RIO ALGOM MINING, LLC's AMBROSIA LAKE MILL SITE

DATA COLLECTION WORK PLAN IN SUPPORT OF ADDITIONAL ALTERNATE CONCENTRATION LIMITS

McKinley County, New Mexico

Prepared for:

Rio Algom Mining, LLC

Prepared by:

INTERA
GEOSCIENCE & ENGINEERING SOLUTIONS

6000 Uptown Boulevard NE, Suite 220
Albuquerque, New Mexico 87110

November 27, 2017

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ACRONYMS AND ABBREVIATIONS

ACL	Alternate Concentration Limit
ACL Program	program to collect or obtain site-specific data to address uncertainties in current understanding of certain Site features and data gaps for development of source area models
Alluvial ACL Application	Maxim (2001)
ASTM International	formerly American Society of Testing and Materials
CAP	Corrective Action Program
CSM	Conceptual Site Model
COPC	constituents of potential concern
DO	dissolved oxygen
DOE	Department of Energy, United States
DQA	Data Quality Assessment
DQO	Data Quality Objective
EA	Environmental Assessment
EPA	Environmental Protection Agency, United States
FONSI	Findings of No Significant Impact
ft	foot *or* feet
GPS	Groundwater Protection Standard
INTERA	INTERA Incorporated
JMW	Westwater Canyon Member
KD	Dakota Sandstone
LCS	laboratory control samples
License	NRC Source Material License SUA-1473
LTSM	proposed Long-Term Surveillance and Maintenance boundary
Mill Site	the Rio Algom Mining, LLC, Ambrosia Lake Mill Facility
mg/L	milligrams per liter

ACRONYMS AND ABBREVIATIONS (Continued)

NRC	Nuclear Regulatory Commission, United States
ORP	oxidation reduction potential
PARCC	precision, accuracy, representativeness, completeness, and comparability
POC	point of compliance
POE	point of exposure
PRRL	program-related reporting limits
QA	quality assurance
QAPP	Quality Assurance Plan
QC	quality control
RAML	Rio Algom Mining LLC
RPD	relative percent difference
s.u.	standard units of Ph
SAP	Sampling and Analysis Plan
SAW	Source Area Well
SCM	Surface Complexation Models
SOP	Standard Operating Procedure
TDS	total dissolved solids
TRA	Tres Hermanos A
TRB	Tres Hermanos B
TRC	Tres Hermanos C
Upper Bedrock ACL Application	AVM and AHA (2000)

1.0 INTRODUCTION

INTERA Incorporated (INTERA) has developed this Work Plan as a guide for obtaining site-specific data to be used in developing additional Alternate Concentration Limits (ACLs) for several constituents at the Rio Algom Mining, LLC (RAML), Ambrosia Lake Mill Facility (Mill Site) (**Figure 1**). Additional ACLs will be proposed for constituents that are present in concentrations greater than their respective Groundwater Protection Standards (GPSs) (**Table 1**), as defined in the Nuclear Regulatory Commission (NRC) Source Material License SUA-1473 (the "License"). In this Work Plan, the Mill Site is defined as the historical Mill and related surface ponds and impoundments located within the proposed Long-Term Surveillance and Maintenance (LTSM) Boundary. The proposed LTSM will be finalized at the time of Site transfer to the Department of Energy (DOE).

1.1 Program Objectives

The objectives of this Work Plan (herein referred to as "the ACL Program") are to collect or obtain the following site-specific data to address uncertainties in current understanding of certain Mill Site features:

1. Groundwater quality data for the extent of the source area,
2. Hydrologic data for development of a source area groundwater flow model, and
3. Geochemical data for development and application of the reactive-transport model.

This ACL Program is designed to guide collection and compilation of site-specific data inputs that will be used to inform an ACL application in accordance with 10 CFR Part 40 Appendix A 5(B)6. A list of the requirements set forth in 10 CFR Part 40 Appendix A 5(B)6 is presented in **Table 2** with an index of the section in this Work Plan that addresses each item in the regulation.

Both field and historical data will be collected to inform this ACL Program. The ACL Program is limited to data collection within the proposed LTSM boundary. The study area includes the four hydrostratigraphic units (the alluvium and upper bedrock units, Dakota Sandstone [KD], Tres Hermanos A sandstone [TRA], and the Tres Hermanos B sandstone [TRB]) and enough of the surrounding San Juan Basin to adequately constrain any modeling or characterization efforts. Site-specific data will be collected from proposed and existing groundwater monitoring wells and from the proposed borings, which will include:

- mineralogical data;
- hydrogeologic parameters including the extent of groundwater saturation;
- groundwater chemistry data from source term areas; and

- groundwater chemistry data from unimpacted downgradient areas.

The United States Environmental Protection Agency's (EPA) seven-step data quality objectives (DQOs) process will be employed to facilitate data collection that supports the goals of this study (**Section 4.0** and **Table 3**), identify the boundaries of the study (**Section 4.1**), identify information inputs (**Section 4.2**), establish acceptability criteria (**Section 5.0**), and develop a plan for obtaining site-specific data (**Section 4.3**). This ACL Program includes a description of how site-specific data will be incorporated into groundwater flow and reactive-transport models that will be used to develop ACLs.

1.2 Alternate Concentration Limits

Previous geochemical and hydrologic modeling at the Mill Site and assumptions used to develop the existing ACLs are available in the following documents:

- Corrective Action Plan and ACL for Upper Most Bedrock Units ML003687843 (AVM and AHA, 2000) (Upper Bedrock ACL Application)
- Application for Alternate Concentration Limits for the Alluvial Materials ML011690068 (Maxim, 2001) (Alluvial ACL Application)
- Final Evaluation of Alternate Concentration Limit Applications, Center for Nuclear Waste Regulatory Analyses ML033490556 (Pickett et al., 2003)
- Response to Request for Additional Information- Corrective Action Program and Alternate Concentration Limits Petition for Uppermost Bedrock Units, Ver. 1.1 ML031080523 (RAML, 2003)
- Evaluation of October 16, 2003 Rio Algom Mining LLC, Submittal Regarding Alternate Concentration Limits for the Ambrosia Lake, New Mexico, Mill Tailings Facility. Center for Nuclear Waste Regulatory Analyses (Pickett and Winterle, 2004) (**Appendix A**)
- Response to October 31, 2005 Request for Additional Information ML051990088 (and incorporation of Non-Hazardous ACLs) (Maxim, 2005)
- Environmental Assessment for Amendment of Source Materials License SUA-1473 ML060130097, (NRC, 2006a)
- Technical Evaluation Report Alternate Concentration Limits Application ML060380387 (NRC, 2006b)

The Federal Register notice of availability of the Environmental Assessment (EA) and Finding of No Significant Impact (FONSI) contains a comprehensive list of all related documents and can be found at:

https://www.federalregister.gov/articles/2006/01/27/E6-1036/notice-of-availability-of-environmental-assessment-and-finding-of-no-significant-impact-for-license

The approach adopted during the original ACL process assumed that uranium is the most mobile constituent of potential concern (COPC) and applied the retardation factor for uranium to other COPCs. In low-pH conditions, certain COPCs (e. g. cadmium and radium) can be more mobile than uranium (Smith, 1999); therefore, the approach adopted during the original ACL process will be modified to support the development of additional ACLs for the COPCs listed in **Table 1**. RAML proposes an approach to calculating ACLs that combines elements of the previous NRC-approved approach used to calculate the existing ACLs (Pickett et al., 2003) and reactive-transport models supported by site-specific mineralogical, groundwater chemistry, and source-term data. Highlights of this approach are given here, and a detailed description of the approach is given in **Section 4.2.4**.

Though important information is included in the historical documents leading to the existing ACLs, collection of site-specific data is important to ensure the new ACLs will be protective of human health and the environment at the Point of Exposure (POE). Initially, a simplified reactive-transport model that focuses on pH evolution between the point of compliance (POC) and POE will be produced. This simplified reactive-transport model (or pH-buffering model) will be used to characterize pH evolution along a calculated reactive flow path using site-specific data. With this reactive flow path, additional reactive-transport models will be developed based on surface complexation models (SCM) of COPC sorption to ferrihydrite and additional attenuation processes (as appropriate). The models will be used to develop an attenuation factor for each of the COPCs that will then be used, along with a maximum contaminant level or risk-based concentration for the same COPC, to calculate an ACL.

1.3 Regulatory Setting

RAML's Mill facility, including the groundwater compliance program, is regulated by the NRC Source Material License SUA-1473. The State of New Mexico relinquished its licensing authority over uranium mill activities in 1986. At that time, NRC reasserted jurisdiction at the Mill Site and required a groundwater detection monitoring program. Data from this program were the basis for the GPSs established for the Mill Site by NRC in 1988; a corrective action program (CAP) for the treatment and containment of milling-related impacts to groundwater was also developed based on this information. The CAP required pumping and treating groundwater to maintain a cone of depression, discharge of treated water into the Arroyo del Puerto to create a hydraulic barrier, and capture of seepage from Tailings Impoundments 1 and 2 (Tailings Impoundments) into

interception trenches (AVM and AHA, 2000). RAML implemented the CAP beginning in the mid-1980s. The CAP ceased when the ACL petition was granted in 2006.

Condition 34 of SUA-1473 defines the groundwater compliance monitoring program, identifying wells, frequency of monitoring, and required parameters dependent on the unit in which the well is completed. RAML began monitoring all wells on a quarterly basis starting in 2006, after the ACLs were granted. Semi-annual reports are submitted to NRC on August 1 and February 1 of each year. These semi-annual reports contain results of the groundwater monitoring, groundwater elevation maps for each of the alluvial and upper bedrock aquifers, time versus concentration plots for all ACLs and GPSs, and a description of the work performed during the six-month reporting period. Constituents that have exceeded GPSs are monitored monthly.

A CAP to address GPS exceedances of cadmium and beryllium concentrations in well 36-06 KD was submitted to NRC on January 15, 2007 (RAML, 2007). The CAP proposed monthly monitoring to obtain additional data to evaluate concentrations. Cadmium and beryllium in well 36-06 KD have been monitored monthly since implementation of the groundwater compliance monitoring program. A CAP to address the exceedance of molybdenum in replacement well 32-45 KD-R was proposed in the *Groundwater Stability Monitoring Report for the Second Half 2014* (RAML, 2015a). The CAP proposed monthly monitoring of molybdenum as the replacement well continued to stabilize.

At the time of the Upper Bedrock ACL application (AVM and AHA, 2000), gross alpha, among other constituents, was in exceedance of the GPS. Since ACLs were being proposed for alpha emitters Th-230 and Ra-226, an ACL for gross alpha was deemed unnecessary and duplicative by RAML. The Upper Bedrock ACL application proposed that the GPS for gross alpha be removed from the License as a hazardous constituent in bedrock aquifers and noted that a GPS for gross alpha is unnecessary since the alpha activity hazard is addressed by ACLs for uranium, Th-230, Ra-226, and Pb-210 (which decays to Po-210). Additionally, the *Proposed Groundwater Stability Monitoring Plan* (included in the December 7, 2005, *Response to Request for Additional Information Accession number ML053480214* [RAML, 2005]) does not list gross alpha as a monitoring constituent for any of the bedrock units. In the *Technical Evaluation Report*, which was prepared by the NRC (NRC, 2006b) to document its review of the of the various submittals during the six-year ACL application process, NRC acknowledges that gross alpha was evaluated as a constituent of concern and that the proposed ACLs (including ACLs for radiologic constituents) are appropriate and protective of human health and the environment. ACLs for gross alpha in the upper bedrock units were never proposed by RAML. An ACL for gross alpha in the alluvium was proposed and is listed in the License.

Gross alpha activity has exceeded GPSs in monitoring wells 36-06 KD and 31-02 TRB, and therefore remains a candidate for ACLs in the KD and TRB. These wells are monitored monthly, and results are reported quarterly and semiannually in accordance with the License. Large laboratory uncertainty is observed in the gross alpha results for the upper bedrock units. The analytical method (EPA 900.0) used to measure gross alpha activity in groundwater is sensitive to total dissolved solids (TDS) in groundwater. When TDS concentrations greater than 500 milligrams per liter (mg/L) are present, the sample volume is reduced, increasing laboratory uncertainty associated with the result. These laboratory uncertainties create a range of potential gross alpha results that mask a direct comparison of gross alpha activity to a regulatory standard. These laboratory uncertainties will necessarily be taken into consideration when ACLs for the upper bedrock units are calculated.

2.0 SITE BACKGROUND

This section presents the natural history of the Mill Site. Facility history is described in detail in previously submitted documents.

2.1 Geology

The geology of the Ambrosia Lake area has been described by numerous authors (Stone et al., 1983; Bostick, 1985; Kernodle, 1996). The sedimentary formations of interest in the Ambrosia Lake area are of upper Jurassic to Cretaceous age and include the Morrison Formation, the Dakota Sandstone, and the Mancos Shale. Quaternary alluvium fills in much of the valley (**Figure 2**).

The Westwater Canyon Member (JMW) and the Brushy Basin Member are the two uppermost members of the Morrison Formation. The JMW is present throughout the San Juan Basin at thicknesses that range from about 50 feet (ft) in the southeast corner of the basin to about 300 ft in the southwest-central part of the basin; in the Ambrosia Lake area, the JMW thickness is roughly 200 ft. It consists of locally conglomeratic sandstone interbedded with sandstone, shale, and claystone; the proportion of sandstone and the grain size of the sandstones decrease toward the northeast. The JMW is the uranium ore-bearing unit in Ambrosia Lake area (McLemore, et al., 2005; McLemore, 2007). The JMW is underlain by the Recapture Member of the Morrison Formation, which is a shaley unit and is considered to be an impermeable lower boundary to groundwater flow in the JMW and shallower sandstone units (QMC, 1994). The Brushy Basin Member consists mainly of calcareous and bentonitic claystone and mudstone and functions as an aquitard throughout the basin. It is generally 100 to 200 ft thick in the Ambrosia Lake area.

The KD overlies the Morrison Formation throughout the San Juan Basin. It consists of a basal section of sandstone and conglomeratic sandstone overlain by a middle section of siltstone, shale, and lenticular sandstone beds, and an upper section of fine-grained sandstone interbedded with shale. The KD ranges from 10 to about 500 ft thick and is commonly 200 to 300 ft thick. Its thickness in the Ambrosia Lake area is generally 100 to 300 ft thick.

The main body of the Mancos Shale is present above the KD throughout the San Juan Basin. In the northern part of the basin, the main body of the Mancos Shale is up to 2,300 ft in thickness. The aggregate thickness of the Mancos tongues in the southern part of the basin is about 1,000 ft. The main body of the Mancos is generally 500 to 800 ft thick in the Ambrosia Lake area. Three sandstone beds are found near the bottom of the Mancos Shale, termed the Tres Hermanos (Bostick, 1985). From highest to lowest the three sandstone beds are the TRC, TRB, and the TRA. They are thin (<10 ft), fine-grained sandstones and do not yield much water.

2.2 Hydrogeology

Groundwater flow in the Ambrosia Lake area has been altered by mining activities that first began in the1950s. Characterization of the surface water and groundwater includes descriptions of the natural flow system as well as modification of the natural system by mining activities. The components of the Ambrosia Lake flow system include the following:

- The bedrock and alluvial units through which groundwater flows, and the hydraulic parameters of the flow units, including hydraulic conductivity, storage, and porosity;
- Natural recharge to the bedrock and alluvial flow units; and
- Regional and local hydraulic gradients.

2.2.1 Hydrostratigraphic Units

Groundwater flows through the alluvium derived from weathering of the Mancos Shale and the permeable sandstone units at the Mill Site. The water-bearing units include (from highest to lowest): the alluvium, the TRC, TRB, TRA, sandstones of the lower Mancos Shale, the KD, and the JMW. Groundwater flow in the alluvium and upper bedrock units of the Mancos Shale (Tres Hermanos) was historically very small or non-existent due to limited natural recharge to these units. Groundwater found within these units was most likely from mining-related discharge of water at the ground surface and seepage from the tailings pile.

Numerous faults have been mapped in the Ambrosia Lake area (Santos and Thaden, 1966; Thaden et al., 1967). Fault orientation varies throughout the area, and vertical offsets for many of the faults have been documented. The ability for faults to transmit water either along the fault due to fault-related fracturing, or for faults to limit cross-fault flow has not been documented with site-specific data for faults in the Ambrosia Lake area.

Fracturing of the sandstone units has been documented; however, detailed mapping of fractures and the potential control of fractures on groundwater flow has not been evaluated using site-specific data. That said, based on estimates of relatively low seepage velocity near the LTSM, groundwater flow is more likely matrix controlled and not fracture controlled. Enhanced fracturing of the KD was documented following roof collapses in the underground mine that extended upward through the Brushy Basin into the KD (Ganus, 1980).

Mine dewatering in the JMW has created a cone of depression. Water wells completed in the JMW show lower water levels in the center of the mine area that began to recover once mining dewatering ended in the mid-1980s. It is estimated that water levels in the JMW will take centuries to fully recover (INTERA, 2007).

The alluvium occurs over much of the Ambrosia Lake Valley. It is composed primarily of Mancos Shale-derived sediments, producing soils ranging from clayey sand to sandy clays. The alluvium is stratified and contains occasional basal gravels (Bostick, 1985). The thickness of the alluvium ranges from 0 ft near outcrops up to 70-ft thick in the center of the valley. A paleochannel occurs within the alluvium in the center of the valley, striking roughly parallel to the modern Arroyo del Puerto (Maxim, 2001).

2.2.2 Recharge

The alluvium and upper bedrock units exhibit limited flow. Natural inflows to the alluvium are from direct recharge, primarily during heavy rainfall and surface water flows in arroyos and washes. The amount of recharge to the alluvium from natural recharge is limited due to the intermittent nature of rainfall in the area and the low permeability of the alluvium, given its primary source is the Mancos Shale. Recharge to the underlying bedrock units would be along sparse rock outcrop to the west and southwest. The Tres Hermanos sandstones are relatively thin and embedded in the Mancos Shale. Therefore, natural recharge to outcrop of these units is expected to be very small. A more significant source of recharge to the alluvium and Tres Hermanos may have occurred local to the RAML tailings area and along Arroyo del Puerto, where surface water and mining discharges would migrate into the alluvium and subsequently intercept and recharge subcrops (Kerr-McGee, 1979) of the different upper bedrock units (**Figure 3**). Water levels in these units have been declining since the cessation of mine dewatering to the extent that the alluvium outside the vicinity of the LTSM and downgradient in Arroyo del Puerto alluvium is dry. The KD outcrops over a larger areal extent to the southwest, which allows for higher direct recharge.

2.2.3 Hydraulic Gradient

Regional groundwater flow is generally towards the center of the San Juan Basin to the northeast where water levels are lowest. Mine dewatering in the JMW has modified the hydraulic gradient by forming a cone of depression in the Ambrosia Lake area. This cone of depression has been documented by water levels measured in JMW monitoring locations. Water levels began to recover following the end of mining and mine dewatering in the 1980s; however, pumping of the JMW continued in certain locations until 2006, as part of in-situ leaching operations and the groundwater CAP in the Mill area.

A cone of depression has also formed in the KD due to downward drainage into mine shafts, ventholes, and leach holes that penetrate to the JMW from the ground surface. The limited number of water wells in the KD make it difficult to accurately map the cone of depression; however, declines in KD water levels have been documented near the RAML facilities and the LTSM.

The extent of groundwater flow in the TRA, TRB, and TRC is not well documented. Saturated conditions in these units may be largely due to mine dewatering-related recharge. Groundwater flow is also expected to be diminished due to downward drainage through shafts, ventholes, and leach holes. The existence of groundwater in the alluvium is predominantly due to mine dewatering-related surface discharges and seepage from the tailings. Currently, the only documented saturated alluvium occurs in the vicinity of mine water discharges, including the LTSM and sections south of the Section 35/36 discharge area. Water-level declines in these areas are well documented. Hydraulic gradients would be influenced by mounding near local surface recharges and by the alluvium-Mancos Shale contact, as well as downward drainage along shafts, ventholes, and leach holes.

2.3 Surface Water

There are no natural perennial streams or other surface water bodies in the Ambrosia Lake Valley. Surface water at the Mill Site resulting from mining and milling activities that existed during operations included:

- Ponds and reservoirs,
- Discharge to Arroyo del Puerto and associated man-made channels, and
- Discharge to man-made conveyances used to transfer pumped water from the underground mine to the Mill facility reservoirs.

Water discharge from mine dewatering resulted in surface water flow in portions of Arroyo del Puerto, one of two major surface water drainages in the area (DOE, 1990). Arroyo del Puerto, the principal drainage channel for the Ambrosia Lake area, is an ephemeral tributary of San Mateo Creek. Prior to mining in the area, Arroyo del Puerto was a dry wash, and flow in the creek occurred only in response to significant rainfall events and periods of prolonged snow melt. Currently, there are no mining or milling-related sources of surface water at the Mill Site.

3.0 CONCEPTUAL SITE MODEL

The foundation for a Conceptual Site Model (CSM) is based on known and reasonably ascertainable information regarding past and current site conditions, known and potential contaminant sources and distribution, potential release mechanisms, contaminant exposure pathways and migration routes, and potential receptors. Information of this type, specific to the ACL Program, is presented as part of this Work Plan to provide a basis for the recommended sampling design presented herein and considers the physical system in the region, current land use, and exposure pathways.

Components of the CSM are summarized in **Section 2.0, Site Background**. Additional information regarding contaminant source areas and potential contaminant migration and exposure pathways is summarized in the following subsection.

3.1 Source Area and Contaminant Migration and Exposure

Likely sources of milling-related contamination to groundwater have been identified as tailings ponds, evaporation ponds, and storage ponds. Seepage from ponds entered into the alluvium and the upper bedrock units where the bedrock units subcrop (AVM and AHA, 2000; Maxim, 2001). Historical Ponds 1 and 2 are now referred to as Tailings Impoundments containing milling related byproduct and waste. Other historical ponds located within the proposed LTSM include unlined Ponds 3 through 8 and lined Pond 9, all of which are no longer present. Historical facilities, including ponds, are shown on **Figure 3** with locations of bedrock subcrops (Kerr McGee, 1979). The source of contamination in well 36-06 KD, screened within the KD, has been identified as milling-related liquids that were disposed of in unlined tailings Ponds 7 and 8 (**Figure 4**). The source of molybdenum observed in 32-45 KD-R has not been identified. Historical document review and additional field data may fill this data gap. As concentrations of molybdenum in 32-45KD-R continue to decrease, an ACL for molybdenum may not be necessary.

