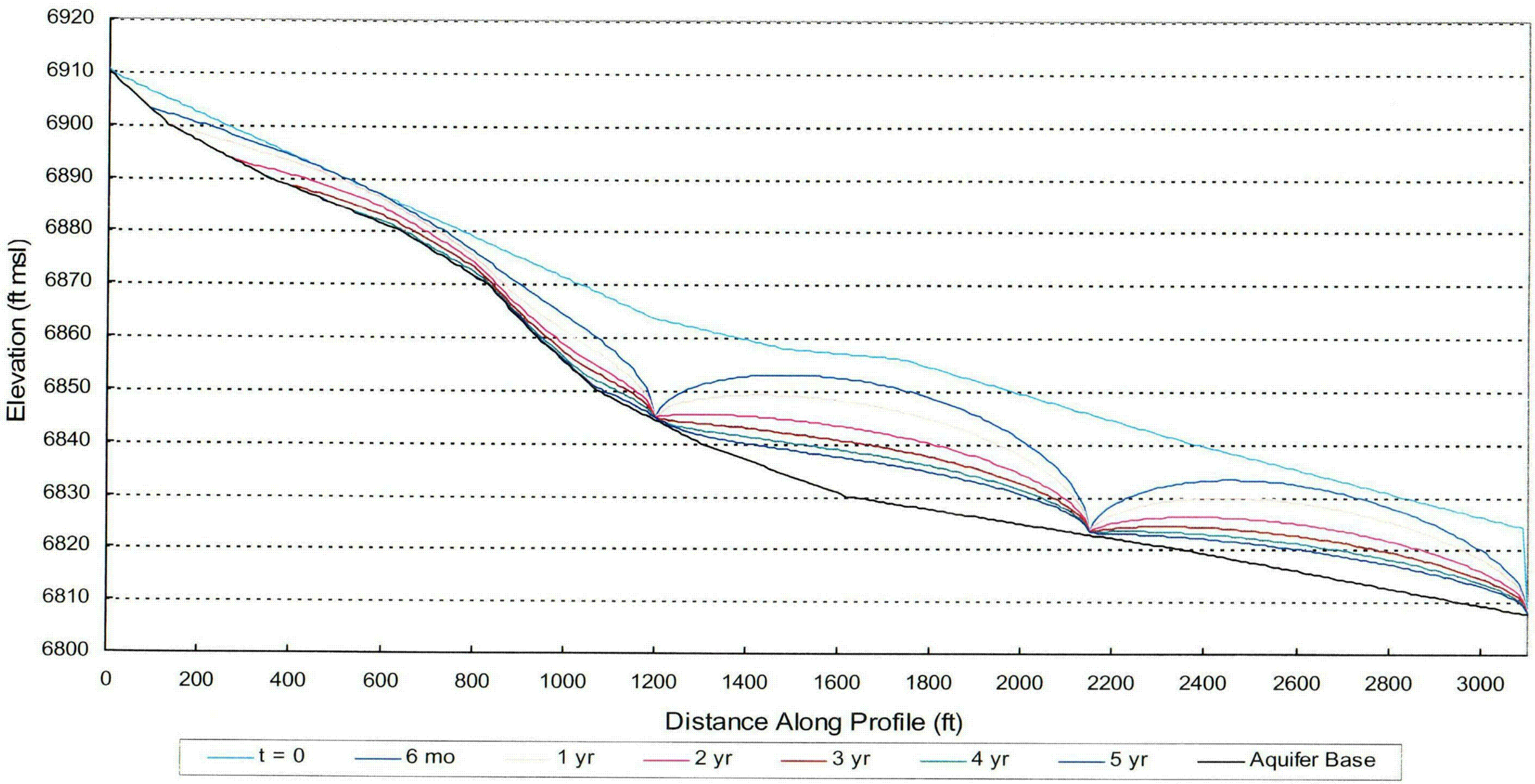
Zone 3 Hydrostratigraphic Unit Drainage - Two Artificial Drains



C08

Figure 22

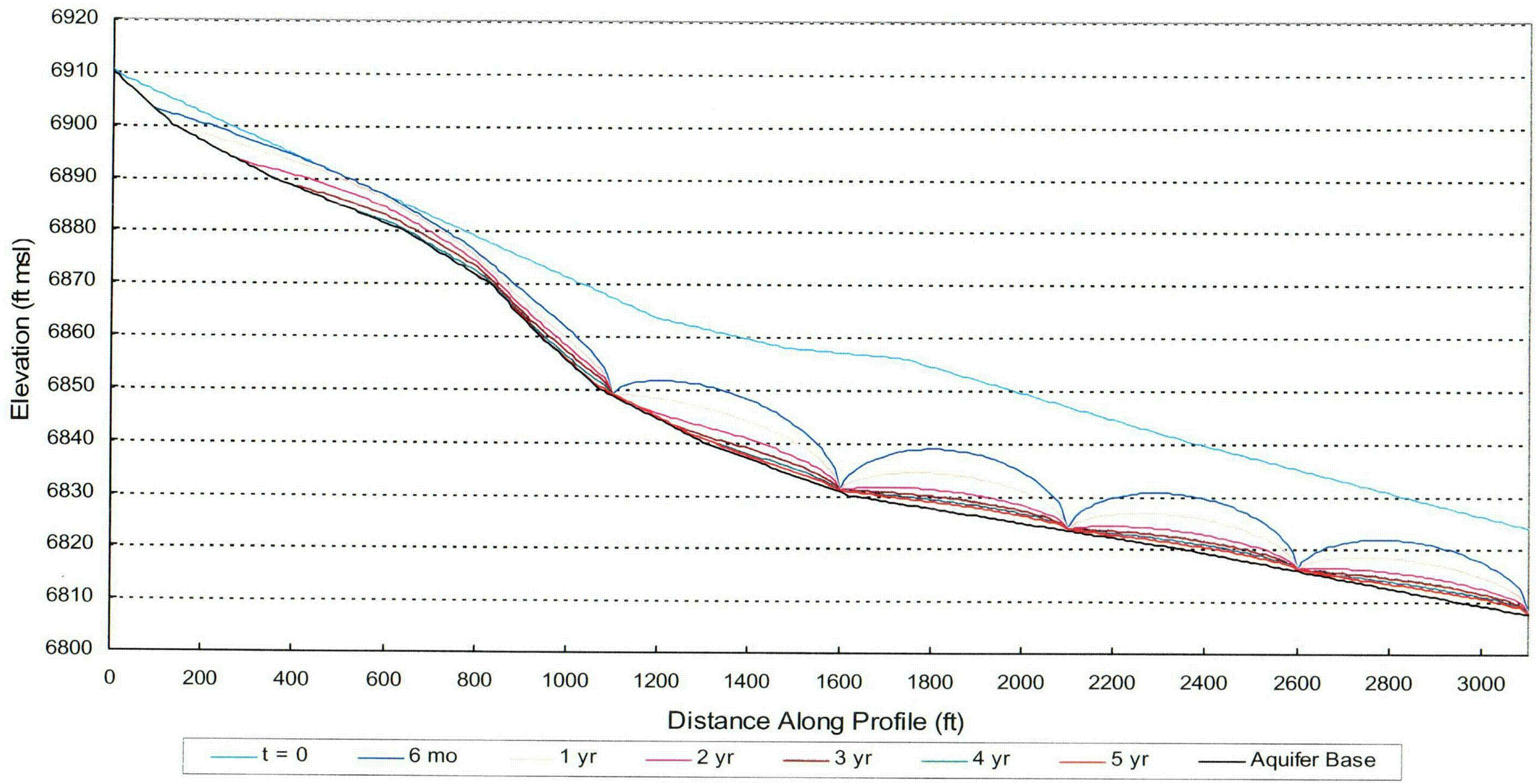
Zone 3 Hydrostratigraphic Unit Drainage - Three Artificial Drains



