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Annual Performance Evaluation of Ground Water Remediation From March 2004 Through March 2005 at the Tuba City, Arizona, Disposal Site

July 2005

U.S. Department of Energy

Office of Legacy Management

Work Performed Under DOE Contract No. DE-AC01-02GJ79491
for the U.S. Department of Energy Office of Legacy Management.

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1.0 Introduction

1.1 Purpose of Report

This report evaluates the performance of the ground water remediation system at the U.S. Department of Energy (DOE) Land Management site near Tuba City, Arizona, for the period of March 2004 through March 2005. The site is located in Coconino County, Arizona, within the Navajo Nation and near Hopi Reservation land (Figure 1). Ground water in an underlying sandstone aquifer is contaminated by inorganic constituents from former uranium-ore milling at the site, including nitrate, uranium, and sulfate, the primary site contaminants. A pump-and-treat remediation system constructed to restore ground water quality began full operation in mid-2002.

1.2 Ground Water Remediation System

The ground water remediation system currently operates 25 extraction wells completed within the most contaminated region of the aquifer. The extracted water is conveyed in underground piping to an on-site facility where it is mechanically distilled following ion exchange pretreatment. Engineered solar evaporation ponds receive the waste liquid (brine), and an infiltration trench located upgradient of the contaminant plume returns the treated water (distillate) to the aquifer. Six injection wells originally intended to create a hydraulic barrier at the downgradient limit of contamination remain unused for that purpose. Eight additional extraction wells (wells 1126 through 1133) installed in summer 2004 were not in service during this review period. These wells, and four monitoring wells recently converted to extraction use (wells 935, 942, 936, and 938), will be in service by summer 2005. Figure 2 shows the primary site features.

1.3 Ground Water Compliance Strategy

The ground water compliance strategy for the Tuba City site, as defined in the *Phase I Ground Water Compliance Action Plan for the Tuba City, Arizona, UMTRA Site* (GCAP) (DOE 1999), is to achieve applicable cleanup levels through active remediation of those portions of the aquifer affected by previous site activities. Cleanup levels for the aquifer comprise restoration "standards" (requirements of 40 CFR 192 [Uranium Mill Tailings Radiation Control Act]), and restoration "goals" (cleanup levels requested by the Navajo Nation but not required by 40 CFR 192).

Ground water contaminants requiring active remediation at the site are molybdenum, nitrate, selenium, sulfate, and uranium [DOE 1999]). Restoration standards (see Table 1) for these constituents, except sulfate, correspond to a maximum concentration limit (MCL) in ground water as established in 40 CFR 192. Sulfate is not regulated by 40 CFR 192. However, a restoration standard was adopted for this constituent because it is present in ground water at the site at concentrations that cause an excess potential risk (DOE 1999). The Navajo Nation also requested that the distillate not exceed 20 mg/L of sodium.

Table 1. Ground Water Remediation Goals

Constituent/Property	Cleanup Level	Baseline Concentrations in Plume
Nitrate[a]	10 mg/L as N (44 mg/L as NO_3^-)	840–1,500 mg/L
Molybdenum[a]	0.10 mg/L	0.01–0.58 mg/L
Selenium[a]	0.01 mg/L	0.01–0.10 mg/L
Uranium[a]	30 pCi/L (0.044 mg/L) U-234 + U-238	0.3–0.6 mg/L
Sulfate[a]	250 mg/L	1,700–3,500 mg/L
TDS[b]	500 mg/L	3,500–10,000 mg/L
Chloride[b]	250 mg/L	20–440 mg/L
pH[b]	6.5–8.5	6.3–7.6
Corrosivity[b]	not corrosive	not applicable

[a]Restoration standard
[b]Restoration goal

1.4 Performance Monitoring and Reporting

Performance of the ground water remediation system is evaluated yearly upon receipt of water quality and water level monitoring data obtained in August and February of each year. These data are compared to baseline conditions to evaluate the capture zone of the extraction system, movement of contamination in the aquifer, and concentration trends, as measures of aquifer restoration progress.

Additionally, the composition and volumetric totals of treatment system inflow and outflows are determined weekly, and each extraction well is sampled monthly for water quality analysis. These data are used to track the extraction and treatment volumes, contaminant mass recovery, distillate composition, and waste production.

The semi-annual monitoring events covered in this report occurred in August 2004 and February 2005. Monitoring data obtained between 1998 and March 2002 represent baseline conditions at the site (DOE 2003). The 13-month review period for this report includes March 2004 through March 2005.

1.5 Ground Water Hydrology

The Tuba City site lies on the middle of three alluvial terraces associated with ancestral flow in Moenkopi Wash, located about 1.25 miles southeast of the site. The regionally extensive Navajo Sandstone, a massively cross-bedded, friable, fine to very fine sandstone and siltstone, underlies coarse, semi-indurated, Quaternary alluvium at most terrace locations. Loose dune sand and silt is prevalent to depths of up to 20 feet except where bedrock slopes and cliffs dominate the terrace escarpments. Regional bedrock dip is about one degree to the northeast.

Within about 200 feet below ground, the eolian dune deposits of the "classic" Navajo Sandstone become interbedded with fine-grained alluvium more typical of the underlying Kayenta Formation. This "inter-tonguing interval" is 400 to 450 feet thick. Occasional thin (≤ 2 feet [ft]), resistant limestone beds occur throughout as relicts of former playa lakes. Locally, the Kayenta Formation consists of 100 ft or more of slope-forming, flat-lying red silt and fine sand.

Ground water beneath the Tuba City site occurs in the regionally extensive "N" multiple-aquifer (Cooley et al. 1969), which in the site area comprises the Navajo Sandstone. From the ambient water table about 50 to 60 feet below ground at the site, the saturated zone extends through the inter-tonguing interval to the upper contact of the Kayenta Formation.

Ground water flow beneath the site is southeast to Moenkopi Wash. There, regional discharge occurs from a laterally extensive (miles) spring zone that outcrops near the exposed base of the inter-tonguing interval. Some local discharge of ground water from higher in the formation occurs to sustain scattered populations of desert phreatophytes, such as in the "greasewood area" shown in Figure 2, where depth to water is only about 20 feet. Plant uptake requires this water to reside in fractured, decomposed, or unconsolidated material rather than competent bedrock. Figure A-1 in Appendix A depicts a conceptual model of the site hydrogeology.

1.5.1 Vertical Discretization of the N-Aquifer

Site hydrostratigraphy is discretized into 50-ft intervals, or "horizons," each with a letter designation. The top of the middle terrace, nominally 5,050 feet in elevation, marks the top of the uppermost horizon (Horizon A). Horizons A, B, C, and possibly D span the interval of "classic" Navajo Sandstone beneath the site, whereas the depths of Horizons E through J include the regions of the inter-tonguing interval. Horizons K, L, and M include the lower intertonguing interval and possibly the upper Kayenta Formation. These stratigraphic relationships to aquifer horizon are shown in Figure A-1.

Related to ground surface topography, the uppermost horizon on the lower terrace progresses from Horizon C to D, north to south. The steep topography at Moenkopi Wash intersects Horizons E through G. Ground water remediation at the site focuses primarily on the upper 250 ft of the bedrock aquifer (Horizons A through E).

Color-coding in Figure 2 identifies the horizon in which the mid-point of each well screen is located for extraction wells (round symbols) and monitoring wells (square symbols). Figure A-2 of Appendix A is a cross-section schematic of the placement depth of well screens in relation to aquifer horizon for all project wells.

2.0 Treatment System Performance

2.1 Bulk Treatment Parameters

During the review period the treatment plant operated for 344 of 392 total days, for a net on-stream factor of 88 percent. About 48-million gallons of water were treated during this 56-week period resulting in an average operating rate of 97 gpm and an effective rate (downtime included) of 85 gpm. The operating capacity of the treatment plant as currently configured is about 120 gallons per minute. Total ground water treatment as of April 1, 2005 was approximately 136-million gallons, equivalent to about 11 percent of the total estimated volume of uranium-contaminated ground water present before the start of remediation (see Section 5.3).

Figure 3 shows the feed rate to the treatment plant and the corresponding concentration of nitrate and sulfate determined from weekly composite samples since the start of remediation. Uranium concentration in the bulk feed for the same period is shown in Figure 4. These figures indicate that contaminant concentrations entering the treatment system have remained relatively stable while the treatment plant is operating. A slight downward trend in uranium concentrations over time is indicated in Figure 4. The masses of nitrate, sulfate, and uranium extracted during the current review period, based on the weekly inflow volume and feed composition are respectively, 159,000 lbs; 389,000 lbs, and 102 lbs (Table 2).

Table 2. Treatment System Performance Summary

Contaminant	Typical Concentration (mg/L)	Distillate Concentration (mg/L)	Mass Removed during Review Period (lb)
Nitrate	400	5-15	159,000
Sulfate	970	20-40	389,000
Uranium	0.25	0.004-0.01	102

2.2 Distillate Quality

Concentrations of nitrate, sulfate, and uranium in the distillate averaged about 9, 30, and 0.008 mg/L, respectively, during the review period (Table 2 and Figure 5). Total dissolved solids (TDS) ranged between about 40 and 80 mg/L, and chloride concentrations were generally less than 2 mg/L with little variation. These results indicate highly effective contaminant removal and very high quality of water returned to the aquifer.

2.3 Return Flow to the Aquifer

Weekly production of wastewater sent to the evaporation pond averaged about 7 percent of the total inflow rate for the year in review. The balance of the treated water (93 percent) was returned to the aquifer at the infiltration trench.

3.0 Extraction & Infiltration System Performance

3.1 Extraction Wells

In Figure 2, the extraction wells that operated during this review period are those labeled 1101 to 1125. They are constructed of 6-inch diameter Schedule 40 PVC solid casing and 6-inch, continuous V-wrap stainless steel (0.017-inch slot). A filter pack of 20-40 graded silica sand completes the 2-in annulus to 30 or 40 feet above the screen slots. Screen lengths are 150-ft, extending from the bottom half of Horizon B to the mid-depth of Horizon E, except for wells 1116, 1117, and 1118, which have 100-ft screens that extend nearly to the base of Horizon D. Extraction wells 1126 to 1133, installed in September 2004, are of similar specification but consist of 4-inch diameter casing and screen. In addition, they are much shallower such that their 30-ft screen is located across most of Horizon B. These latter wells will become operational in summer 2005, but currently serve as monitoring wells. All extraction pumps are 1/4 to 1/3

horsepower submersible type, located 10 to 15 ft above the bottom of the well. Pumping is interrupted when the water level reaches the pump intake and resumes after a prescribed period of water level recovery.

The production rate of the well field is generally equivalent to the treatment plant feed rate shown in Figures 3 and 4. Although not obvious in the figures, total well-field production increased during the review period by about 10 gpm after wells 1116 and 1117 were returned to service in July after pump failures in March and December 2003, respectively. In addition, pump controls were adjusted in July 2004 to maximize well yield and minimize on-off cycling due to excessive drawdown. As a result, pumping is nearly continuous at all but wells 1123 and 1120. Continuous pumping rates range between 2 and 5.5 gpm, and average 4 gpm. Wells 1120 and 1123 operate half-time at rates of 7 and 0.5 gpm, respectively. In map view, there is no apparent relationship between location and extraction rate. The operational history of each extraction well for the evaluation period is included in Appendix A, Table A–1.

4.0 Extent of Ground Water Contamination

Figures 6a through 14a illustrate the concentrations of nitrate, sulfate, and uranium in ground water before the start of remediation. Most of the information is from sample collection in March 2002 but extends back to 1999 for some locations. These figures define contaminant distribution during the baseline period in the various aquifer horizons shown. Figures 6b through 14b show contaminant distribution in February 2005 (new extraction wells 1126 through 1133 were not operating during the review period). Although each well location sampled for the respective period is shown, a concentration value is posted only where the applicable remediation standard was exceeded. Tabulated analytical results for August 2004, February 2005, and the baseline period for each contaminant requiring remediation are included in Appendix B.

In map view, the horizontal extents of contamination in the various horizons are not significantly different from the baseline condition, indicating no lateral spreading of the contaminant plume (sentinel well 271, located southwest of well 267, was not sampled in February 2005 but remained uncontaminated as of August 2005; see also Section 5.1 for additional discussion regarding plume expansion). The new wells installed on the middle terrace (extraction wells 1126 through 1133 and monitoring wells 281 through 283) confirmed suspected contamination in Horizons A and B at each of those locations within the previously defined plume boundary.

Before installation of wells 272 through 276 in August and September 2004, discrete depth monitoring of Horizons C and D in the main area of the plume was not possible. Sample collection in February 2005 indicates contamination at the respective depths of wells 273 and 275 (Figures 7b, 10b, and 13b), but no contamination in the screened intervals at the remaining locations (wells 272, 274, and 276). The absence of contamination in Horizon E (see Figures 8b, 11b, and 14b) suggests no downward plume movement to this depth. Deeper in the aquifer, contamination remains at Horizon I wells 254 and 256, and Horizon M wells 255 and 257. As discussed in Section 6.2, the origin of contamination at these latter locations is attributed to downward leakage of shallower ground water through failed annular seals. Contamination at well 251 (Horizon E) during the later portion of the baseline period, before which the contamination was not present, is possibly of the same origin. Contaminant concentrations at

well 251 have since decreased to below cleanup standards in response to ground water extraction.

On the lower terrace, nitrate and sulfate contamination remains minor and localized to one or two wells (Figures 7b and 10b). Uranium contamination at the single lower terrace location decreased to less than the remediation standard during the review period (see also Section 5.1 for additional information on concentration trends). New monitor wells installed on the lower terrace during the review period (wells 277, 278, and 279) confirmed the absence of contamination at those locations.

4.1 Capture Analysis

4.1.1 Water Table Configuration

Figure 15 shows the phreatic surface for the baseline period estimated using water levels in Horizon A and B monitor wells for the middle terrace and Horizon C wells for the lower terrace. On the middle terrace, water levels from deeper wells are not representative of water table conditions because of pronounced vertical hydraulic gradients (see Section 4.1.4), and within the network of monitoring wells between the escarpment and greasewood area, the water table beneath the lower terrace occurs in Horizon C. The horizontal direction of ground water flow was predominantly south during the baseline period. A steeper hydraulic gradient corresponds to aquifer thinning at the escarpment (Figure 15).

Figure 16 shows a similarly constructed water table for February 2005. At that time, ground water mounding and increased hydraulic gradients in Horizons A and B were evident along the north edge of the disposal cell due to infiltration of treatment system distillate at the trench. Comparison of Figures 15 and 16 indicates that operation of the extraction wells has significantly depressed the water table and consequently changed flow directions in the shallow ground water throughout the area of extraction where shallow monitor wells are present. Insufficient well control in the area of ground water extraction on the east side of the site prevents analysis of water table conditions there. The water table underlying the escarpment and lower terrace appears unaffected by ground water extraction.

4.1.1.1 Infiltration Trench

The infiltration trench is constructed into bedrock along the north side of the site (see Figure 2 for trench location). Distillate enters the trench at its mid-point from where it can flow in either direction in perforated pipe embedded in a 3 ft thick gravel pack. Through mid-2003, non-uniform infiltration caused greater than 20 ft of ground water mounding beneath the southwest section of the trench but only about 1 ft beneath the northeast section. The ground water mound has become more symmetrical since November 2003 when flow valves were installed and all inflowing water was diverted to the northeast segment of the trench. Water level hydrographs for wells located near the respective ends of the trench (wells 687 and 688, Figure C-1, Appendix C) indicated that the northeast section would soon experience excessive mounding if a correction were not made. Since April 2005 therefore, a portion of the inflow was diverted to the southwest section of the trench.

The absence of ground water in new wells 284 and 285 (see Figure 2 for location), screened across the contact of the terrace alluvium and bedrock immediately downgradient of the trench,

indicates that mounding has not over-topped the trench to saturate the alluvium. Ground water flow from the trench area is south to the extraction wells to assist in flushing the main region of contamination.

4.1.2 Water Level Drawdown

Figure 17 further illustrates the effect of ground water extraction and infiltration on water levels in Horizons A and B by showing the difference between baseline and February 2005 water levels as the computed drawdown. Figures 18 and 19 plot the drawdowns for the deeper horizons for the same period. Positive values identify locations where the water level in February 2005 is less than the baseline value. Negative values, such as those at the wells surrounding the infiltration trench (Figure 17), indicate that water levels at the respective locations are presently higher than during the base-line period. Well hydrographs in Appendix C provide an additional view of water level drawdowns over time at numerous site monitoring wells.

The overall pattern of water level drawdown reflects three-dimensional converging flow to the extraction wells. Because the water level in each extraction well is generally maintained near the base of the well (Horizon D or E), the greatest drawdown (44 ft) is observed at the Horizon E wells (wells 251 and 268) located within the extraction field. Among all monitor wells, the intakes of wells 251 and 268 are nearest in radial distance to the interval of ground water extraction. Consistent with convergent flow, drawdown at the remaining monitor wells is observed to decrease with distance from the extraction zone. Although water level drawdown in response to ground water extraction affects the entire aquifer within the region of contamination, it does not imply capture of all contaminated ground water.

4.1.3 Horizontal Capture

Figures 20 and 21 depict the estimated zone of ground water capture by the extraction system for Horizons A and B combined, and Horizons C and D combined, respectively. In these figures, the extent of contamination (solid line) is generalized from the distributions presented in Figures 6a through 14b. The dashed line represents the capture zone as determined by hydraulic gradient vector analysis within respective depth intervals using a model of triangulation with linear interpolation and February 2005 water levels. Water levels in the extraction wells were not included in either analysis.

The results indicate that the estimated capture zone of Horizons A and B (Figure 20), within which all ground water ultimately reaches an extraction well, does not fully encompass the extent of contamination. The residual area between the extent of contamination and capture zone on the middle terrace is the targeted zone for the extraction wells installed in 2004. In the east area of the site, where A and B Horizon monitoring wells are absent, the estimated capture zone assumes that significant drawdown (20 ft) in Horizon C at wells 683 and 684 (not contaminated) implies local capture of the shallower water. Vector analysis predicts that contamination in Horizons C and D wells on the middle terrace is fully captured (Figure 21). The horizontal extent of capture in Horizon E and deeper cannot be determined with the available wells completed in those horizons. This limitation is of no consequence because contamination is absent from these horizons.

4.1.4 Vertical Capture

Hydrographs included in Appendix C for selected sets of co-located monitor wells illustrate that at a given location, the piezometric head is a function of well-intake depth. This relationship clearly identifies vertical flow components throughout the entire monitored thickness of the aquifer, both before and since the start of ground water remediation. With few exceptions, the vertical potentials were downward during the baseline period.

Since that time, the magnitude of downward flow in the horizons above the extraction interval has increased, as seen as the greater water level differences in the hydrographs for the respective locations of well pairs 265/266, 263/264, 908/912, and 909/932, since about mid-2002 (see Appendix C, Figures C-4 through C-7). In the main region of contamination, these increased gradients imply capture of ground water from the upper horizons by the extraction wells.

In the deeper horizons, vertical gradients are now generally upward to the extraction intakes. For example, the vertical flow potentials have reversed to upward between Horizons M, I, and E at co-located wells 268/256/257 in response to ground water extraction (Figure C-8). A similar result between Horizons E and I, and possibly M, is apparent at the location of wells 251/252/253 (see Figure C-9, the monitoring record is incomplete for well 253, a former Horizon M well that was abandoned in 2001). A downward flow potential remains between Horizon I and M at wells 254/255 (Figure C-10); however, there is an upward gradient at that location between Horizon I (well 254) and Horizon D (well 277). The apparent vertical flow divide at this location implies ground water capture possibly to Horizon I but not Horizon M.

Because the observed vertical influence of the extraction wells extends much deeper than the presumed depth of contamination, it is likely that the remediation system captures the full vertical extent of the contaminant plume. Although ground water extraction has no affect on downward flow between Horizons D and G at wells 915 and 916 (Figure C-11), this region of the aquifer is not contaminated. Downward flow potentials in lower terrace ground water also remain unaffected by ground water extraction (Figure C-12) but contamination there is only minor and limited to the shallowest horizon and there is no evidence of vertical or lateral spreading of contamination in the lower terrace ground water.

5.0 Remediation Progress

5.1 Contaminant Concentration Trends at Monitor Wells

Appendix D contains time-series graphs of nitrate, sulfate, and uranium concentrations, respectively, in ground water at selected monitor wells located throughout the project area.

Within Horizons A and B, wells 940, 941, and 942 are nearest the south side of the disposal cell and so are likely to first detect return flow from the infiltration trench as a pronounced decrease in contaminant concentration. Such trending at these locations has not yet been observed (see Figure D–1 through D–3). Assuming porous media flow under the observed water table gradient (Figure 16) and hydraulic conductivity of 1 ft/day, the calculated travel time from the infiltration trench to well 940 is 17 years, which is greater than the cumulative remediation period to date.

Farther south in the mid-section of the plume (near Horizon A and B wells 262, 906, 908, 934, 935, and 936), concentrations generally remain relatively stable, with local exceptions of either increasing or decreasing trends. Toward the outer (south) margin of the plume (near wells 263, 265, 267, and 909), contaminant concentrations are relatively stable or decreasing. Horizon A and B sentinel wells, specifically those located near the plume boundary (wells 271, 683, 684, 914, and 921), remain uncontaminated with the exception of minor but stable nitrate contamination at well 929, indicating no significant expansion of the contaminant plume (Figures D–4 through D–6).

Stable concentrations below remediation standards in Horizon C and D wells 264, 266, 915, and 932 (Figures D–7 through D–8) indicates no southward plume expansion to these locations at this depth of the aquifer. In these figures, elevated nitrate and sulfate concentrations at well 912 (Horizon C) are seen to decrease over time, which also indicates that contaminants are not spreading to the west of that location. In ground water beneath the lower terrace, uranium contamination did not exceed the restoration standard at any location during the past year. Previously, uranium contamination in lower terrace ground water was limited to low levels at co-located wells 691 and 1003. These are also the only wells with appreciable nitrate and sulfate contamination on the lower terrace. Stable concentration trends have not developed for these constituents at these wells. At three other nearby wells, stable nitrate values only marginally exceed the restoration standard. Migration of the very localized and relatively low magnitude contamination on the lower terrace apparently is not significant, as indicated by persistent background levels at nearby wells located farther downgradient. Contaminant concentration plots for lower terrace monitor wells are include in Appendix D (Figures D–10 through D–12).