Based on the location of TRA subcrop, former Ponds 7 and 8 may be a source of milling-related liquids to the TRA; however, the TRA monitoring well network does not provide enough coverage to confirm or rule out this possibility. Liquids were stored in these ponds from the commencement of milling activities in 1961 through 1983, when it was discovered that groundwater in the vicinity was being impacted by seepage from the ponds. Although the ponds are no longer present, how the ponds were reclaimed and whether the source was completely removed are uncertain.

The Tailings Impoundments are the most likely source of milling-related liquids to the alluvium and the TRB, which subcrops beneath the Tailings Impoundments. The former unlined Ponds 4 through 6, which have been reclaimed, may have been a potential source of seepage to the alluvium and/or TRB.

The alluvium and each of the upper bedrock hydrostratigraphic units (KD, TRB, TRA) have an existing monitoring well network (**Figures 4** through **7**). Groundwater is collected and analyzed semiannually as required in the License. These groundwater data can be used to define the areas where contaminants may have migrated; however, what is known about groundwater concentrations is limited to locations where monitoring wells exist. **Section 4.2.1** of this Work Plan describes data collection design in potential source areas.

Surface impacts related to mining discharges are observed in the northern area of the proposed LTSM boundary (**Figure 8**). The extent of surface impact has been characterized using ground-based gamma surveys and surface soil samples.

3.2 Potential Human Receptors and Applicable Exposure Scenarios

The potential for health risks caused by human exposure to waste constituents and the potential damage to wildlife, crops, vegetation, and physical structures caused by exposure to waste constituents will be evaluated through review of historical documents, review of the socioeconomic outlook for the Mill Site area, and risk evaluation. Current and future uses for groundwater and surface water will be evaluated to best characterize risks for exposure.

An exposure assessment is a required component of an ACL application (NUREG 1620). Concentrations in groundwater at the POE must be at or below acceptable standards for human health using an appropriate exposure scenario.

The five elements of an exposure pathway are as follows:

1. Source of contamination into the environment
2. Environmental transport medium for the released constituents (e.g., air, water, soil)
3. Point of potential human contact with the affected medium (POE)
4. Human exposure route (e.g., inhalation, ingestion, or dermal contact)
5. Potential human receptor at the POE

All five of these elements must be present to consider a pathway complete. Although there is currently no exposure pathway or human receptor at the POE, to be conservative, a human receptor at the POE will be assumed for the exposure scenario.

The historical Ponds 7 and 8 and surface reclamation work related to those ponds have been identified as the likely source of elevated beryllium and cadmium concentrations in monitoring well 36-06 KD. The transport medium for the released constituents is groundwater. The proposed POE is the LTSM boundary as presented on **Figure 1**. The location of the LTSM boundary will be finalized at the time of Mill Site transfer to DOE. Once finalized, the LTSM boundary will be

an institutional control managed by DOE that strictly limits access and future use of the land in perpetuity. The proposed LTSM boundary prevents humans from developing the land in any way that would provide an exposure route (e.g., installing a drinking water well and/or living on the land). Furthermore, groundwater in the upper bedrock and alluvial hydrostratigraphic units does not naturally discharge to the surface at or near the proposed LTSM boundary. Since there is no exposure route and no potential human receptors at the POE (the proposed LTSM boundary), the exposure pathway is incomplete. To be conservative, however, an exposure pathway for a human receptor will be assumed at the POE.

4.0 ACL FIELD PROGRAM

Site-specific data are required to inform the flow and transport models that will be used to develop ACLs. This section presents the study area (**Table 3, Step 4**) and data collection design and rationale (**Table 3, Step 5**).

4.1 Study Area

The study boundary includes the alluvium and upper bedrock units (KD, TRB, TRA) within the proposed LTSM, and enough of the surrounding San Juan Basin to adequately constrain initial and boundary conditions in the groundwater flow and transport models. Study areas within the proposed LTSM include the following:

- Downgradient LTSM boundary to represent the POE,
- Tailings Impoundments 1 and 2, and
- Unlined ponds 3 through 8.

4.2 Data Collection Design, Rationale, and Methods

Field data collection will serve to reduce uncertainty associated with data gaps in the current source-area CSM. Data collection rationale (**Table 3, Step 5**) has been designed to address the four main goals of the study:

1. Characterize the Source(s)
2. Update the CSM
3. Develop and apply a groundwater flow model based on the CSM
4. Develop and apply a solute transport model based on the groundwater flow model

Meeting these goals will provide RAML with constituent-specific attenuation factors supported by site-specific data. These attenuation factors will be used with maximum contamination limits or human health risk-based values to calculate proposed ACL values that will be developed using industry standard technology supported by site-specific data inputs. The existing CSM will be updated as the groundwater flow model and solute transport models evolve.

4.2.1 Characterizing the Source(s)

Potential milling-related source areas vary for each aquifer. The geochemical evaluation of source areas will be performed through a drilling and sampling program designed to characterize the chemistry of porewaters, mineralogy, the geochemistry and mineralogy of tailings solids, and/or the chemistry of nearby impacted wells. Where possible, the source may be sampled. A suitable substitute may be used, however, if the original source has been reclaimed, cannot be sampled due

to regulatory restrictions, or is otherwise inaccessible. Note that all ponds have been reclaimed and are no longer in service, although details surrounding reclamation and complete removal of sources are not available at this time.

Former Ponds 7 and 8 have been identified as a source of impacts to the KD Sandstone (AVM and AHA, 2000). Monitoring well 36-06 KD is about 800 ft downgradient from the ponds and is the most impacted groundwater monitoring well in the KD based on the existing monitoring well network. Due to the proximity of well 36-06 KD to the source, it has been designated the POC well (AVM and AHA, 2000; SUA-1473). The Dakota subcrops beneath the alluvium just south of the location of Ponds 7 and 8 and dips to the north, which likely provided a pathway for liquids from these ponds to enter the KD (**Figure 4**). North of Ponds 7 and 8, the Mancos Formation acts as an aquitard between the Dakota and stratigraphically higher units, limiting communication between the KD and the TRA and TRB. The input to define the source term for the KD will be groundwater data from 36-06 KD or a proposed adjacent source area well (SAW) (36-07 SAW) since Ponds 7 and 8 have been reclaimed.

Based on the location of TRA subcrop, Ponds 7 and 8 may also be a source of milling-related liquids to the TRA; however, the TRA monitoring well network does not provide enough coverage to confirm or rule out this possibility (**Figure 6**). The nearest TRA monitoring well, POC well 31-01 TRA-R, is nearly one mile downgradient at the northern end of the Tailings Impoundments. Although 31-01 TRA-R has been designated a POC well (AVM and AHA, 2000; SUA-1473), there is no potential source in the immediate vicinity, as the Tailings Impoundments and the TRA are separated by the Mancos Shale. The TRA monitoring program is comprised of three wells (**Figure 6**):

- MW 31-01 TRA-R;
- MW 33-01 TRA, which is cross-gradient from the LTSM; and
- MW 30-01 TRA, which is located in an area where the TRA is dry.

Analytical data from proposed MW 36-08 (TRA-SAW) will be used to evaluate the potential of impacts from Ponds 7 and 8 to the TRA (**Figure 6**).

Ponds 1 and 2, now referred to as the Tailings Impoundments, are a potential source of impacts to the TRB. The TRB subcrops beneath the southern half of the Tailings Impoundments (**Figure 5**). The TRB also subcrops beneath Pond 9, but Pond 9 was lined prior to installation, reducing the likelihood of Pond 9 as a potential source.

Potential sources of mill-impacted water to the alluvium include the Tailings Impoundments and former Ponds 3 through 8. The most significant alluvial impacts have been observed at the eastern

edge of Pond 3, suggesting that the Tailings Impoundments are contributors of impacts to the alluvium. The Tailings Impoundments and Pond 3 will be evaluated as potential sources of mill-related impacts to the TRB and alluvium (**Figure 7**).

The source terms may be evaluated using historical records, data obtained through source area characterization activities, and/or analytical data from the most impacted POC wells.

4.2.2 Proposed Monitoring and Sampling Locations

Seven new wells will be installed to support the ACL Program and long-term monitoring of groundwater to facilitate transfer to DOE (**Figure 9** and **Table 4**). These locations include SAWs in the KD and TRA, a well at the POE for each of the units (KD, TRB, TRA, alluvium), and one well to characterize the pH-impacted portions of the KD (**Figure 4** and **Table 4**). Three KD borings will penetrate the alluvium, TRB, TRA, and KD during drilling. These three locations will be cored prior to well installation, allowing for sampling of the alluvium and all three upper bedrock units from each boring.

4.2.2.1 Source Area Wells

SAWs are proposed to identify whether groundwater is present and to characterize the source terms for each unit. Potential source areas are identified on **Figure 3**. Existing wells MW 31-61 ALL, 36-06 KD, and 31-02 TRB-R fulfill the SAW role for the alluvium, KD, and TRB, respectively. Two proposed SAWs will be installed adjacent to the former Ponds 7 and 8; one in the TRA (36-08 TRA) and one in the KD (36-07 KD), near the existing POC well 36-06 KD. The proposed TRA SAW well will be used to determine the presence and quality of groundwater in the TRA near Ponds 7 and 8. The KD SAW well will be used to characterize the KD source term, provide a well of known quality for aquifer testing, allow evaluation of the quality of 36-06 KD by comparison, and provide a source for rock cores.

4.2.2.2 pH Investigation Wells

The proposed pH investigation well, tentatively named 36-09 KD, will support the evaluation of the evolution of pH from 36-06 KD downgradient along the flow path. Reactive-transport modeling is sensitive to pH conditions in the KD along the flow path between the source, Ponds 7 and 8, and the northern edge of the LTSM. The pH at monitoring well 36-06 KD, near the source, ranges from 3 to 4 pH standard units (s.u.), while downgradient wells contain circumneutral groundwater. Nearly one mile separates 36-06 KD and the nearest downgradient monitoring well 30-48 KD-R (**Figure 4**). The approximate location of the proposed pH investigation well based on the current understanding of Site conditions is shown on **Figure 4**. The location of this well may change based on two criteria: 1) the minimum reaction pathway required to produce ACLs that are protective of human health and the environment, and 2) a conceptual model of pH migration that

is currently being developed. Monitoring well names are subject to change based on the final location of the wells in order to adhere to the existing RAML monitoring well naming conventions.

4.2.2.3 Direct-Push Investigation

Four direct-push borings will be advanced into the alluvium along the southern edge of the LTSM to determine whether groundwater is present in the alluvium at the proposed LTSM boundary (**Figure 7**). The results of the direct-push investigation will also be used determine the precise location for a well located near the alluvial POE.

4.2.2.4 Points of Exposure

The proposed POE at the Mill Site is the proposed LTSM boundary, downgradient of the source(s), in each hydrostratigraphic unit. The proposed POE for the KD, TRB, and TRA is the north-northeastern boundary of the proposed LTSM. The proposed POE for the alluvium is the southeastern boundary of the proposed LTSM. In accordance with the License #34D, RAML has been submitting hydrographs for the downgradient-most POC well in the Semiannual Groundwater Stability Monitoring Report. The downgradient POC wells have been acting as *de facto* POE wells; however, there are no wells located at the POE in any of the hydrostratigraphic units. Wells at the POE are important to determining whether COPCs are attenuated prior to reaching the POE/LTSM. Four wells will be installed at the POE (**Figures 4** through **7**). The alluvial well at the POE (5-09 ALL) will be installed on the southeastern edge of the proposed LTSM boundary near the Arroyo del Puerto if alluvial groundwater is found during the direct push investigation. Alluvial groundwater flows to the southeast in the Ambrosia Lake Valley, parallel to the modern Arroyo del Puerto surface drainage. Wells at the POE for the upper bedrock units (30-05 TRA, 30-06 TRB, and 30-07 KD) will be placed near the northern boundary of the proposed LTSM, as groundwater flows down dip to the north-northeast in the upper bedrock units.

The proposed LTSM boundary incorporates and is adjacent to areas impacted by mining. In particular, surface impacts believed to be related to mining discharges are observed in the northern area of the proposed LTSM boundary (**Figure 8**). The extent of surface impact has been characterized using ground-based gamma surveys and surface soil samples. Locations of proposed upper bedrock wells near the proposed POE have been identified to avoid surface impact areas and may be modified if potential impacts extend into the proposed locations.

4.2.3 Inputs to the Groundwater Flow Model

Based on available data, groundwater flow in the KD is considered to be fairly uniform in the vicinity of the LTSM with little, if any, vertical flow. Site-specific data collected during the ACL Program will be used to support this hypothesis. Given the relatively short travel distances being evaluated within the LTSM, along with a uniform flow field, a one-dimensional flow model is suitable. A one-dimensional flow model will be developed based on Darcy's Law. Calculation of

Darcy flux requires estimation of hydraulic conductivity and hydraulic gradient. Hydraulic conductivity will be estimated using pneumatic aquifer testing methods. Well testing procedures are described in **Appendix B**. Pneumatic tests are preferable to traditional pumping or slug tests at the Mill Site because they do not require that a pump be installed, and they do not result in any produced water. Pneumatic aquifer testing requires the water column to extend above the top of the screened interval. If wells in the upper bedrock units do not contain an adequate water column, other methods of aquifer testing (e.g. traditional slug tests) may be used. The hydraulic gradient will be determined from measured water levels in wells at the Mill Site.

The velocity of dissolved constituents through the aquifer, the seepage velocity, is required for use in the transport model. The seepage velocity is calculated from Darcy flux divided by the aquifer porosity. Porosity will be measured from core samples taken from cores collected at the Mill Site.

4.2.4 Inputs to the Reactive-Transport Model

Site-specific data will be obtained through the collection of core from new borings, groundwater samples from new monitoring wells, and groundwater samples from existing monitoring wells as described in **Section 4.3.1**. Reactive-transport models will be used in an updated approach to calculating the ACLs. This updated modeling approach will combine elements of the previously used models and reactive-transport models supported by the site-specific data inputs.

Coring near the POC (adjacent to 36-06 KD) and at the POE will allow for assessment of the mineralogy of the KD. An additional KD monitoring well will be installed between the POC and POE, allowing for evaluation of the pH plume model and further refinement of this approach **(Figure 4, Table 4)**.

The data inputs that will be used to calculate ACLs are outlined as follows:

- Site-specific mineralogy and groundwater pH will be used to develop a pH-buffering model that will predict pH changes between the POC and POE for units with large pH gradients, considering only the pH-buffering reactions likely to occur.
- The pH-buffering model will be used to estimate the length of the flow path over which elevated pH and enhanced COPC attenuation would occur (i.e., the reaction length).
- The resulting reaction length will then be used with mineralogy and groundwater chemistry data from the source area in a sorption surface complexation model with ferrihydrite to predict COPC concentrations between the POC and POE.
- Accounting for sorption alone may be adequate to calculate ACLs for some COPCs. These ACLs will be calculated by combining elements of both reactive-transport and the NRC-approved approach used to calculate ACLs.

For other COPCs, it may be necessary to account for additional geochemical processes (e.g., mineral precipitation/dissolution, coprecipitation, ion exchange, etc.) to calculate ACLs. Additional geochemical processes will be added to the reactive-transport model as needed.

4.3 Field Activities and Sampling Methods

Field activities and sampling methods have been identified in a plan for obtaining data (**Table 3, Step 7**). Field activities will be performed in accordance with the Site-Specific Health and Safety Plan and the Site Radiation Program. To assure that ACL Program objectives can be achieved (**Section 1.1**), all field activities performed and samples collected must be completed using approved industry-standard sampling methods and guidance. This is typically achieved through field personnel training and use of applicable Standard Operating Procedures (SOPs) and/or American Society for Testing and Materials (ASTM, now ASTM International) standard methods. **Appendix C** contains SOPs for data collection.

4.3.1 Installation of Borings and/or Monitoring Wells

Installation of borings and monitoring wells is planned to collect site-specific geochemical data to address the goals of this study. Drilling, core collection, and installation of monitoring wells will follow ASTM guidelines ASTM D6286-12 and ASTM D5092-16 (ASTM, 2012, 2016b) and INTERA SOP-07 (**Appendix C**; INTERA, 2015b). Well development will be performed per ASTM D5521M-13 (ASTM, 2016a) and INTERA SOP-08 (**Appendix C**; INTERA, 2015c). Typical monitoring well development practices include removing three casing volumes of groundwater plus additional volume to account for any fluids added during the drilling process.

4.3.2 Groundwater Sampling Methods

Groundwater sampling will be performed per the methods defined in the Sampling and Analysis Plan (SAP) (INTERA, 2015a) and *Standard Operating Procedure for Groundwater Sampling* (RAML, 2015b). Dedicated bladder pumps will be installed in each of the new wells, provided they contain adequate water for sampling. If adequate water is not present, bailers or portable electric sampling pumps may be used.

4.3.2.1 Field Quality Control Samples

Duplicate groundwater samples will be collected and submitted to the laboratory with the primary samples. The duplicates will be analyzed for the same parameters as the primary samples. The association of a duplicate sample with a primary sample will be recorded on the sample form and in the field notes, but the duplicate will bear a sample identity different than the identity of the primary sample. Duplicates will be collected at a rate of one duplicate per 20 samples, rounded up (INTERA, 2015a).

Equipment rinsate samples will be collected for any groundwater sampling method that requires the decontamination and reuse of primary sampling equipment. Rinsates are currently collected from the following pieces of equipment during any sampling event in which they are used:

- The pump-head adapter for any well sampled via a dedicated, electric submersible pump.
- Any portable, submersible pump which is decontaminated between uses. Examples include the GeoSub and Monsoon electric submersible pumps.

If any additional portable sampling equipment (e.g., a reusable bailer) is used, an equipment rinsate sample will be collected during that event for which the equipment is used.

4.3.3 Core Sampling Methods

Core will be collected from each of the hydrostratigraphic units from each of the three borings into the KD (**Figure 4**). Core samples will be split lengthwise, logged by a field geologist, and photographed prior to subsampling (ASTM D2113-14). Cores may be stored in core boxes if storage facilities are available on-site. A minimum of one subsample will be collected from each of the hydrostratigraphic units at each boring location to characterize the spatial heterogeneity within each aquifer. More samples may be collected to better characterize the vertical heterogeneity at each boring. Changes in grain size, mineralogy, or structure may justify the collection of multiple samples from a single core from a single hydrostratigraphic unit. Cores will be stored on-site, and samples from the cores will be shipped to the analytical laboratory for analysis.

4.3.4 Hydraulic testing

Hydraulic testing will be performed on up to three wells per aquifer to allow for observation of spatial variation in aquifer parameters. All proposed wells installed as part of this ACL Program will be constructed to meet the criteria for pneumatic sinusoidal aquifer testing; however, if a well does not contain enough water, other methods of aquifer testing (e.g. traditional slug tests) that are more appropriate to the well or aquifer conditions may be used. Monitoring wells will be identified for hydraulic testing after the proposed wells have been installed; based on location, proximity to other wells, amount of water column present, and other factors identified during installation and development.

5.0 ANALYTICAL PROGRAM

The ACL Program will generate groundwater and rock samples that will be analyzed by analytical laboratories. The types and amounts of samples are described in the following subsections.

5.1 Groundwater Chemistry

Groundwater samples collected from monitoring wells will be analyzed by ACZ Laboratories in Steamboat Springs, Colorado, or a laboratory with similar accreditations and capabilities, for the NRC parameter suites appropriate to each aquifer as listed in Condition 34 of SUA-1473 (**Table 5**). Additional analyses beyond the NRC parameter suites will be performed to support geochemical modeling. Oxidation-reduction potential (ORP) measurements combined with dissolved oxygen (DO), iron redox species, and sulfur redox species can be useful for evaluating the redox conditions at a given sampling site. Redox conditions have important implications for COPC mobility. These data are also useful as geochemical modeling inputs. Routine measurement of ORP and DO will continue, and in-field measurement of iron and sulfur redox species using a portable colorimeter will be added to the ACL Program. These additional measurements will be included as part of the ACL Program, but not necessarily as part of the routine SAP at the Mill Site, as outlined by the License.

5.2 Solid Chemistry

Chemical analysis of the cores will be performed by ACZ Laboratories or a comparable laboratory with appropriate certifications for New Mexico. Separate aliquots of each core sample will be subject to EPA Method 3052 extraction (EPA, 1996) and Steps 1 through 4 (**Table 6**) of the step-wise extraction for iron phases (Dold, 2003a; Dold, 2003b). The solution generated from EPA method 3052 will be analyzed for the metals and radionuclide component of the appropriate analytical suite. The step-wise extraction leachates will be analyzed for iron and other metal concentrations to characterize the presence of solid phases, such as ferrihydrite, that may host COPCs in each hydrostratigraphic unit. Acid-base accounting and porosity of core samples will be measured using EPA 600/2-7-054 3.2.2.

Mineralogical analysis of all collected core samples will be performed using quantitative X-ray diffraction by Hazen Research, Inc., in Golden, Colorado.

5.3 Laboratory Performance Criteria

All laboratory analytical results will be evaluated in accordance with precision, accuracy, representativeness, completeness, and comparability (PARCC) parameters to document the quality of the data and promote data that are of sufficient quality to meet ACL Program objectives as defined in the SAP (INTERA, 2015a). With regard to these PARCC parameters, precision and

accuracy method blanks will be prepared at the frequency prescribed in the individual analytical method.

Precision

Precision is the degree of mutual agreement between individual measurements of the same property under similar conditions. Usually, combined field and laboratory precision is evaluated by collecting and analyzing duplicate samples and then calculating the variance between the samples, typically as a relative percent difference (RPD).

[Equation 1]

$$RPD = \left| \frac{A - B}{\frac{A + B}{2}} \right| * 100\%$$

where:

A = primary sample concentration
B = duplicate sample concentration

Field sampling precision is evaluated by laboratory analysis of duplicate samples. Duplicate groundwater samples will be collected as part of the ACL program in accordance with the SAP.