C09

Figure 23

Zone 3 Hydrostratigraphic Unit Drainage - Five Artificial Drains



C10

Figure 24
3A. Tunnel
Drawdown
1 Year

Note: April 2002 plume outline shown by black outline

C11

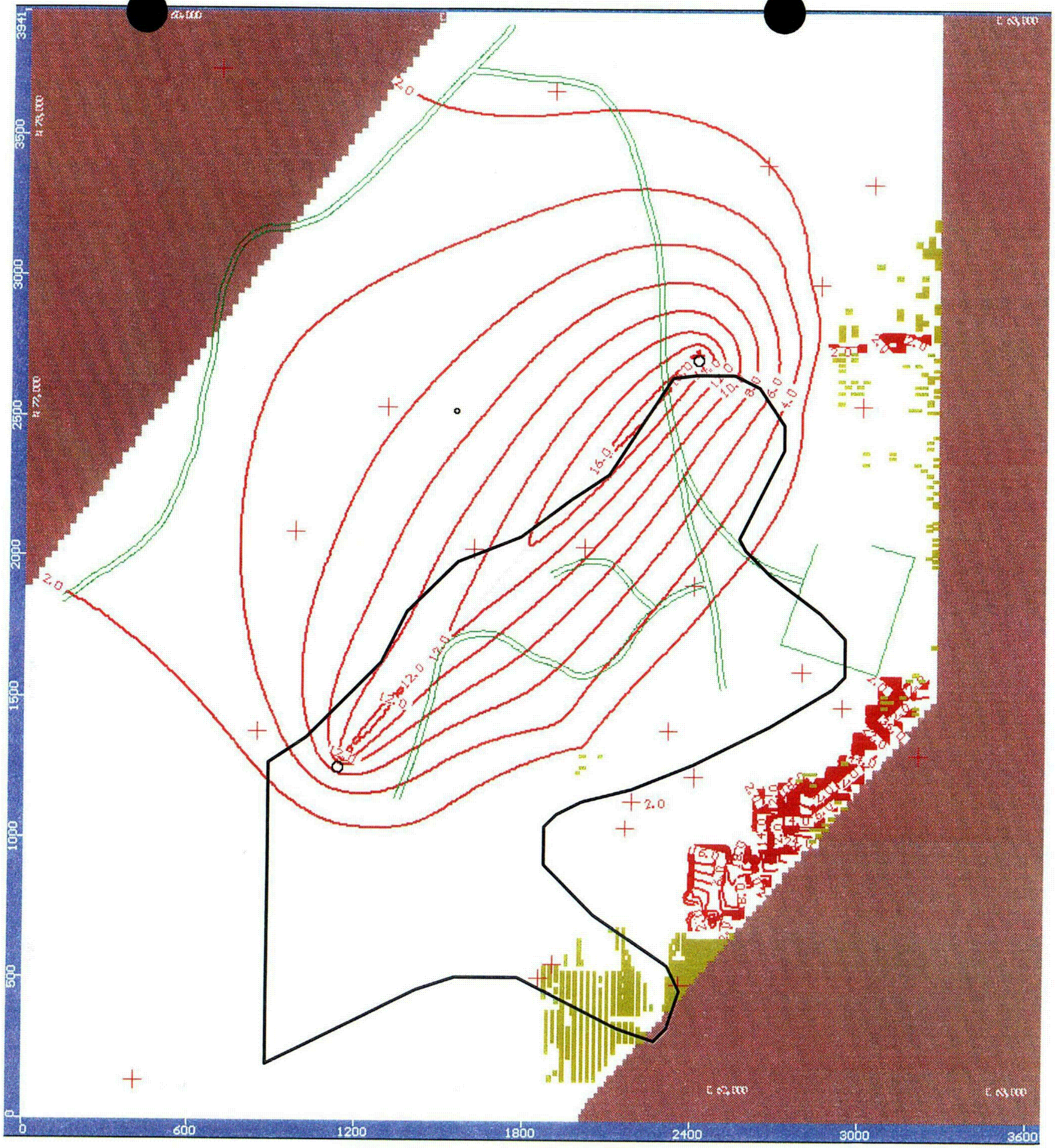


Figure 25
3A. Tunnel
Drawdown
3 Years

Note: April 2002 plume outline shown by black outline

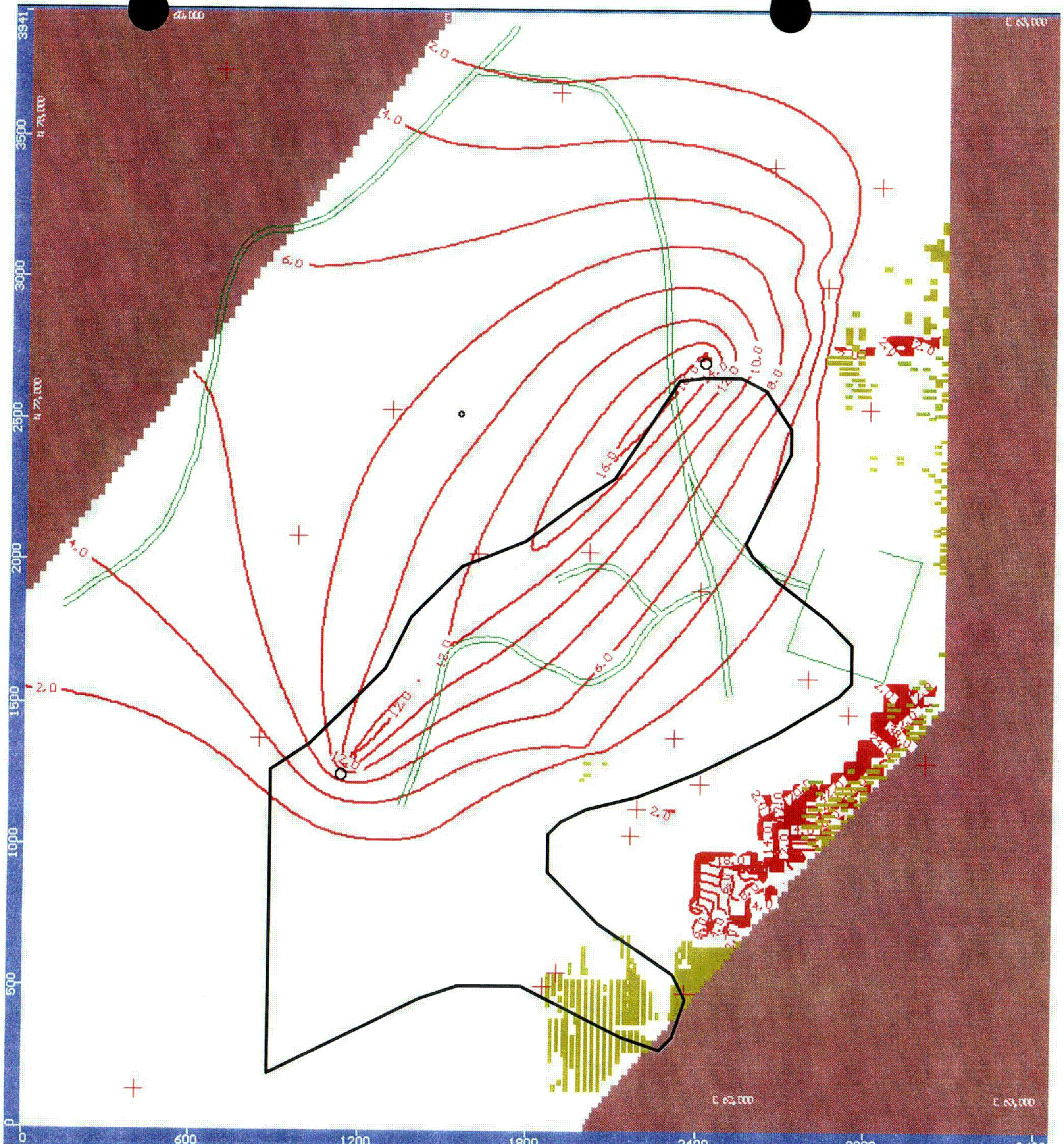


Figure 26
3A. Tunnel Drawdown 5 Years

Note: April 2002 plume outline shown by black outline

Figure 27
3B. Tunnel
(with Drifts)
Drawdown
1 Year

Note: April 2002 plume outline
shown by black outline