5.2 Contaminant Concentration Trends at Extraction Wells

Figures 22, 23, and 24 illustrate concentration trends at the extraction wells for nitrate, sulfate, and uranium, respectively. For each contaminant, the trend at most wells is of decreasing concentration as contaminant mass is removed from the aquifer. Appendix E contains concentration plots for each extraction well based on the monthly on-site sampling and analysis (in Appendix E, concentration units are mg/L for nitrate as NO_3 and sulfate, and µg/L for uranium).

Figures 25, 26, and 27 are identical to the previous three figures but at a finer concentration scale to highlight occurrences of ground water extraction at concentrations less than the respective remediation standards. In a summary of that information, Table 3 identifies that at no location is the extract below the remediation standard for all three contaminants, although very nearly so at wells 1113 and 1125.

Table 3. Pumping Wells where a Contaminant Concentration is Below the Remediation Standard in the Extract

Nitrate	Sulfate	Uranium
--	1107	--
--	1112	1112
1113[a]	1113	1113
--	--	1114
--	1116	1116
--	--	1117
--	1123	1123
1125[a]	1125	1125

[a]Concentration is currently 45 mg/L nitrate as NO_3.

5.3 Contaminant Inventory and Removal Rates

Table 4 compares cumulative quantities of contamination removed from the aquifer as of April 1, 2005. Calculation methods to estimate the initial volume of contaminated ground water and initial contaminant mass listed in Table 4 are included in Appendix F. The listed initial mass of solute in ground water above remediation standards assumes a geometric average of measured baseline concentrations at numerous monitoring wells, per respective contaminant, in the corresponding estimated volume of contaminated ground water.

By these estimates, at current mass recovery rates of about 2 to 5 percent per year, ground water restoration will require between 20 and 50 years to complete since its inception in mid-2002. The corresponding minimum volume of extracted ground water, assuming constant withdrawal of 85 gpm, is 890-million gallons, approximately equivalent to one estimated pore volume of the contaminant plume.

Table 4. Summary of Cumulative Mass and Volume Recovery

Contaminant	Initial Mass (lb)[a]	Cumulative Mass Removed (lb)	Cumulative Percent Mass Reduction	Initial Volume (gal)[a]	Volume Treated (gal)	Percent Plume Volume Reduction
Nitrate	9,500,000	459,000	5	1.2E+09	135,900,000	11
Sulfate	20,150,000	1,123,000	6	1.2E+09	135,900,000	11
Uranium	2,300	325	14	1.2E+09	135,900,000	11

[a]Source: see Appendix F

5.3.1 Aquifer Restoration Index

Using a similar approach to that described in the preceding section, but independent of the estimated volume of contaminated ground water, the average concentration of a contaminant, when computed for each sampling event from a selected group of wells provides an additional measure of restoration progress when viewed over time. By this method, the composition of the ground water plume is represented as a single concentration value for a given contaminant at a given time. Figures 28 and 29 illustrate respectively how the geometric mean of the sulfate and uranium concentration for the individual sampling events varies since the baseline period. The selected monitor wells for this analysis are those located throughout the contaminant plume and

sampled most regularly. Appendix G provides calculation information for this performance metric.

Despite the small increment of change and the relatively brief period of observation, the results presented in Figures 28 and 29 suggest a developing trend showing the effects of remediation in reducing the bulk concentration of the uranium and sulfate plume (nitrate results not analyzed). Linear projection of these data predict a total restoration time of 20 years since the inception of active remediation in mid-2002. This compares to an estimated 25 years to remove one pore volume of the initial contaminant plume (Table 4) at the current extraction rate of approximately 4 percent per year.

6.0 Special Topics

6.1 Concentration Rebound Study

A field study conducted during January 2004 evaluated the extent of contaminant rebound at the extraction wells after a scheduled 9-day maintenance shutdown (DOE 2004a). This was done to determine if contaminant removal could be enhanced by cyclic or "pulsed" pumping of the extraction wells (periods of pumping and non pumping of a given well or group of wells). Test results showed significant concentration rebound at most locations after the wells were idle followed by rapidly decreasing concentrations once pumping resumed. Because the overall benefit was short-lived (< 1 day), effective pulsed pumping would require rapid cycling. The associated operational and maintenance requirements suggest that pulsed pumping is not practical at this time.

6.2 Deep Wells

DOE issued a draft report in April 2004 (DOE 2004b) addressing the origin of ground water contamination at wells 251 through 257, installed in May 2000 and comprising the deepest wells at the site (up to 700 ft deep). In September 2000, significant grout accumulation in the bottom of well 253 was discovered. A sudden increase in contaminant concentration also occurred at that time. Previous samplings or well 253 indicated that contaminant concentrations in the screened interval (600 to 700 ft deep) were consistent with background levels. These findings indicated that the annual seal had failed, thus allowing downward migration of contaminants through the well bore, and so the well was soon abandoned.

A similar pattern of apparent well failure and delayed arrival of contamination to the screened interval occurred later at several other deep wells. Further investigation using down-hole video imaging during October 2000 and August 2002 identified grout seeping through the screen slots and accumulations of 10 to 20 feet of grout in the bottom of wells 254 and 256. About 5-ft of grout accumulated in well 256 during this 2-yr period. Fifteen to 20 ft of unidentified foreign material was also observed at the bottom of well 255. Imaging of well 257 was not conducted. Visual inspection of samples collected at well 254 in November 2003 confirmed the material in the bottom of that well to be grout.

In their report, DOE cited these and other lines of evidence in concluding that the apparent contamination of the deep wells is the result of failed annular seals and consequent downward

flow of ground water through the well bore from the shallower contaminated horizons. Ambient downward flow potentials before the start of ground water remediation provided the necessary driving force. Since the start of active remediation, deep vertical flow potentials have reversed to upward at well pair 251/252, and the contamination in the screened interval of well 251 (Horizon E) has decreased to less than the remediation standards. Well 252 (Horizon I) has shown no evidence of contamination at any time.

Vertical flow potentials have also reversed to upward at well pair 256/257 in response to pumping. At well 256 (Horizon I), slightly elevated concentrations of nitrate, sulfate, and uranium have gradually decreased from peak levels in February 2002 such that only nitrate, at 48 mg/L, presently exceeds its restoration standard. As of February 2005, deep well 257 (Horizon M) is contaminated only by sulfate, but concentrations of that constituent continue to rise (see Appendix D, Figures D–13 through D–15 for time-series concentration graphs for the deep wells).

A downward flow potential remains between Horizons I and M at well pair 254/255, but shallower in the aquifer at that location, upward flow is indicated between Horizon I (well 254) and Horizon D (well 273), which should limit downward migration of contamination (see also Section 4.1.4). Both nitrate and sulfate continue to rise at well 254 to now exceed restoration goals by an order of magnitude, while uranium has simultaneously decreased from its peak of 0.21 to 0.09 mg/L between in February 2002 and 2005. As of February 2005, deep well 255 (Horizon M) is contaminated only by sulfate, but concentrations of that constituent continue to rise (see Appendix D). Similar to well 257, sulfate contamination in the absence of other site related constituents, possibly originates from the bentonite grout used to complete the wells.

As per the recommendations in DOE 2004b, proceedings are underway to abandon wells 254, 255, 256, and 257. The abandonment will occur during calendar year 2005. Deep wells 251 and 252 will be retained to maintain at-depth monitoring capability.

6.3 Well Field Expansion

Eight ground water extraction wells (wells 1126 to 1133) and 14 monitoring wells (wells 272 to 285) were installed during August and September 2004. The extraction wells will capture contaminated ground water in portions of the contaminant plume on the middle terrace that are currently unaffected by pumping. Based on contaminant concentration data for paired monitoring wells along the escarpment separating the middle and lower terraces (wells 263/264, 265/266, 909/932), the new extraction wells were installed to intercept Horizon B only to thus minimize capture of deeper ground water in this area that is not contaminated. Two of the three primary site contaminants exceed their respective restoration standards at each new extraction well. Preliminary flow rates for the new extraction wells range from about 0.5 to 3 gpm. These rates are not unexpectedly low considering the corresponding screens lengths (30 to 40 ft) are much shorter than those of the previously installed extraction wells (150 ft). The new extraction wells will begin operating in summer 2005.

Data uses for the new monitoring wells include: (1) determine ground water quality and capture in Horizon D in the main area of pumping (new monitor wells 272-276), (2) evaluate the capture zone of the new extraction wells (new monitor wells 281-283), (3) determine vertical flow relationships and water quality on the lower terrace near the greasewood area (new monitor

wells 277-280), and (4) evaluate performance of the infiltration trench (new monitor wells 284 and 285). Data obtained from the new monitoring wells (and the non-operating new extraction wells) are incorporated in previous sections of this report.

6.4 Aquifer Isolation Tests

In March and June, 2004, field testing was conducted to evaluate the vertical distribution of contamination in the aquifer using three existing extraction wells. The objective of the tests was to determine if the wells penetrate uncontaminated intervals of the aquifer at depth that do not require capture and treatment. None of the tests recognized a well-defined base of contamination, but interpretation of test results was subject to considerable uncertainty arising from the test methods and field conditions (DOE 2005). Monitoring results for newly installed wells completed in Horizon D (wells 272-276) and mass balance analysis (DOE 2005) suggest that contamination in Horizon D is not pervasive but rather may be a localized occurrence. Currently, there are no plans to modify the existing extraction wells for the purpose of limiting ground water extraction from deeper portions of their screened interval. Additional field investigation of contaminant stratification may be conducted, which could eventually lead to a pumping scheme that focuses on the shallow Horizons A through C.

6.5 Geologic Reconnaissance

Field investigation of the Navajo Sandstone was conducted on January 12 to 14, 2005 by project personnel to identify features that might affect hydrogeological conditions at the site. This activity was prompted by depth-dependent water levels in wells and drill holes in the area of the middle terrace near the escarpment. Water levels in shallow wells (< 100 ft) are about 20 to 30 ft higher than the wells 50 to 100 feet deeper in the area. For example, at the location of well 1130, the initial borehole remained open at a depth of about 75 ft for more than one week during which the water level remained at about 60 ft below ground surface. In an adjacent borehole advanced to 125 ft, the static water level was about 90 ft below ground surface. Lithologic contrasts to account for the water level difference were not apparent during drilling. However, the field reconnaissance and additional review of project well logs tentatively identified a depositional bounding surface, possibly of low permeability, in this depth interval. Such a feature, acting locally either as a leaky aquitard or aquiclude could account in part for the locally strong downward flow gradient. The low permeability interval, and perhaps similar others, may also explain decreasing contaminant concentrations with depth across Horizons A through D.

7.0 Year in Review Summary

- On-stream extraction and treatment flow rates meet design objectives.
- Distillate quality meets or exceeds design objectives.
- Return flow to the aquifer as a percentage of extracted water meets design objectives.

- The current configuration and operation of the extraction system effectively captures the region of maximum ground water contamination.
- The current configuration and operation of the extraction system likely captures the full vertical extent of ground water contamination.
- Plume expansion is not significant on either the middle or lower terrace.
- Uranium concentrations have decreased to less than the restoration standard at all lower terrace monitoring locations.
- New extraction wells installed in 2004 will extend the capture zone to include regions of contamination on the middle terrace currently not captured.
- Developing bulk concentration trends indicate measurable progress in contaminant mass removal from the aquifer.

8.0 Recommendations

- Reduce ground water monitoring (except that conducted for treatment plant operations) to one annual event.
- Continue ground water extraction, treatment, and infiltration as currently conducted, with the addition of the new extraction wells to become operational in summer 2005.

9.0 References

Cooley, M.E., J.W. Harshbarger, J.P. Akers, and W.F. Hardt, 1969. *Regional Hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico and Utah*, U.S. Geological Survey Professional Paper 521-A.

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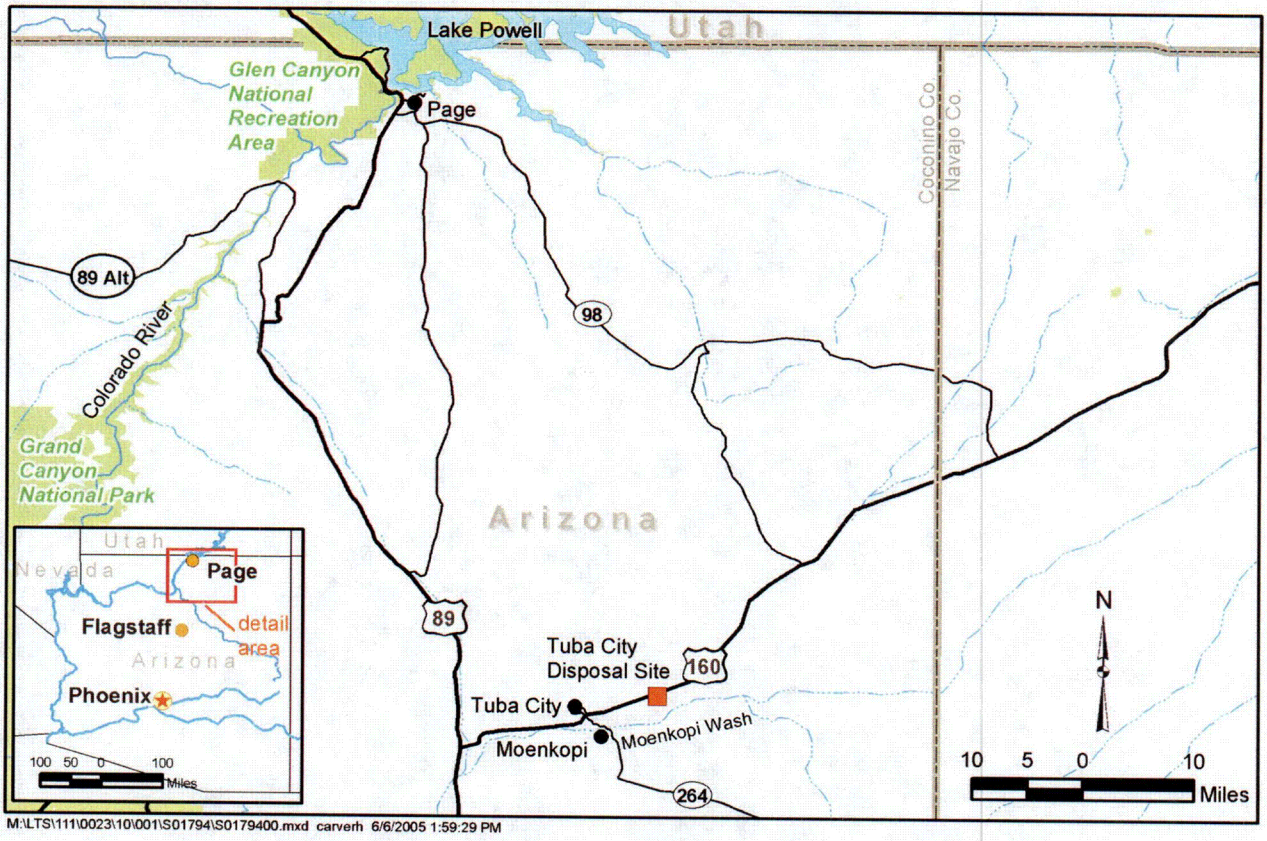