Laboratory analytical precision is evaluated by analyzing matrix (laboratory) duplicates. Results for each laboratory duplicate pair will be used to determine the RPD in order to evaluate precision.

Accuracy

A program of sample spiking will be conducted to evaluate laboratory accuracy. This program will include analysis of laboratory control samples (LCS) or blank spikes, and method blanks. LCSs or blank spikes will also be analyzed at a frequency of 5%.

The results for the spiked samples will be used to calculate the percent recovery for use in evaluating accuracy.

[Equation 2]

$$Percent\ Recovery = \frac{S-C}{T} * 100\%$$

where:

S = Measured spike sample concentration
C = Sample concentration
T = True or actual concentration of the spike

The analytical laboratory's Quality Assurance Plan (QAP) presents accuracy goals for groundwater samples on the percent recovery of matrix spikes and LCSs. Results that fall outside the accuracy goals will be further evaluated on the basis of the results of other quality control (QC) samples.

Representativeness

Representativeness expresses the degree to which sample data accurately and precisely represent 1) the characteristics of a population, 2) variations in a parameter at a sampling point, or 3) an environmental condition they are intended to represent. For this ACL Program, representative data will be obtained through careful selection of sampling locations and analytical parameters. Representative data will also be obtained through proper collection and handling of samples to avoid interference and minimize contamination.

Representativeness of data will also be promoted through the consistent application of established field and laboratory procedures. Equipment rinsate blanks and laboratory blanks will be evaluated for the presence of contaminants to aid in evaluating the representativeness of sample results. Data determined to be non-representative by comparison with existing data will be used only if accompanied by appropriate qualifiers.

Completeness

Completeness is a measure of the percentage of ACL Program-specific data that are valid. Valid data will be obtained when samples are collected and analyzed in accordance with QC procedures outlined in the SAP and when none of the QC criteria that affect data usability are exceeded. When all data evaluation is completed, a percent completeness value can be calculated by dividing the number of useable sample results by the total number of sample results planned for the ACL Program.

As discussed further in **Section 8**, completeness will also be evaluated as part of the data quality assessment (DQA) process. This evaluation will help assess whether any limitations are associated with the decisions to be made based on the data collected.

Comparability

Comparability expresses the confidence with which one data set can be compared with another. Comparability of data will be achieved by consistently following standard field and laboratory SOPs as identified in this Work Plan and by using standard measurement units in reporting analytical data.

Program-related reporting limits (PRRLs) are contractually specified minimum quantitation limits for specific analytical methods and sample matrices. PRRLs are set to establish minimum criteria for laboratory performance. Actual laboratory quantitation limits may be substantially lower. This procedure is adopted to help ensure that analytical results can be effectively compared with screening levels for certain compounds where the PRRL is near or below the level. This procedure also will help to ensure that subsequent statistical evaluations of the data will not be biased by high-value non-detect results.

6.0 DATA MANAGEMENT, EVALUATION, AND USABILITY

Review and evaluation of data generated during field activities, and laboratory analysis are essential to obtaining defensible data of acceptable quality to meet ACL Program objectives. All data obtained as part of the ACL Program will be assessed for completeness, as well as inconsistent or anomalous values. Any inconsistencies discovered will be resolved as soon as possible by seeking clarification from either field personnel responsible for data collection or laboratory personnel responsible for analytical analysis. All field personnel will be responsible for following the sampling and documentation procedures described in the SAP (INTERA, 2015a) so that defensible and justifiable data are obtained. All laboratory personnel are responsible for following the sampling and documentation procedures described in the associated laboratory QAP.

Field data will be recorded in the logbook and/or field forms and shall be made available for review upon request. All completed field forms and ACL Program logbooks will be filed at the INTERA office.

Analytical data will be tabulated and uploaded electronically into the RAML database. Original laboratory data will be filed at the INTERA office and shall be made available for review upon request.

7.0 ASSESSMENT, OVERSIGHT, AND REPORTS TO MANAGEMENT

INTERA is responsible for the oversight of environmental data collection using appropriate assessment and audit activities. Any problems encountered during an assessment of field investigation or laboratory activities will require appropriate corrective action to ensure that the problems are resolved.

Effective management of environmental data collection requires 1) timely assessment and review of all activities and 2) open communication, interaction, and feedback among all project participants. Effective communication may be achieved through verbal and electronic venues, whichever is most appropriate to facilitate the timely communication of a quality issue requiring reconciliation.

8.0 RECONCILIATION WITH USER REQUIREMENTS

After data have been reviewed and evaluated in accordance with the procedures described in this ACL Program, data must be further evaluated to assess whether the ACL Program DQOs have been met.

To the extent practicable, INTERA will follow EPA's DQA process to verify that the type, quality, and quantity of data collected are appropriate for their intended use (EPA, 2006). The DQA process includes five steps: 1) review the DQOs and sampling design, 2) conduct a preliminary data review, 3) select a statistical test, 4) verify the assumptions of the statistical test, and 5) draw conclusions from the data.

INTERA will also complete a systematic assessment of data quality and data usability for the ACL Program that includes the following:

- review of the sampling design and sampling methods to verify that these were implemented as planned and are adequate to support ACL Program objectives,
- review of ACL Program-specific data quality indicators for PARCC and laboratory data reporting limits to evaluate whether acceptance criteria have been met,
- review of ACL Program-specific DQOs to assess whether they have been achieved by the data collected, and
- evaluation of any limitations associated with the decisions to be made based on the data collected (for example, if data completeness is only 90% compared to a project-specific completeness objective of 95%, the data may still be usable to support a decision, but at a lower level of confidence).

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FIGURES

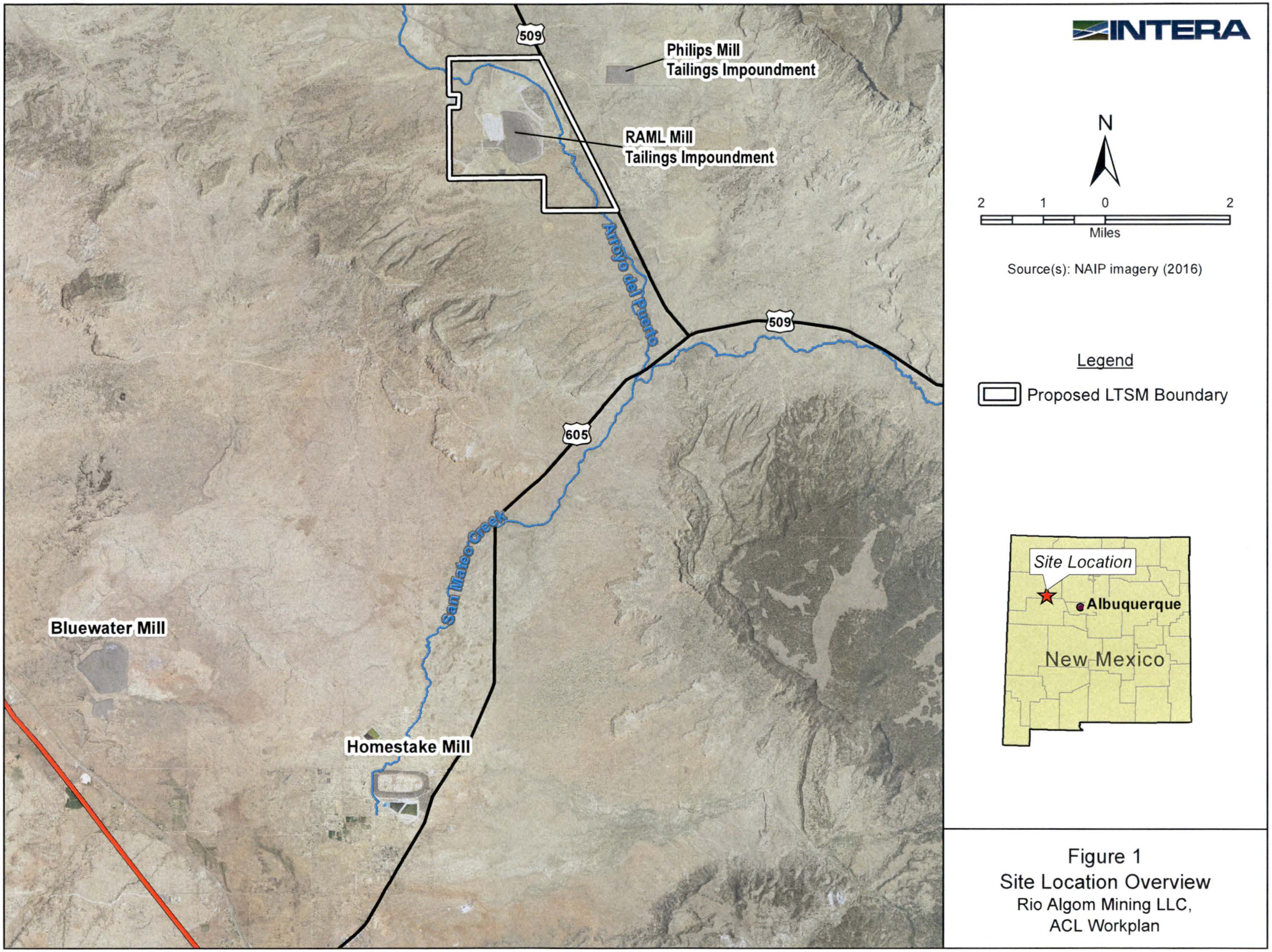

Figure 1
Site Location Overview
Rio Algom Mining LLC,
ACL Workplan

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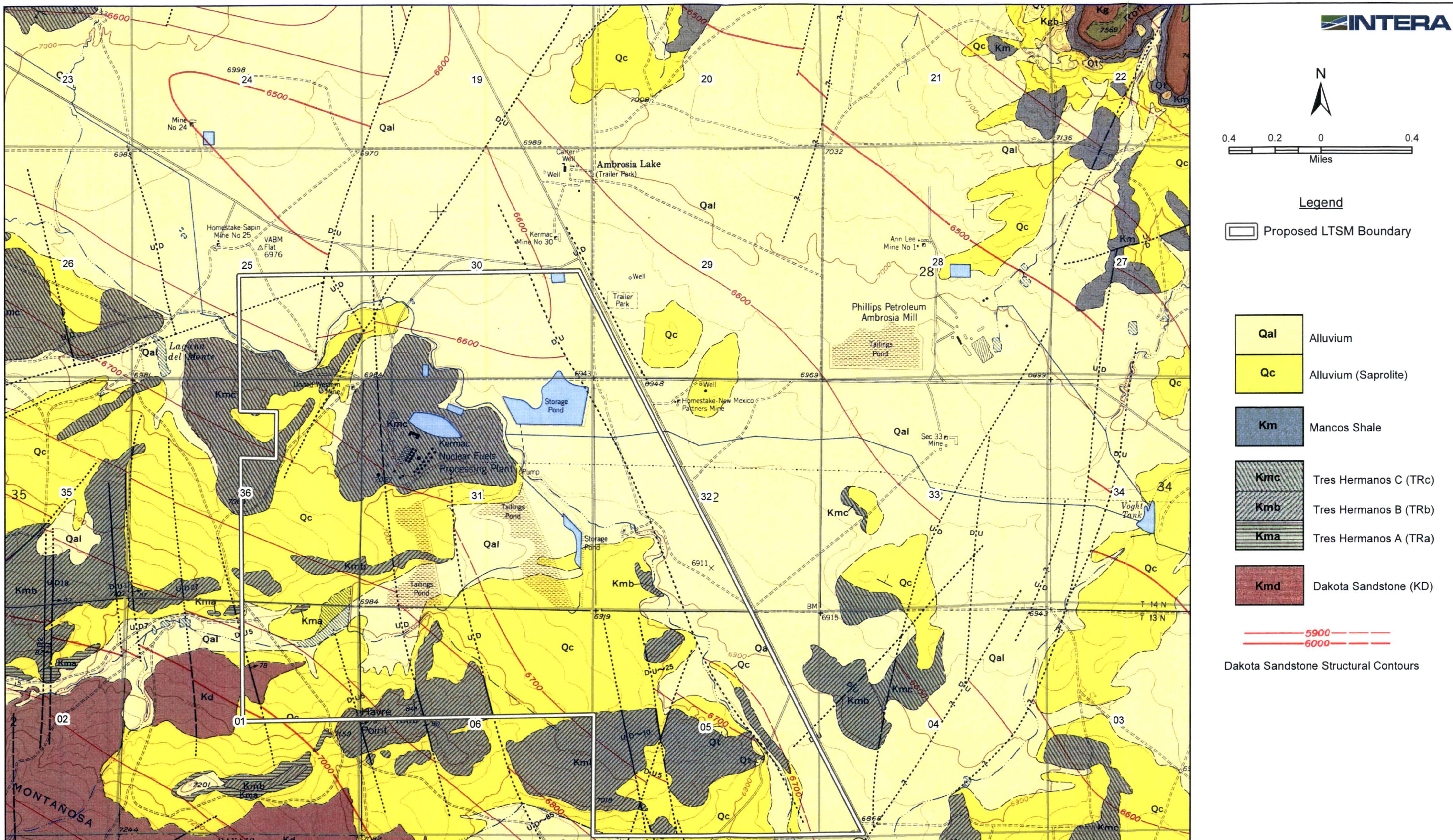

Figure 2
Ambrosia Lake Geologic Map
Rio Algom Mining LLC,
ACL Workplan

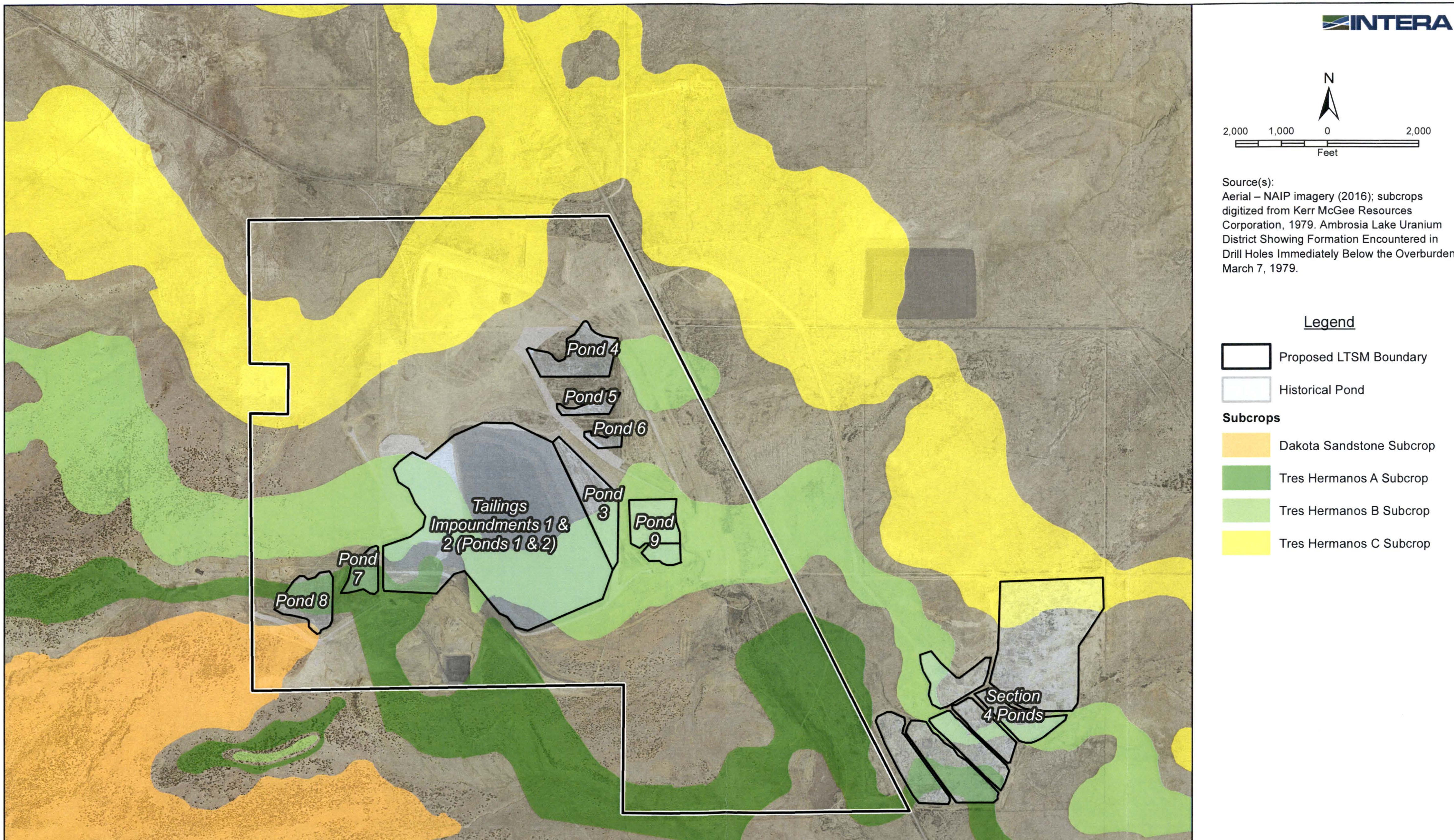

Figure 3
Site Map with Subcrops and Historical Facilities
Rio Algom Mining LLC, ACL Workplan

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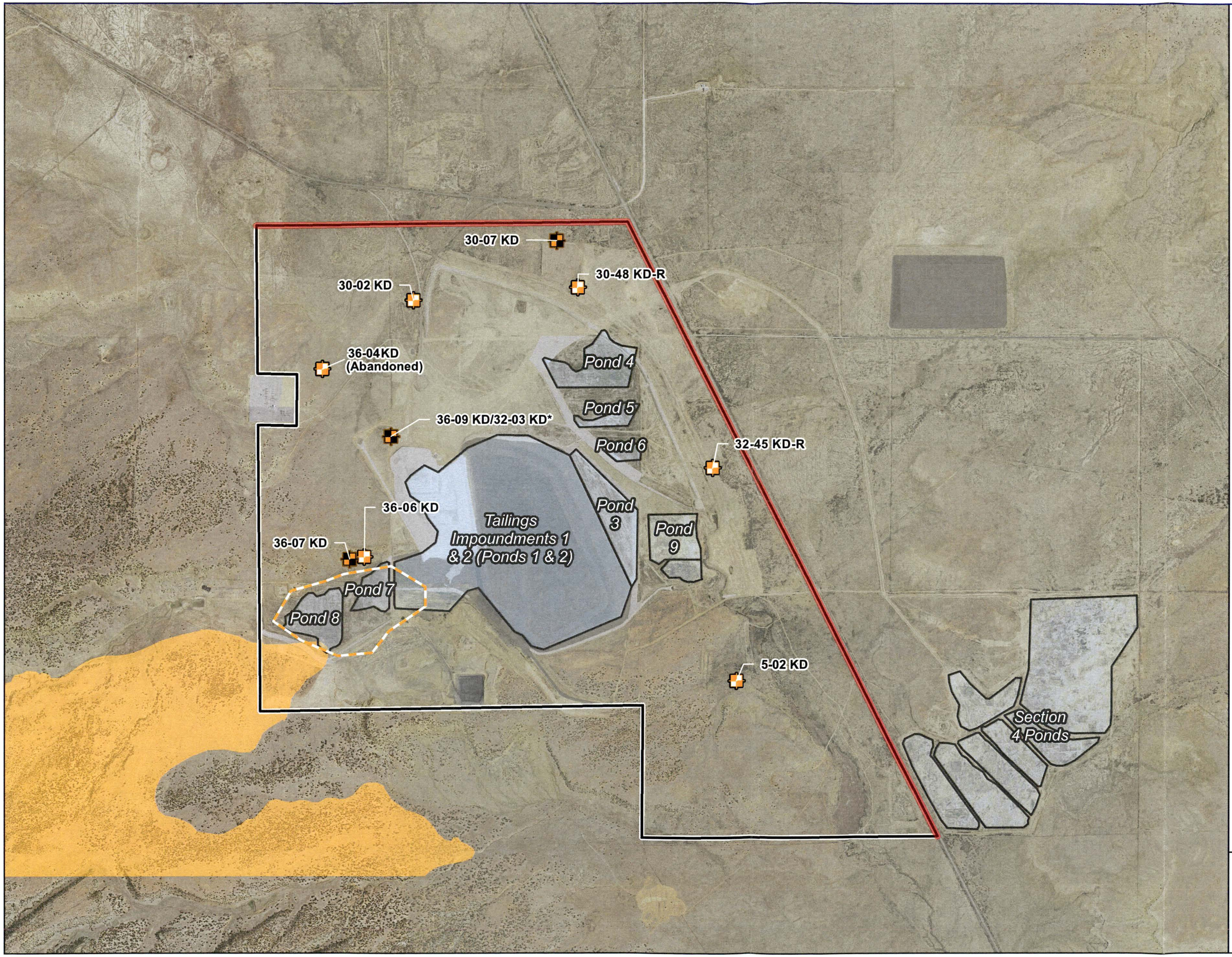

INTERA

N

2,000 1,000 0 2,000

Feet

Source(s):
Aerial – NAIP imagery (2016); subcrops digitized from Kerr McGee Resources Corporation, 1979. Ambrosia Lake Uranium District Showing Formation Encountered in Drill Holes Immediately Below the Overburden. March 7, 1979.