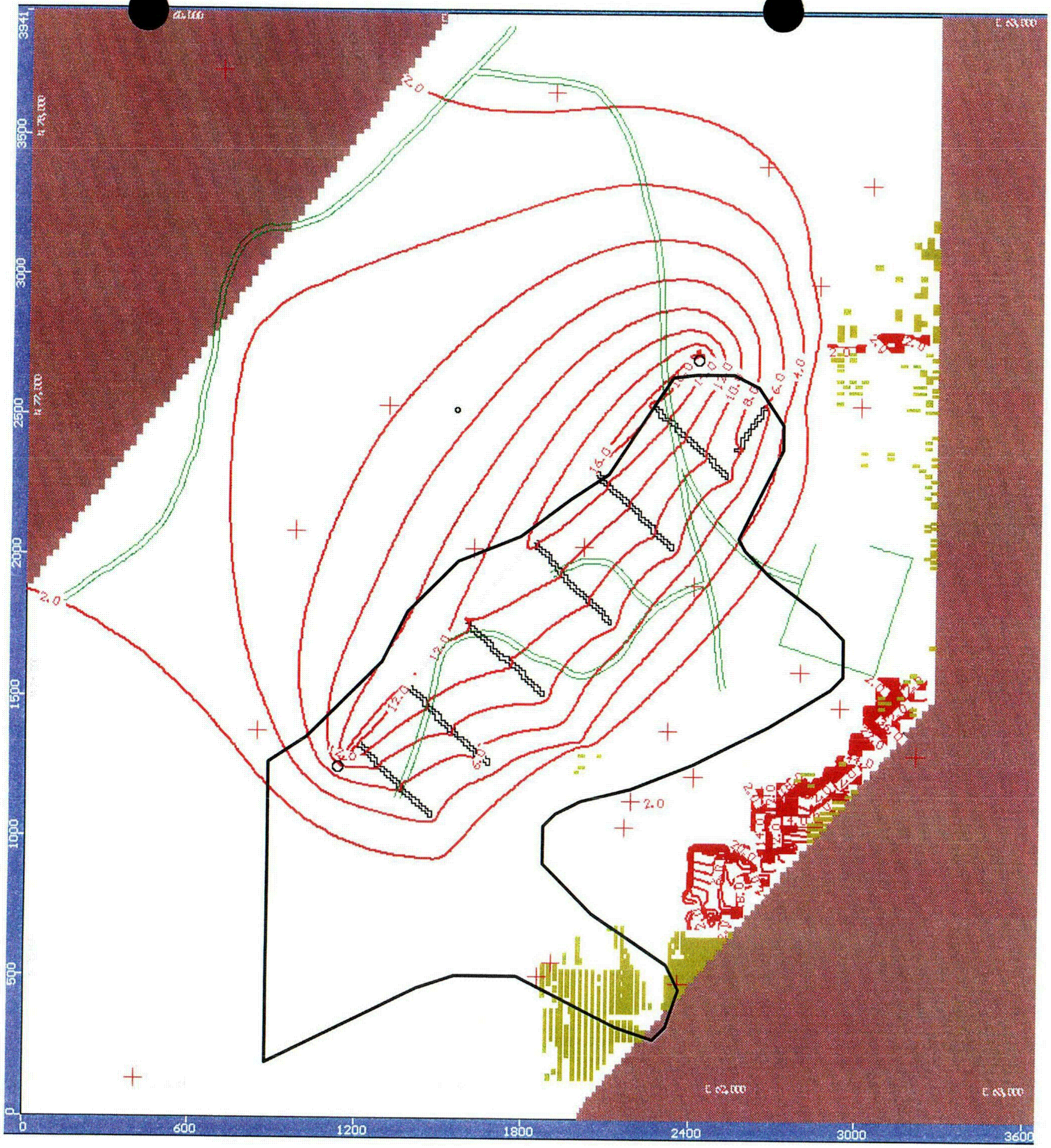


Figure 28
3B. Tunnel
(with Drifts)
Drawdown
3 Years

Note: April 2002 plume outline shown by black outline

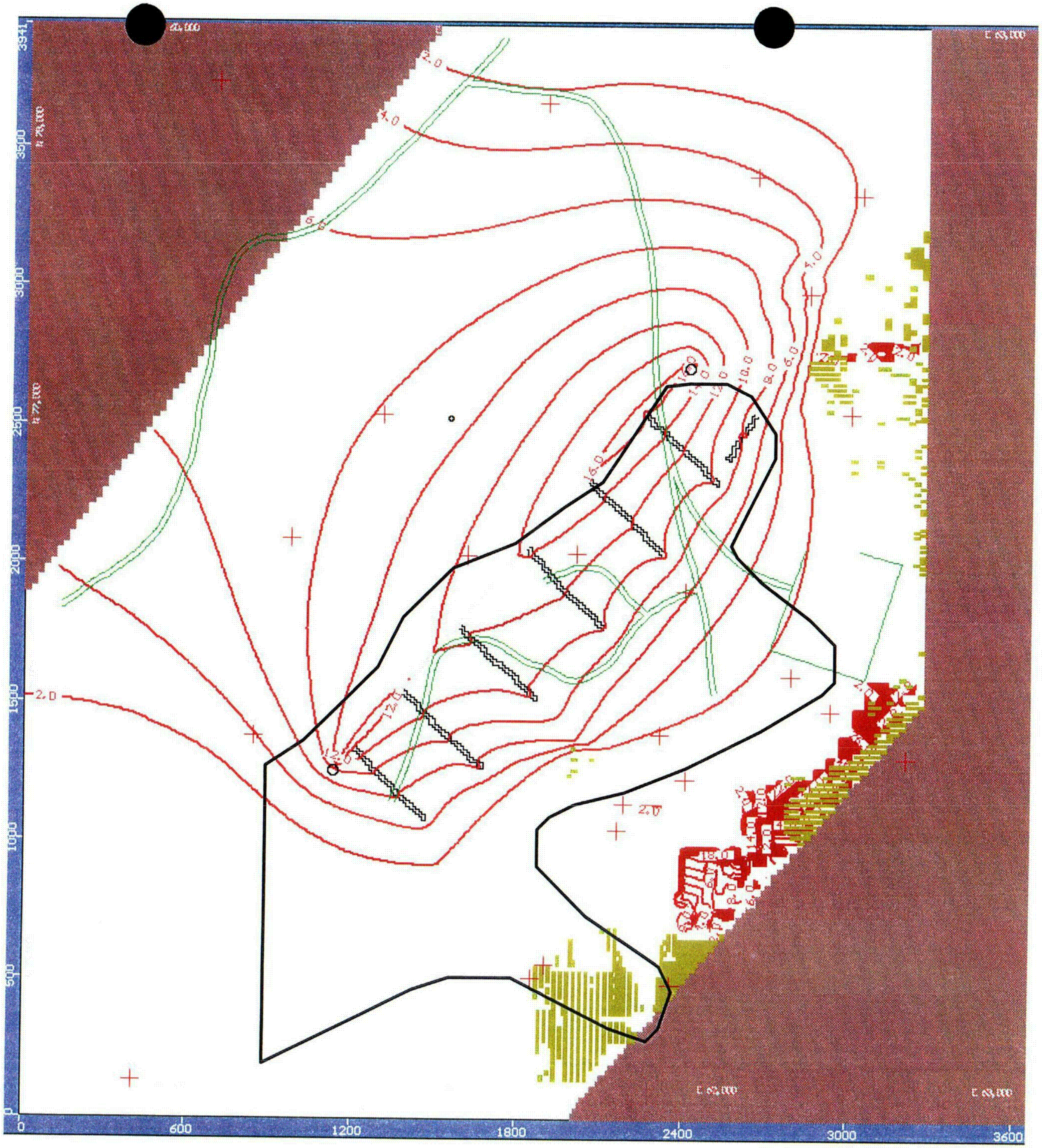


Figure 29
3B. Tunnel (with Drifts) Drawdown
5 Years

Note: April 2002 plume outline shown by black outline

C16

Figure 30
4. Open Pit
Drawdown
1 Year

Note: April 2002 plume outline shown by black outline

Figure 31
4. Open Pit
Drawdown
3 Years

Note: April 2002 plume outline shown by black outline

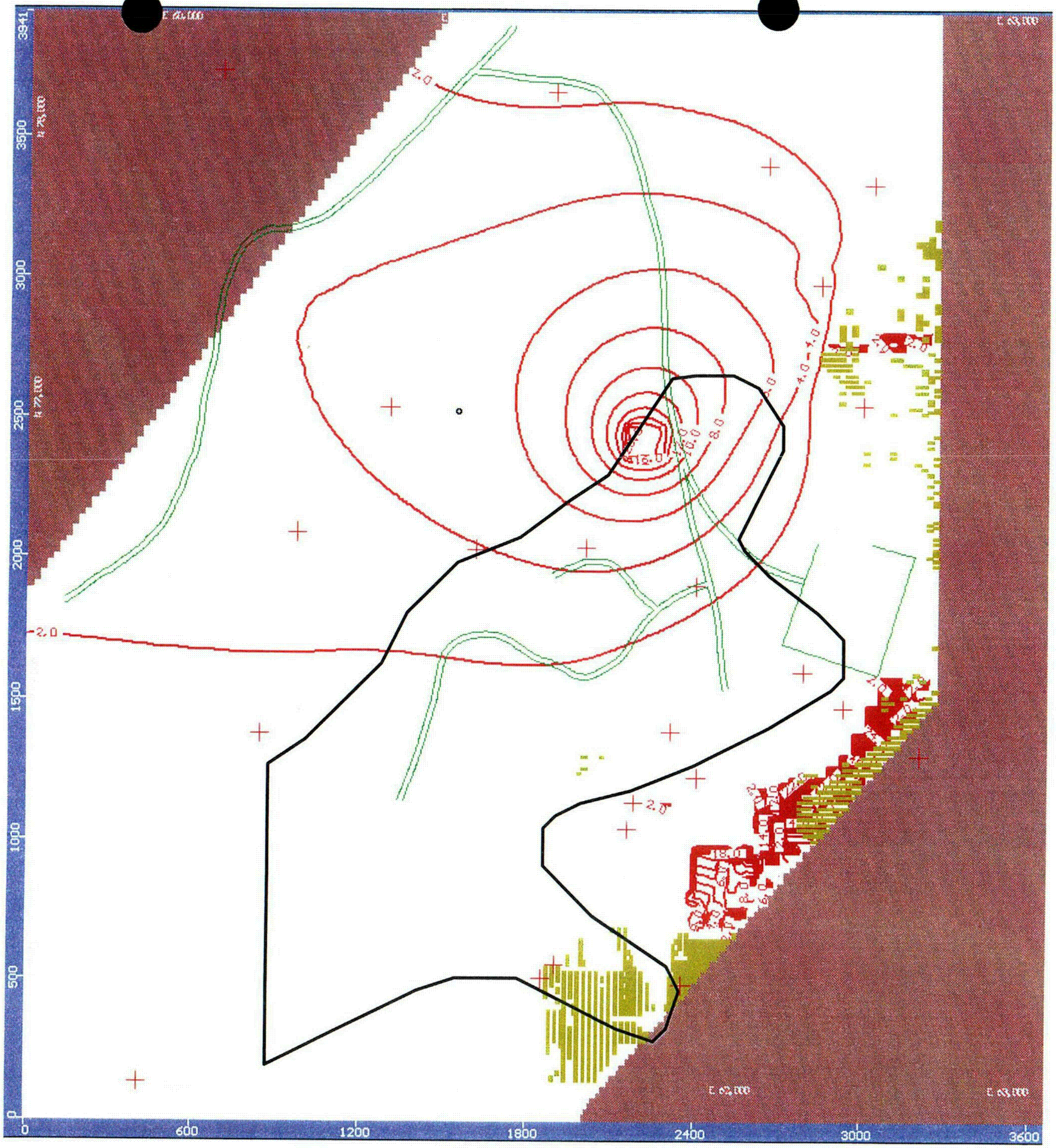


Figure 32
4. Open Pit
Drawdown