Figure 1. Tuba City Site Location

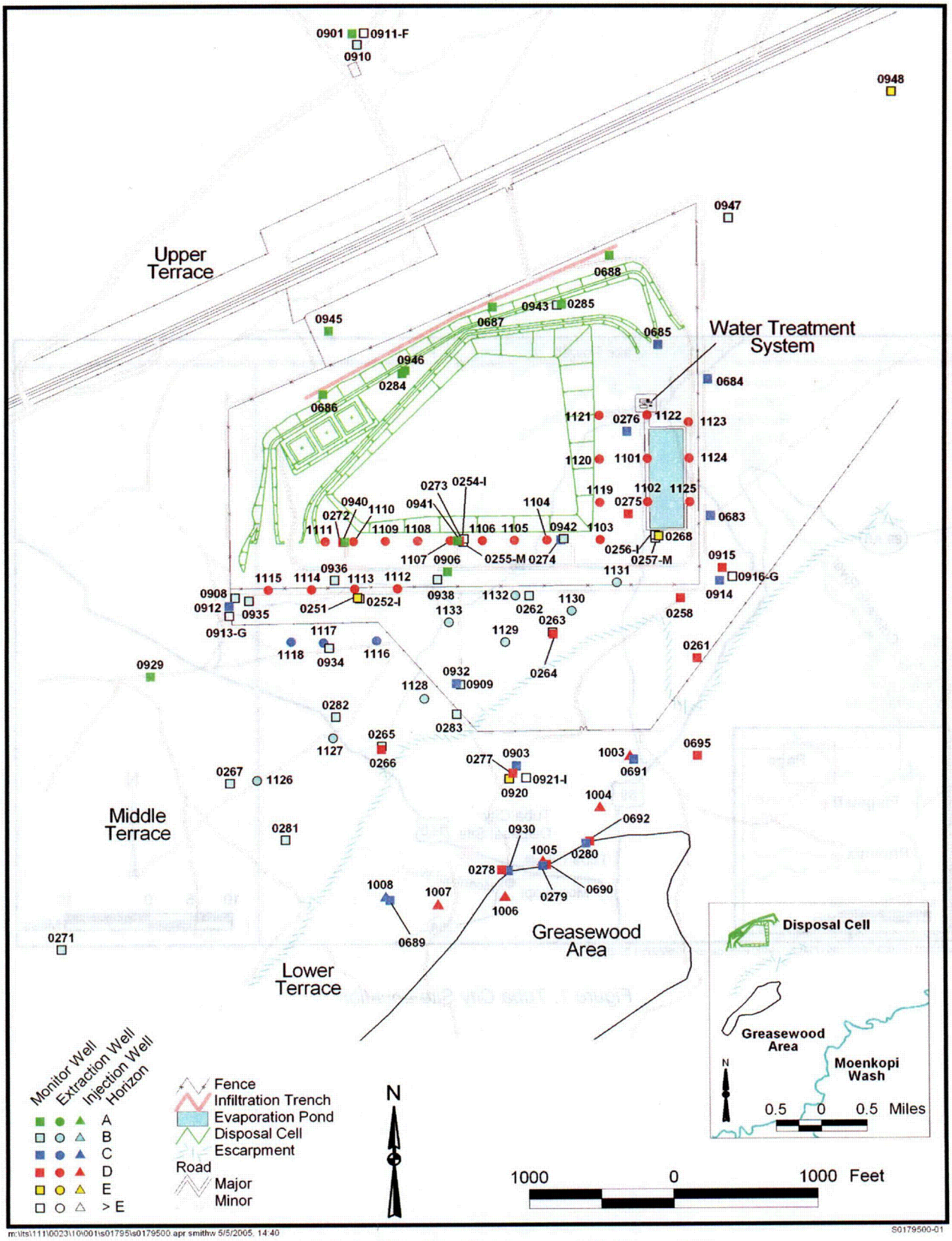

Figure 2. Tuba City Site Features and Well Locations

C02

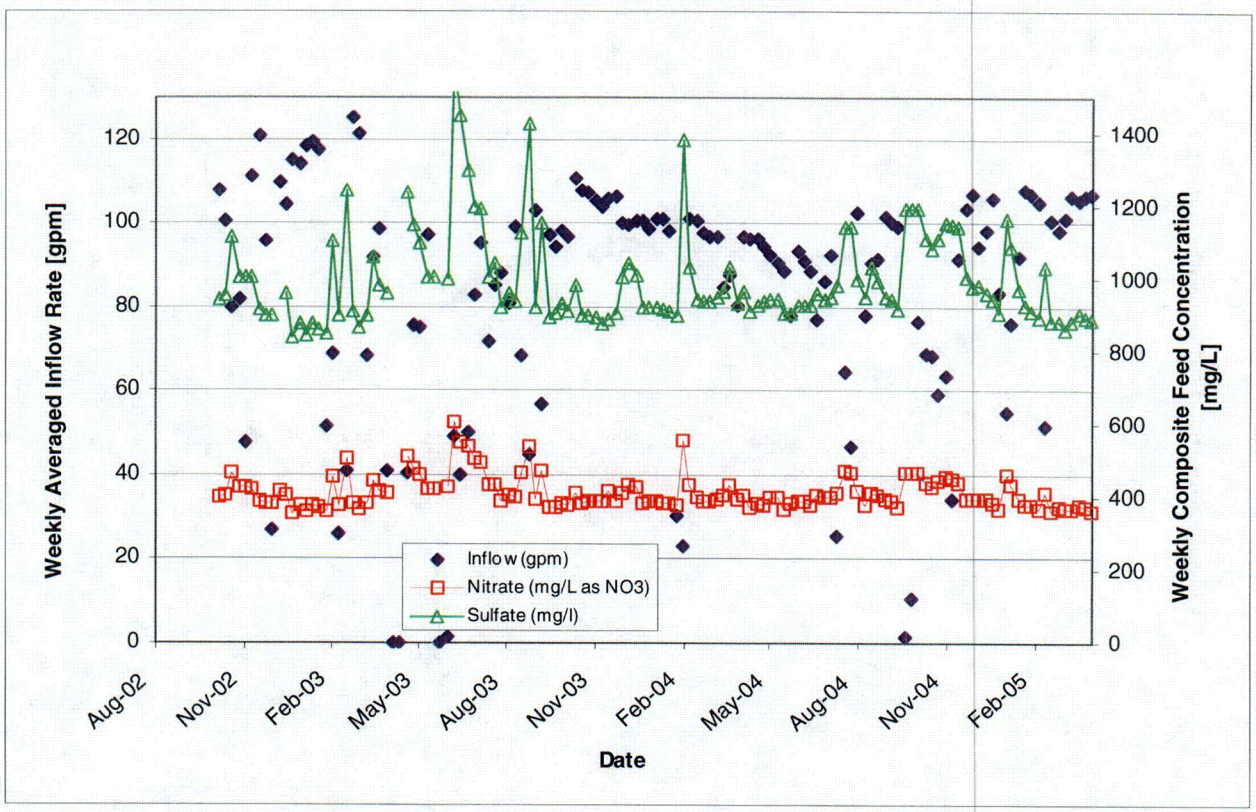

Figure 3. Treatment Plant Inflow Rate and Nitrate and Sulfate Concentration

C03

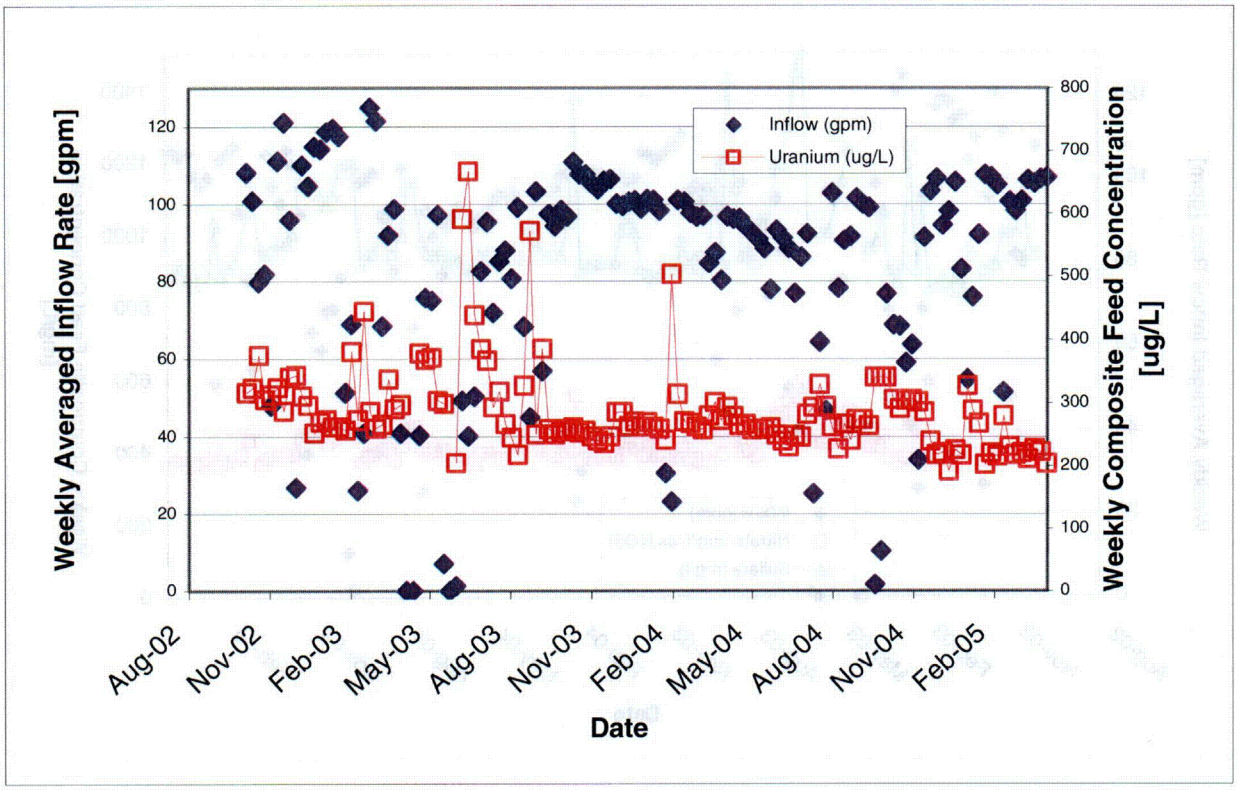

Figure 4. Treatment Plant Inflow Rate and Uranium Concentration

C04

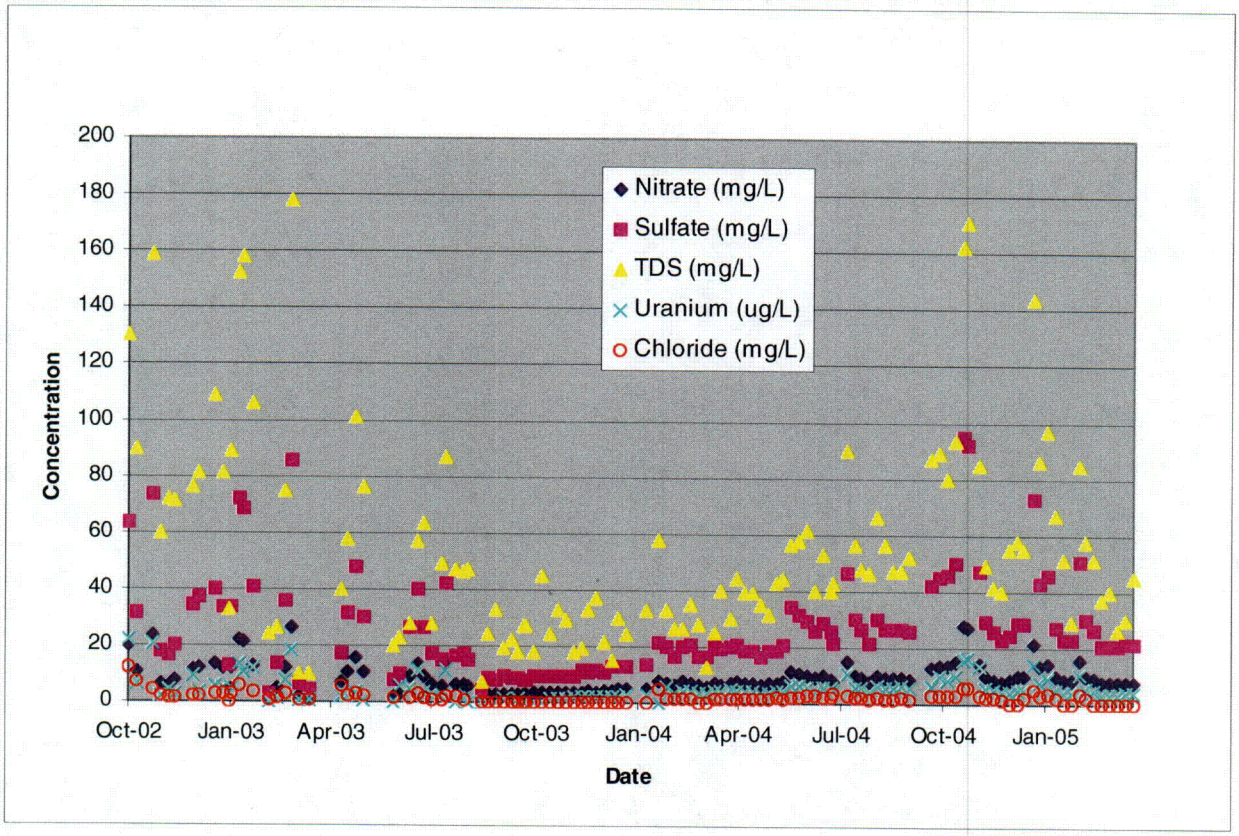

Figure 5. Treatment Plant Distillate Quality

C05

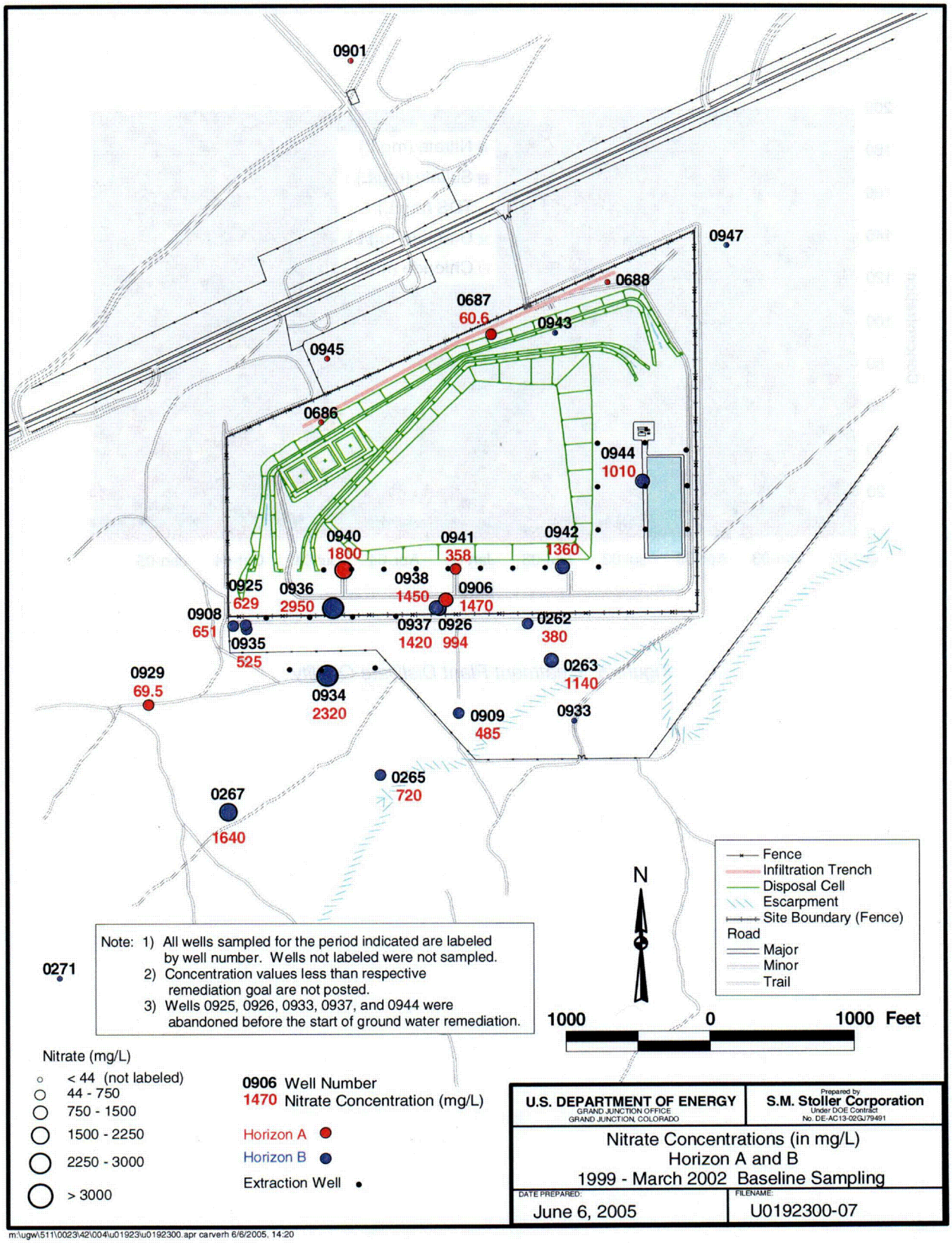

Figure 6a. Nitrate Concentrations in Ground Water, Horizons A and B, Baseline Period

COC

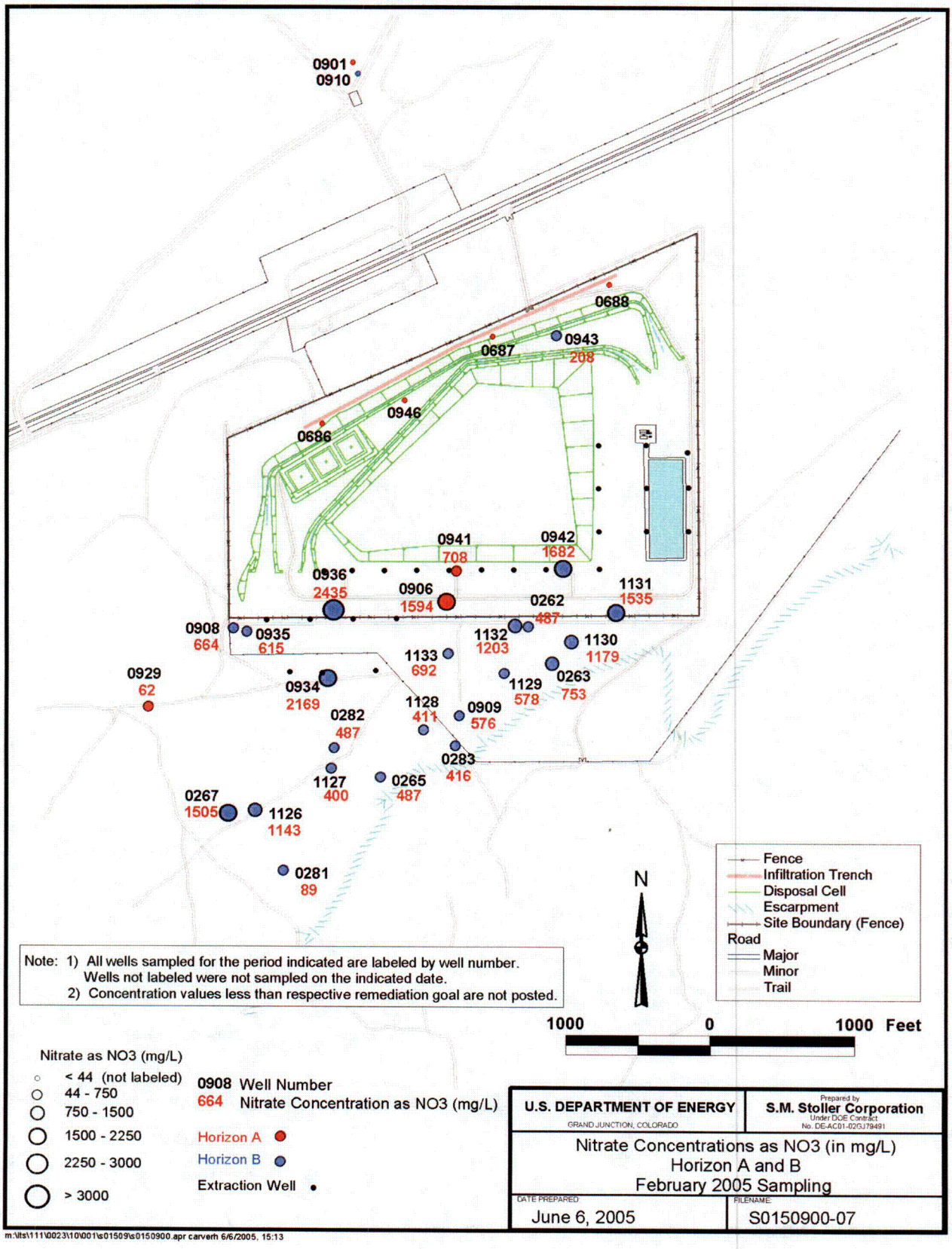

Figure 6b. Nitrate Concentrations in Ground Water, Horizons A and B, February 2005

C07

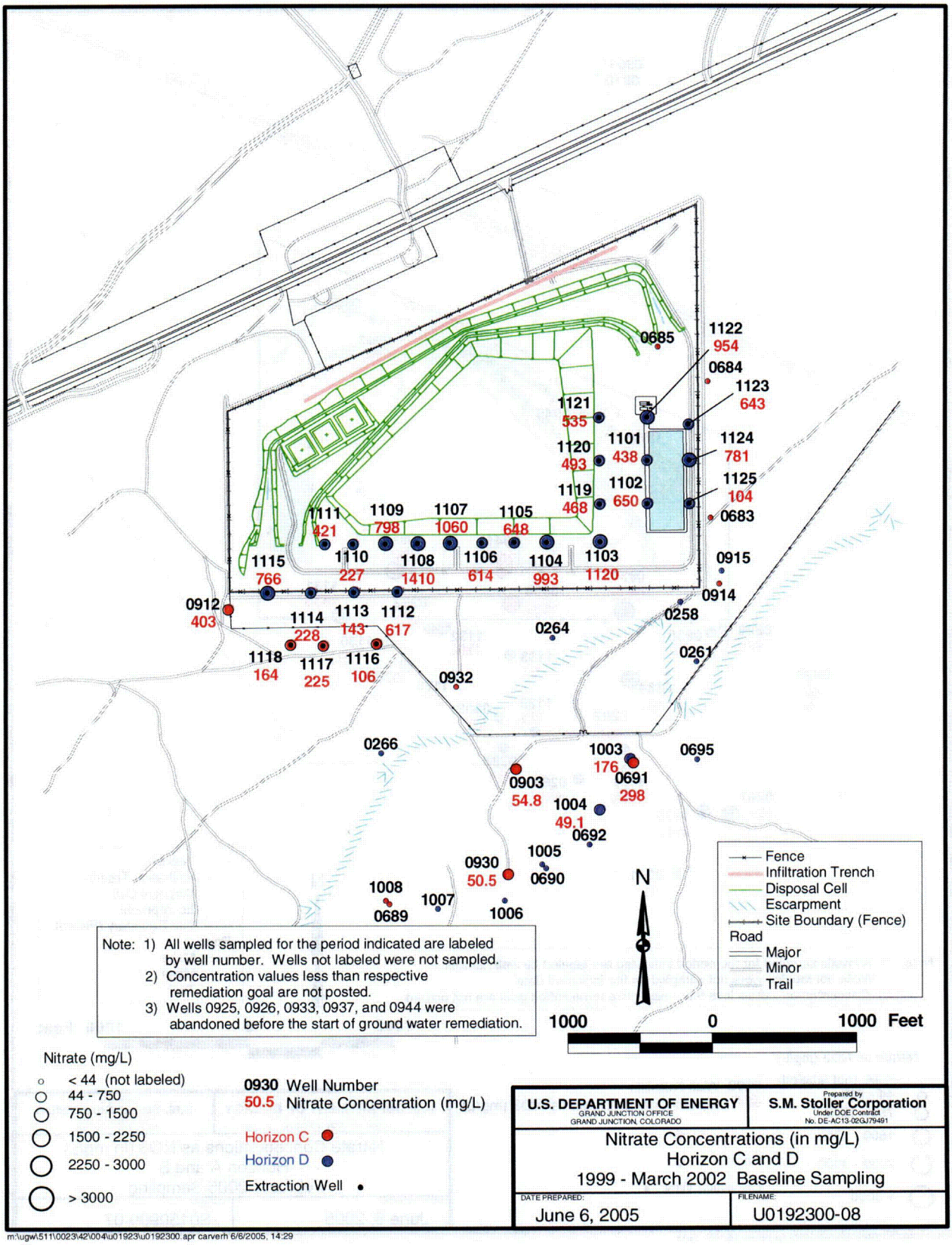

Figure 7a. Nitrate Concentrations in Ground Water, Horizons C and D, Baseline Period

C08

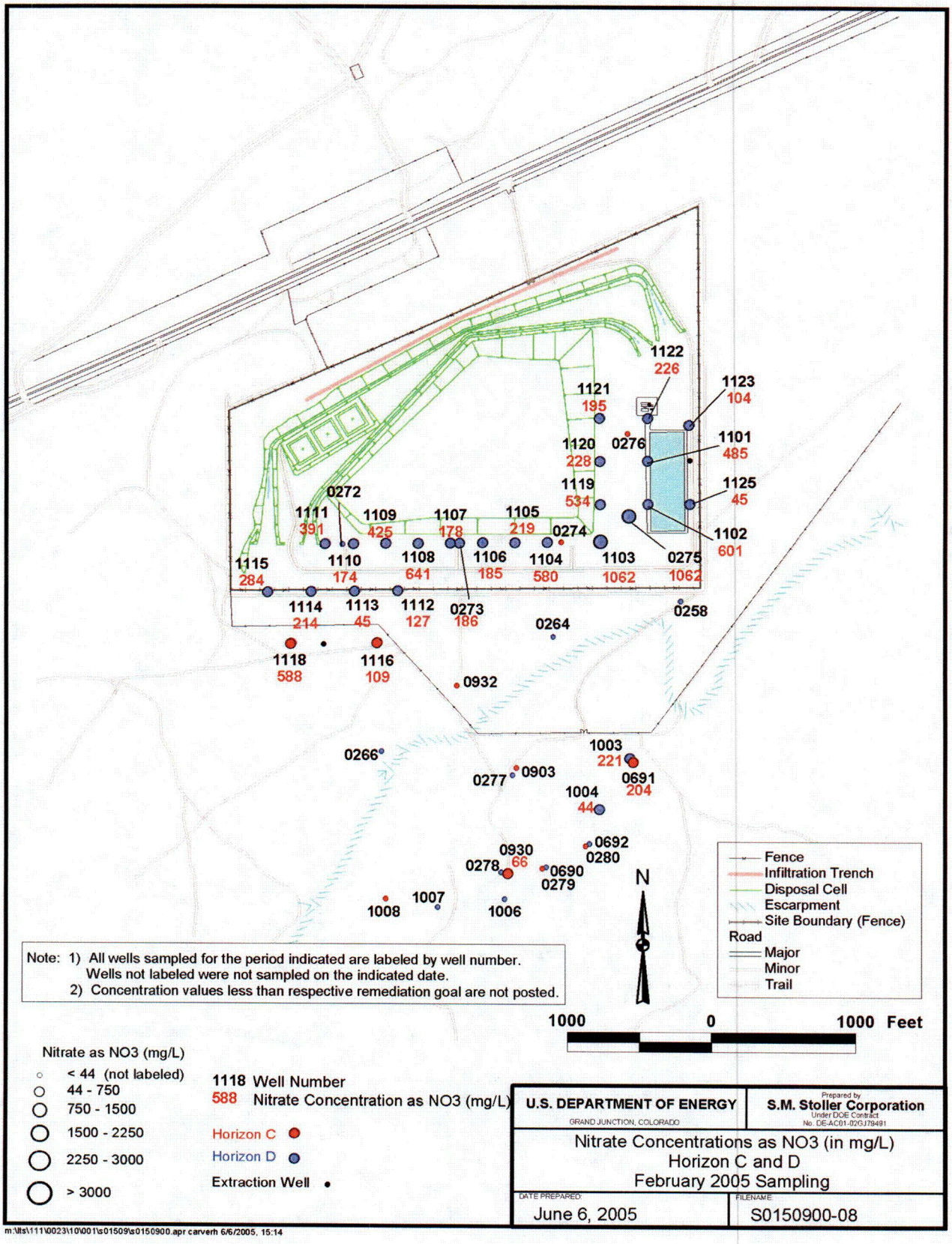

Figure 7b. Nitrate Concentrations in Ground Water, Horizons C and D, February 2005