Legend

- Proposed Well Location
- Dakota Monitoring Well
- Proposed POE
- Proposed LTSM Boundary
- KD Potential Source Area
- Historical Pond

Subcrops

- Dakota Sandstone Subcrop

Note(s):
* = Name of well will be chosen depending on finalized location in accordance with RAML well naming convention

Figure 4
Dakota Monitoring Well Network with Proposed Monitoring Wells
Rio Algom Mining LLC,
ACL Workplan

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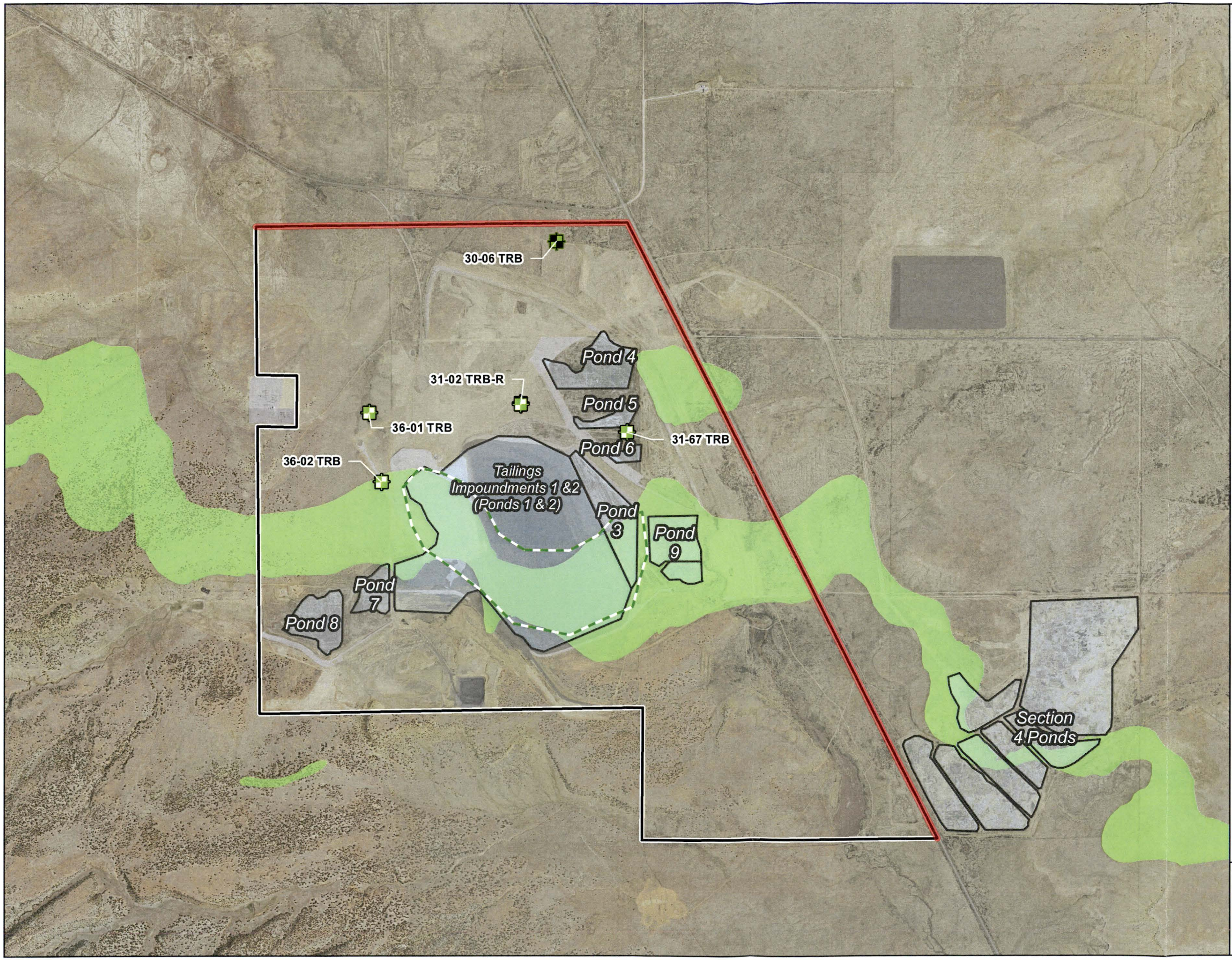

INTERA

N

2,000 1,000 0 2,000
Feet

Source(s):
Aerial – NAIP imagery (2016); subcrops digitized from Kerr McGee Resources Corporation, 1979. Ambrosia Lake Uranium District Showing Formation Encountered in Drill Holes Immediately Below the Overburden. March 7, 1979.

Legend

- Proposed Well Location
- TRB Monitoring Well
- Proposed POE
- Proposed LTSM Boundary
- TRB Potential Source Area
- Historical Pond

Subcrops

- Tres Hermanos B Subcrop

Figure 5
Tres Hermanos B Monitoring Well Network with Proposed Monitoring Wells
Rio Algom Mining LLC,
ACL Workplan

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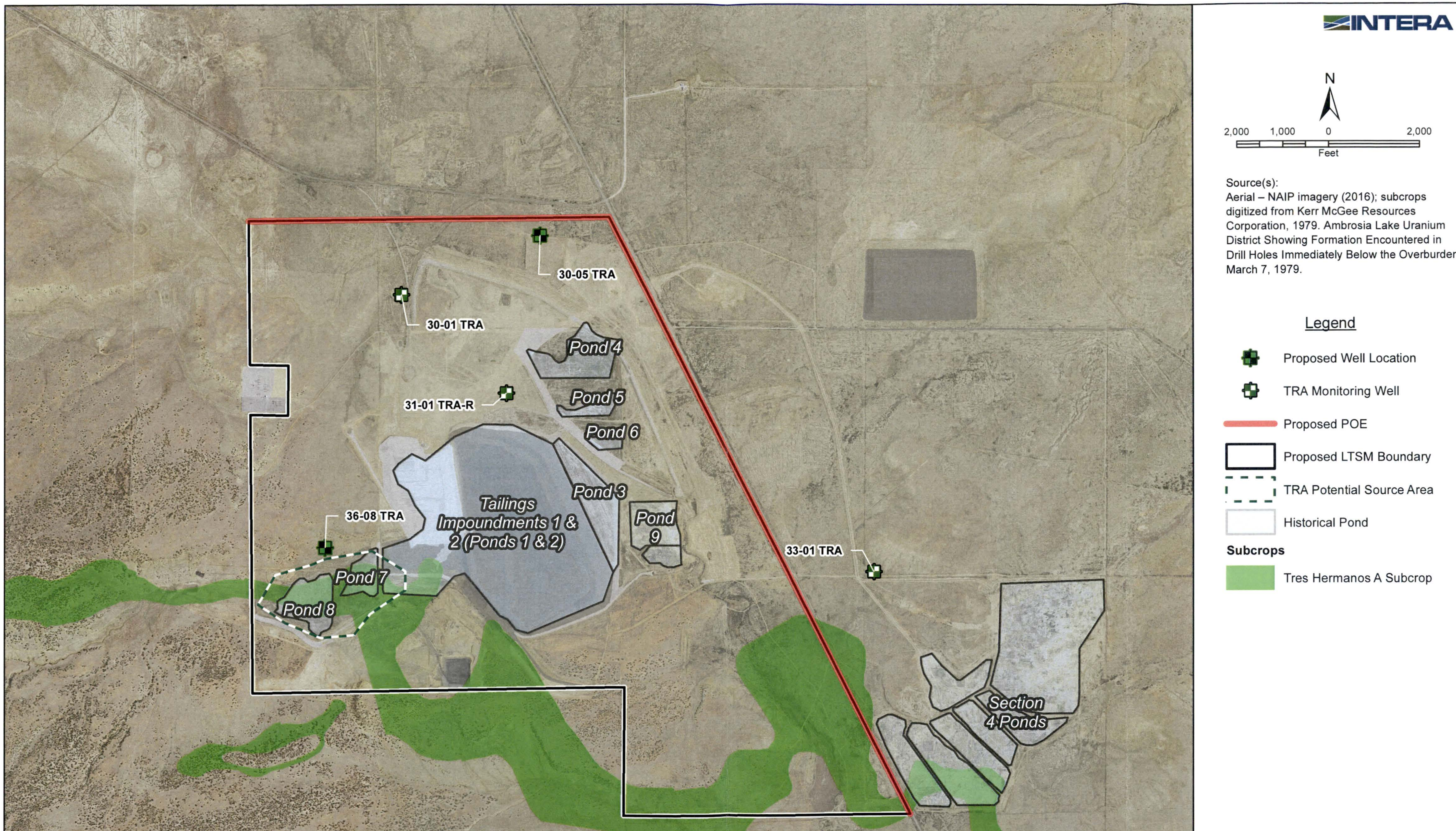

Figure 6
Tres Hermanos A Monitoring Well Network with Proposed Monitoring Wells
ACL Workplan
Rio Algom Mining LLC

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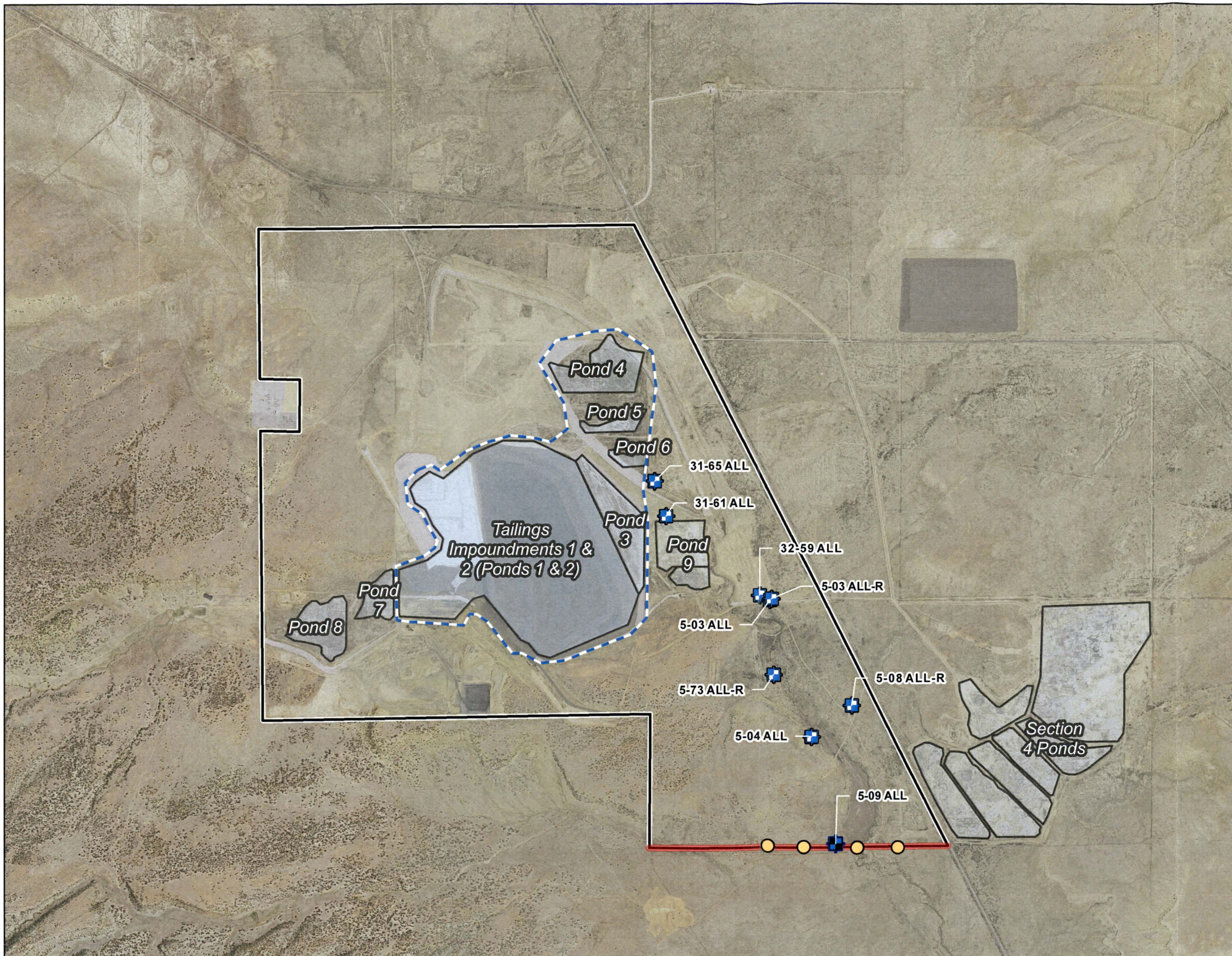

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2,000 1,000 0 2,000

Feet

Source(s):
Aerial – NAIP imagery (2016); subcrops digitized from Kerr McGee Resources Corporation, 1979. Ambrosia Lake Uranium District Showing Formation Encountered in Drill Holes Immediately Below the Overburden. March 7, 1979.

Legend

- Alluvium Monitoring Well
- Proposed Well Location
- Proposed Geoprobe Location
- Proposed POE
- Proposed LTSM Boundary
- Alluvium Potential Source Area
- Historical Pond

Figure 7
Alluvial Monitoring Well Network with Proposed Monitoring Wells
Rio Algom Mining LLC,
ACL Workplan

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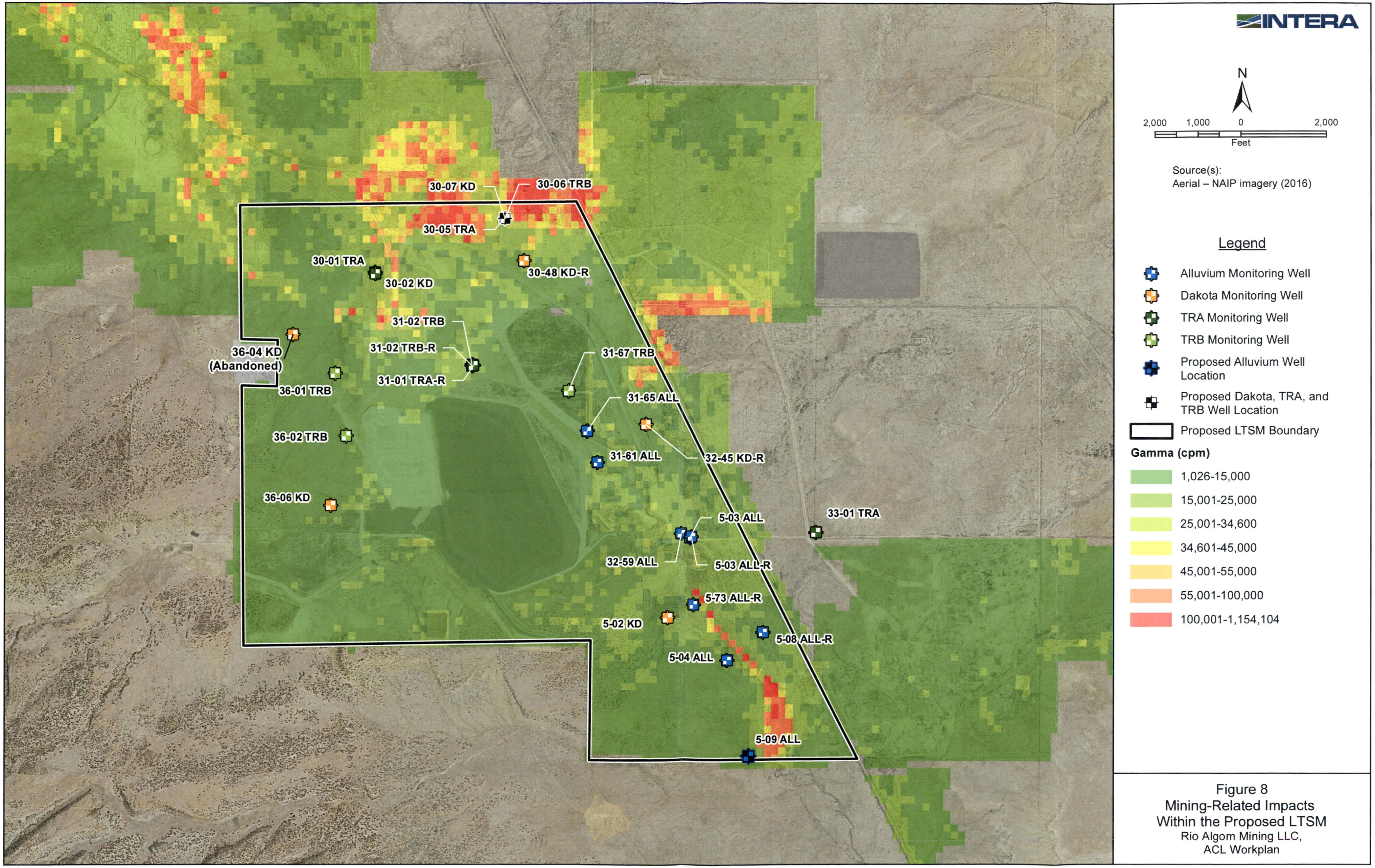

Figure 8
Mining-Related Impacts
Within the Proposed LTSM
Rio Algom Mining LLC,
ACL Workplan

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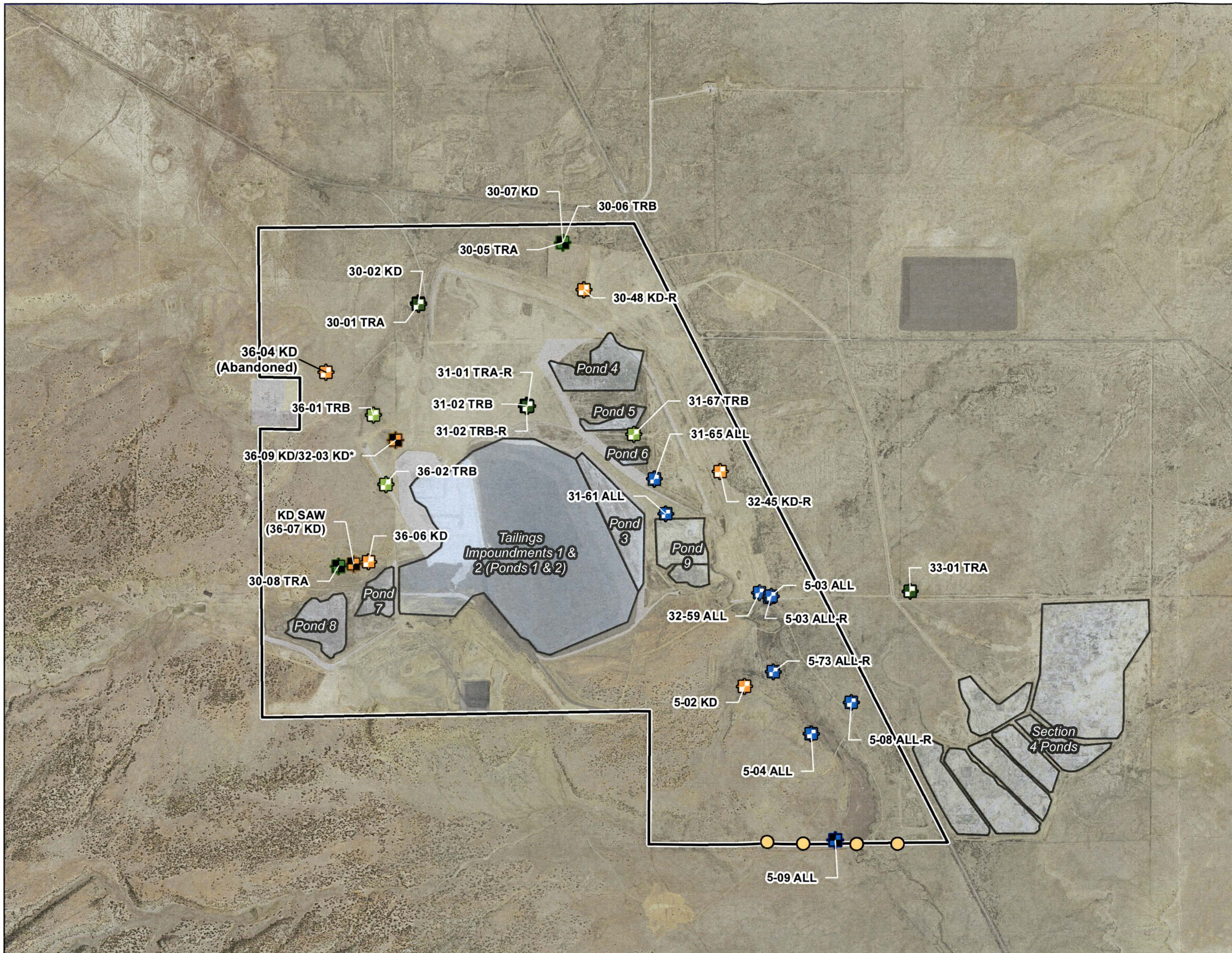

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Feet

Source(s):
Aerial – NAIP imagery (2016)

Legend

- Dakota Monitoring Well
- Proposed Dakota Well Location
- TRB Monitoring Well
- Proposed TRB Well Location
- TRA Monitoring Well
- Proposed Well Location
- Alluvium Monitoring Well
- Proposed Alluvium Well Location
- Proposed Geoprobe Location
- Proposed LTSM Boundary
- Historical Pond

Note(s):
* = Name of well will be chosen depending on finalized location in accordance with RAML well naming convention

Figure 9
Existing and Proposed
Monitoring Wells
Rio Algom Mining LLC,
ACL Workplan

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TABLES

TABLE 1

Constituents Exceeding Groundwater Protection Standards

Rio Algom Mining LLC's Ambrosia Lake Mill Site Alternate Concentration Limit Work Plan

Constituent	Hydrostratigraphic Unit	GPS	Result
Beryllium	Dakota Sandstone	0.01 mg/L	0.0125 mg/L
Cadmium	Dakota Sandstone	0.01 mg/L	0.0076 mg/L
Molybdenum	Dakota Sandstone	0.06 mg/L	0.171 mg/L
Gross Alpha	Dakota Sandstone	56 pCi/L	-4.2 pCi/L
Gross Alpha	Tres Hermanos A	18 pCi/L	2.2 pCi/L
Gross Alpha	Tres Hermanos B	21 pCi/L	-14 pCi/L

Notes:

mg/L = milligrams per liter

pCi/L = picoCuries per liter

GPS = Groundwater Protection Standard as stated in SUA-1473

Latest results are taken from July, 2017 monthly sampling with the exception of Gross Alpha for Tres Hermanos A, which was based on February, 2017 sampling. No monitoring wells in the TRA are sampled monthly.