5 Years

Note: April 2002 plume outline shown by black outline

C19

Figure 33
5A. Well Field Drawdown
1 Year

Note: April 2002 plume outline shown by black outline

Pumps set to 6 ft above the base of Z3

C20

Figure 34
5A. Well Field Drawdown 3 Years

Note: April 2002 plume outline shown by black outline

Pumps set to 6 ft above the base of Z3

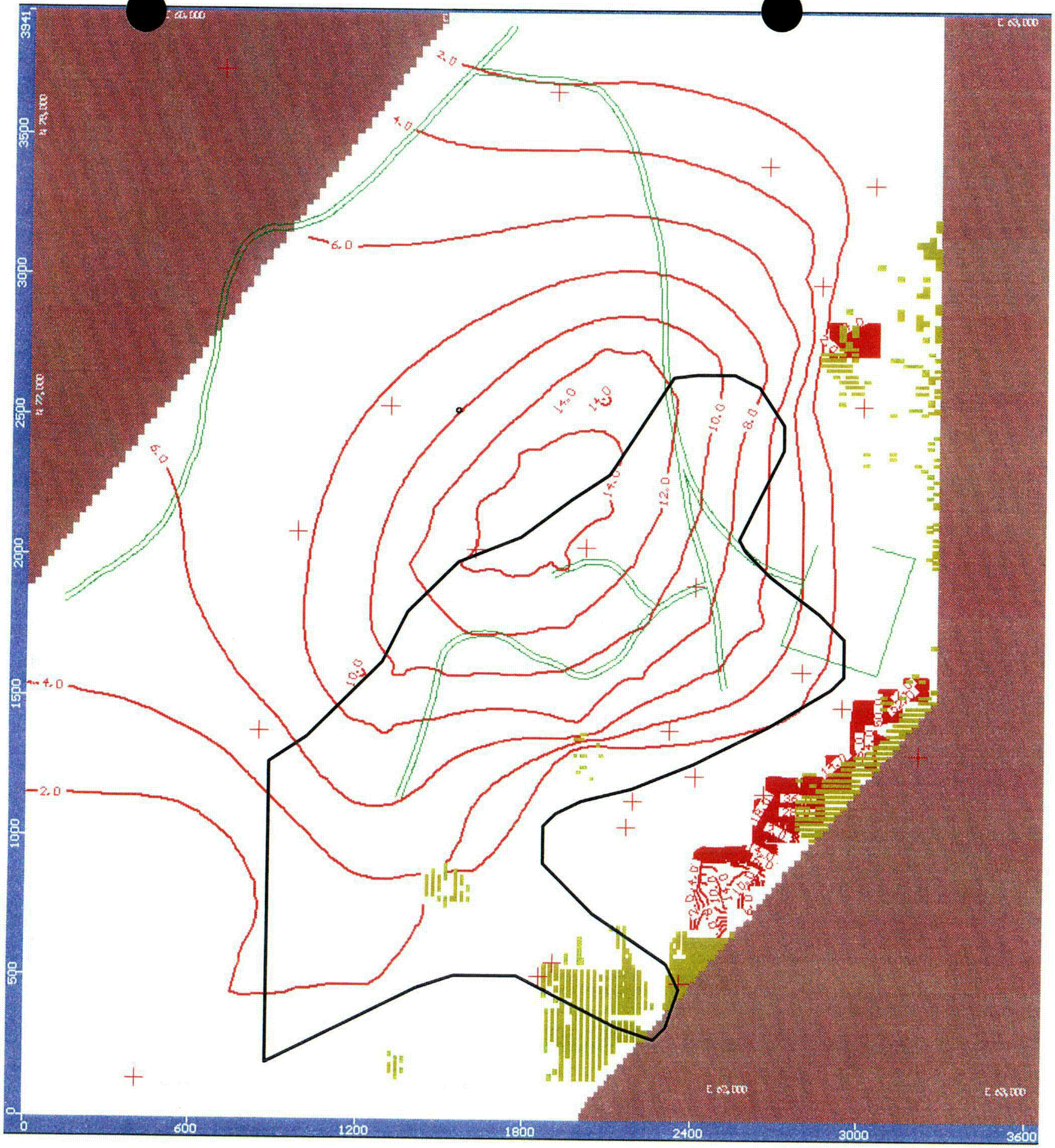


Figure 35
5A. Well Field
Drawdown
5 Years

Note: April 2002 plume outline shown by black outline

Pumps set to 6 ft above the base of Z3

C22

Figure 36
5B. Well Field Drawdown 1 Year