C09

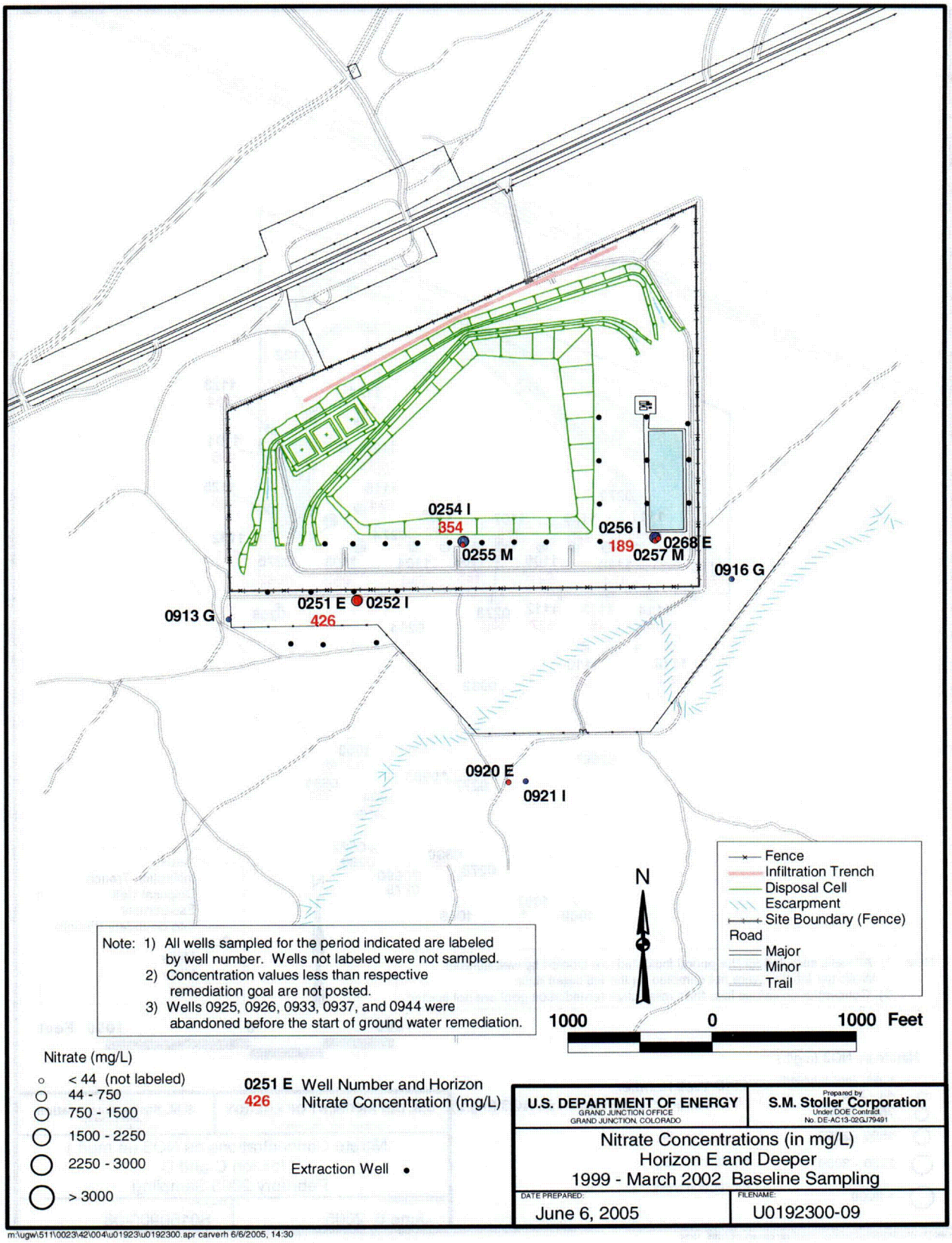

Figure 8a. Nitrate Concentrations in Ground Water, Horizons E and Deeper, Baseline Period

C10

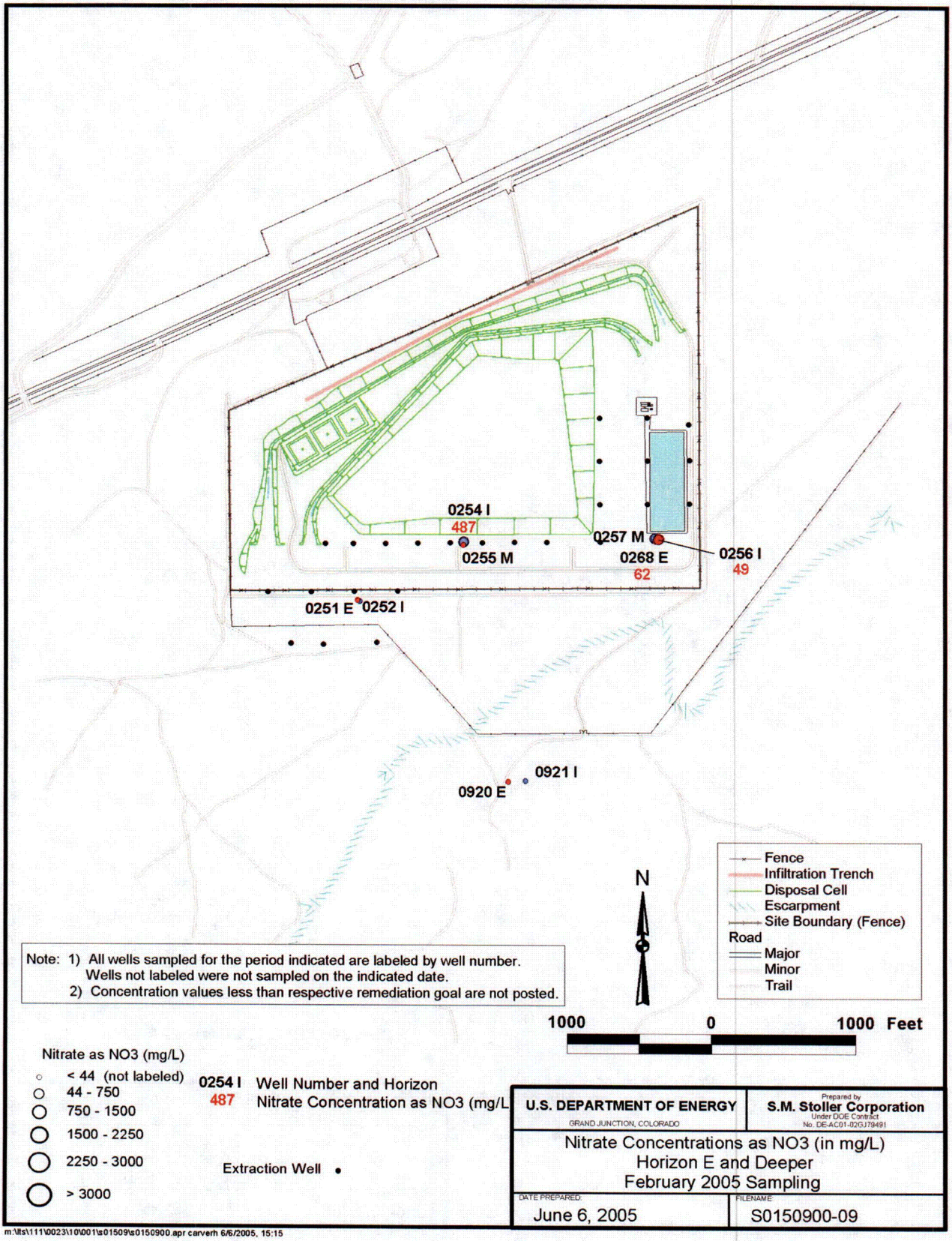

Figure 8b. Nitrate Concentrations in Ground Water, Horizons E and Deeper, February 2005

C11

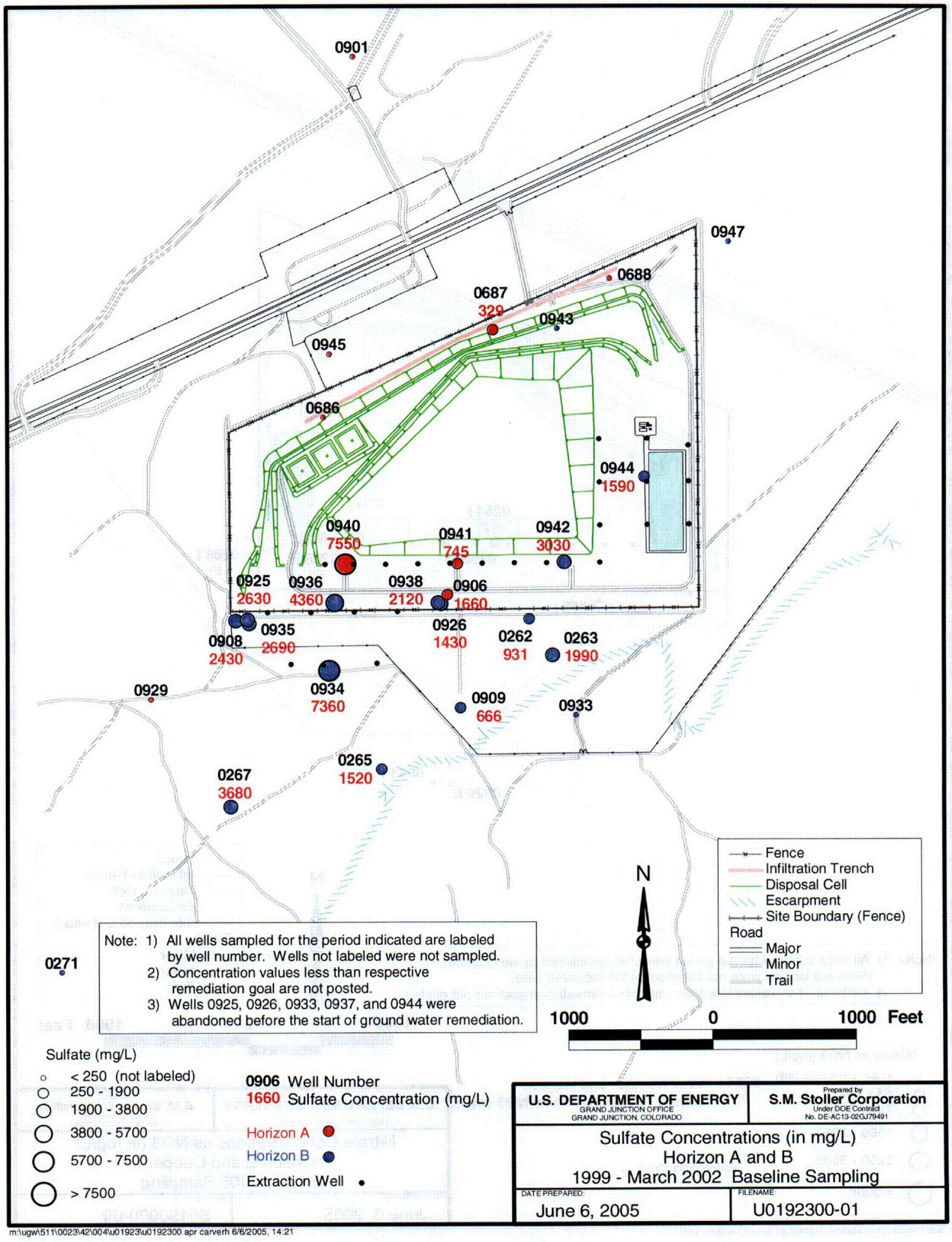

Figure 9a. Sulfate Concentrations in Ground Water, Horizons A and B, Baseline Period

C12

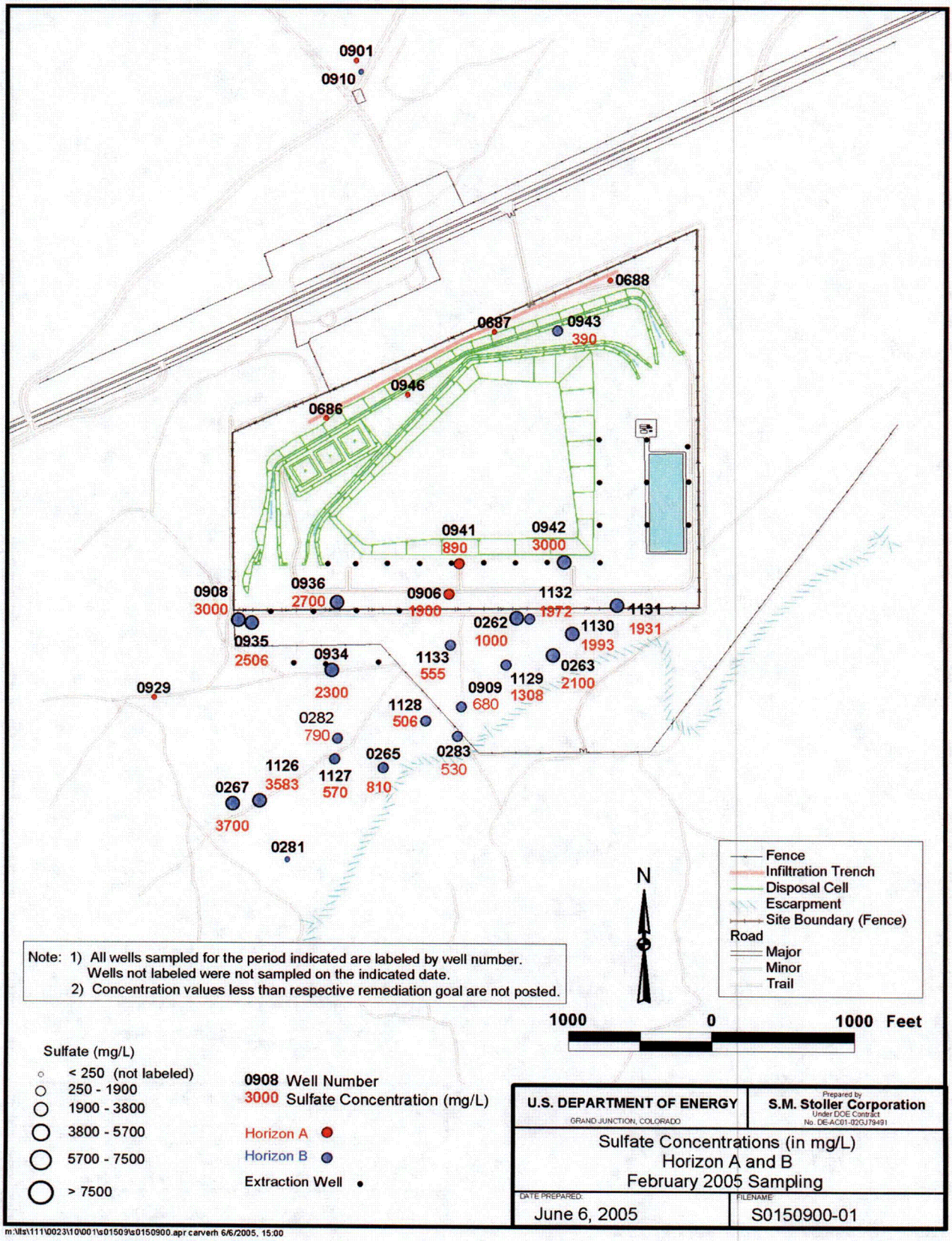

Figure 9b. Sulfate Concentrations in Ground Water, Horizons A and B, February 2005

C13

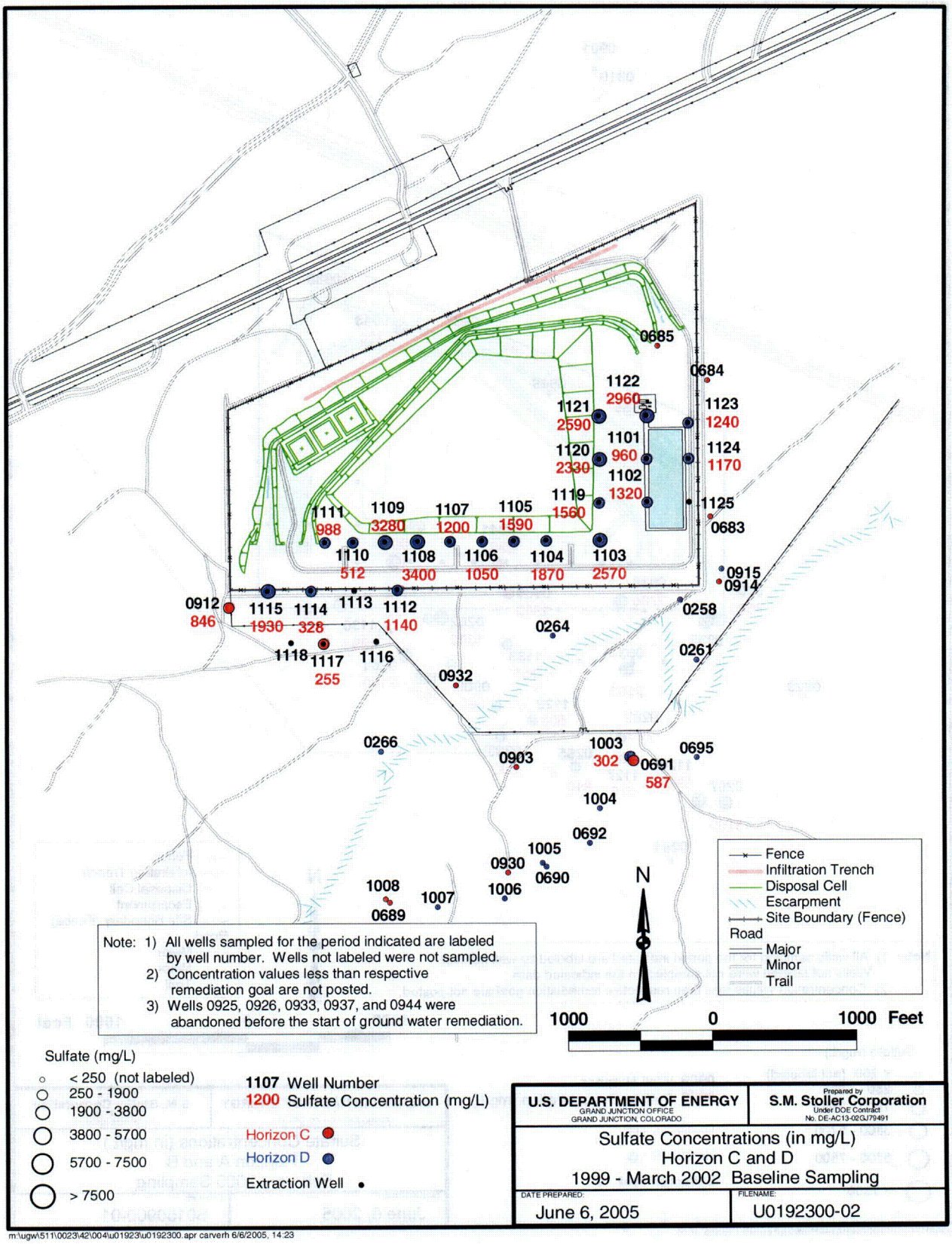

Figure 10a. Sulfate Concentrations in Ground Water, Horizons C and D, Baseline Period

C14

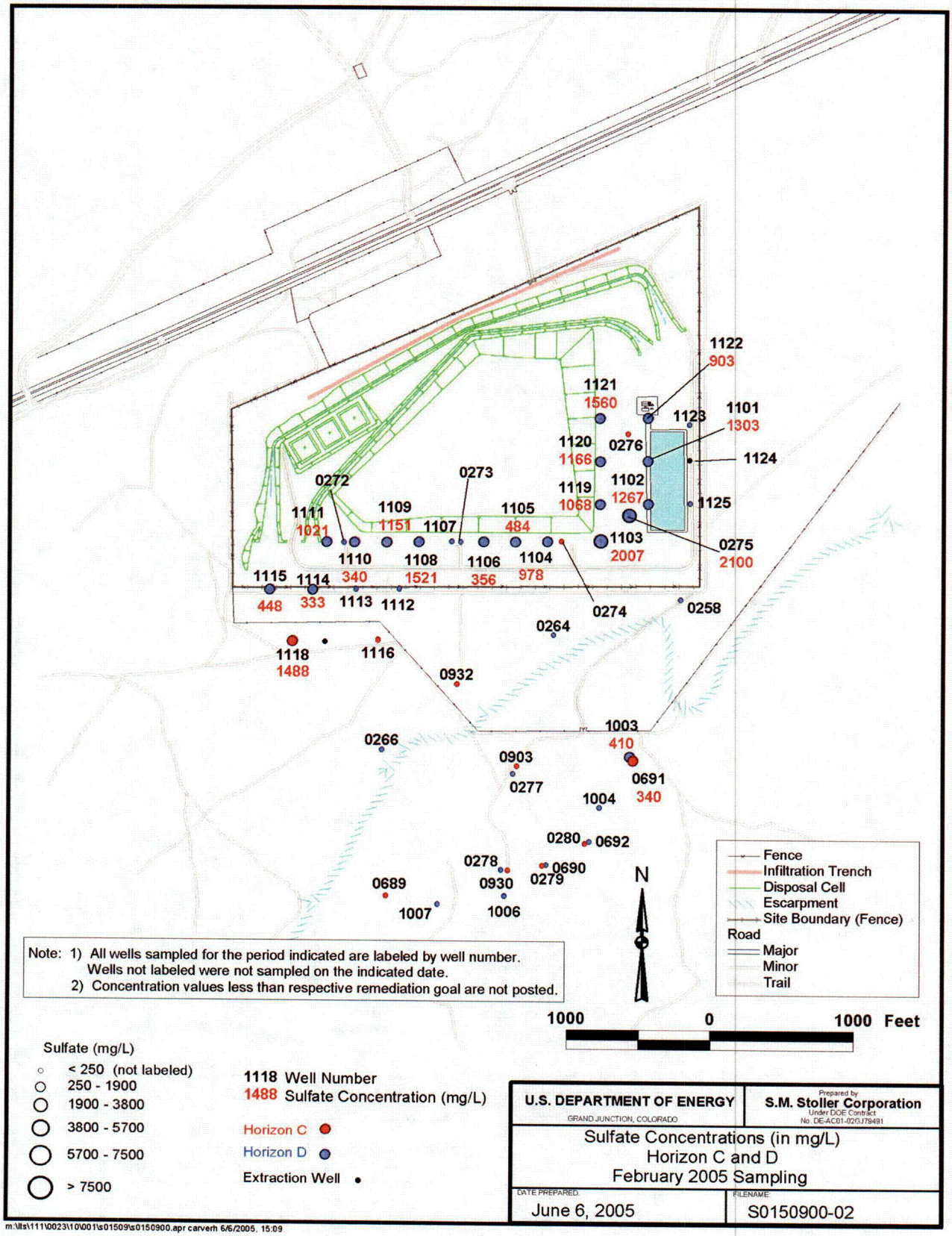

Figure 10b. Sulfate Concentrations in Ground Water, Horizons C and D, February 2005