TABLE 2

Requirements of 10 CFR Part 40 Appendix A 5 (B) 6 and their Occurrence in this Work Plan

Rio Algom Mining, LLC's Ambrosia Lake Mill Site Alternate Concentration Limit Work Plan

Report Section Number	Report Section Name	10 CFR Part 40 App A, §5B(6) Item Number	10 CFR Part 40 App A, §5B(6) Item Description
3.1	Source Area and Contaminant Migration and Exposure	a.i	The physical and chemical characteristics of the waste in the licensed site including its potential for migration
4.2.2	Characterizing the Source(s)	a.i	The physical and chemical characteristics of the waste in the licensed site including its potential for migration
4.3	Field Activities and Sampling Methods	a.ii	The hydrogeological characteristics of the facility and surrounding land.
4.3	Field Activities and Sampling Methods	a.iii	The quantity of groundwater and the direction of groundwater flow.
3.2	Document Review	a.iv	The proximity and withdrawal rates of groundwater users.
3.2	Potential Human Receptors and Applicable Exposure Scenarios	a.v	The current and future uses of groundwater in the area.
4.3	Field Activities and Sampling Methods	a.vi	The existing quality of groundwater, including other sources of contamination and their cumulative impact on the
3.2	Potential Human Receptors and Applicable Exposure Scenarios	a.vii	The potential for health risks caused by human exposure to waste constituents.
3.2	Potential Human Receptors and Applicable Exposure Scenarios	a.viii	The potential damage to wildlife, crops, vegetation, and physical structures caused by exposure to waste constituents.
4.2.3	Inputs to the Solute Transport Model	a.ix	The persistence and permanence of the potential adverse effects.
4.2.2	Tailings and Process Water Chemical Data	b.i	The volume and physical and chemical characteristics of the waste in the licensed site.
4.2.1	Characterizing the Source(s)	b.i	The volume and physical and chemical characteristics of the
4.3	Field Activities and Sampling Methods	b.ii	The hydrogeological characteristics of the facility and surrounding land.
4.4	Hydraulic Testing	b.iii	The quantity and quality of groundwater, and the direction of
4.2.2	Inputs to the Groundwater Flow Model	b.iii	The quantity and quality of groundwater, and the direction of groundwater flow.
2.2.2	Document Review	b.iv	The patterns of rainfall in the region.
2.3	Quality of Surface Waters	b.v	The proximity of the licensed site to surface waters.
2.3	Quality of Surface Waters	b.vi	The current and future uses of surface waters in the area and any water quality standards established for those surface
3.2	Potential Human Receptors and Applicable Exposure Scenarios	b.vi	The current and future uses of surface waters in the area and any water quality standards established for those surface
2.3	Quality of Surface Waters	b.vii	The existing quality of surface water including other sources of contamination and the cumulative impact on surface water quality.
3.2	Potential Human Receptors and Applicable Exposure Scenarios	b.viii	The potential for health risks caused by human exposure to waste constituents.
3.2	Potential Human Receptors and Applicable Exposure Scenarios	b.ix	The potential damage to wildlife, crops, vegetation, and physical structures caused by exposure to waste constituents. and
2.3	Quality of Surface Waters	b.x	The persistence and permanence of the potential adverse effects.

TABLE 3
Data Quality Objectives for the ACL Program
Rio Algom Mining, LLC's Ambrosia Lake Mill Site Alternate Concentration Limit Work Plan

1.0 State the Problem	**Concentrations of contaminants of potential concern (COPCs) at RAML's closed mill and tailings facility exceed water quality standards at the POC. Due to the infeasibility of cleaning up the site to acceptable background levels, the site will be evaluated for alternative concentration limits (ACLs) that result in COPCs at the downgradient point of exposure (POE) that are protective of human health and the environment for 1000 years. Site specific data are required to inform the flow and transport model.**			
	1	**2**	**3**	**4**
2.0 Identify the Goals of the Study	Characterize COPC sources	Update Conceptual Site Model (CSM)	Develop and apply a groundwater flow model based on the CSM.	Develop and apply a reactive-transport model based on the groundwater flow model. The model will be simplified (i.e., only a sorption version), or, if necessary, more comprehensive (reactive-transport). It will be used to carry out sensitivity/uncertainty analyses and to calculate ACLs.
3.0 Identify Information Inputs	Information inputs will include historical documentation describing the mill's uranium leach circuit, tailings/evaporation pond characteristics and construction/operational history, and groundwater sampling results at POCs. Documentation may also include inputs from installation and sampling of new monitoring wells, e.g., in tailings impoundments.	The CSM will be based in part on information derived from the source-characterization activity. It will also include input information for the groundwater flow and tranpsort models, as well as ancillary information more broadly supporting the CSM (e.g., isotopic and/or other tracer analyses to distinguish the characteristics of upgradient/downgradient groundwater, process solutions, tailings/pond waters, and mine water disharge).	The groundwater flow model will be consistent with the CSM, but simplified for use with transport models (hybrid or reactive-transport). The simplified model, based on Darcy's law, will consider steady-state flow in one dimension. Information inputs include geologic and hydrogeologic structure, hydraulic conductivity, porosity, and storage. Model outputs (to transport models) include Darcy flux, pore velocity, and longitudinal dispersivity.	Hybrid approach will be based on pH-dependent retardation factors, which can be estimated using a surface-complexation model (SCM). Information inputs include SC parameters [initial water chemistry at the POC, sorbant (e.g., ferrihydrite) characteristics and concentrations, temperature] and constraints on changes in pH along the flow path. Information inputs for Reactive-transport models, if necessary, will be similar to, but more mineralogically comprehensive than, those for pH-buffering models. Information inputs for flow behavior in reactive-transport models are as described above for the groundwater flow models.
4.0 Define Boundaries of the Study	Study boundaries approximately coincide with the LTSM boundary, and include tailings impoundments 1 & 2, unlined ponds 3 - 8, the mill reservoir and BaCl2 pond, and locations affected by mine water discharge to Arroyo del Puerto.	Study boundaries include the LTSM and enough of the surrounding San Juan Basin to adequately constrain initial and boundary conditions in the groundwater flow and transport models. The alluvium, upper bedrock units, and mine-affected regions of the Westwater Canyon and Brushy Basin Members of the Morrison Formation will be included in the study boundaries.	Upper bedrock units within the LTSM.	Boundaries coincide with the LTSM. As a reference case, COPC transport will be assumed to occur within the Dakota Formation along a flow path from the POC (near Ponds 7/8) to the POE (near the northern boundary of the LTSM). The extent to which COPC transport is attenuated in the TRA andTRB may be assessed qualitatively based on differences in sorbant characteristics and concentrations between the KD and TRA/TRB.
5.0 Develop the Analytic Approach	Historical records from RAML archives and other documentation will be reviewed. Based on review results, water quality characteristics (including COPC concentrations) among tailings solutions, pond waters, mine discharge, and groundwaters (both affected and unaffected by mining/milling activities) will be determined. The source term at POC wells will be defined for use in transport models. To support the CSM, the source term will, if possible, be related to various source locations and types based on discharge rates, operational history, and solution compositions (chemical and isotopic).	A synthesis of information characterizing the geological, hydrogeological, and geochemical conditions within the LTSM and surrounding area will be developed based on expert judgement and used to update and revise the CSM. Additional updates and revisions will be carried out periodically as new information becomes available.	Hydraulic parameters in the KD will be estimated based on analysis of aquifer pumping test data.	Dakota groundwaters will be sampled at the POC. Analytes include physico-chemical parameters (temperature, conductivity, pH, ORP, dissolved oxygen), major cations and anions (Na, K, Ca, Mg, Cl, SO4, alkalinity), minor elements (e.g., Si, Al, Mn, Fe, NO3/NO2, organic carbon), and COPCs. Redox pairs will also be measured. Dakota groundwaters will also be sampled at POE wells, and at other wells that exist or may be installed between the POE and POC. The mineralogy and paragensis of the KD will be characterized based on a review of relevant documentation, and by petrographic analysis of core samples. The petrographic analyses will include whole-rock chemistry, optical microscopy, XRD, and SEM/ EDS. Sorbant (e.g., ferrihydrite) concentrations will be determined by selective-extraction. The neutralization potential of core samples will also be measured.
6.0 Specify Performance or Acceptance Criteria	The review of historical documentation should provide various types of data (e.g., estimates for seepage rates, evaporation rates, discharge rates, tailings mineralogy and porewater chemistry) from referenceable sources. The quality of the data may be variable. Data coverage may be sparse with few details beyond a value and its units. Professional judgment may be required to evaluate the data, but selected data must at a minimum be (a) site-specific, (b) from a referenceable source, and (c) available with explicitly documented reporting units.	Performance and acceptance criteria will be those specified for the source-characterization, groundwater flow modeling, and transport modeling activities.	Hydraulic parameters derived from aquifer pump testing will be collected using modern testing & data analysis methods in compliance with industry QA/QC standards. Analytical data, such as porosity, will be compiled from the average of no less than 10 samples of KD cores collected within the LTSM. Core samples will be randomly selected from the available material to minimize the effects of selection bias. All data will be collected by appropriately certified labs working under their own QA/QC program. Duplicate and split samples will be submitted for analysis at a minimum of 1/20th of the number of submitted samples to allow for evaluation of laboratory accuracy.	Groundwater quality data will be collected by appropriately certified labs working under their own QA/QC program. Duplicate and split samples will be submitted for analysis at a minimum of 1/20th of the number of submitted samples to allow for evaluation of laboratory accuracy. EPA-approved analytical methods may be changed as necessary to achieve project objectives. Use of professional judgment will be required to evaluate historical data sources. Selected historical data will (a) be site-specific, (b) come from a referenceable source, and (c) have explicitly documented reporting units. Mineralogical parameters will be collected by appropriately certified labs working under their own QA/QC program. Duplicate and split samples will be submitted for analysis at a minimum of 1/20th of the number of submitted samples to allow for evaluation of laboratory accuracy.
7.0 Develop Plan for Obtaining Data	Identify data/knowledge gaps in source characterization through review of available documentation. If necessary, install one boring/ coring/ monitoring well near each potential source if none already exist, and sample for parameters that are relevant to source characterization.	Plans for obtaining data are specified in the source-characterization, groundwater flow modeling, and transport modeling activities. The groundwater monitoring program in the Ambrosia Lake Sampling and Analysis Plan (SAP) will be continued. New sample parameters (e.g., stable/radiogenic isotope ratios) will be obtained as necessary.	One borings/corings/well will be installed in the KD along the flow path from the source/POC to the POE. Aquifer tests will be conducted to provide estimates of hydraulic conductivity and aquifer storage in each hydrostratigraphic unit. Porosity will be determined from cores.	POE corings/wells will be installed near the LTSM boundary. Water quality and COPC concentrations in the POC and POE wells will be determined. Petrography, sorbant concentrations, and NP values will be determined for core samples. Model predictions of the propagation velocity of reaction fronts (e.g., pH) will be tested by locating and installing a monitoring well downgradient of the maximum predicted extent of front migration.

TABLE 4

Proposed New Monitoring Wells and Borings

Rio Algom Mining LLC's Ambrosia Lake Mill Site Alternate Concentration Limit Work Plan

Well Name	Unit	Proposed Purpose	Candidate for Aquifer Testing	Core Analysis	X Coordinate	Y Coordinate
5-09 ALL	ALL	Well at proposed alluvial POE	x		501597	1605160
30-05 TRA	TRA	Well at proposed TRA POE	x		501597	1605160
36-08 TRA	TRA	TRA Source Area Well	x		496897	1598380
30-06 TRB	TRB	Well at proposed TRB POE	x		501786	1605410
30-07 KD	KD	Well at proposed KD POE, pH Investigation	x	x	501597	1605160
36-07 KD	KD	KD Source Area Well, pH Investigation	x	x	497211	1598420
36-09 KD/ 32-03 KD*	KD	pH Investigation	x	x	498081	1601030
Geoprobe 1	ALL	Extent of Alluvial Groundwater near proposed POE			505892	1592570
Geoprobe 2	ALL	Extent of Alluvial Groundwater near proposed POE			506650	1592540
Geoprobe 3	ALL	Extent of Alluvial Groundwater near proposed POE			507776	1592520
Geoprobe 4	ALL	Extent of Alluvial Groundwater near proposed POE			508629	1592520

Notes:

* = The name of this well will be confirmed depending on location

All coordinates presented in New Mexico West, State Plane, NAD 27

ALL = Alluvium

TRA = Tres Hermanos A

TRB = Tres Hermanos B

KD = Dakota Sandstone

POE= point of exosure

TABLE 5
Analyte List for Groundwater and Core Samples
Rio Algom Mining, LLC's Ambrosia Lake Mill Site Alternate Concentration Limit Work Plan

Metals	Matrix	Filter Status	Analytical Method	Detection Limit	Reporting Units	Type	Alluvium Analytical Suite	KD Analytical Suite	TRA/TRB Analytical Suite	10 CFR Part 40, App. A
Antimony	Water/Solids*	Dissolved	M200.8	0.0004	mg/L	Metals		x		
Arsenic	Water/Solids*	Dissolved	M200.8	0.0002	mg/L	Metals		x		x
Beryllium	Water/Solids*	Dissolved	M200.8	0.00005	mg/L	Metals		x		
Barium	Water/Solids*	Dissolved	M200.8	0.003	mg/L	Metals				x
Cadmium	Water/Solids*	Dissolved	M200.8	0.0001	mg/L	Metals		x		x
Chromium	Water/Solids*	Dissolved	M200.8	0.01	mg/L	Metals				x
Lead	Water/Solids*	Dissolved	M200.8	0.0001	mg/L	Metals		x		x
Mercury	Water/Solids*	Total	SM 7470A	0.0002	mg/L	Metals				x
Molybdenum	Water/Solids*	Dissolved	M200.8	0.0005	mg/L	Metals	x	x	x	
Nickel	Water/Solids*	Dissolved	M200.8	0.0006	mg/L	Metals	x	x	x	
Selenium	Water/Solids*	Dissolved	SM 3114 B	0.001	mg/L	Metals	x	x	x	x
Silver	Water/Solids*	Dissolved	M200.8	0.01	mg/L	Metals				x
Uranium	Water/Solids*	Dissolved	M200.8	0.0001	mg/L	Metals	x	x	x	
Magnesium	Water/Solids*	Dissolved	M200.7	4	mg/L	Metals	x	x	x	
Potassium	Water/Solids*	Dissolved	M200.7	4	mg/L	Metals	x	x	x	
Sodium	Water/Solids*	Dissolved	M200.7	4	mg/L	Metals	x	x	x	
Calcium	Water/Solids*	Dissolved	M200.7	2	mg/L	Metals	x	x	x	
Gross Alpha	Water/Solids*	Dissolved	M9310	2	pCi/L	Radiochemistry	x	x	x	x
Lead 210	Water/Solids*	Dissolved	EICHROM, OTW-01	4	pCi/L	Radiochemistry	x	x	x	
Radium 226	Water/Solids*	Dissolved	M903.1	0.4	pCi/L	Radiochemistry	x	x	x	x
Radium 228	Water/Solids*	Dissolved	M9320	1.5	pCi/L	Radiochemistry	x	x	x	x
Thorium 230	Water/Solids*	Dissolved	ESM 4506	0.6	pCi/L	Radiochemistry	x	x	x	
Chloride	Water	NA	SM4500Cl-E	0.5	mg/L	Wet Chemistry	x	x	x	
Conductivity	Water	NA	SM2510B	1	umhos/cm	Wet Chemistry	x	x	x	
Cyanide	Water	Total	D7511-09	0.003	mg/L	Wet Chemistry		x	x	
Nitrate/Nitrite as N	Water	NA	M353.2	0.02	mg/L	Wet Chemistry	x	x	x	
pH	Water	NA	SM4500H+ B	0.1	C	Wet Chemistry		x		
TDS	Water	NA	SM2540C	10	mg/L	Wet Chemistry	x	x	x	
Sulfate	Water	NA	D516-02/-07	1	mg/L	Wet Chemistry	x	x	x	
Alkalinity	Water	NA								
ORP	Water	NA								
Dissolved Oxygen	Water	NA								
Iron redox	Water	Dissolved	10249 FerroVer, 8146	0.1 (Fe), 0.02 (Fe^{2+})	mg/L	Wet Chemistry				
Sulfur redox	Water	Dissolved	10248 SulfaVer 4, 10254	2 (SO4), 0.01 (S^{2-})	mg/L	Wet Chemistry				

Notes:
NA = Not Applicable
* = Solids analysis requires EPA 3052 extraction.
10 CFR Part 40, Appendix A parameters are those identified explicitly within the Appendix.
Parameters which are included in the GW monitoring program were identified by the NRC during he ACL application process.

TABLE 6
Step-wise Extraction Methods
Rio Algom Mining, LLC's Ambrosia Lake Mill Site Alternate Concentration Limit Work Plan

Step #	Target	Method	Preferentially Dissolved Minerals	Analyses
1	Water soluble fraction	1.0 g sample into 50 mL deionized water, shake for 1 hour at room temperature.	secondary sulfate minerals	Iron
2	Exchangeable fraction	1 M NH4-acetate at pH 4.5, shake for 2 hours at room temperature.	calcite, adsorbed and exchangeable ions	Metals
3	Fe(III) oxyhydroxides	0.2 M NH4-Oxalate at pH 3.0, shake for 1 hour in darkness at room temperature	schwertmannite, two-line ferrihydrite, secondary jarosite, manganese oxide	Iron
4	Fe(III) oxides	0.2 M NH4-oxalate at pH 3.0, heat in water bath at 80 degrees C for 2 hours	goethite, jarosite, sodium jarosite, hematite, magnetite, higher order ferrihydrites	Iron

Notes:

After Dold, 2003b, Table 1, Sequence B. Steps 5-7 omitted, as more refractory minerals are not pertinent to this study.

Metals analyses after step 2 will allow for esimation of the sorbed component for each of the metals.

APPENDIX A

Evaluation of October 16, 2005 Rio Algom Mining LLC, Submittal Regarding Alternate Concentration Limits for the Ambrosia Lake, New Mexico, Mill Tailings Facility. Center for Nuclear Waste Regulatory Analyses (Pickett and Winterle, 2004)

EVALUATION OF OCTOBER 16, 2003, RIO ALGOM MINING, LLC, SUBMITTAL REGARDING ALTERNATE CONCENTRATION LIMITS FOR THE AMBROSIA LAKE, NEW MEXICO, MILL TAILINGS FACILITY

Prepared for

U.S. Nuclear Regulatory Commission
Contract NRC–02–04–001

Prepared by

David A. Pickett
James R. Winterle

Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

March 2004

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FIGURES

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ACKNOWLEDGMENTS

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the U.S. Nuclear Regulatory Commission (NRC) under Contract No. NRC–02–04–001. The activities reported here were performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards, Division of Fuel Cycle Safety and Safeguards, Fuel Cycle Facilities Branch. The report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

The authors thank D. Turner for technical review, and B. Sagar for programmatic review of this report. The authors also thank B. Long and L. Selvey for editorial and secretarial support in the preparation of the document.

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: No CNWRA-generated original data are contained in this report.

ANALYSES AND CODES: Calculations of one-dimensional advective-dispersive solute transport were performed using a computer algorithm written in the FORTRAN programming language. These calculations and verification checks are documented in CNWRA Scientific Notebook 595E. In addition, Microsoft® Excel 2002 SP–2 was used to generate plots presented in this report.

Reference:

Microsoft Corporation. "Microsoft® Excel 2002." Redmond, Washington: Microsoft Corporation. 2002.

1 INTRODUCTION

In a document dated October 16, 2003 (Attachment 1), Rio Algom Mining, LLC (RAM), responded to an August 22, 2003, letter from the U.S. Nuclear Regulatory Commission (NRC) (Attachment 2) requesting followup actions after a meeting at the RAM Ambrosia Lake facility. The meeting concerned potential establishment of alternate concentration limits (ACLs)for the RAM uranium mill tailings disposal facility at Ambrosia Lake in light of a Center for Nuclear Waste Regulatory Analyses (CNWRA) review of the technical and regulatory bases for the request (Pickett, et al., 2003). RAM is attempting to discontinue the groundwater corrective action program established in the NRC materials license SUA–1473.

We now report our response to the RAM proposals contained in the October 16, 2003, document. The key areas addressed in the RAM response are

- Designation of point of compliance (POC) wells for the alluvial and bedrock aquifers
- Designation of trend wells for the alluvial and bedrock aquifers
- Revision of alternate concentration limits for contaminants in the alluvial and bedrock aquifers
- Definition of methodology and schedule for the groundwater monitoring plan

2 DESIGNATION OF POINT OF COMPLIANCE WELLS

2.1 Alluvium

RAM proposes 31-61 and S–9 as POC wells. The 31-61 designation and elimination of 32-59 as POC wells are consistent with our earlier report (Pickett, et al., 2003), and S–9 is located appropriately at the downgradient edge of the tailings impoundment [Quivira Mining Company (QMC), 2001, Figure 1.2].

2.2 Tres Hermanos B Sandstone Unit

RAM proposes 31-02, 31-67, and 36-02 as POC wells. Designation of 31-67 and 36-02 and elimination of 36-01 are consistent with Pickett, et al. (2003). Replacement of 31-66 with 31-02 as a POC well was discussed by the RAM and NRC staffs and is reasonable. Well 31-02 is located downgradient of the central portion of Tres Hermanos B Sandstone Unit (TRB) outcrop and subcrop beneath Impoundment 1 (QMC, 2000, Drawing 2-1) and, so, is well-positioned to capture any contamination originating from site activities. Elevated uranium concentrations in 31-02 relative to 31-66 in recent monitoring data[1] support the choice.

[1] Luthiger, P. "sua1473_gwdata.xls." Microsoft Excel® file (November) provided on diskette to NRC. Grants, New Mexico: RAM. 2002.

2.3 Tres Hermanos A Sandstone Unit

RAM proposes 31-01 as the sole POC well. Such designation is consistent with our earlier report (Pickett, et al., 2003).

2.4 Dakota Sandstone Unit

RAM proposes 36-06 as the sole POC well. Such designation and elimination of Wells 30-48, 30–02, and 32–45 as POC locations are consistent with Pickett, et al. (2003).

In summary, the POC wells proposed in Attachment 1 are acceptable.