Note: April 2002 plume outline shown by black outline

Pumps set to 3 ft above the base of Z3

CZ3

Figure 37
5B. Well Field Drawdown
3 Years

Note: April 2002 plume outline shown by black outline

Pumps set to 3 ft above the base of Z3

C24

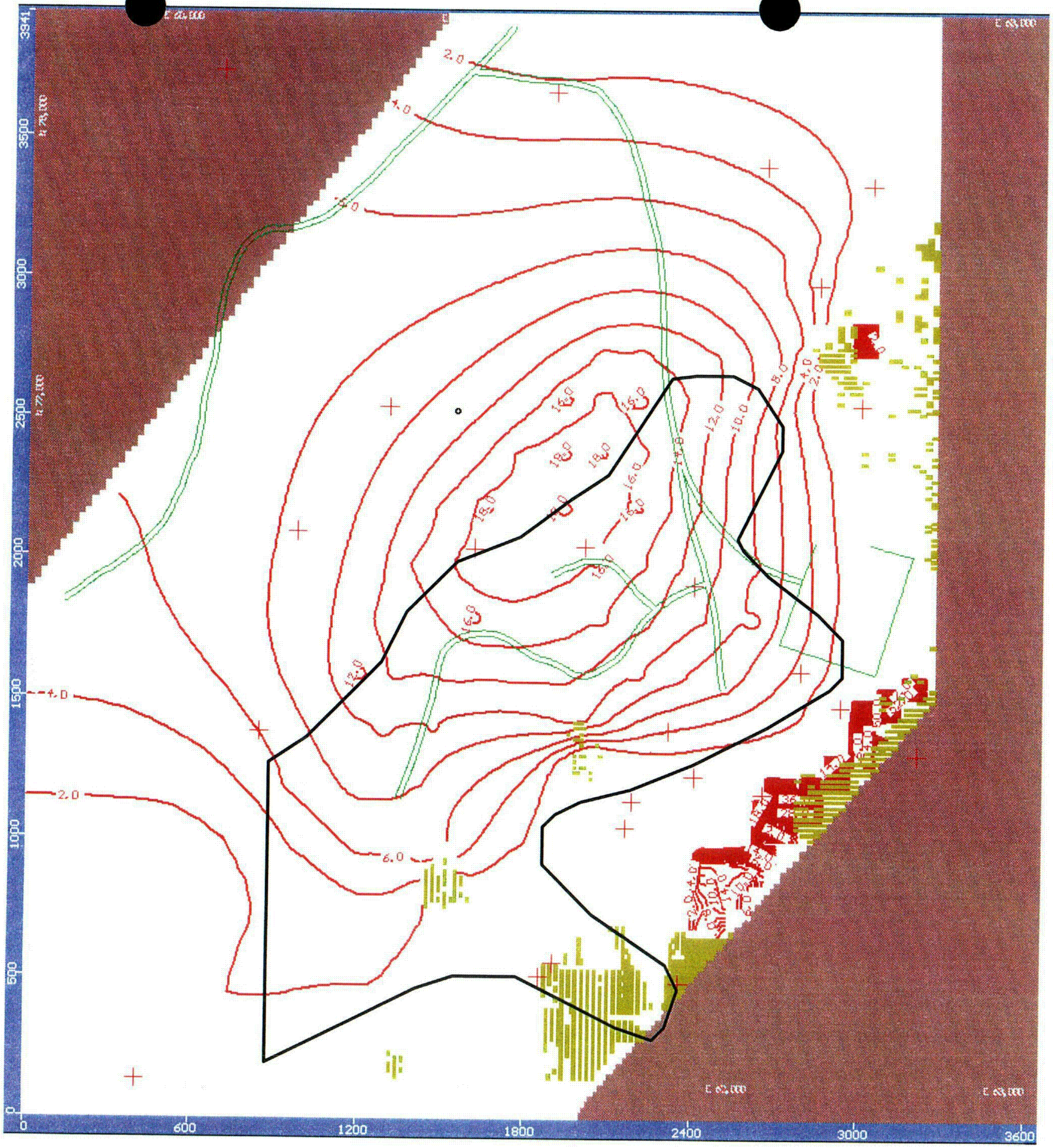


Figure 38
5B. Well Field
Drawdown
5 Years

Note: April 2002 plume outline shown by black outline

Pumps set to 3 ft above the base of Z3

C25

Figure 39
5B. Well Field Additional Drawdown from 5 to 10 Years

(5-year simulation using output from 5 years of pumping as initial heads.)