C15

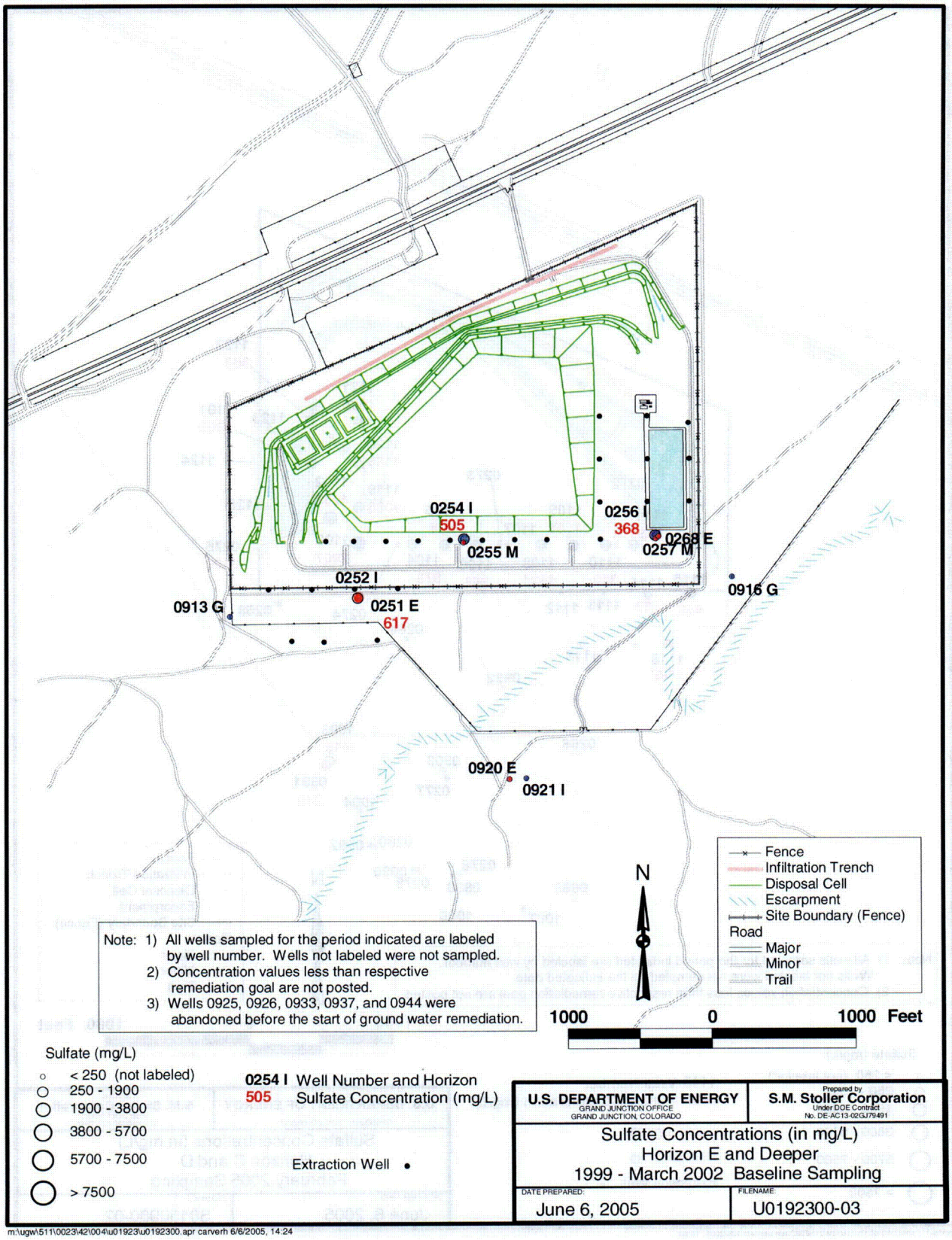

Figure 11a. Sulfate Concentrations in Ground Water, Horizons E and Deeper, Baseline Period

C16

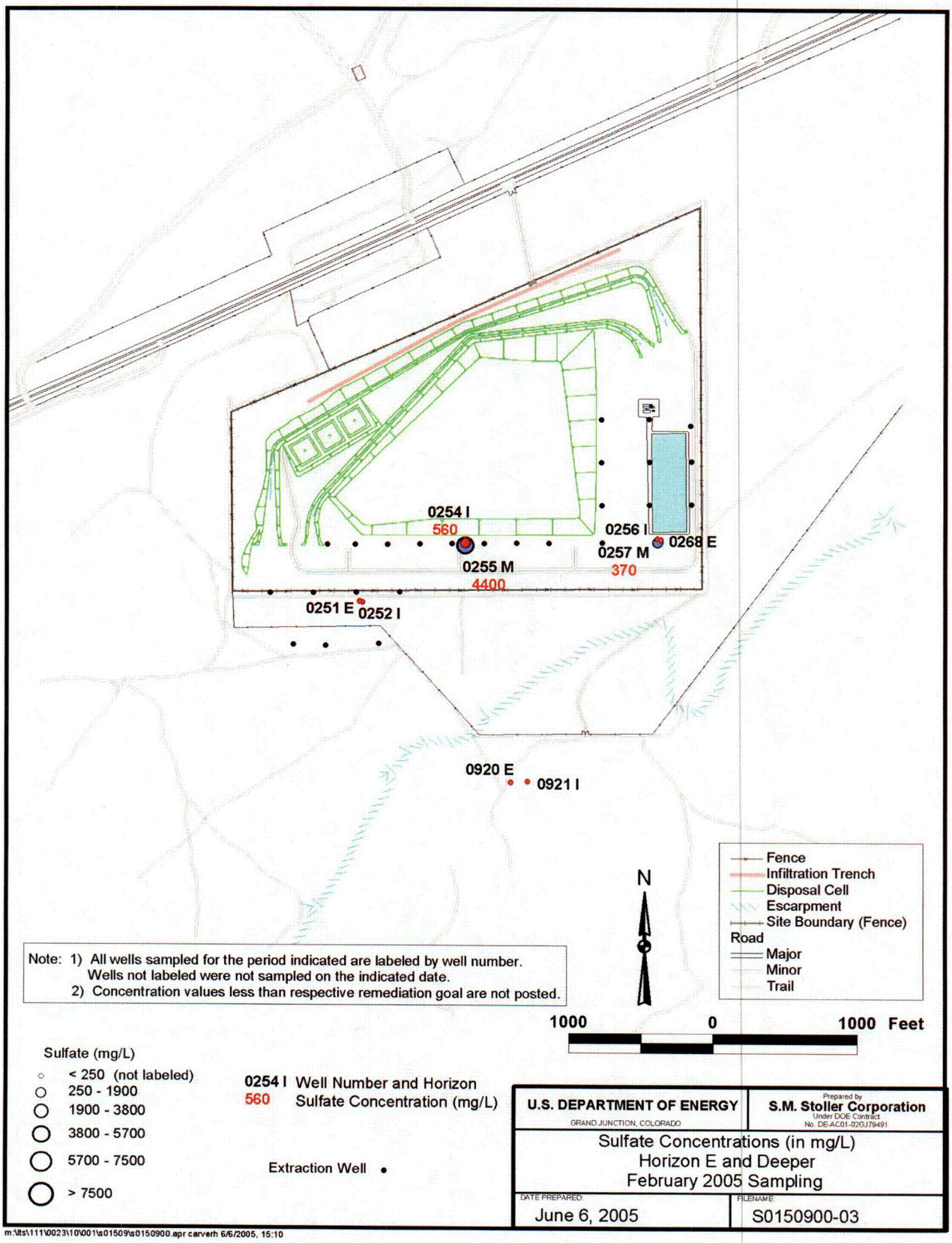

Figure 11b. Sulfate Concentrations in Ground Water, Horizons E and Deeper, February 2005

C17

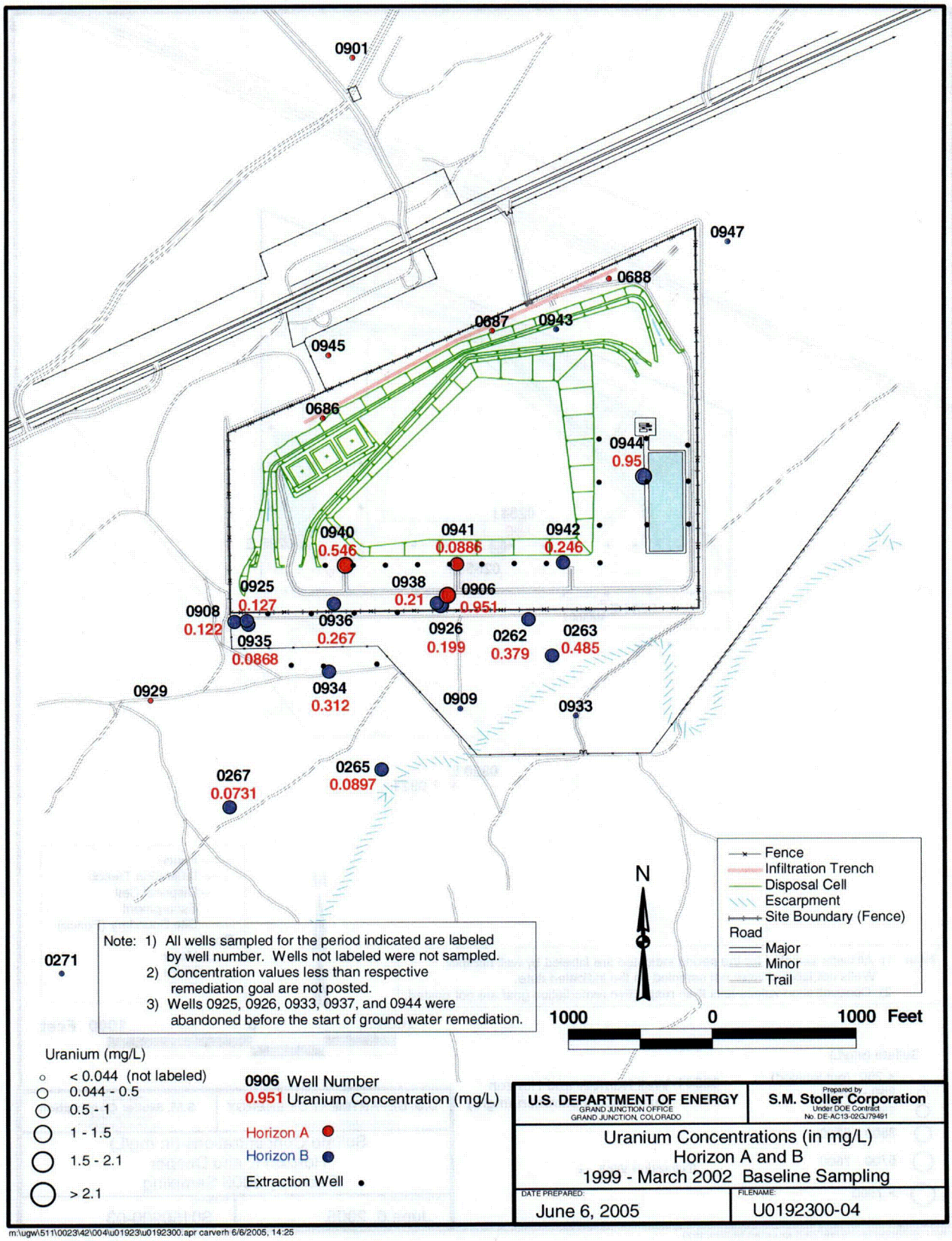

Figure 12a. Uranium Concentrations in Ground Water, Horizons A and B, Baseline Period

C18

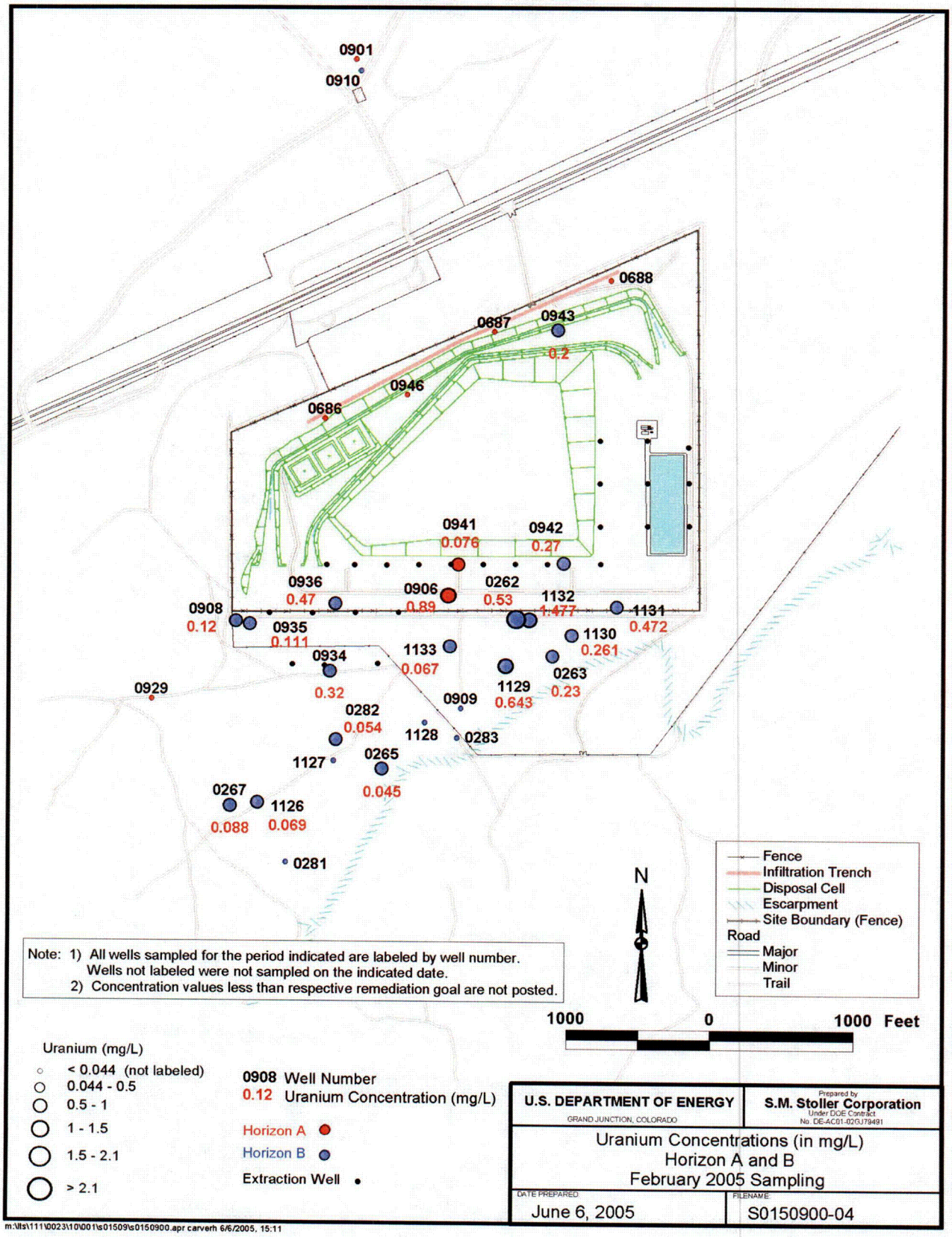

Figure 12b. Uranium Concentrations in Ground Water, Horizons A and B, February 2005

C19

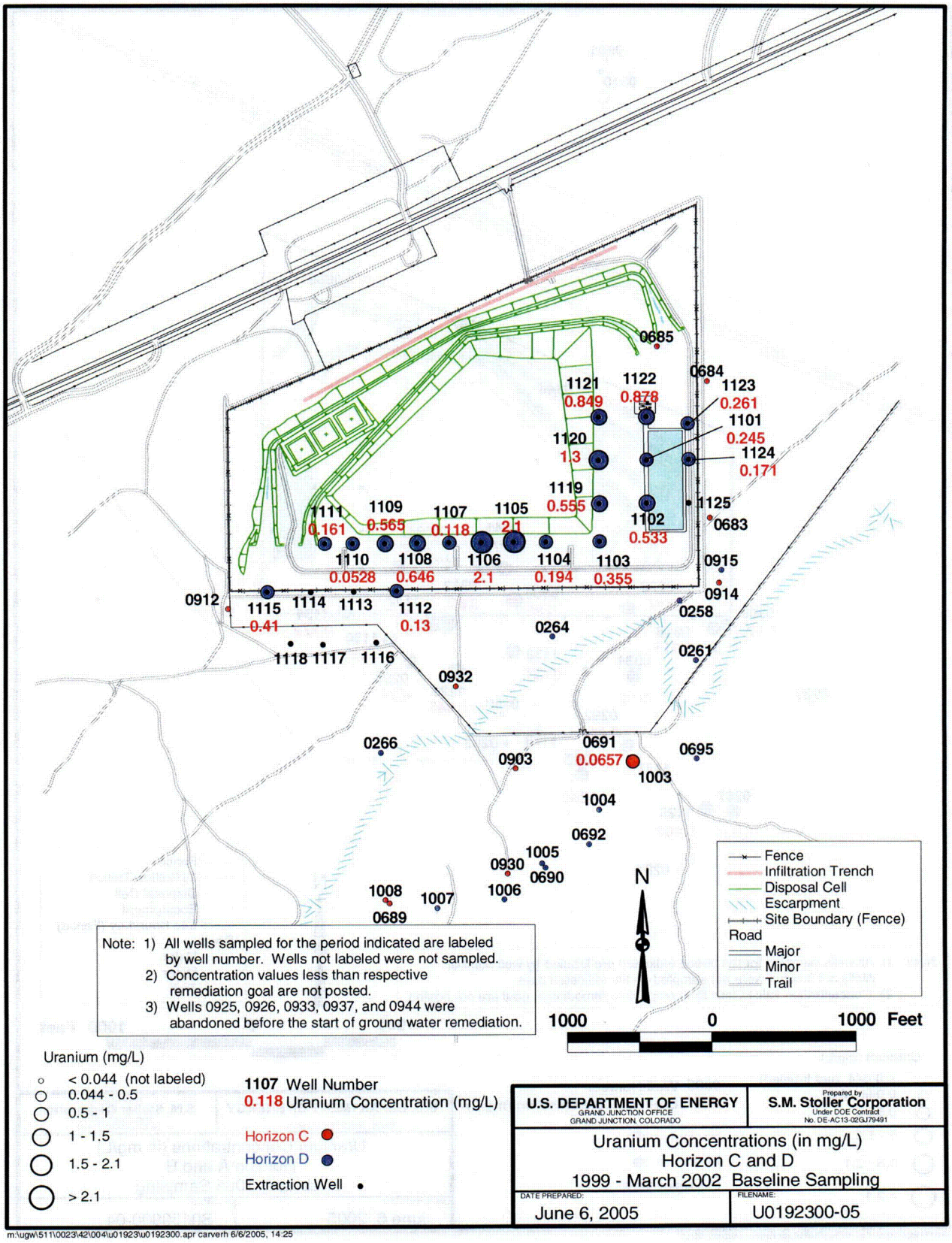

Figure 13a. Uranium Concentrations in Ground Water, Horizons C and D, Baseline

C20

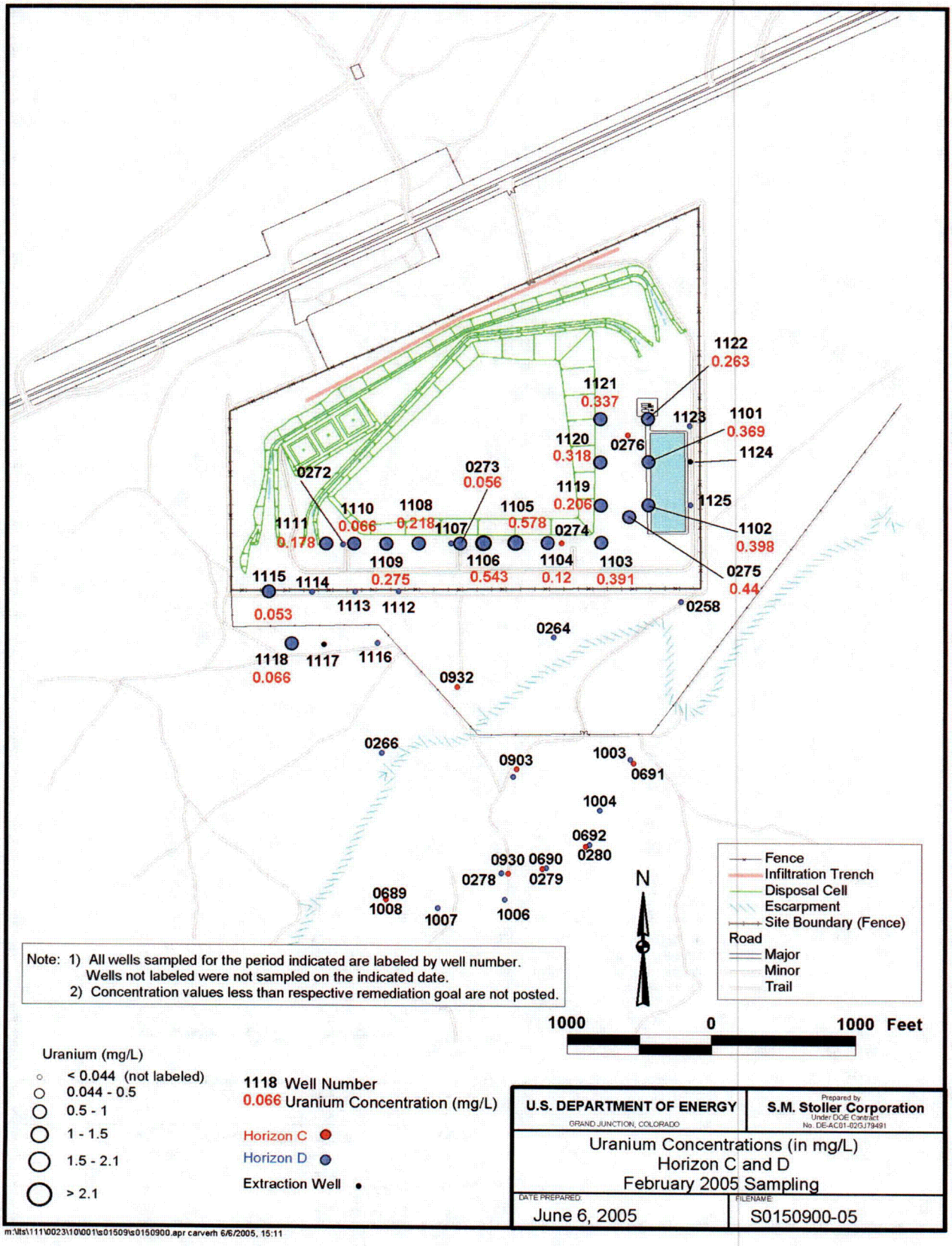

Figure 13b. Uranium Concentrations in Ground Water, Horizons C and D, February 2005