3 DESIGNATION OF TREND WELLS

3.1 Alluvium

RAM proposes 32-59 and 5-08 as trend wells. For 5-08, RAM also proposes that only uranium be monitored, consistent with our agreement (Pickett, et al., 2003) with the contention that radium in this well arises from sources other than the RAM facility (RAM, 2003). Our earlier report recommended 5-01, 5-02, 5-04, and 5-73 be considered as trend wells, however, we concur the combination of 32-59 and 5-08 is adequate to monitor contaminants along this axial portion of the alluvial aquifer (QMC, 2001, Figure 1.2).

3.2 Tres Hermanos B Sandstone Unit

Well 36-01 is proposed by RAM as a trend well, consistent with our earlier report (Pickett, et al., 2003).

3.3 Tres Hermanos A Sandstone Unit

RAM proposes 30-01 as a trend well. This location is appropriate because it is downgradient of the area of potential Tres Hermanos A Sandstone Unit (TRA) contamination and is closer to the point of exposure (POE) than POC Well 31-01 (QMC, 2000, Map 1-1).

3.4 Dakota Sandstone Unit

Three trend well locations are proposed by RAM: 30-02, 30-48, and 32-45. These designations are consistent with Pickett, et al. (2003).

In summary, the trend wells proposed in Attachment 1 are acceptable.

4 PROPOSED ALTERNATE CONCENTRATION LIMITS

4.1 Alluvium

RAM proposes ACLs for the alluvial aquifer based on a total health risk of 10^{-4} at the POE. The adopted health risk-based limits, as accepted in our earlier report (Pickett, et al., 2003), are

shown in Table 4-1. RAM used a simplified contaminant transport model—assuming a continuous source, a uranium retardation factor of 20, transport distance of 4,000 ft, and simulation time of 100 years—using the SOLUTE code, to calculate an attenuation factor of 0.001. Applying this factor to the health risk-based limits resulted in ACLs that are a factor of approximately 1,000 higher than the health risk-based limits. These ACLs are shown in Table 4-1 along with earlier proposed ACLs.

As discussed in recent RAM and NRC documents (RAM, 2003; Pickett, et al., 2003), the use of a simple transport model for the alluvium is uncertain because of, among other factors, potential

Table 4-1. Alluvial Aquifer Health Risk-Based Limits and Proposed Alternate Concentration Limits (ACLs)*

Contaminant	Health Risk-Based Limit†	Proposed Alternate Concentration Limit		
		Original‡	April 2003§	October 2003‖
Molybdenum (mg/L)	0.18	83	3.92	176
Nickel (mg/L)	0.1	0.14	0.14	98
Selenium (mg/L)	0.05	3.1	3.1	49
Gross alpha (pCi/L)	8.57	16,726	720	8,402
Ra-226+228 (combined radium) (pCi/L)	3.23	196.1	196.1	3,167
Th-230 (pCi/L)	13.9	10	5	13,627
U-nat (mg/L)	0.025	11.1	11.1	23
Pb-210 (pCi/L)	1.3	58	36	1,274

*Only includes constituents for which ACLs were requested.
†For molybdenum, nickel, and selenium: Quivira Mining Company (QMC). "Application for Alternate Concentration Limits in the Alluvial Materials at the Quivira Mill Facility, Ambrosia Lake, New Mexico." Grants, New Mexico: QMC. p. 2-41. 2001. For others: Rio Algom Mining, LLC (RAM). "Response to Request for Additional Information—Corrective Action Program and Alternate Concentration Limits Petition for Uppermost Bedrock Units, Ambrosia Lake Uranium Mill Facility near Grants, New Mexico, and Application for Alternate Concentration Limits in the Alluvial Materials at the Quivira Mill Facility, Ambrosia Lake, New Mexico." Ver. 1.1. Grants, New Mexico: RAM. p. 1. 2003. Radium value is for Ra-226 alone; combined limit will be lower.
‡QMC. "Application for Alternate Concentration Limits in the Alluvial Materials at the Quivira Mill Facility, Ambrosia Lake, New Mexico." Table 1.2. Grants, New Mexico: QMC. 2001.
§RAM. "Response to Request for Additional Information—Corrective Action Program and Alternate Concentration Limits Petition for Uppermost Bedrock Units, Ambrosia Lake Uranium Mill Facility near Grants, New Mexico, and Application for Alternate Concentration Limits in the Alluvial Materials at the Quivira Mill Facility Ambrosia Lake, New Mexico." Ver. 1.1. Table 5. Grants, New Mexico: RAM. 2003.
‖Attachment 1.

multiple sources and geochemical heterogeneity. In our final report, we suggested such a simple approach would be acceptable if parameters were conservatively chosen. We concluded that discussion (Picket, et al., 2003, Section 3.4.1) with the following:

> In devising a new transport model for demonstrating protection, rationale should be provided for any changes to transport model parameters (e.g., retardation coefficient for uranium) from those used in the previous model or suggested in this report. In addition, the licensee should ensure that its modeled attenuation factor is not overly dependent on a model period of 100 years. In other words, sensitivity of the attenuation factor to the model period should be assessed.

RAM did not, however, provide a rationale for a retardation factor of 20. We previously concluded a value of 100 was not sufficiently conservative (Pickett, et al., 2003). Again using our approach from that report (employing Eq. 3-1), we calculated that a retardation factor of 20 corresponds roughly to a K_d of 2.4 ml/g. The discussion in Section 3.4.1 (Pickett, et al., 2003) concluded a value of 12 ml/g may be reasonable, but data and model uncertainties are too numerous and unquantified to allow its use with confidence. The value corresponding to the RAM retardation factor—2.4 ml/g—is a factor of five smaller. We consider this factor to add a reasonable level of assurance that retardation is not overestimated, provided that other model uncertainties are accounted for.

The RAM response to agreements from the August 12, 2003, meeting with NRC indicates the POC location for the alluvial aquifer will be changed from Well 31-61 to Well S–9 (Attachment 1). For the previous POC location at Well 31-61, RAM used the following model inputs: transport distance = 5,500 ft; retardation factor = 10; dispersion length = 500 ft; groundwater velocity = 185.5 ft/yr. For the new POC location at Well S–9, model transport distance was decreased to 4,000 ft, and the retardation factor was increased to 20. In both these calculations, it was assumed that groundwater in the alluvial formation would drain within 100 years, and the solute source would remain fixed at a constant concentration. These revisions resulted in a calculated attenuation factor for alluvium of 0.001; whereas, the previously calculated attenuation factor was 0.005.

The CNWRA staff used an analytical solution for the one-dimensional convective dispersive transport equation (van Genuchten and Alves, 1982) to check the calculated attenuation factors for alluvium. The model results (Figure 4-1) show at a time of 100 years (assumed time for drainage of alluvium), the relative concentration (i.e., attenuation factor) is 0.005 for transport to the POE from the location of Well 31-61 and 0.001 for transport to the POE from the location of Well S–9. These transport calculations are in agreement with those performed by RAM. These solute transport curves also show that uncertainty in the time it takes for the alluvial formation to drain can make a significant difference in the calculated attenuation factor. For example, if alluvium takes 150 years to drain instead of 100 years, the calculated attenuation for Well S–9 increases by a factor of 20, from 0.001 to 0.02. It is, therefore, advisable to revise the attenuation factor proposed by RAM to account for uncertainty in the amount of time it may take for drainage of the alluvium unit following cessation of discharges to Arroyo del Puerto. This recommendation was noted previously in the CNWRA review of the RAM application for alternate concentration limits (Pickett, et al., 2003). Alternatively, consideration should be given to establish criteria for the monitoring program to verify the alluvium drains within the timeframe assumed in the transport calculations (see monitoring discussion that follows).

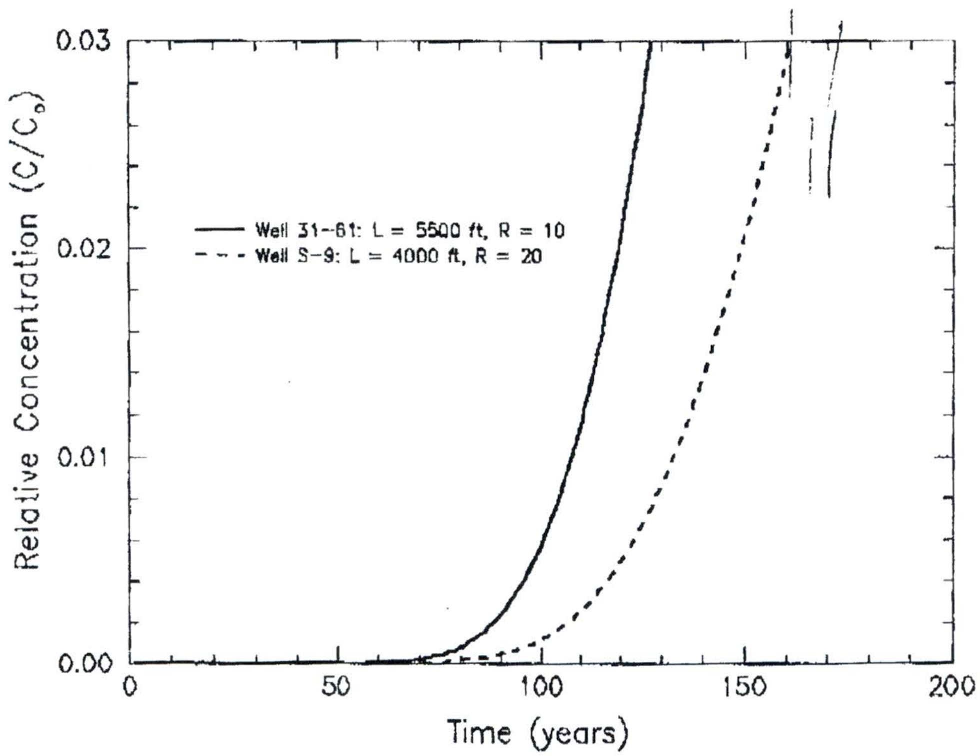

Figure 4-1. Relative Concentration Curves for One-Dimensional Transport in Alluvium for Different Point of Compliance Locations and Retardation Factors

RAM has not addressed whether or not the new proposed alluvial aquifer ACLs are as low as is reasonably achievable (ALARA), as required by 10 CFR Part 40, Appendix A, Criterion 5B(6). We must assume any ACLs proposed by RAM are achievable by reasonable means—and the licensee did supply an ALARA argument in its earlier submittal (QMC, 2001). We, therefore, conclude that, for a given contaminant in Table 4-1, the lowest ACL to have been proposed by RAM must be reasonably achievable. The corollary conclusion is that any higher values are not ALARA. Thus, any ACLs subsequently proposed by the licensee should not be higher than any proposed in April 2003 (Table 4-1), unless RAM revises its ALARA argument.

4.2 Bedrock

RAM proposes ACLs for the bedrock aquifers based on a total health risk of 10^{-4} at the POE (Attachment 1). The adopted health risk-based limits, as accepted in our earlier report (Pickett, et al., 2003), are shown in Table 4-2. RAM used a simplified SOLUTE contaminant transport model—assuming a uranium retardation factor of 50 and transport distance of 4,700 ft—to calculate an attenuation factor of 0.0147. Applying this factor to the health risk-based limits resulted in the new proposed ACLs for all three bedrock units, shown in Table 4-2 along with earlier proposed ACLs.

Table 4-2. Uppermost Bedrock Aquifer Units Health Risk-Based Limits and Proposed Alternate Concentration Limits (ACLs)*				
Contaminant	Health Risk-Based Limit†	Proposed Alternate Concentration Limit		
		Original‡	April 2003§	October 2003‖
Tres Hermanos B Sandstone Unit				
Nickel (mg/L)	0.1	0.37	0.37	6.8
Ra-226+228 (pCi/L)	3.23	41	41	218
Th-230 (pCi/L)	13.9	139	139	945
U-nat (mg/L)	0.025	0.25	1.56	1.6
Pb-210 (pCi/L)	1.3	13	13	88
Tres Hermanos A Sandstone Unit				
Ra-226+228 (combined radium; pCi/L)	3.23	41	41	218
Th-230 (pCi/L)	13.9	139	139	945
Pb-210 (pCi/L)	1.3	13	13	88
Dakota Sandstone Unit				
Nickel (mg/L)	0.1	0.12	0.12	6.8
Ra-226+228 (pCi/L)	3.23	41	41	218
Th-230 (pCi/L)	13.9	869	869	945
U-nat (mg/L)	0.025	0.81	0.81	1.6
Pb-210 (pCi/L)	1.3	57	57	88

*Only includes constituents for which ACLs were requested.
†For nickel: Quivira Mining Company (QMC). "Corrective Action Program and Alternate Concentration Limits Petition for Uppermost Bedrock Units, Ambrosia Lake Uranium Mill Facility near Grants, New Mexico." Table 2-8. Grants, New Mexico: QMC. 2000. For others: Rio Algom Mining, LLC (RAM). "Response to Request for Additional Information—Corrective Action Program and Alternate Concentration Limits Petition for Uppermost Bedrock Units Ambrosia Lake Uranium Mill Facility near Grants, New Mexico, and Application for Alternate Concentration Limits in the Alluvial Materials at the Quivira Mill Facility, Ambrosia Lake, New Mexico." Ver. 1.1. p. 1. Grants, New Mexico: RAM. 2003. Radium value is for Ra-226 alone; combined limit will be lower.
‡QMC. "Corrective Action Program and Alternate Concentration Limits Petition for Uppermost Bedrock Units, Ambrosia Lake Uranium Mill Facility near Grants, New Mexico." Table 1-5. Grants, New Mexico: QMC. 2000
§For Tres Hermanos B Sandstone Unit requested ACL for natural uranium (U-nat): RAM. "Response to Request for Additional Information—Corrective Action Program... ." p. 16. Grants, New Mexico: RAM. 2003. For others: QMC. "Corrective Action Program and Alternate Concentration Limits Petition... ." Table 1-5. Grants, New Mexico: QMC. 2000.
‖Attachment 1.

As discussed previously, our earlier report requested that RAM provide justification for any retardation factor employed in setting ACLs. Attachment 1 does not include justification for the selected value of 50. We previously concluded a value of 100 was not sufficiently conservative. Also, we calculated that a retardation factor of 50 corresponds roughly to a K_d of 6 ml/g (Pickett, et al., 2003). The discussion in Section 3.4.1 of Pickett, et al. (2003) concluded a value of 12 ml/g may be reasonable, but data and model uncertainties are too numerous and unquantified to allow its use with confidence. The value corresponding to the RAM retardation factor—6 ml/g—is half that value. We consider this factor to add a reasonable level of assurance that retardation is not overestimated, provided that other model uncertainties are accounted for.

RAM states that it used a transport distance of 4,700 ft for transport calculations between the POC and POE wells, because "no POC is less than this distance from a POE" (Attachment 1, page 4). It should be clarified that 4,700 ft actually represents the distance between the contaminant source in the Dakota Aquifer and POE Well 36–04KD. The distance between POC Well 36-06KD and POE Well 36–04KD is 3,900 ft, and this was the distance actually used by RAM in its SOLUTE transport calculations to estimate an attenuation factor of 0.0147.[2] The CNWRA staff were able to reproduce this calculation using an analytical solution for the one-dimensional convective dispersive transport equation (van Genuchten and Alves, 1982). The result, shown in Figure 4-2, indicates a peak attenuation factor of 0.0147 is obtained for a model using the following input values: source duration = 22 years; transport distance = 3,900 ft; groundwater velocity = 125 ft/yr; retardation factor = 50; dispersion length = 500 ft.

There is a flaw in this modeling approach, which assumes a pulsed solute source with a duration of 22 years at the same location as POC Well 36–06KD. In reality, the solute source is located approximately 800 ft upgradient from the POC well. Previously, RAM calculated an attenuation factor for the Dakota Sandstone unit by performing solute transport calculations from the solute source to the POC well and from the solute source to the POE well (QMC, 2000). An attenuation factor of 0.16 was then calculated as the ratio of relative solute concentrations between these two well locations. We believe this previously used approach (QMC, 2000) is the appropriate method for estimating attenuation of solutes between two wells located at different distances downstream from a limited-duration source.

Figure 4-3 shows results of the solute transport calculations with the same parameter values used for Figure 4-2, except that relative concentration curves are shown for distances of 800 and 4,700 ft from the source. These are the approximate distances of POC Well 36–06KD and POE Well 36–04KD from the Dakota Sandstone unit contaminant source. The ratio of peak concentrations of solutes between these two well locations reflects the degree of attenuation between POC and POE locations. Calculated peak relative concentrations shown in Figure 4-3 are 0.0125 for the POE well and 0.079 for the POC well. The ratio of these peak concentrations yields an attenuation factor of 0.158, which is one order of magnitude greater than the value of 0.0147 proposed by RAM in Attachment 1. We conclude the inappropriate choice of transport model results in a significant overestimation of the attenuating capacity of the aquifer.

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[2]Goranson, P. Email (February 17) to J. Caverly, NRC. Excel file "36-06KD to POE OCT10 2003-OUT xls" (attachment to email). Grants, New Mexico: RAM. 2004.

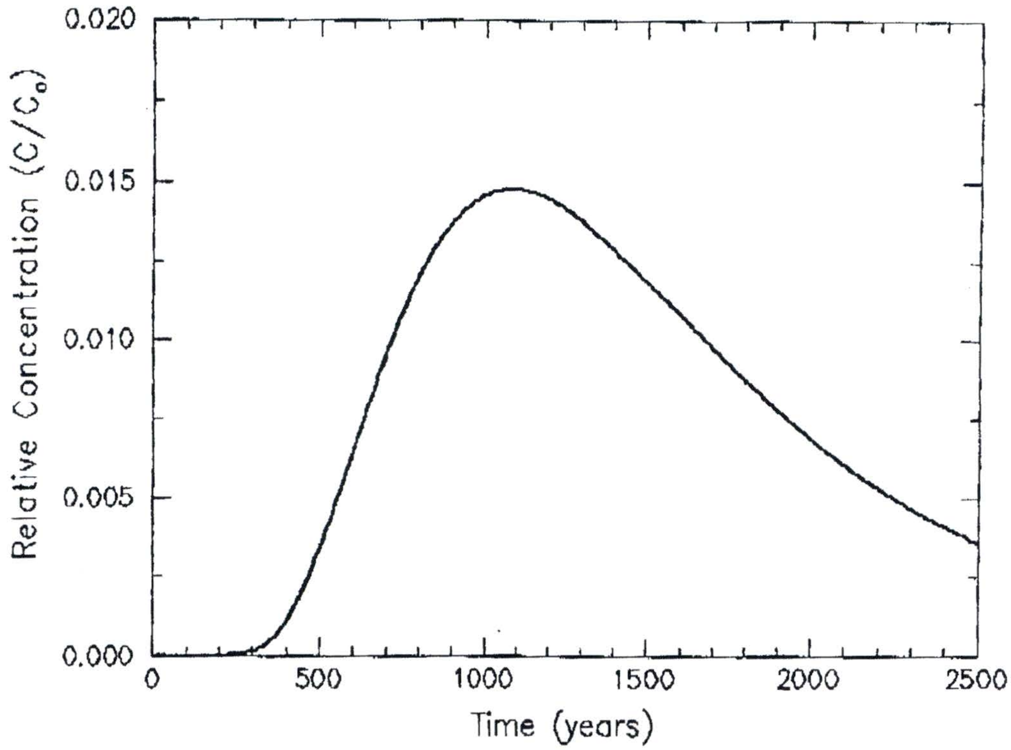

Figure 4-2. Calculation of Relative Solute Concentration for a Location 3,900 ft Downstream of Source Location with a 22-Year Duration, Dispersion Length of 500 ft, Groundwater Velocity of 125 ft/yr, and Retardation Factor of 50

The NRC Standard Review Plan for Title II tailings sites states that exposure impacts need be evaluated only to 1,000 years (NRC, 2003, page 4-34). In Figure 4-3, the height of the POE concentration curve at 1,000 years is 0.0096. Therefore, an attenuation factor of 0.0096/0.079 = 0.12 would be appropriate for the Dakota POC.

RAM asserts no transport distances from other bedrock POC wells to the POE are shorter than the distance used in the transport calculation for the Dakota Sandstone unit (3,900 ft). Thus, attenuation factors calculated for the Dakota Sandstone unit are applicable to the other POC locations. It can be seen from the preceding calculations, however, that distance from the source location to the POC also must be factored into the calculation of attenuation factors. The original bedrock ACL application (QMC, 2000) states groundwater flow in the bedrock units varies from northward to northeastward. Our inspection of Map 1-1 from QMC (2000) shows POC to POE distances for the bedrock aquifers are as short as 2,600 ft (POC Well 36-02 to the institutional control boundary for the TRB) and source-to-POC distances are as long as 1,800 ft (also for the TRB). The Dakota model is clearly not bounding for all aquifers and POC locations. It is advisable, therefore, that solute transport calculations be performed for all POC locations to ensure attenuation factors are chosen appropriately.