Note: April 2002 plume outline shown by black outline

Pumps set to 3 ft above the base of Z3

Figure 40
5C. Well Field
Sy = 0.10

Drawdown
1 Year

Note: April 2002 plume outline shown by black outline

Pumps set to 3 ft above the base of Z3

C27

Figure 41
5C. Well Field
Sy = 0.10

Drawdown
3 Years

Note: April 2002 plume outline shown by black outline

Pumps set to 3 ft above the base of Z3

CZ8

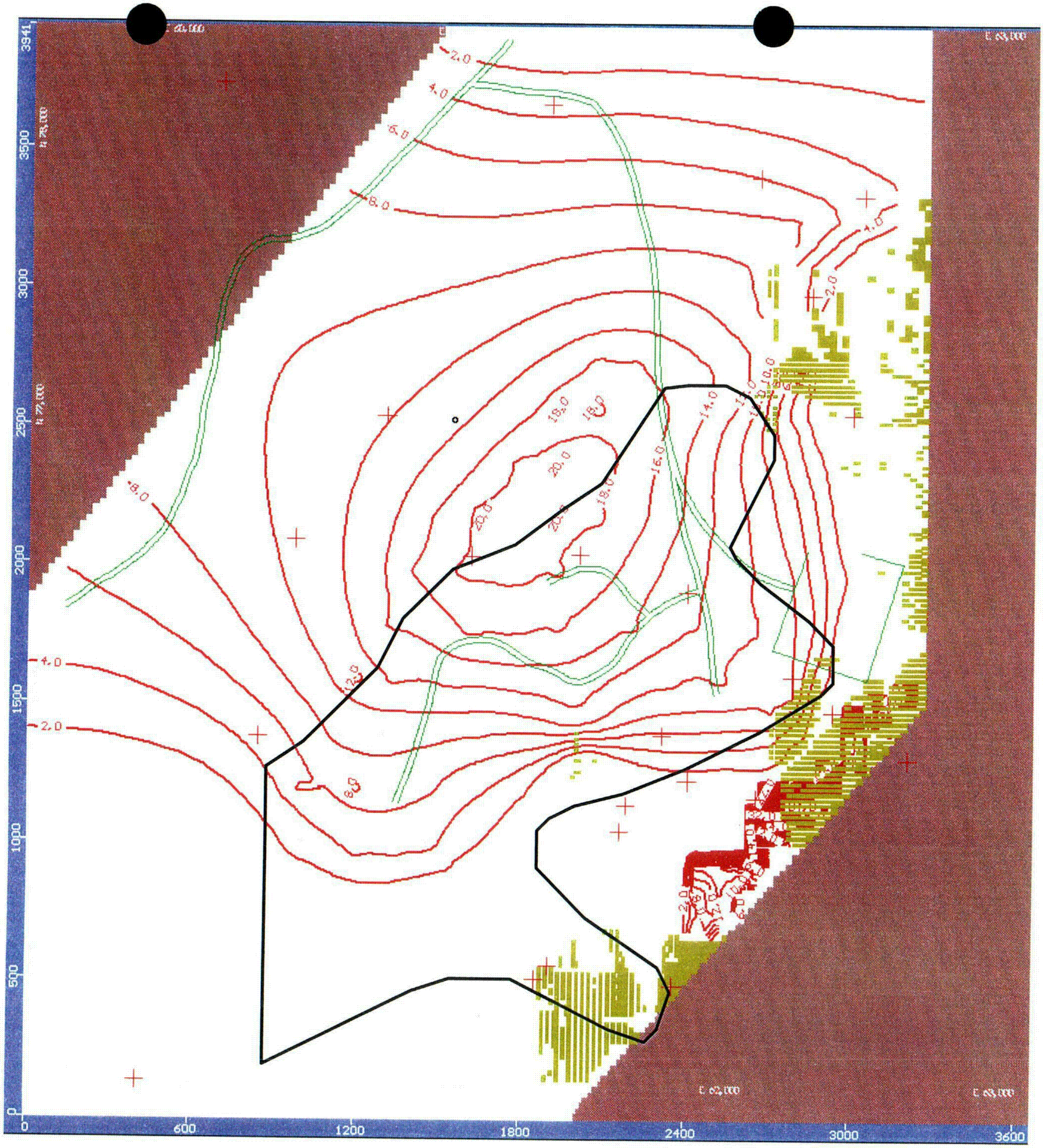


Figure 42
5C. Well Field
Sy = 0.10

Drawdown
5 Years

Note: April 2002 plume outline shown by black outline

Pumps set to 3 ft above the base of Z3

Figure 43
5D. Well Field
No Recharge

Drawdown
1 Year

Note: April 2002 plume outline shown by black outline