C21

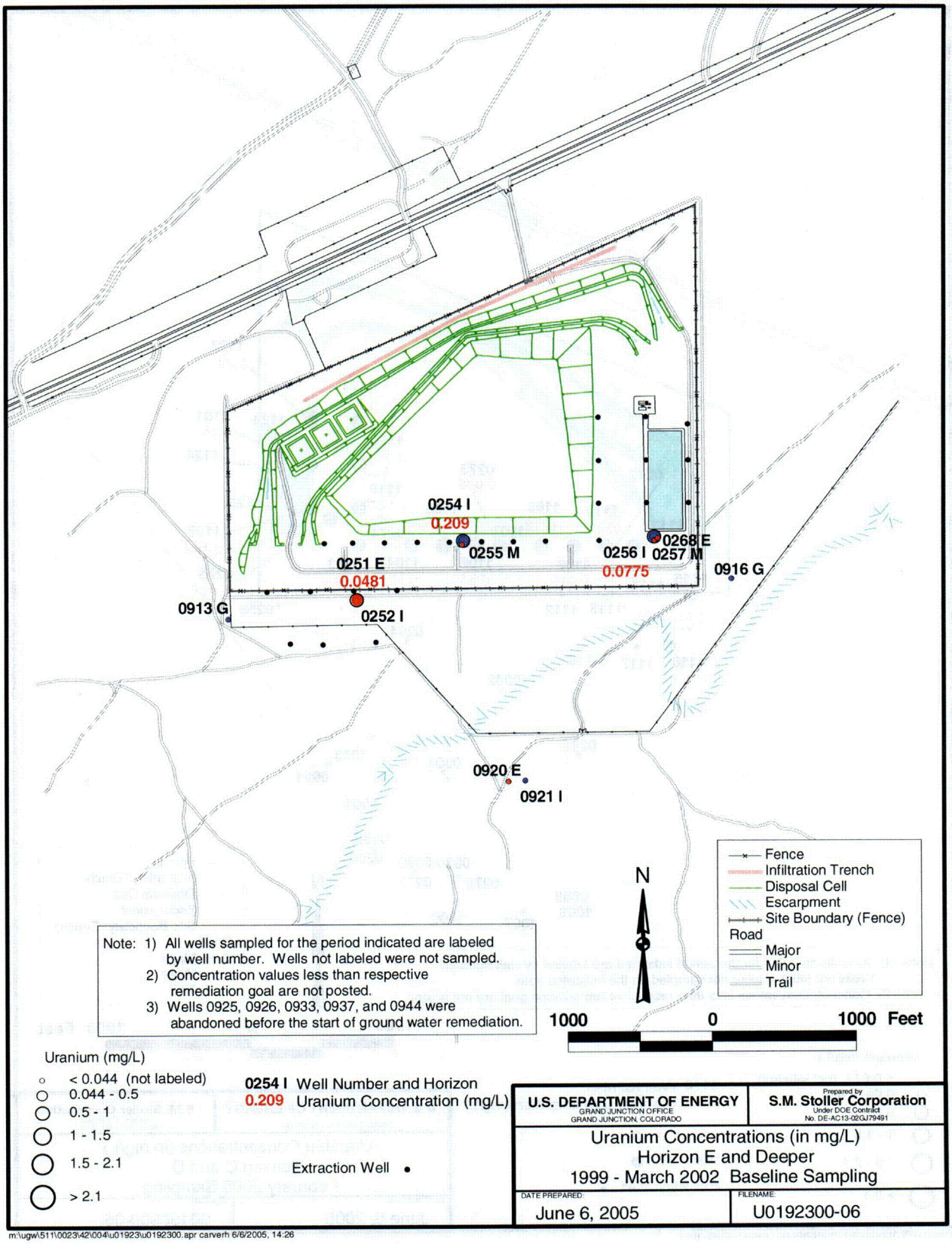

Figure 14a. Uranium Concentrations in Ground Water, Horizons E and Deeper, Baseline Period

C22

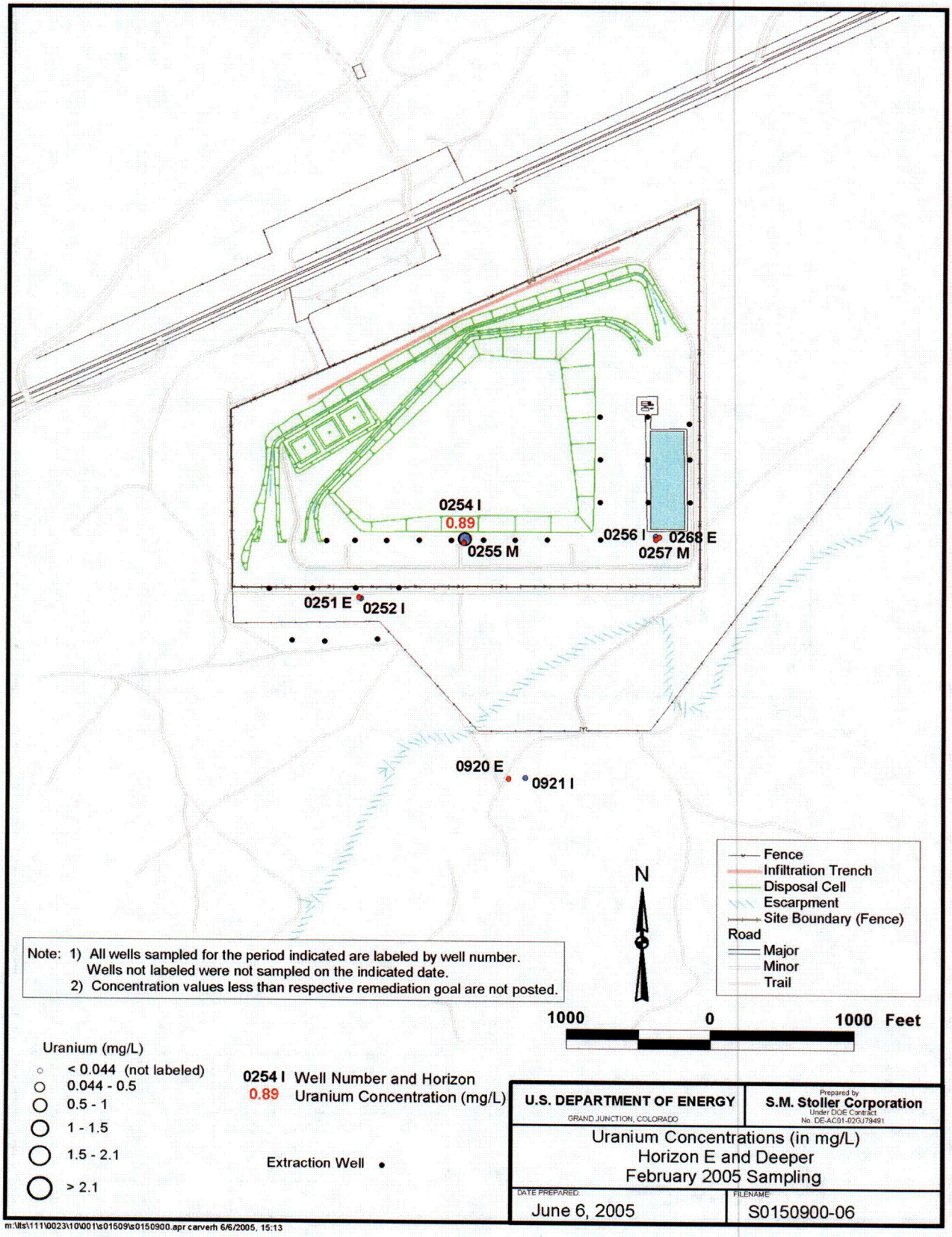

Figure 14b. Uranium Concentrations in Ground Water, Horizons E and Deeper, February 2005

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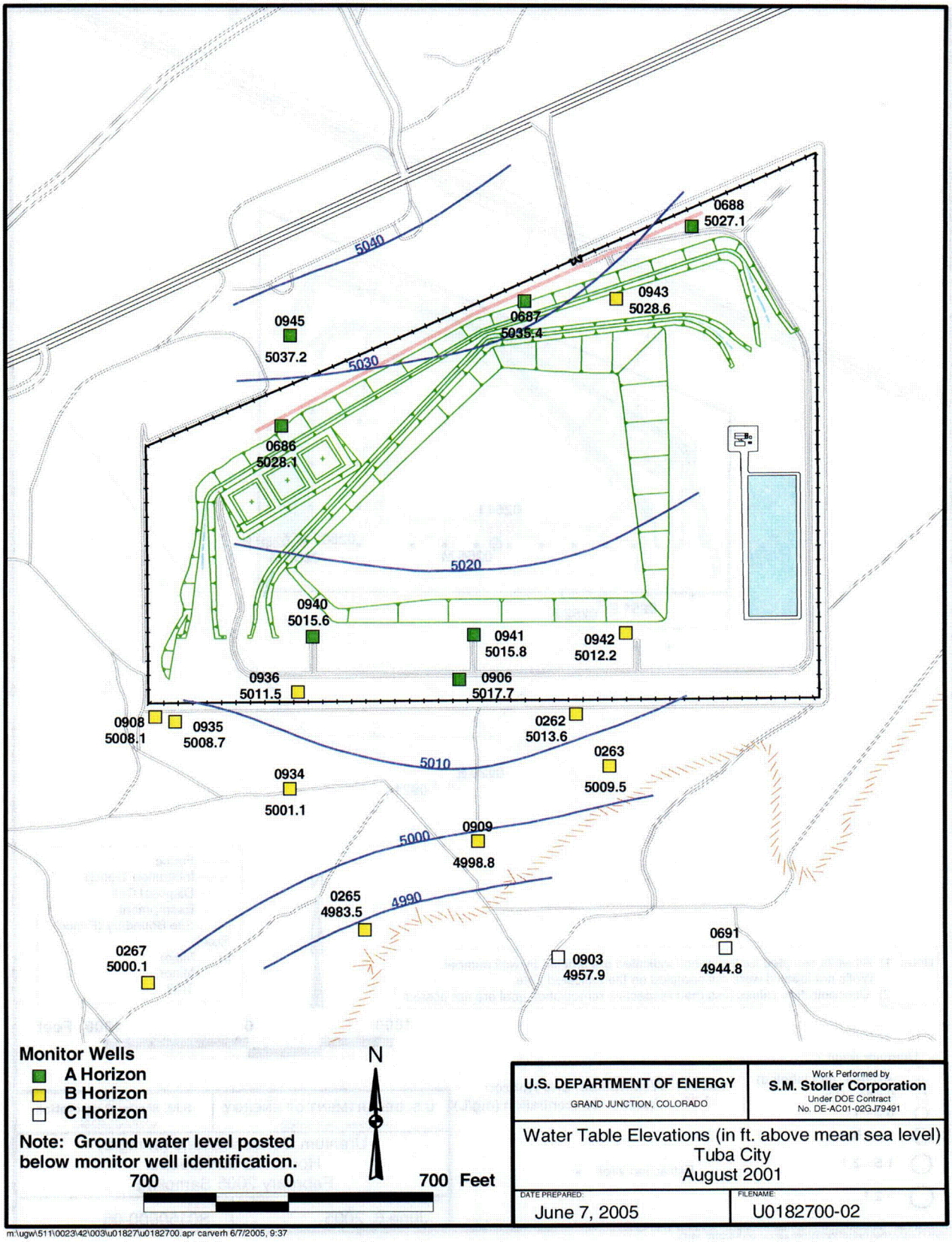

Figure 15. Water Table Elevations (in ft. above mean sea level), Tuba City Site, August 2001