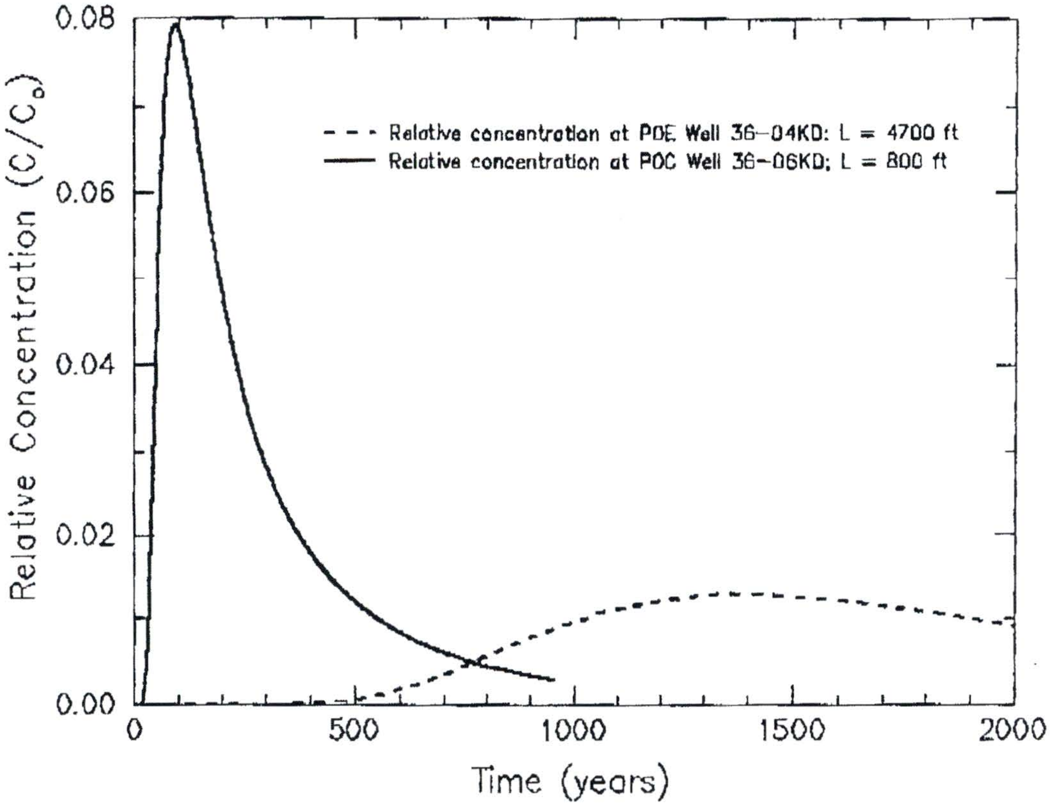

Figure 4-3. Relative Concentration at Locations 800 and 4,700 ft Downgradient from the Source Location. All Other Model Inputs Are the Same As Used for Figure 4-1.

RAM has not addressed whether or not the new proposed bedrock aquifer ACLs are ALARA, as required by 10 CFR Part 40, Appendix A, Criterion 5B(6). We must assume any ACLs proposed by RAM are achievable by reasonable means—and the licensee did supply an ALARA argument in its earlier submittal (QMC, 2000). We, therefore, conclude that, for a given contaminant in Table 4-2, the lowest ACL to have been proposed by RAM must be reasonably achievable. The corollary conclusion is that any higher values are not ALARA. Thus, any ACLs subsequently proposed by the licensee should not be higher than any in Table 4-2, unless RAM revises its ALARA argument.

5 MONITORING METHODOLOGY AND SCHEDULE

In Attachment 1, RAM proposes to regularly sample POC and trend wells subsequent to ACL approval. The proposed schedule calls for sampling "twice a year for the first two years and once during the third year" and then once every three years until transfer to the U.S. Department of Energy. This schedule may be appropriate for the bedrock aquifers, for which flow and transport are better constrained. The changes in frequency, however, would be best supported by objective analysis of monitoring results, with approval from the NRC staff. For example, the frequency should not be decreased if contaminants are rising with time.

The flow and attenuation models for the alluvial aquifer are highly uncertain, and this uncertainty reasonably should be reflected in the monitoring schedule. The case for such a high degree of attenuation rests on the implication from flow models (QMC, 2001) that the alluvium will be essentially dry by 100 years. This prediction, as well as contaminant levels, must be tested during monitoring. Staff should consider establishing objective criteria for judging the reliability of the prediction before approving a reduction in sampling frequency. It is our judgment that a sampling interval longer than 1 year is not appropriate until the continuing decline of alluvium water levels is confirmed.

The proposed lists of analytes to be monitored (Table 4 of Attachment 1) include only the contaminants for which ACLs have been requested, plus chloride and pH. This list should include all contaminants and parameters currently listed in the site license for each aquifer, to provide confidence, in light of model uncertainties, that the corrective action program was successful. The additional analytes will aid in interpreting any trends noted in the contaminants for which ACLs were requested.

6 SUMMARY

1 • The proposed set of POC and trend wells is acceptable for the alluvial and bedrock aquifers.

2 • Although the retardation factor employed in alluvial aquifer transport modeling was acceptable, the attenuation factor for setting ACLs in the alluvial aquifer does not consider the high degree of model sensitivity to the simulation period. Given the poorly constrained nature of alluvial transport modeling, as well as the rapid rise in attenuation factor with time at approximately 100 years (Figure 4-1), we recommend use of an attenuation factor of 0.02.

3 • An incorrect modeling method, resulting in overestimation of attenuating capacity (i.e., underestimation of attenuation factor), was used for establishing an attenuation factor for the bedrock aquifers. The licensee should revise the modeling method and propose a new set of ACLs. The retardation factor employed in bedrock modeling is acceptable.

4 • Revised ACLs should not be higher than any previously proposed, because those previous values were assumed to be ALARA. (October 2003 revision ?) Original Application + RAI

5 • The NRC staff should consider making monitoring schedule decisions based on objective criteria. This approach is particularly important for the alluvial aquifer, because of uncertainty in its flow and attenuation behavior.

6 • The NRC staff should consider making the lists of analytes for monitoring the same as the current lists in the site license.

7 REFERENCES

NRC. NUREG–1620, "Standard Review Plan for the Review of a Reclamation Plan for Mill Tailings Sites under Title II of the Uranium Mill Tailings Radiation Control Act of 1978." Rev. 1. Washington, DC: NRC. 2003.

Pickett, D.A., J.R. Winterle, and L.D. Howard. "Final Evaluation of Alternate Concentration Limit Applications, Rio Algom Mining, LLC, Mill Facility, Ambrosia Lake, New Mexico." San Antonio, Texas: CNWRA. 2003.

QMC. "Application for Alternate Concentration Limits in the Alluvial Materials at the Quivira Mill Facility Ambrosia Lake, New Mexico." Grants, New Mexico: QMC. 2001.

———. "Corrective Action Program and Alternate Concentration Limits Petition for Uppermost Bedrock Units Ambrosia Lake Uranium Mill Facility near Grants, New Mexico." Grants, New Mexico: QMC. 2000.

RAM. "Response to Request for Additional Information—Corrective Action Program and Alternate Concentration Limits Petition for Uppermost Bedrock Units, Ambrosia Lake Uranium Mill Facility near Grants, New Mexico, and Application for Alternate Concentration Limits in the Alluvial Materials at the Quivira Mill Facility Ambrosia Lake, New Mexico." Ver. 1.1. Grants, New Mexico: RAM. 2003.

van Genuchten, M.Th. and W.J. Alves. "Analytical Solutions of the One-Dimensional Convective-Dispersive Solute Transport Equation." *Technical Bulletin of the U.S. Department of Agriculture, 1661*. Washington, DC: U.S. Department of Agriculture. 1982.

APPENDIX B

Well Testing Procedures

1 Straddle-Packer Hydraulic Testing Procedure

1.1 Measurement and Test Equipment

Equipment needed for the straddle-packer hydraulic testing activities consists of equipment at the land surface and downhole equipment to be installed in the core holes. Equipment largely consists of "off-the-shelf" items ordered directly from qualified suppliers or standard equipment provided by qualified service companies. All equipment used will follow the supplier's operation and calibration specifications and will be documented as part of the QA records.

The downhole equipment (collectively referred to as the test tool) consists of two inflatable Baski packers, a shut-in valve, a pulse generator, a slotted test zone section, feedthroughs (tubes passing through the packers) to connect the pressure transducers to the intervals monitored, and gauge carriers to house the transducers, as shown in Figure D-1 (not to scale).

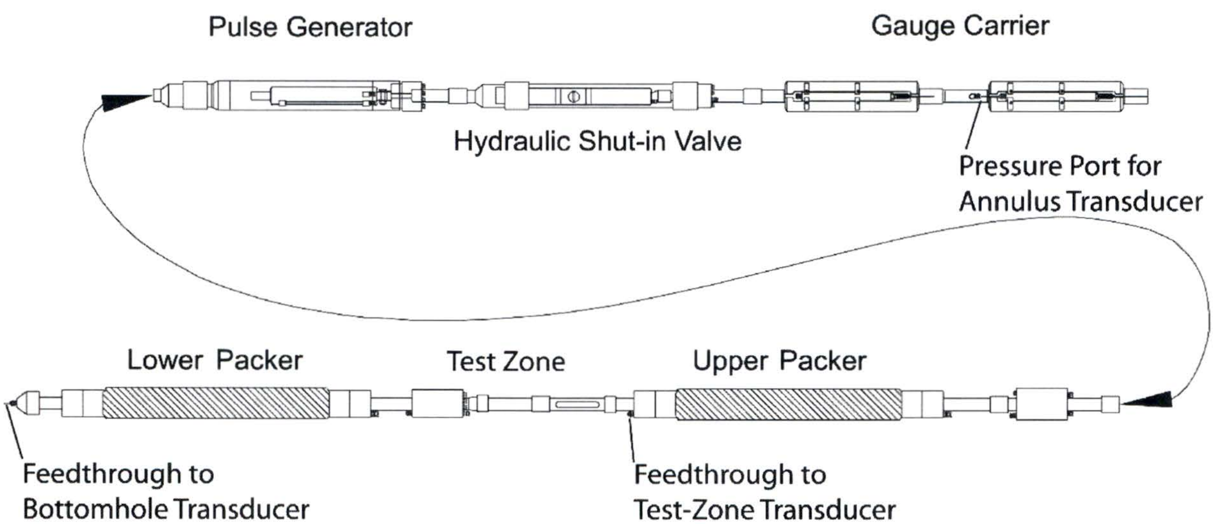

Figure D-1. Schematic of straddle-packer test tool.

The packers have sealing elements approximately 3 feet (ft) long to isolate the section of formation to be tested. The shut-in valve is a zero-displacement hydraulically actuated ball valve that separates the test interval from the tubing string that connects the test interval to ground surface. When the packers are fully inflated, closing the shut-in valve isolates the test interval. High-precision pressure transducers are mounted above the shut-in valve on gauge carriers and are connected to measurement points below the bottom packer and between the two packers by stainless steel lines and feedthroughs. Pressures are also monitored in the annulus between the borehole wall and pipe string above the top packer and in the pipe string.

The pulse tool is a hydraulic piston mounted in a sealed chamber connected to the test interval. In an isolated, or shut-in, test interval, extending or retracting the piston creates a near-instantaneous step change in pressure referred to as a "pulse" injection or withdrawal. Pistons with different

displacements are available so that, depending on the length of the test interval, an appropriate piston can be selected to create pulses typically between 10 and 20 psi. Pulse withdrawals can be created by extending the piston prior to shut-in, and subsequently retracting the piston after the shut-in valve is closed. As the volumes of the piston and test zone are known, the magnitude of a pulse can be used to directly and precisely calculate test-zone compressibility (C_{tz}), which is a composite compressibility that includes contributions from the test equipment ("compliance"), the borehole fluid, and the geomechanical response of the borehole wall.

The downhole equipment is connected to the surface with hydraulic lines and an armored umbilical cable with transducer power and communication lines. The hydraulic lines and umbilical cable are secured to the outside of the galvanized pipe string that provides the overall mechanical connection between the service rig at surface and the downhole tool.

With the exception of reels for the stainless steel hydraulic lines and the umbilical cable, all surface equipment is contained within a customized trailer. The trailer contains the data-acquisition system (DAS) computer and equipment, intensifier pumps, and the hydraulic line control panel. The DAS acquires data from the downhole gauges, as well as additional transducers measuring barometric pressure and pressures on each hydraulic line. Data can be queried and viewed on-site, or can be accessed remotely over the internet using a secure web-based interface, allowing real-time interaction between personnel performing the tests and analysts at other locations to ensure that the proper tests are performed and the data are acceptable.

1.2 Straddle-Packer Hydraulic Testing Procedures

Straddle-packer hydraulic testing involves the following sequential activities:

- The test tool will be assembled, insofar as possible, on racks or on the ground in pieces as large as the pulling unit or workover rig can handle. The pieces so constructed will be connected in/over the hole, suspended from the rig. Pup joints will be used to provide the desired straddle length. All fittings will be carefully tightened. The packer-inflation line will be filled with water before connecting the line to the top packer. The lengths, diameters, and placement of all tool elements and gauges will be measured, and a sketch of the tool showing all of the measurements will be made in the Scientific Notebook (SN). Digital photographs of the tool, showing a scale, will also be taken and inserted in the SN.
- Once the tool is completely assembled, the straddle-packer portion will be put inside a length of 6-inch-diameter steel casing for leak testing. The packers will be inflated inside the casing to provide an isolated interval in the casing. Within the radially unsupported casing, packers should be inflated to a maximum of 500 psi to avoid overpressures leading to casing failure. A compressed nitrogen (or air) source will be connected to the tubing at the top of the tool and the isolated interval will be pressurized to at least 100 psi (maximum of 200 psi). All fittings and connections will then be sprayed with soapy water to check for leaks. Any fittings or connections found to be leaking will be tightened or replaced until no leaks remain. The packers shall then be deflated. The shut-in (SI) valve will then be closed, and the interior

section of the upper tool (open to the inside of the tubing string) will be filled with fluid and pressurized to at least 300 psi with the intensifier pump. The connections on the sediment trap and SI valve housing will be carefully examined for leaks.

- If any portion of the leak test fails, all exposed fittings and connections will again be checked for leaks and repaired as needed. After all leaks have been corrected, the tool will be reset in the casing and the entire leak-test process will be repeated until there is no further evidence of leaks. All gauges will be mounted in the gauge carriers and connected to the communication cable. Communication between the gauges and DAS will be verified.
- A pipe tally will be prepared by measuring and recording (to the nearest 0.01 ft) the lengths of enough joints of galvanized pipe to reach the desired test depth. The joints will be measured from the top of the coupling on one end to the point at which threads begin on the other end of the joint. The joints will be numbered sequentially, writing with chalk on the joint or coupling. All available pup joints will also be tallied.
- Based on the target depth and tool measurements, the number of full joints of pipe needed for the tool installation will be calculated. Pup joints will be added as needed to position the tool precisely. In selecting pup joints, allowance will be made for handling requirements at the surface. All pipe tallies and depth calculations will be checked by a second individual before testing of an interval begins.
- The test tool will be lowered into the core hole on galvanized pipe to its desired position with respect to the first interval to be tested.
- Once the tool is at the desired depth, all transducers will be connected to the DAS and data acquisition will be initiated. The shut-in valve will be maintained in an open position while the packers are inflated. The packers will be inflated to a pressure between 400 and 500 psi (measured at ground surface).
- The pulse piston will be set in its extended position (to enable a pulse-withdrawal test), after which the shut-in valve will be closed. The test-zone pressure should then begin to change relative to the annulus pressure (which might change slowly) and the pressure in the pipe (which should be constant) as the test-zone pressure equilibrates with the pressure of the interval to be tested. The bottom-hole pressure should show a pressure increase during packer inflation, and then may either increase or decrease depending on the natural formation pressure in the interval isolated.
- Enough water should be bailed or otherwise removed from the pipe to lower the pressure, which should be similar to the annulus pressure, by ~10 psi. This provides evidence that the shut-in valve is not leaking during a pulse test and prepares the tool for a slug-withdrawal test, if one is planned or necessary. The system will then be allowed to stabilize for up to 1 hr.
- The Test Leader will monitor the test-zone equilibration trend to determine when it is well-enough defined to allow testing to begin. Once the Test Leader determines that testing can begin, the pulse piston will be retracted to initiate a pulse-withdrawal test.
- The pulse test should continue until the pressure has recovered to within 0.5 psi of its pre-test value, or until on-going real-time analysis of the test data indicates that the hydraulic conductivity of the interval has been estimated to within less than an order of magnitude of uncertainty.

- If full pulse recovery occurs in less than 15 minutes, a test more appropriate to the apparently high hydraulic conductivity will be performed. The shut-in valve will be opened to initiate a slug-withdrawal (rising head) test. The Test Leader will evaluate the pressure data from the test zone in real time to determine if the test should be continued as a slug test or converted to a DST. Subject to the discretion of the Test Leader, the following guidelines will be used to determine if and when a slug-withdrawal test will be converted to a DST:
  - If 30% of the initial slug has dissipated after 1 hour (hr), the test will remain a slug test.
  - If 30% of the initial slug has not dissipated after 1 hr, the shut-in valve will be closed and the test will be converted to a DST. The time during which the shut-in valve was open will constitute the DST flow period and the time after shut-in will constitute the DST buildup period.
- Slug tests and DST buildup periods should ideally continue until at least 98% pressure recovery has occurred. They may be terminated sooner if the Test Leader determines that the data already collected are adequate for test analysis.
- After testing is terminated, the shut-in valve will be set to its normal open position, the packers will be deflated, and the test tool will be moved down to the next interval to be tested in the borehole. Careful records will be kept in the SN of the pipe joints added to or removed from the tool string and the pup joints used for the new installation. Packer inflation and testing will then proceed as described above.

After all testing is complete, the tool will be removed from the core hole and reinstalled in the 6-inch casing at the surface. The packers will be inflated with the shut-in valve open, after which the shut-in valve will be closed. After a few minutes of pressure stabilization, the pulse piston will be extended to create a pressure pulse in the test interval. The test interval pressure will then be monitored to verify that the tool was leak-free throughout the testing.

2 Pneumatic Hydraulic Testing Procedure

2.1 Measurement and Test Equipment

Equipment needed for the pneumatic hydraulic testing activities consists of equipment to be installed in the wells and equipment to control and monitor the tests. Equipment largely consists of "off-the-shelf" items ordered directly from qualified suppliers or standard equipment provided by qualified service companies. All equipment used will follow the supplier's operation and calibration specifications and will be documented as part of the QA records.

The equipment installed in the wells includes a Kapsoid wellhead and two pressure transducers, one installed in the air-filled headspace between the water surface in the well and the Kapsoid wellhead and the other installed below the water surface in the screened interval of the well. The Kapsoid wellhead creates a pressure-tight seal at the top of the well casing, and has fittings to allow gas entry to and exit from the well as well as pressure measurements in the well. If any monitoring wells are nearby, pressure transducers are also installed in them below the water surface.

The pneumatic test control system comprises an air compressor, two flow control devices, the Kapsoid wellhead, connectors, hoses, and a data acquisition and control system (DACS), all housed within a customized trailer. The maximum pressure that may be applied to this system is 150 psi and is controlled by the output of the compressor system. Because all assembles have a safety pressure rating of at least 180 psi, a pressure relief control is not needed in the system. A sketch of the pneumatic test system is show in Figure D-2.

An air compressor generates the air pressure necessary to conduct the test. The compressor has a maximum pressure generation of 150 psi. The air compressor outputs pressurized air to a 3/8" I.D. braided hose (rated to 300 psi), which is connected to ½" Stainless Swagelok Tubing (rated to 3700 psi). The ½" Swagelok Tubing connects to Goodyear Horizon ½" I.D. braided hose (rated at 200 psi). The Goodyear Horizon hose attaches to one of the two Alicat Scientific Precision Gas Mass Flow Controllers (casing rated to 500 psi) which is immediately connected to a Swagelok "T" fitting (rated to a minimum of 4900 psi). The output of the Alicat Flow Controllers requires a ¾" OD down-step to ½" OD Swagelok fittings. It is important to note that the listed rating of 145 psi given on the spec sheets for the Alicat Flow Controllers is the working pressure for its internal valve, and the burst pressure is 180 psi. Exceeding the 145 working pressure will not create a hazard to personnel because the valve is contained within the stainless steel housing for the sensor (rated at 180 psi).The "T" fitting is connected to the second Alicat Scientific Flow Controller and a second section of Goodyear Horizon ½" I.D. braided hose (rated to 200 psi). The second Alicat Gas Flow Controller vents to the atmosphere. The output hose connects to the Kapsoid wellhead (rated to 384 psi) which is secured inside the top of the well casing. The configuration of the flow controllers is such that the first will regulate pressure increases into the well and the second will regulate pressure decreases out of the well. There is also a locked arm valve on the Kapsoid wellhead to allow for direct pressure release.

The Alicat Flow Controllers are controlled by the data acquisition and control system (DACS), utilizing a feedback loop that maintains the flow settings specified by the user. The DACS acquires data from the transducers and the flow controllers, as well as an additional transducer measuring barometric pressure. Data can be queried and viewed on-site, or can be accessed remotely over the internet using a secure web-based interface, allowing real-time interaction between personnel performing the tests and analysts at other locations to ensure that the proper tests are performed and the data are acceptable.

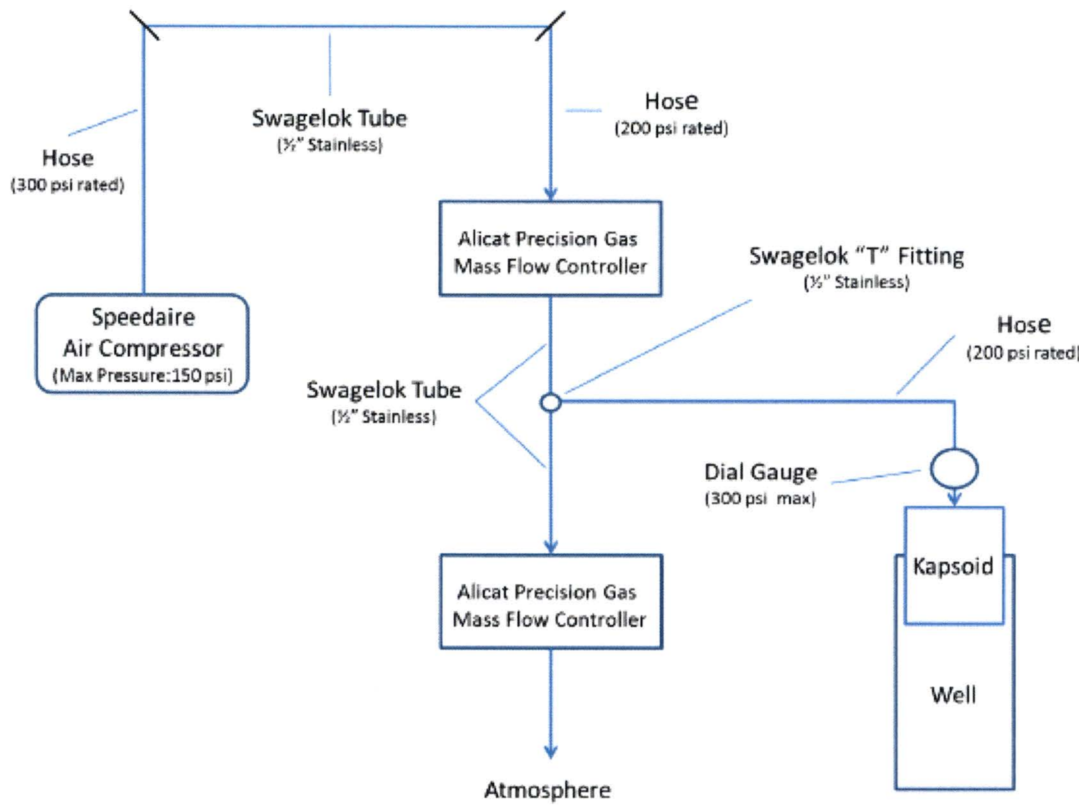

Figure D-2. Schematic of pneumatic testing system.