Pumps set to 3 ft above the base of Z3

C3D

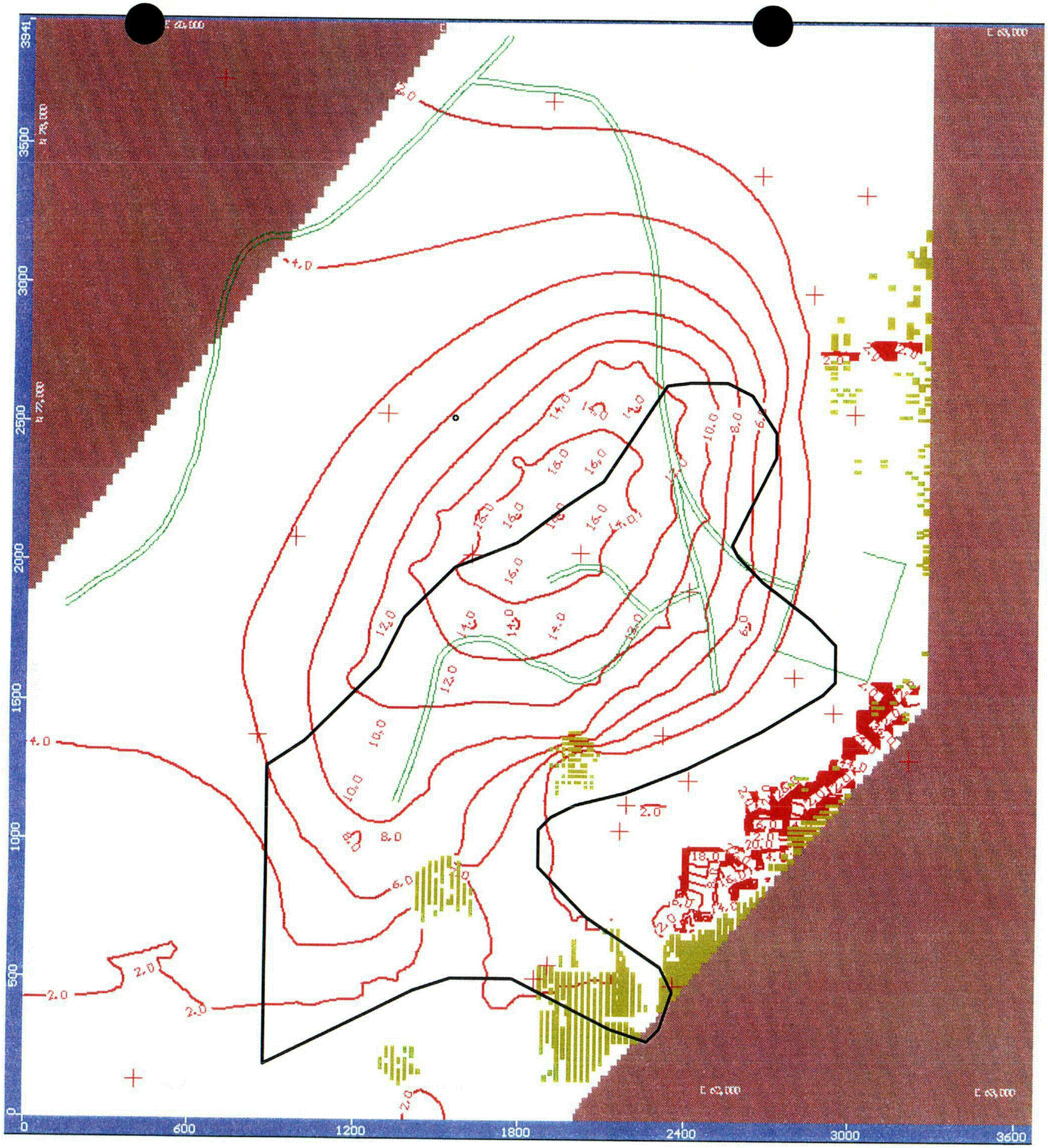


Figure 44
5D. Well Field
No Recharge

Drawdown
3 Years

Note: April 2002 plume outline shown by black outline

Pumps set to 3 ft above the base of Z3

C31

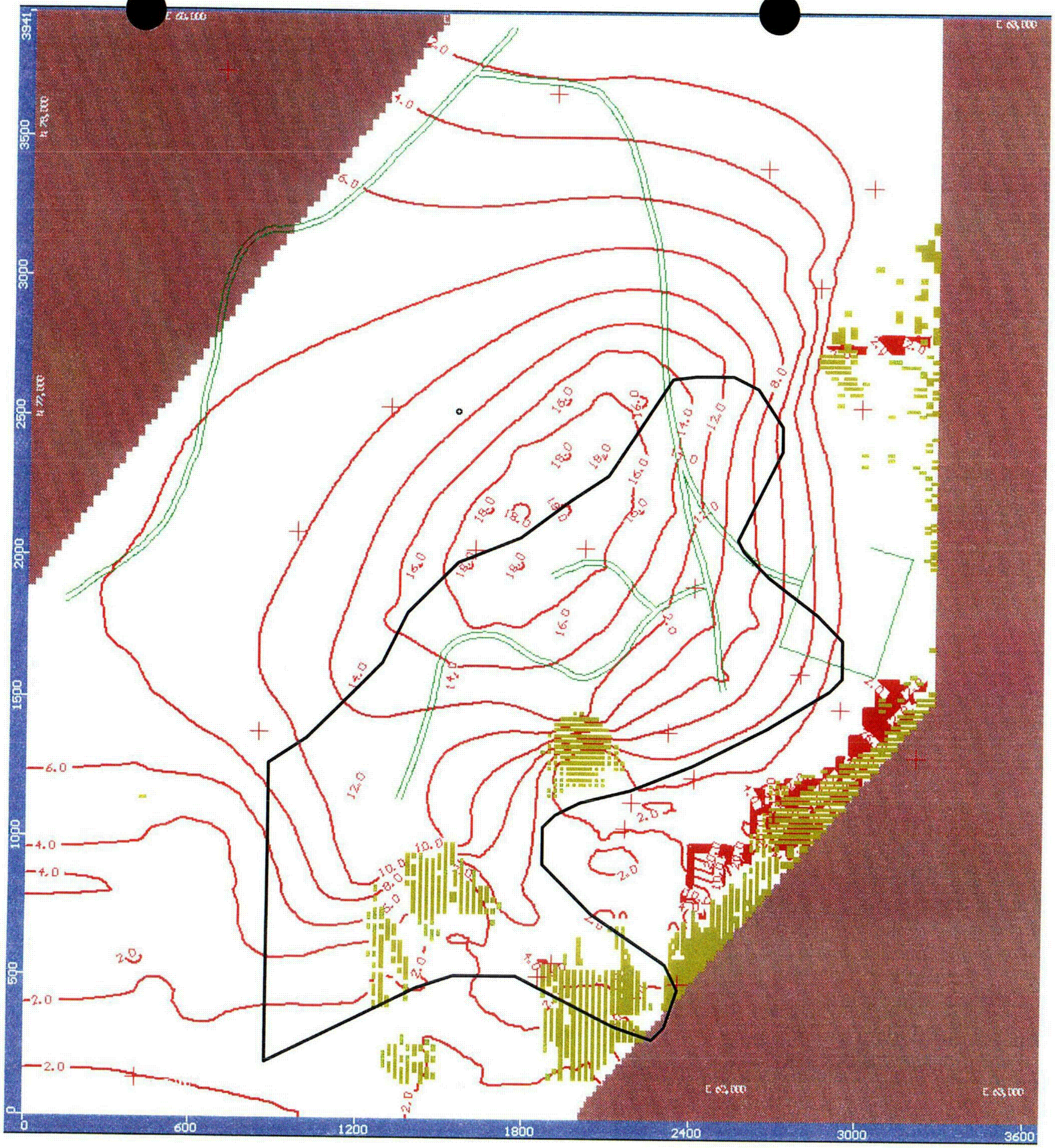


Figure 45
5D. Well Field
No Recharge

Drawdown
5 Years

Note: April 2002 plume outline shown by black outline

Pumps set to 3 ft above the base of Z3

C32

Figure 46
5D. Well Field No Recharge

Additional Drawdown from 5 to 10 Years

(5-year simulation using output from 5 years of pumping as initial heads.)

Note: April 2002 plume outline shown by black outline