C24

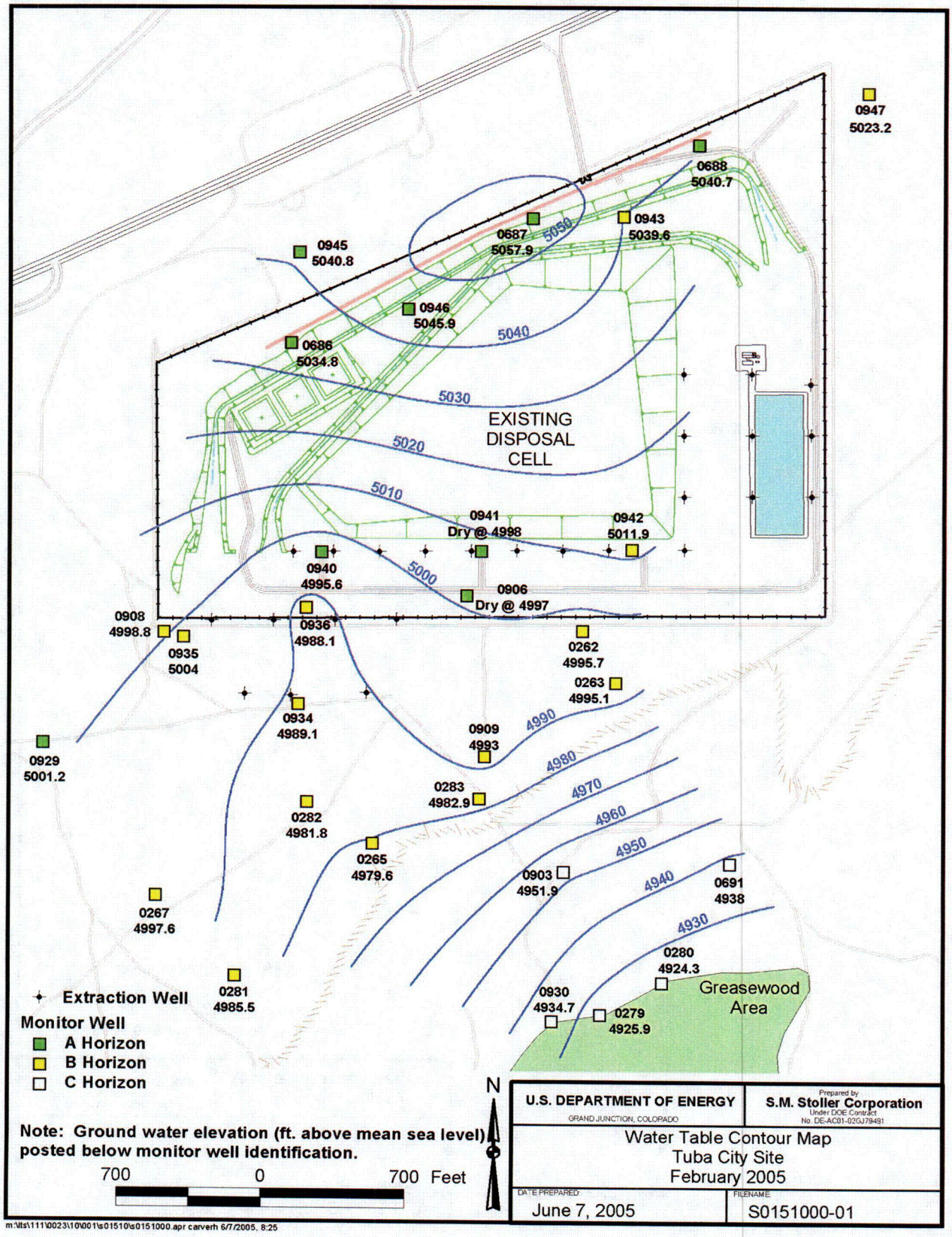

Figure 16. Water Table Contour Map, Tuba City Site, February 2005

C25

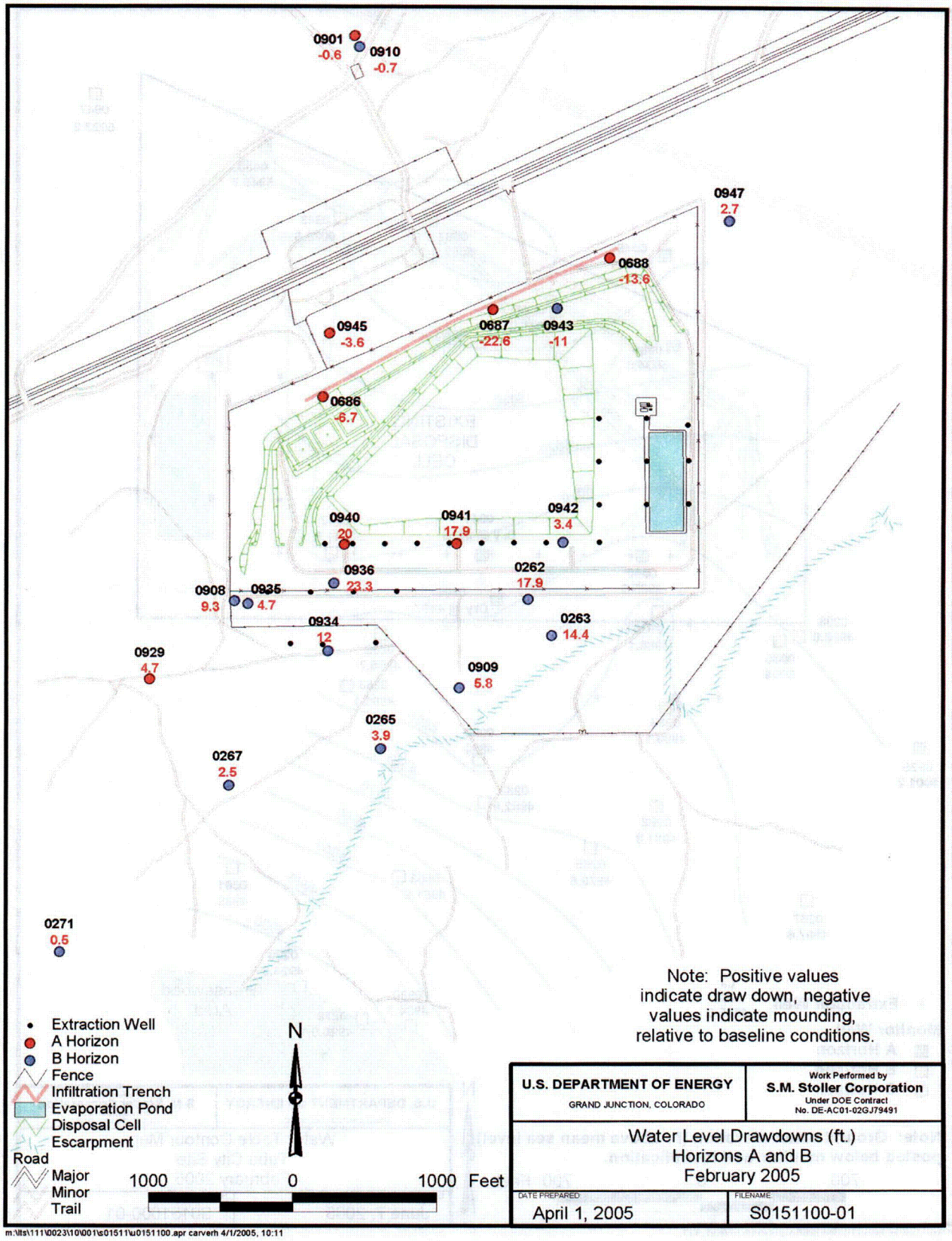

Figure 17. Water Level Drawdowns (ft), Horizons A and B, February 2005

CZ6

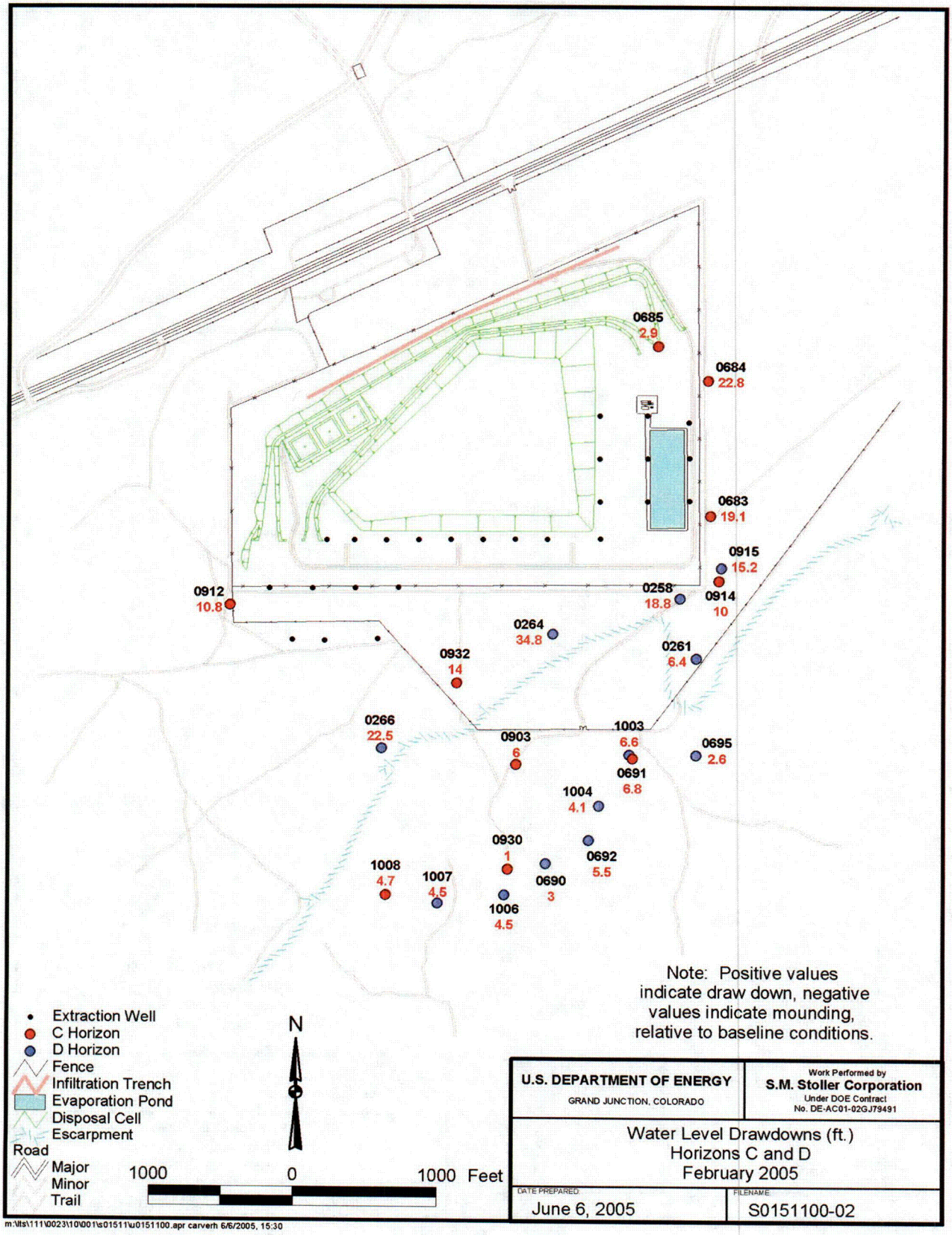

Figure 18. Water Level Drawdowns (ft), Horizons C and D, February 2005

C27

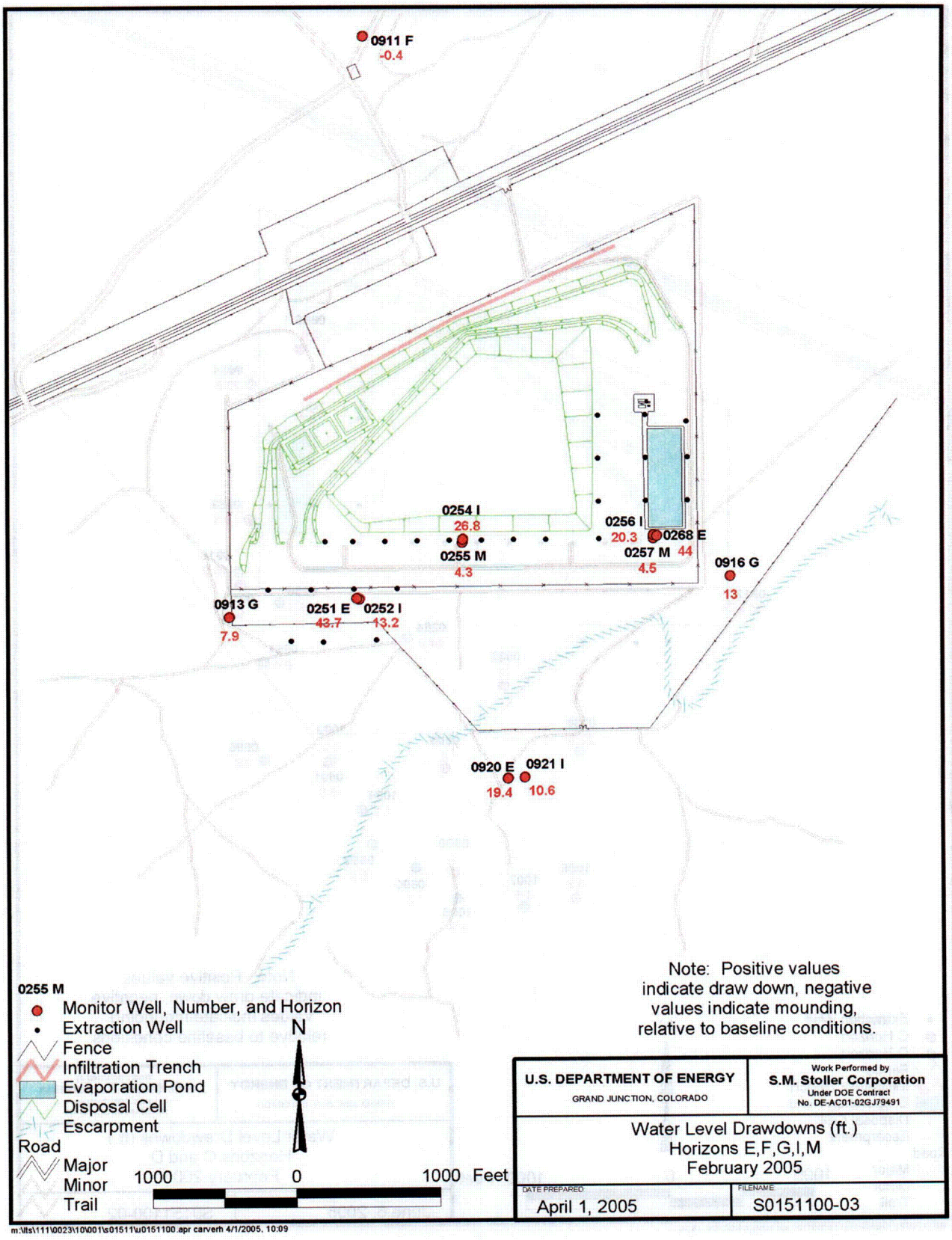

Figure 19. Water Level Drawdowns (ft), Horizons E, F, G, I, and M, February 2005

C28

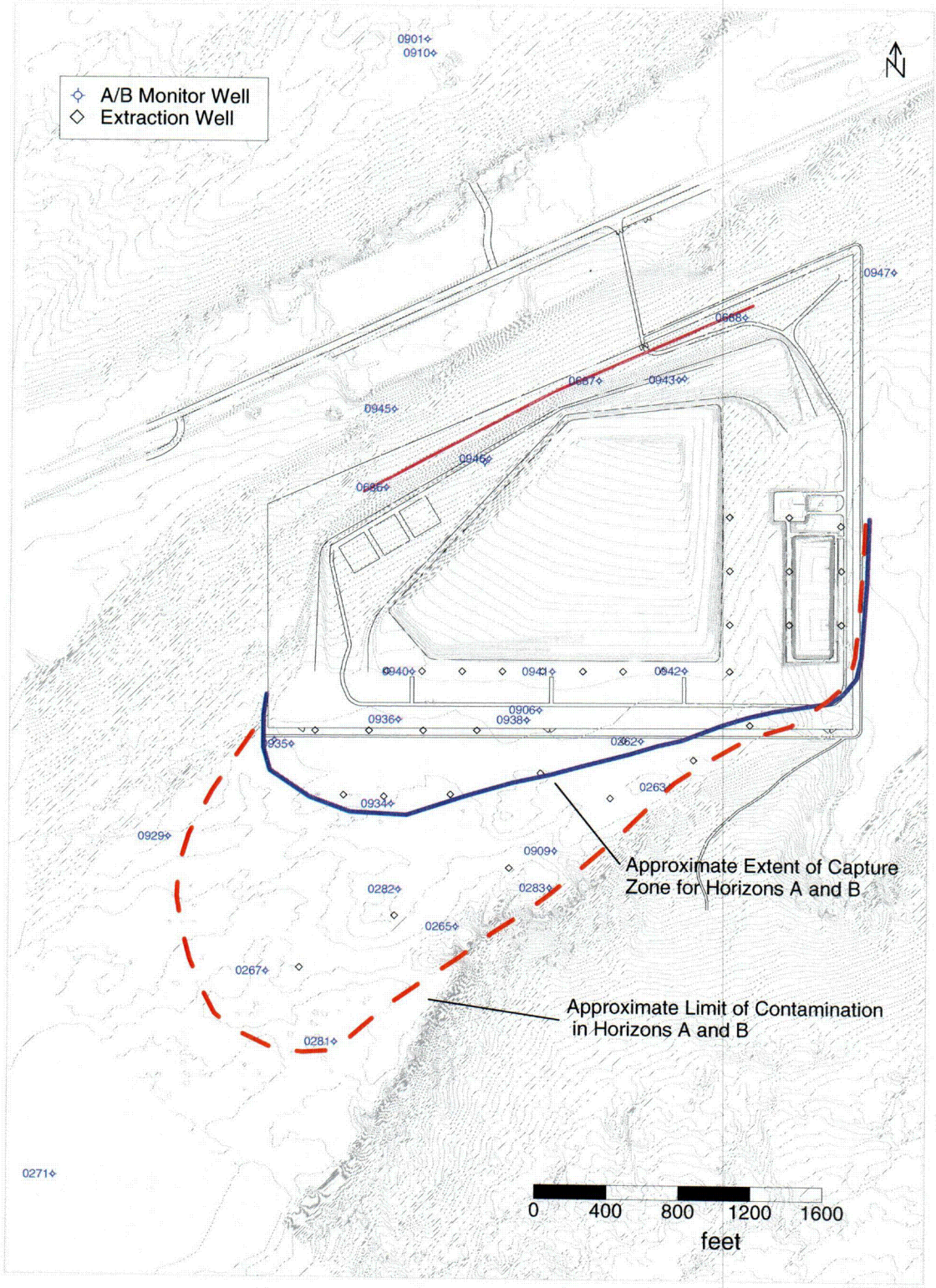

Figure 20. Extent of Ground Water Contamination and Extraction System Capture Zone: Horizons A and B

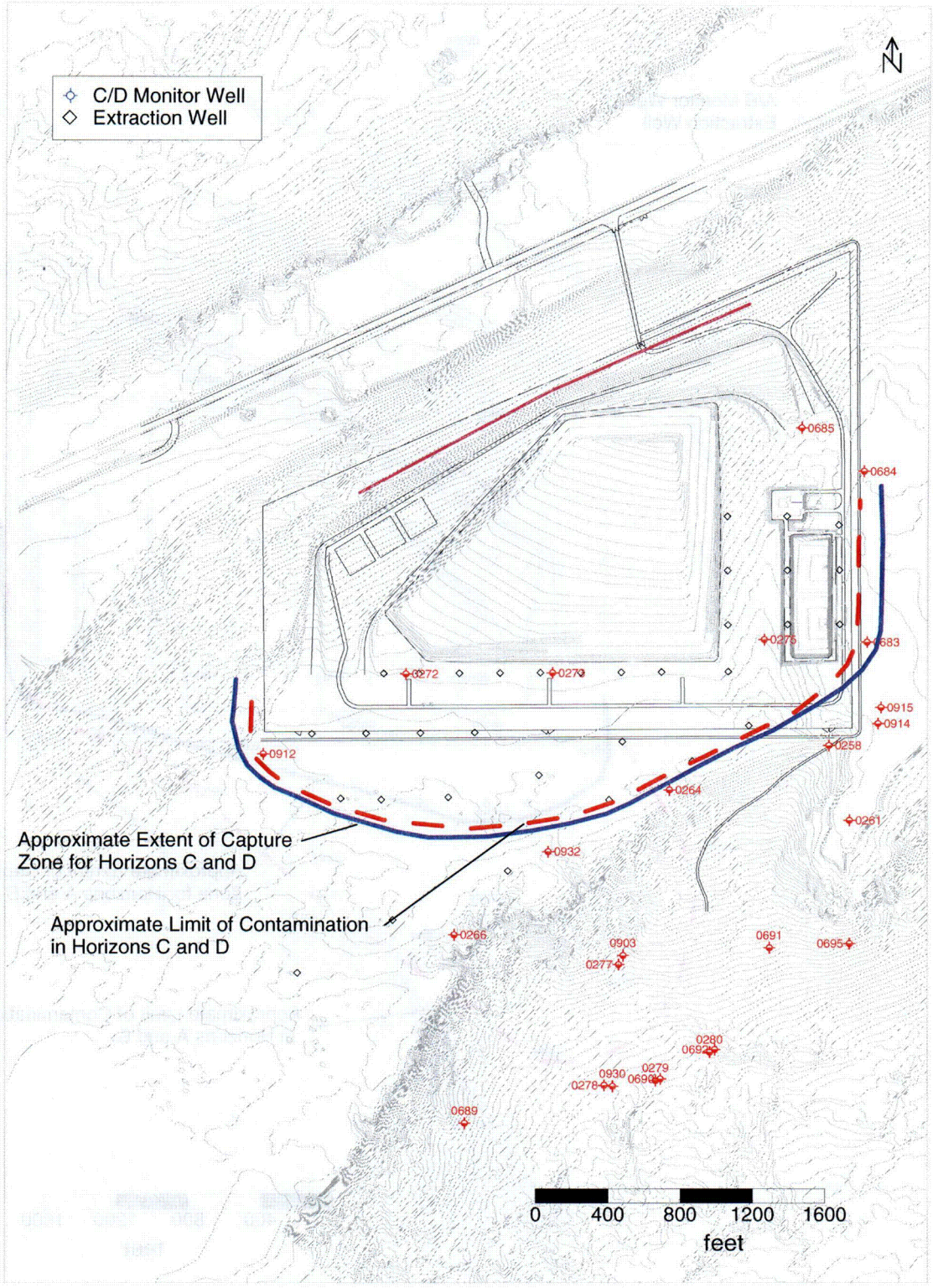

Figure 21. Extent of Ground Water Contamination and Extraction System Capture Zone: Horizons C and D