Pumps set to 3 ft above the base of Z3

Figure 47
5E.Well Field
Drawdown
5 Years
(70 Wells)

General Head
Boundary
(Virtual Boundary Moved
1000 Ft North)

Note: April 2002 plume outline
shown by black outline

Pumps set to 3 ft above the base of Z3

C34

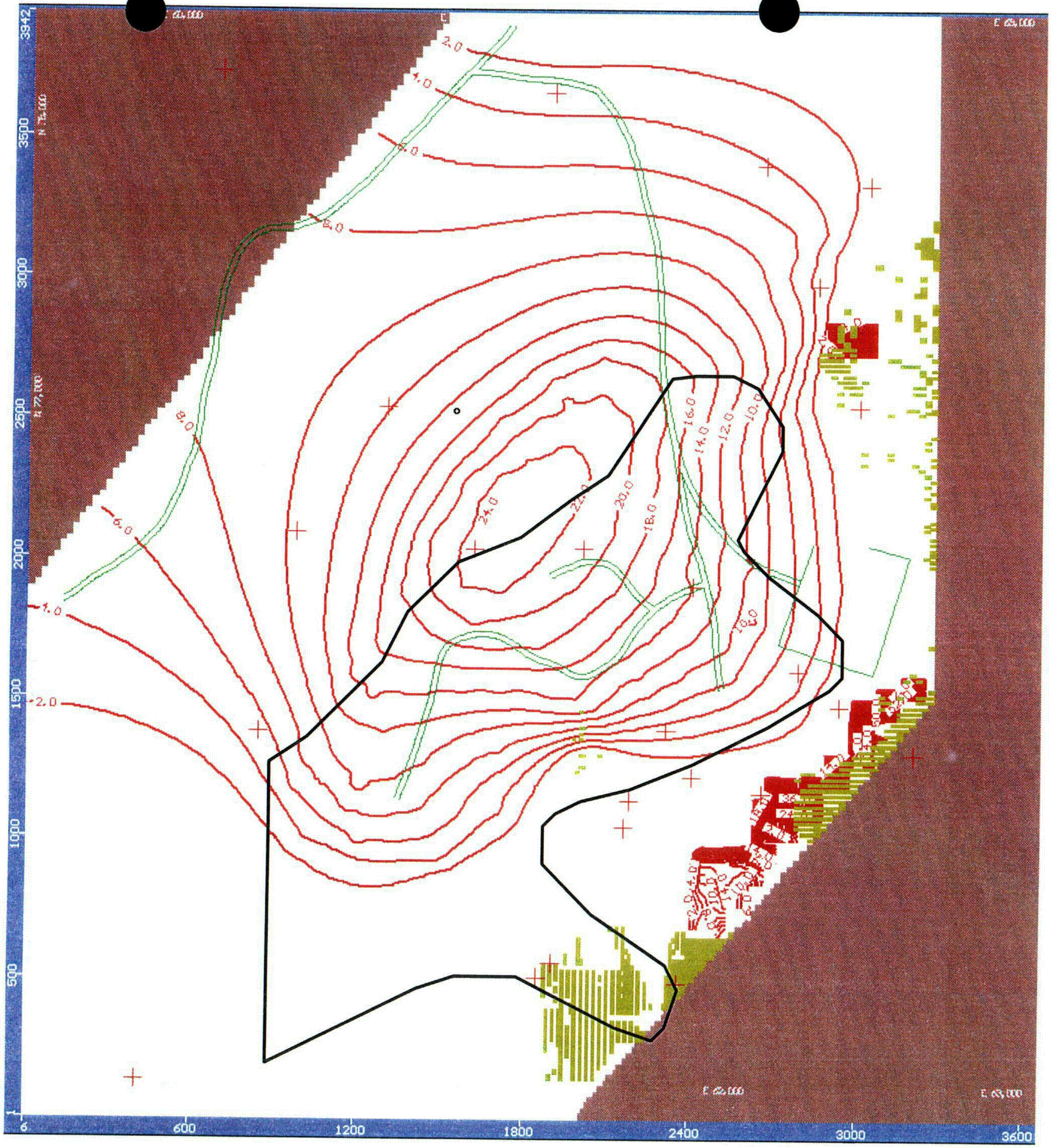


Figure 48
5F. Well Field Drawdown 5 Years (140 Wells)

Note: April 2002 plume outline shown by black outline

Pumps set to 3 ft above the base of Z3

C35

Figure 49
5F. Well Field Additional Drawdown from 5 to 10 Years (140 Wells)

(5-year simulation using output from 5 years of pumping as initial heads.)

Note: April 2002 plume outline shown by black outline

Pumps set to 3 ft above the base of Z3

C36