C30

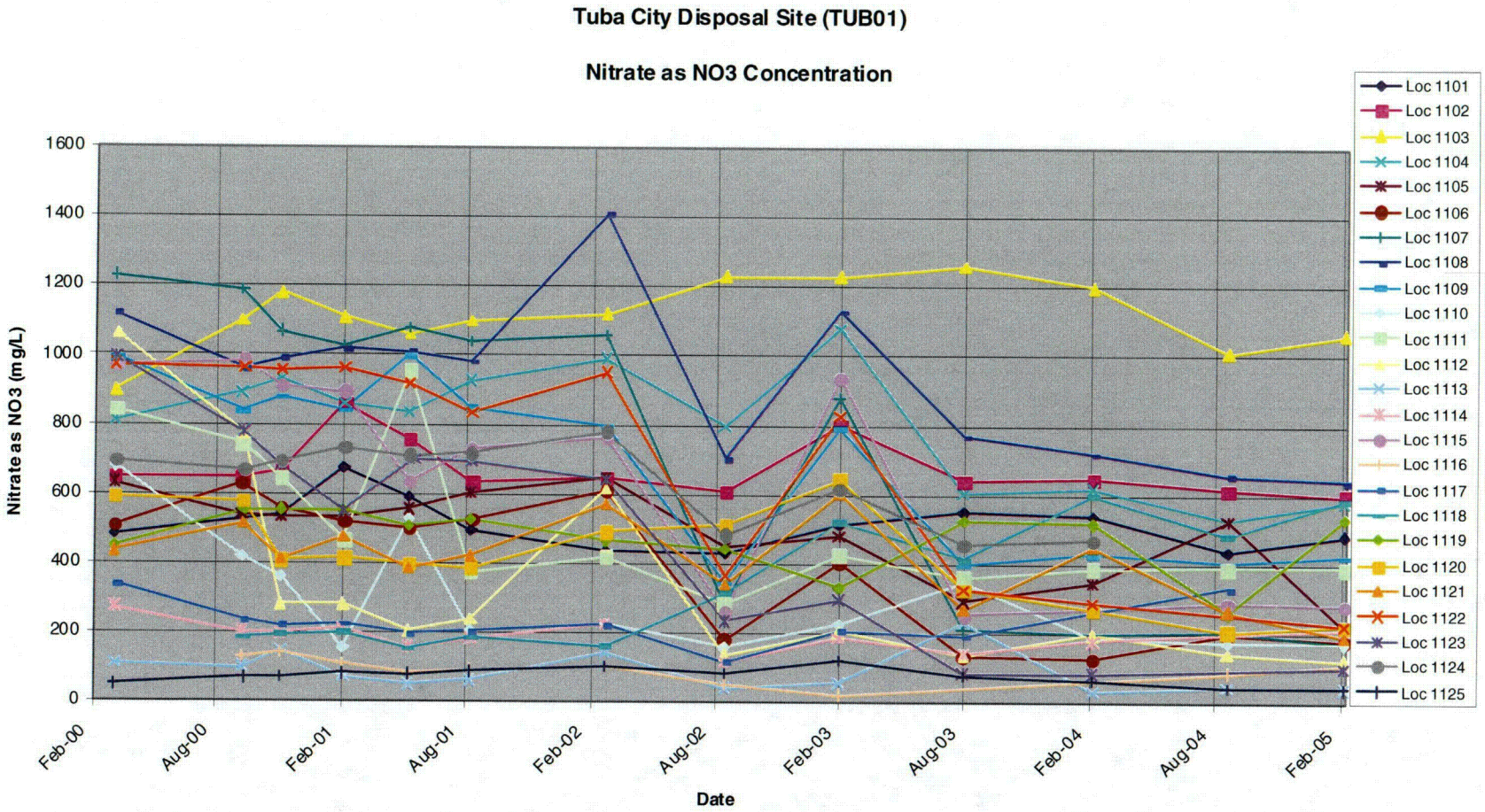

Figure 22. Nitrate Concentration Trends at Extraction Wells

C31

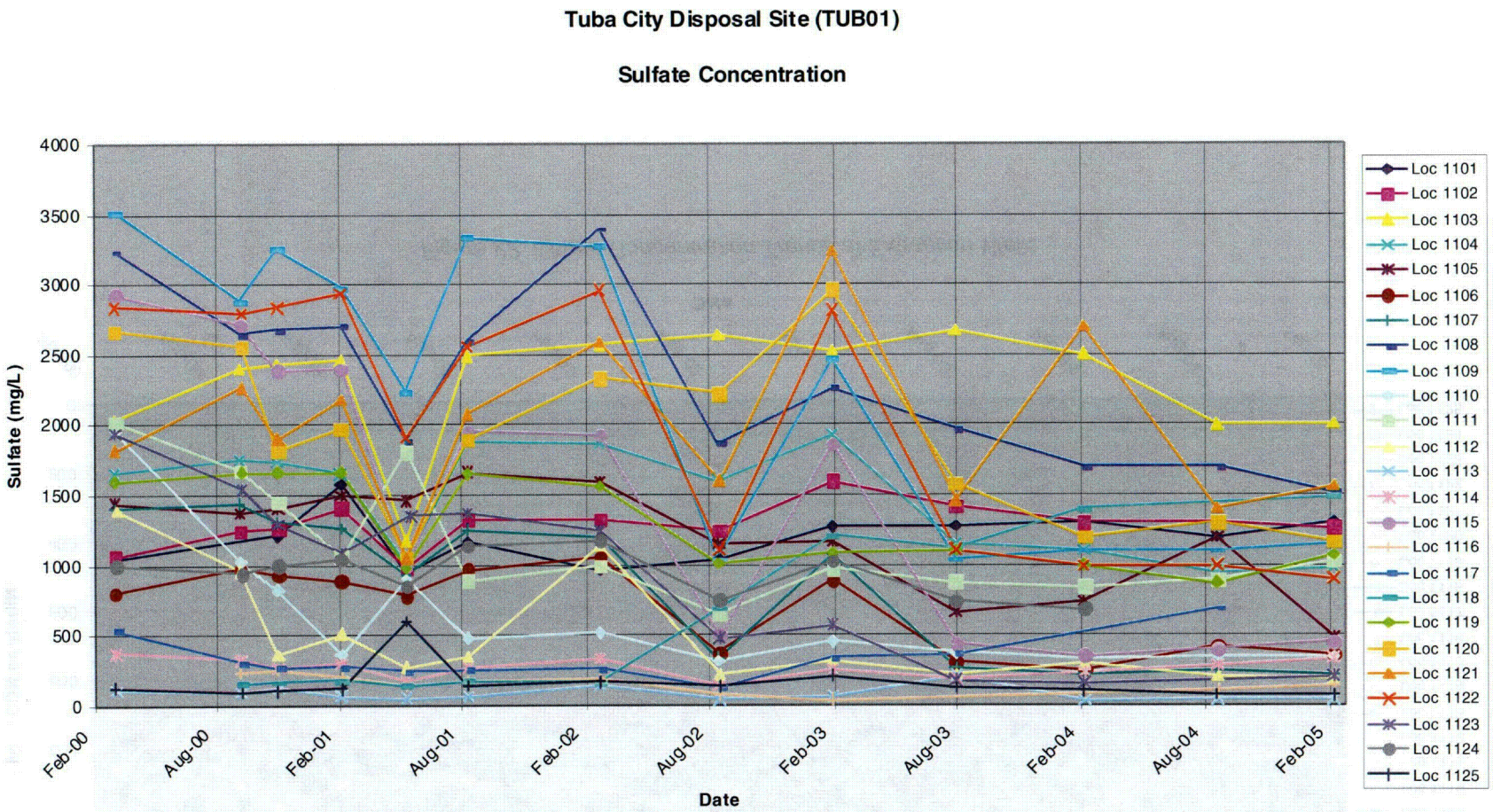

Figure 23. Sulfate Concentration Trends at Extraction Wells

C32

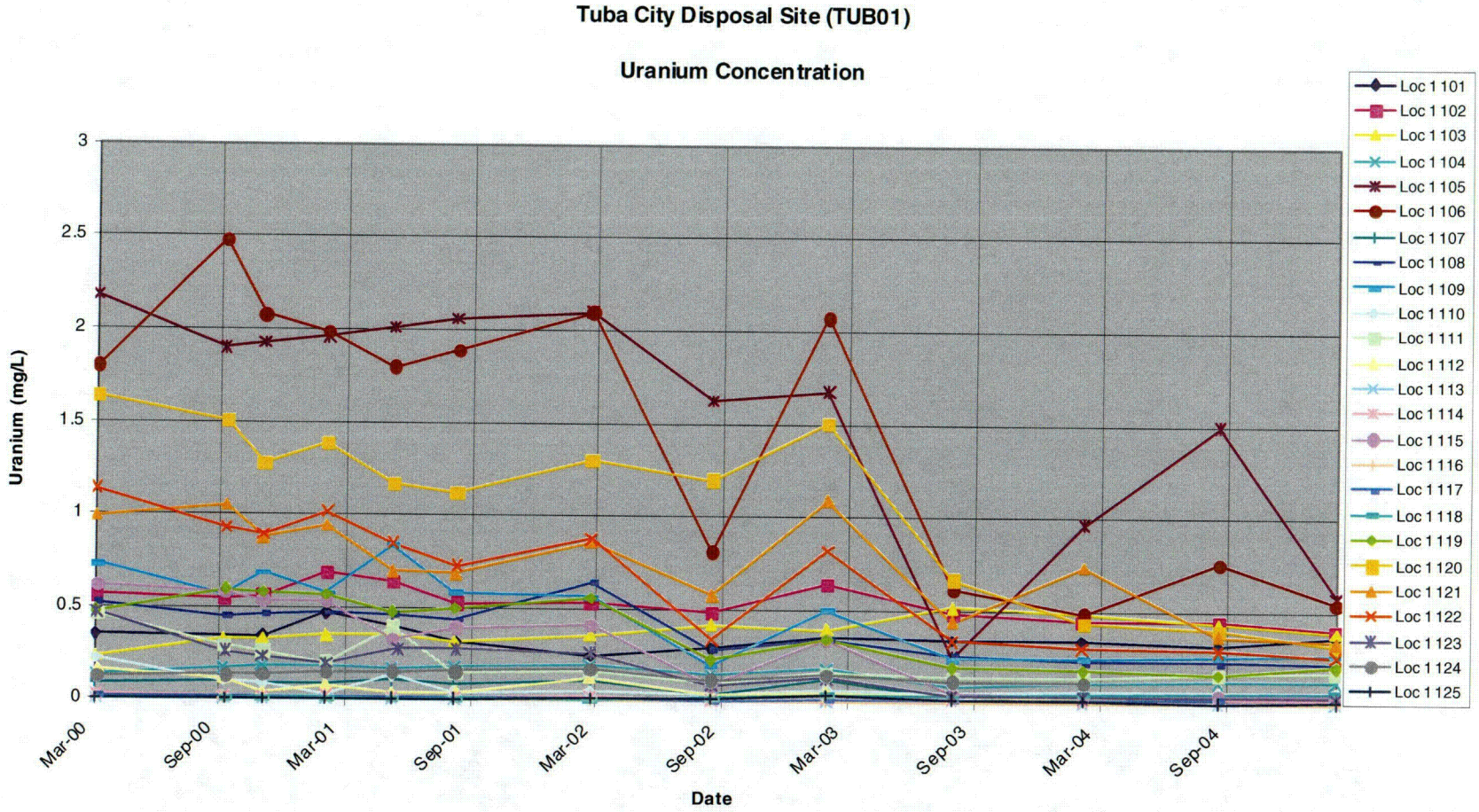

Figure 24. Uranium Concentration Trends at Extraction Wells

C33

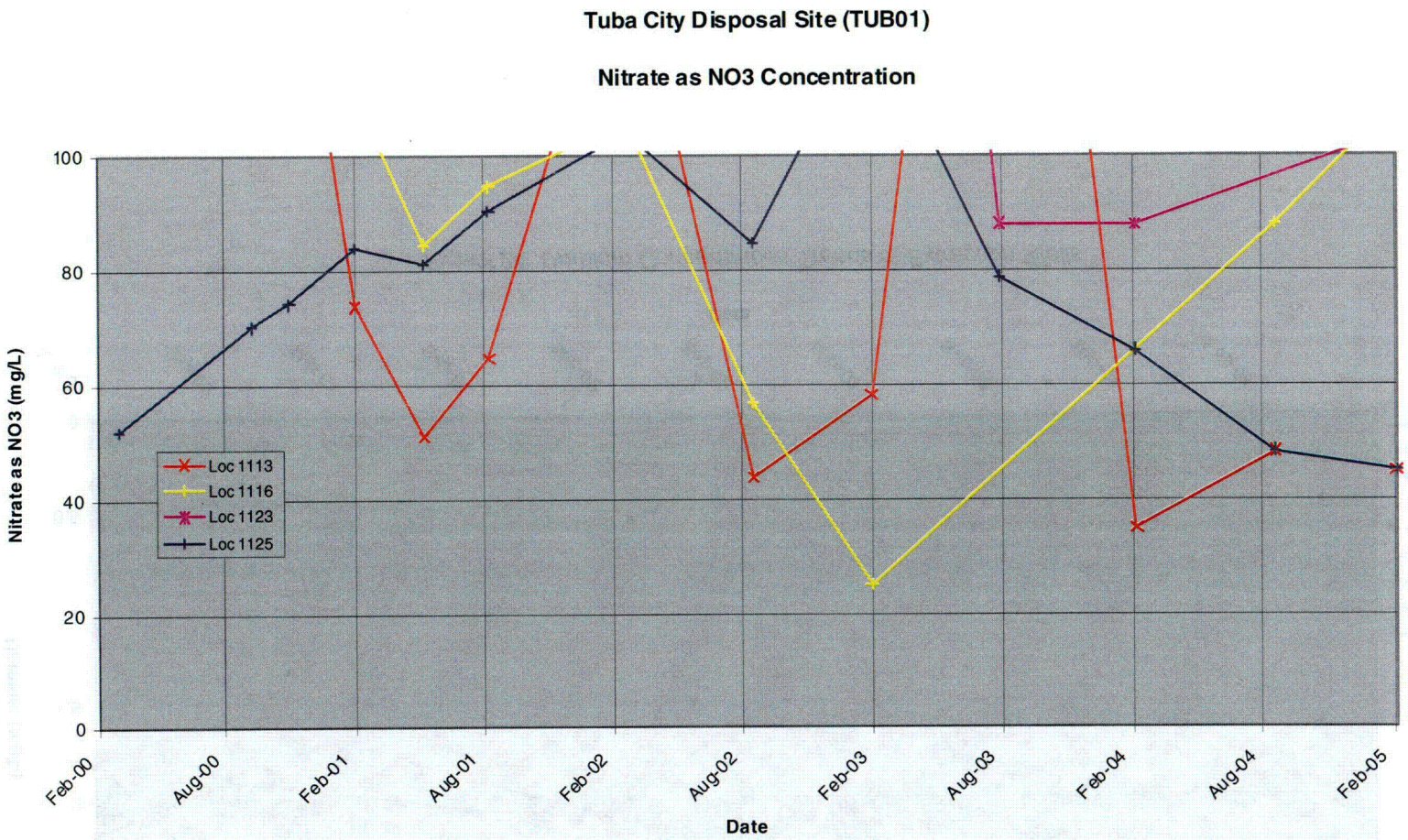

Figure 25. Nitrate Concentrations Trends Near Remediation Standard (44 mg/L as NO_3) at Extraction Wells

C34

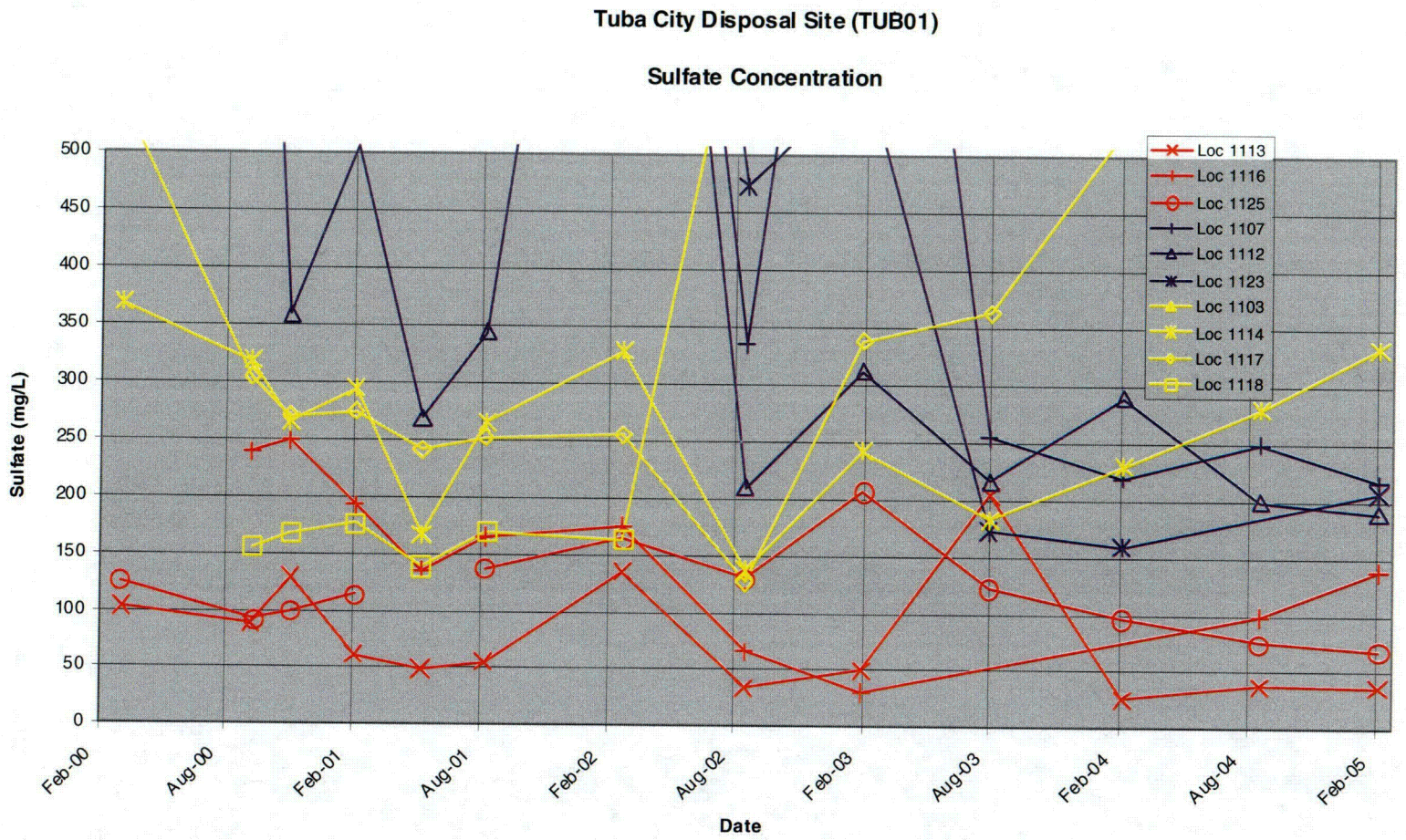

Figure 26. Sulfate Concentrations Trends Near Remediation Standard (250 mg/L) at Extraction Wells

C35

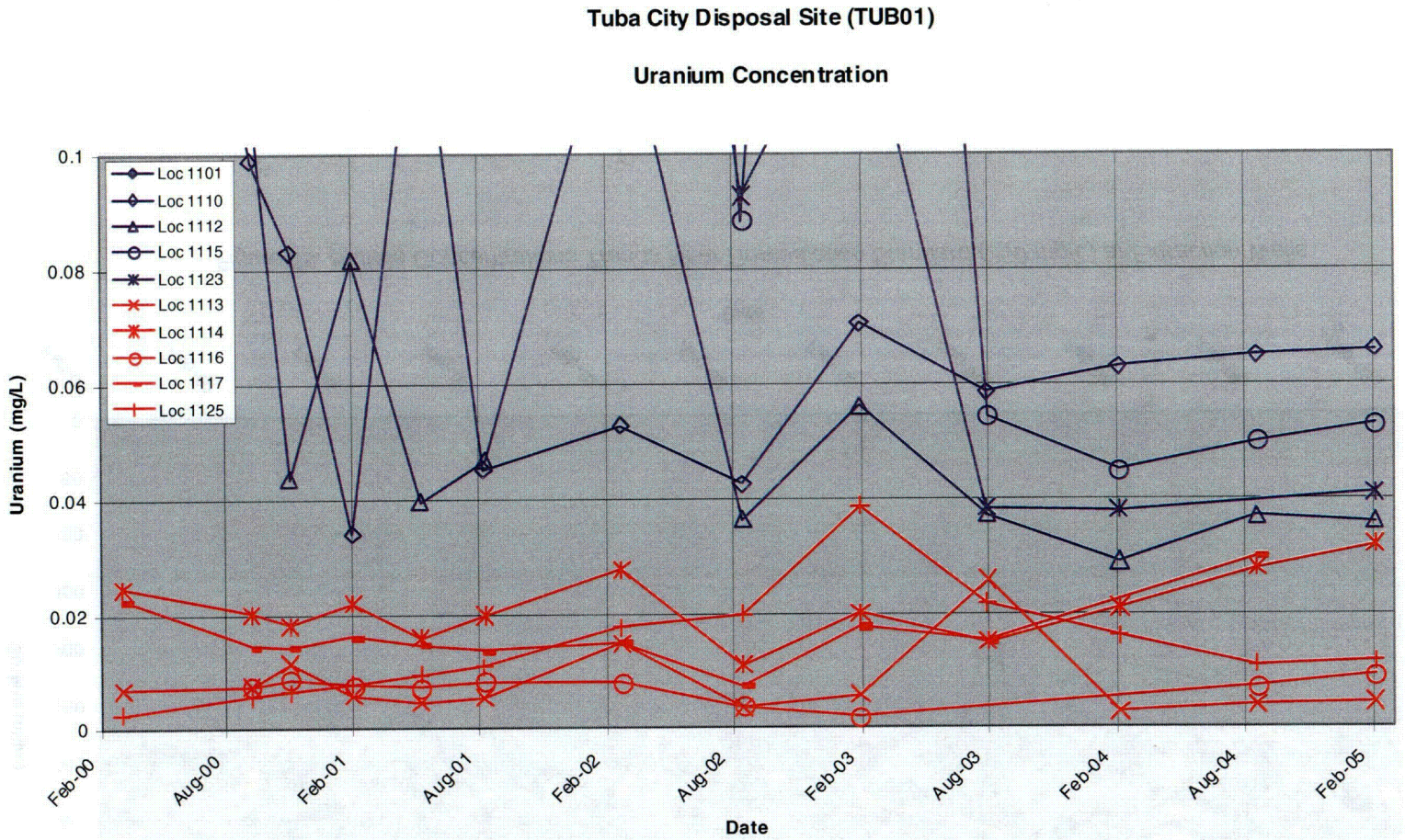

Figure 27. Uranium Concentrations Trends Near Remediation Standard (0.044 mg/L) at Extraction Wells

C36

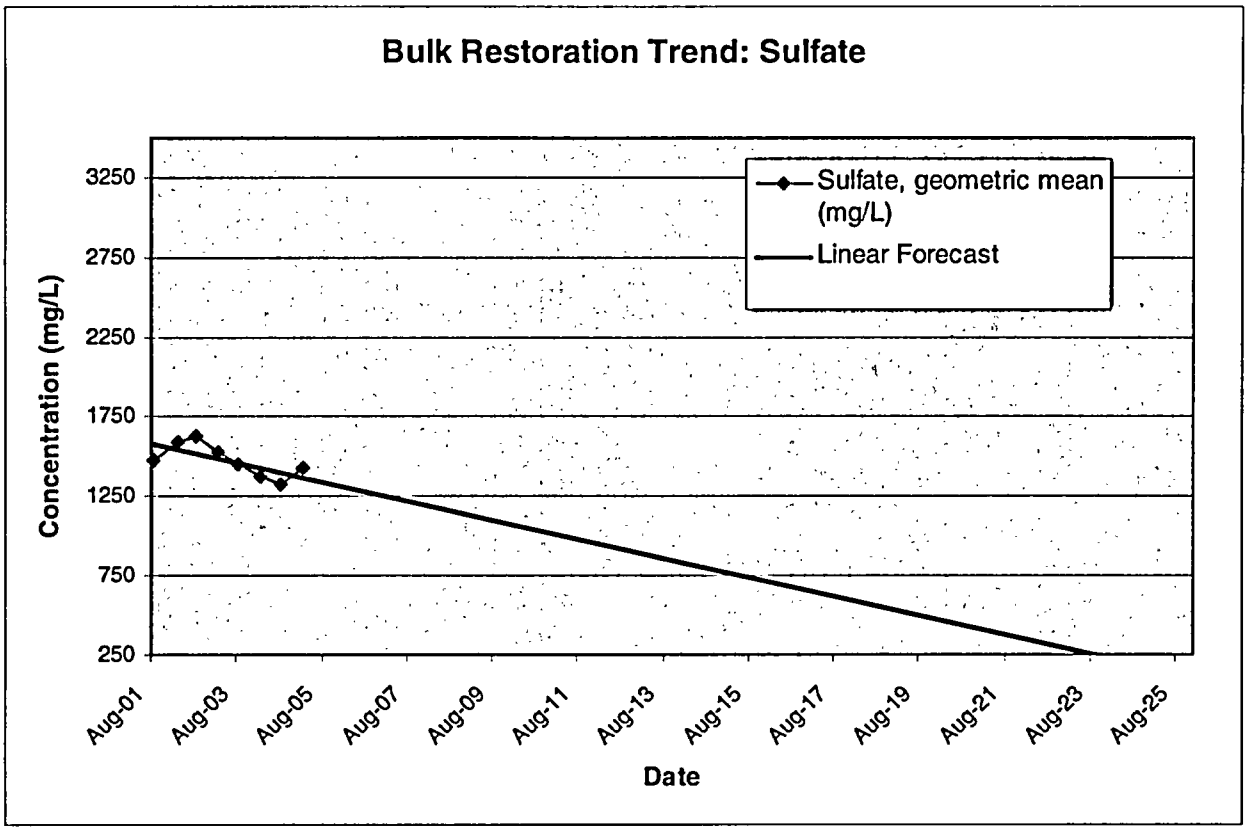

Figure 28. Bulk Restoration Trend for Sulfate

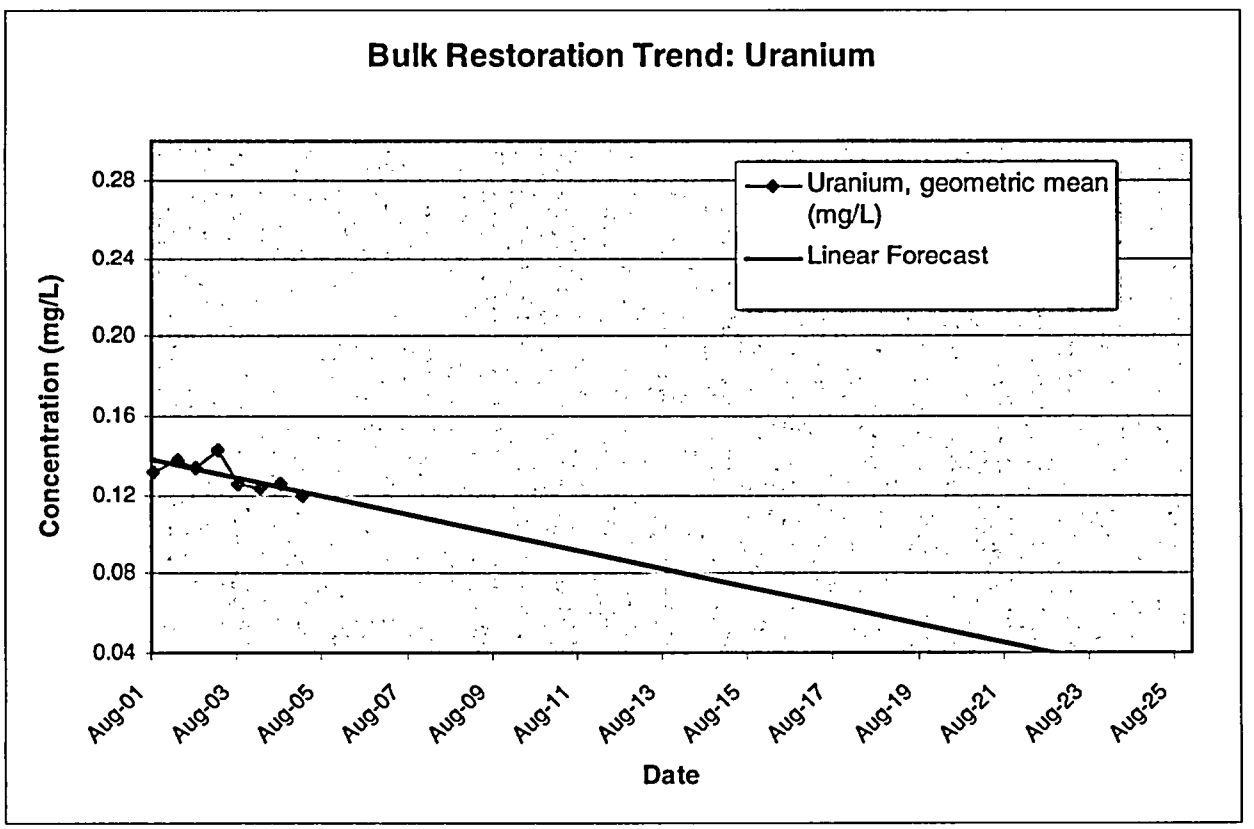

Figure 29. Bulk Restoration Trend for Uranium

End of current text