2.2 Pneumatic Hydraulic Testing Procedures

To conduct a pneumatic rising-head slug test, the air pressure in the headspace of the well is increased by the desired amount (e.g., 10 psi), which causes the water level in the well to go down. Once stable conditions are achieved, the air pressure is vented as rapidly as possible, and the water level begins to recover back to its original position. The recovery data can be analyzed as for any other slug test. Note that the water level should not be depressed below the top of the well screen.

A pneumatic sinusoidal test uses pneumatic pressure to create a sinusoidally varying pressure signal in a test well by manipulating the water level in the wellbore. By positioning pressure transducers both below the water level and in the head space above the water, both the total pressure (gas pressure + water pressure) acting on the formation and the changes in water level can be monitored. Changes in water level are used to calculate the flow rate into and out of the well.

Pre-test calculations/simulations are used to determine the optimal frequencies that will result in test objectives being met. Real-time analysis can then be used during actual test execution to determine if the estimated input frequencies need to be changed.

The procedures for conducting a pneumatic sinusoidal test are as follows:

- Increase the gas pressure in the test well, resulting in an increase in the total pressure. The system is then allowed to equilibrate for some period of time as the height of the water column decreases in response to the increased gas pressure, allowing the total pressure to return to static pressure (pre-test total pressure). During this equilibration period, a constant gas pressure above the water column is maintained.
- At the end of the equilibration period, the top of the water column is located at the desired position for the start of the sinusoidal test. From this position, gas pressure is used to control the rise/fall of the water column such that a sinusoidal pressure signal with a specified frequency is produced. The entire process is controlled by the DACS, utilizing a feedback loop that maintains the sinusoidal frequency specified by the user. The initial period of the sinusoidal cycle should be on the order of 1 minute.
- After two complete sine wave cycles, pause at the initial pressure to allow conditions to stabilize in the well.
- Initiate the next cycles with a period a factor of 2 to 3 greater than that of the previous cycles.
- After two complete sine wave cycles, pause at the initial pressure to allow conditions to stabilize in the well.

  Continue incrementing period by a factor of 2 to 3 until real-time analysis of the data from the test and observation wells shows test objectives have been achieved.

A pumping test is used to determine hydraulic properties of an aquifer by pumping one well for a specified length of time while collecting periodic water level measurements. Aquifer properties that can potentially be estimated using a pumping test include transmissivity (i.e., hydraulic conductivity multiplied by aquifer thickness), horizontal or vertical hydraulic conductivity, coefficient of storage, specific yield, and confining layer leakage. The two types of pumping tests most useful in determine aquifer hydraulic properties are the constant rate pumping test and the step-drawdown pumping test. The latter is best suited to determining the well's reduction in specific capacity (i.e., specific yield per unit of drawdown) with increasing yields while the former is the most widely used pumping test in determining the transmissivity and storage values for an aquifer.

A pumping test can be performed using only the pumping well, however specific information such as aquifer storage will not be obtainable. The use of observation wells in obtaining additional drawdown and/or recovery data over time is recommended whenever possible, especially when information on aquifer storage, anisotropy, vertical leakage, or the distance to a recharge or no–flow (i.e., barrier) boundary is needed.

In comparison to a slug test, a pumping test is representative of a much larger area and is therefore a better estimation of the hydraulic parameters of an aquifer. Conversely, a pumping test requires a greater commitment of resources (time, money, and equipment) and produces large volumes of

water that usually need to be containerized during the test.

Several analytical solution methods are available, two of the most widely used are the Theis (1935) equation and the Cooper and Jacob (1946) equation (often referred to as the Jacob straight–line method). A multitude of pumping test analysis software is available, though users are cautioned to make sure to understand all model or spreadsheet inputs as well as the assumptions of the governing equations. Far more extensive information on the design and analysis of pumping tests is covered in texts including, to name a few, Driscoll (1986), Kruseman and de Ridder (1991), Dawson and Istok (1991), Osborne (1993), and Fetter (1988).

Analyses of pumping tests require the following assumptions:

1. The water–bearing formation is homogeneous, isotropic, uniform in thickness, and infinite in areal extent.
2. The formation receives no recharge from any source.
3. The pumping well (i.e., the screened section) is fully penetrating the entire thickness of the water–bearing formation.
4. The water removed from storage is discharged instantaneously when the head is lowered.
5. The pumping well is 100% efficient.
6. All water removed from the well comes from aquifer storage.
7. Laminar flow exists throughout the well and aquifer.
8. The water table or potentiometric surface has no slope.

In reality, most pumping tests violate many of the above–mentioned assumptions to some degree or another. It is important to take all feasible measures to limit the extent of these violations whenever possible. Certainly, discussing these assumptions and any possible violations to them is important to any pumping test report.

3 Pumping Test Procedures

3.1 Design Considerations

Prior to performing an aquifer pumping test, all available site and regional hydrogeologic information should be assembled and evaluated. If retrievable, such data should include ground–water flow direction(s), hydraulic gradients, other geohydraulic properties, site stratigraphy, well construction details, regional water level trends, and the performance of other pumping wells in the vicinity of the test area. This information is used to select test duration, proposed pumping rates, and pumping well and equipment dimensions.

The precise location of an aquifer test is chosen to be representative of the area under study. In addition, the location is selected on the basis of numerous other criteria, including:

- Size of the investigation area;
- Uniformity and homogeneity of the aquifer;
- Distribution of contaminant sources and dissolved contaminant plumes;
- Location of known or suspected recharge or barrier boundary conditions;
- Availability of pumping and/or observation wells of appropriate dimension and screened at the desired depth; and
- Requirements for handling discharge.

The dimensions and screened interval of the pumping well must be appropriate for the tested aquifer. For example, the diameter of the well must be sufficient to accommodate pumping equipment capable of sustaining the desired flow rate at the given water depth. In addition, if testing a confined aquifer that is relatively thin, the pumping well should be screened for the entire thickness of the aquifer. For an unconfined aquifer, the wells should be screened at least in the bottom one– to two–thirds of the saturated zone and they may be screened throughout the entire thickness of the saturated zone.

Any number of observation wells may be used. The number chosen is contingent upon both cost and the need to obtain the maximum amount of accurate and reliable data. If at least three observation wells are to be installed and there is a known boundary condition, the wells should be configured such that water levels can be monitored both perpendicular and parallel to the boundary, with the pumping well at the intersection of the two well lines. If two observation wells are to be installed, they should be placed in a triangular pattern, non–equidistant from the pumping well. If observation wells are placed at 90–degree angles from the pumping well, radial anisotropy can be easily calculated. When observation wells are installed for aquifer testing purposes, they should be located at distances and depths appropriate for the planned method for analysis of the aquifer test data. Observation well spacing should be determined based upon expected drawdown conditions that are the result of the studies of geohydraulic properties, proposed pumping test duration, and proposed pumping rate.

3.2 Equipment

The equipment necessary to conduct a pumping test includes:

- a pump (suited for site conditions and requirements of the test)
- a water–level measuring devices (pressure transducers and/or electronic water–level indicators) accurate to at least 0.01 feet;
- a flow meter with totalizer (something as simple as a graduated bucket can also suffice, especially as backup);
- a digital watch with stopwatch function (used to keep time and to help determine discharge rate when using graduated containers);
- an electrical source (generator or electrical receptacle on site)

- an electronic data recorder programmed to suitable data collection intervals);
- barometer
- water quality meter(s) for noting changes as a function of capture zone
- hose or pipe to route pumped water away from test area
- gate valve
- adequately sized tank/container for storing water
- portable computer for preliminary analysis of data (optional)
- field forms and log book
- pen and paper
- backup equipment if feasible

Pumping equipment should conform to the size of the well and be capable of delivering the estimated range of pumping rates. The selection of flow meter, gate valve, and water transfer lines should be based on anticipated rates of water discharge. Both the discharge rate and test duration should be considered when selecting a tank for storing discharge water if the water cannot be released directly to the ground, sanitary sewer, storm sewer, or nearby water treatment facility.

3.3 Pumping-Test Preparations

If feasible for the site, slug tests or preliminary pumping tests (constant-rate or step drawdown) should be performed on the pumping well prior to the actual test. The preliminary pumping should determine the maximum drawdown in the well and the proper pumping rate should be determined by step drawdown testing. If the discharge rate varied by less than 5% (i.e., a constant–rate–pumping test), the time versus drawdown data from the pumping well can be used to estimate aquifer transmissivity. The preliminary pumping will also provide redevelopment of the pumping well by removing fines the adjacent formation and from the filter pack. Redevelopment of the pumping well will improve well efficiency during the pumping test and thus will allow for a better estimation of the aquifer's hydraulic properties. The aquifer should then be given time to recover before the actual pumping test begins (as a rule–of–thumb, one day). A record should be maintained in the field logbook of the times of pumping and discharge of other wells in the area, and if their radii of influence intersect the cone of depression of the test well.

Barometric changes may affect water levels in wells, particularly in semiconfined and confined aquifers. Therefore, it is advisable to monitor (perhaps hourly) the barometric pressure and water levels in key wells at least 24 hours (if possible) prior to performing a pumping test. If a ground–water fluctuation trend is apparent, the barometric pressure should be used to develop curves depicting the change in water level versus time. These curves should be used to correct the water levels observed during the pumping test. Ground–water levels and barometric pressures in the background should continue to be recorded throughout the duration of the test. If data loggers with transducers are used, backup field measurements should be collected in case of data logger malfunction. All measurements and observations should be recorded in a field notebook or on appropriate field forms.

All equipment should receive calibration, function checks, and fresh or charged batteries if needed.

3.4 Conducting the Pumping Test

Prior to the start of the pumping test, the following checks should be made:

- Ensure all piping, valves, and flow meters are properly installed.
- Ensure that all containers are in place to capture all pumped water.
- Ensure that the energy needs (batteries, electricity, or gas) for all equipment are provided, including backup energy sources for key equipment.
- Verify all equipment is present and place it at locations where it will be needed most.
- Verify the pump intake in located at the proper interval in the pumping well.
- Verify all transducers are placed at the proper depth and are properly secured so they will not move or be susceptible to contact form site personnel.
- Verify the data logger is properly programmed to record (typically logarithmically).
- Lower electronic water level tapes to just above the water levels inside each well.
- Warm up all equipment (such as a generator) that perform better after initial operations
- Ensure all personnel and field forms are in their start–of–test locations

Immediately prior to starting the pump, the water levels should be measured and recorded for all wells to determine the static–water levels upon which all drawdowns will be based. Data loggers should be reset for each well to a starting water level of 0.00 foot. At this time, a pumping test is initiated by starting the data logger and then starting the pump. The data logger needs to be started at least a split second before the pumping begins. Immediately afterwards, the time pumping started needs to be recorded along with water–level readings, especially at or near the pumping well. A suggested schedule for recording water–level measurements made by hand is as follows:

- 0 to 10 minutes – 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, and 10 minutes. It is important in the early part of the test to record with maximum accuracy the time at which readings are taken;
- 10 to 100 minutes – 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, and 100 minutes; and
- 120 minutes to end of test – every 1 hour (60 minutes).

At least 10 measurements of drawdown for each log cycle of time should be made both in the test well and the observation wells. Data loggers can be set to record in log time, which is very useful for data analysis. When logging data by hand, there should initially be sufficient field personnel to station one person at each well used in the pumping test. After the first two hours of pumping, two people are usually sufficient to complete most simplistic tests. It is advisable for at least one field member to have experience in the performance of pumping tests, and for all field personnel to have a basic familiarity with conducting the test and gathering data.

The discharge rate should be measured frequently throughout the test with a flow meter equipped with a totalizer and controlled to maintain a constant pump. This can be achieved, in part, by using a control valve. If used properly, the flow control valve can be pre-set for the test and will not have to be adjusted during pumping. When the pumping is complete, the total gallons pumped are divided by the time of pumping to obtain the average discharge rate for the test.

For a confined aquifer, the water level in the pumping well should not be allowed, if possible, to fall below the bottom of the upper confining stratum during a pumping test. The pitch or rhythm of the pump or generator provides a check on performance. If there is a sudden change in pitch, the discharge should be checked immediately and proper adjustments to the control valve or the generator engine speed should be made, if necessary. Do not allow the pump to break suction during the test. If the pump stops working during the test, make necessary adjustments and restart the test after the well has stabilized.

Water pumped from an aquifer during a pumping test should be disposed of in such a manner as to not allow the aquifer to recharge during the test. This means that the water must be piped away from the well and associated observation wells. Also, if contaminated water is pumped during the test, the water must be stored and treated or disposed of according to project specifications. The discharge water may be temporarily stored in drums, a lined, bermed area, or tanks. If necessary, it should be transported and staged in a designated secure area.

Field personnel should be aware that electronic equipment sometimes fails in the field. It is a good idea to record key data in the field logbook or on field forms as the data are produced. That way, the data are not lost should the equipment fail.

The total pumping time for a test depends on the type of aquifer and degree of accuracy desired. Economizing on the duration of pumping may yield less reliable results. It is always recommended to pump long enough to ensure the cone of depression achieves a stabilized condition. The cone of depression will continue to expand at an ever–decreasing rate until recharge of the aquifer equals the pumping rate, and a steady–state condition is established. The time required for steady–state flow to occur varies considerably from site to site. If steady–state conditions cannot be achieved in a reasonable time frame for the project, consider a test duration of at least 24 hours. A longer duration of pumping may reveal the presence of boundary conditions or delayed yield.

Use of portable computers allows time/drawdown plots to be made in the field. If data loggers are used to monitor water levels, the electronic data can be reviewed by scrolling with the data logger screen or via a portable computer. It is advisable to download the water level data before transporting the logger from the site.

3.5 References

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APPENDIX C

Standard Operating Procedures

7.0 SCOPE AND APPLICABILITY

This Standard Operating Procedure (SOP) covers common installation methods for a groundwater monitor well that may be implemented by INTERA field personnel during characterization, remediation, or monitoring of environmental sites.

Monitor wells are typically installed for monitoring purposes and as a primary mechanism by which representative groundwater samples are collected. Depending on site conditions, a groundwater monitor well may be screened across one or more interval(s) and the annulus around the well screen is packed with granular material appropriately-sized to reduce the migration of fines into the well. Typically groundwater monitor wells are installed via a two-stage drilling procedure: The upper soil/strata will be sealed from the aquifer using a cement–bentonite grout.

For most environmental characterization and monitoring purposes performed by INTERA personnel, a 2-inch (in) inside diameter (ID) monitor well completed via hollow stem auger (HSA) drilling method is sufficient and the most commonly applied. As such, methods outlined in this SOP are tailored to detail well installation procedures of this size and method; however, installation of monitor wells of different sizes or into borings completed by other methods follow the same general procedures outlined below.

Methods outlined in this SOP comply with the following ASTM Standard:

- D5092-04(2010)e1, *Standard Practice for Design and Installation of Groundwater Monitoring Wells* (ASTM, 2010).

This SOP should be used in conjunction with procedures presented in the Site-Specific Health and Safety Plan (SSHASP) and in site-specific investigation planning documents such as a Sampling and Analysis Plan (SAP), Field Sampling Plan (FSP), or Work Plan (WP). This SOP will also be commonly used in conjunction with and is referenced in the following INTERA SOPs:

- SOP 2, *Decontamination*;
- SOP 5, *Hollow-Stem Auger Drilling*; and
- SOP 8 *Monitor Well Development*.

7.1 General Monitor Well Construction via HSA

Schematic of a typical 2-in groundwater monitor well (above-ground completion or flush-grade completion) for the purposes of environmental characterization is presented as **Attachment 1**. Soil borings intended for 2-in well installation are typically advanced utilizing 4¼-inch ID HSA with an 8¾-in outside diameter (OD) auger bit. Procedure implementation of the HSA drilling method is detailed in INTERA SOP 5, *Hollow-Stem Auger Drilling.*

The borehole or HSA should be of sufficient diameter so that well construction can proceed without major difficulties. For open boreholes, the annular space should be

approximately 2 in to allow the uniform deposition of well materials around the screen and riser, and to allow the passage of tremie pipes and well materials without unduly disturbing the borehole wall. By this means, a 2-in well casing would require a 6" ID borehole.

If the projected total depth (TD) of the well is 20 feet (ft) or greater, the boring may require reaming with 6-in ID HSA with a 10-in OD auger bit. Installation of the well in a larger diameter boring reduces the problem of bridging of the filter pack or bentonite pellets.

Sometimes it is necessary to over-drill the borehole in anticipation of material entering the augers during center bit removal or knocking out of the bottom plug. Normally, 3 to 5 ft is sufficient for over-drilling. If a borehole is inadvertently drilled deeper than desired, it can be backfilled to the design depth with bentonite pellets, chips, or the filter sand that is to be used for the filter pack.

A borehole may also be over-drilled to allow for an extra space for a "sump" area below the well screen. This "sump" area provides a space to attach a 5 or 10 ft section of blank well casing to the bottom of the well screen. The extra space or "sump" below the well screen serves as a catch basin or storage area for sediment that flows into the well and drops out of suspension. As appropriate, these "sumps" are added to the well screens when wells are screened in aquifers that are naturally turbid and will not yield clear formation water (free of visible sediment) even after extensive development. The sediment can then be periodically pumped out of the "sump" preventing the well screen from clogging or "silting up". If sump installation is considered for a site, however, approval should be sought from the applicable regulatory agency prior to installation.

7.2 Application of Surface Casing

Surface casing is used as a means of isolating known or potentially contaminated soil, thus preventing possible downward migration of contamination in the borehole. Surface casing is a secondary casing surrounding a borehole down to the desired TD. It serves as an additional annular seal by not allowing upper intervals of soil to come into contact with advancing drilling and sampling equipment therefore minimizing the potential for cross-contamination.

When surface casing is required, care must be given to selecting the appropriate diameter of surface casing, ream auger, and lead auger to advance the boring to the desired TD. A minimum of a 14-in auger is needed to ream the borehole for installation of 10-in surface casing. This allows for the latter advancement of 4¼-inch ID by 8¾-in OD HSA. Similarly, a 16-in auger is utilized to ream the borehole for installation of a 12-in surface casing. This allows for the latter advancement of 6-in ID by 10-in OD HSA.

To isolate the upper portion of the borehole for installation of a 2–in monitor well, 10–inch diameter, Schedule 40 PVC casing (or other appropriate material) is set to the desired depth to seal off surface contamination. It is preferred that the base of the surface casing be seated in clay if stratigraphy permits.

The bottom of the casing is then sealed with a casing shoe to prevent entry of potentially contaminated water or soil into the casing during subsequent well installation. The casing shoe can be made using PVC coupling half filled with plaster-of-Paris or Portland cement. The shoe can be anchored to the base of the surface casing using stainless–steel sheet metal screws or pop rivets. A stainless–steel centralizer will be placed on the lower portion of the casing to ensure alignment of the casing within the borehole.

7.3 Procedure – Groundwater Monitor Well Installation

The borehole advanced for the purposes of installing a permanent groundwater monitor well should be bored, drilled, or augured as close to vertical as possible, and checked with a plumb bob or level. Deviation from plumb should be within 1° per 50 ft of depth. Slanted boreholes are undesirable and should be noted in the boring logs, final well construction logs, and the field logbook, as appropriate. Template well construction log forms are provided in the **Forms** section of this SOP.

1. The TD and volume of the borehole, including over-drilling if applicable, should be calculated and the appropriate materials (e.g. selected well casing and screen) procured and inspected prior to drilling and installation.
2. If placement of surface casing is required:
   - Drill borehole larger than the diameter of the surface casing down to the depth desired for the bottom of the surface casing
   - Set surface casing so that it extends from slightly above the ground surface, through the contaminated zone, and into uncontaminated material below
   - Grout the annulus between borehole and surface casing with a cement/bentonite slurry.The slurry can be mixed at a ratio of 6.5 gallons of potable water per 94-pound sack of Type I Portland cement. Bentonite powder should be added to the slurry at a ratio of 3% of the total Portland cement weight. Grout is typically tremied into place utilizing 1¼-in to 1½-in tremie pipe.
   - Wait at least 24 hours for the grout to cure prior to continuing drilling through the cased section of the borehole to the desired TD.
3. After completing the boring to the desired TD, well casing will be placed into the HSA pipe. Schedule 40 PVC (or heavier) or stainless steel (preferred for organic COCs), threaded, flush-joint casing is typically used. Alternate casing material may be utilized as approved by the overseeing regulatory agency. In all cases, the casing material selected for use must be compatible with the anticipated chemistry of the groundwater and identified COCs. Casing sections are typically applied in 5 or 10 ft lengths. When completed, the well casing should extend a minimum of 1 ft

above ground surface (if above grade completion) or 6 to 12 in below ground surface [bgs] (if completed below grade).

4. Well screen shall also be inspected prior to placement into the HSA pipe. Individual well screen sections are also typically 5 or 10 ft long and often have 0.010-in slot or 0.020-in slot openings.
   - Unless otherwise approved by the applicable oversight agency, a 20-foot section (maximum) of continuous-slot, machine slotted, or other manufactured PVC or stainless steel well screen shall be installed across the water table.
   - The bottom of the screen must be installed no more than 15 ft below the water table; the top of the well screen must be positioned not less than 5 ft above the water table.
   - For sites requiring a screen length exceeding 20 ft shall be carefully evaluated for the introduction of possible dilution effects during sampling.
   - Well screen slots must be appropriately sized for the formation materials and should be selected to retain 90 percent of the filter pack. A slot size 0.010-in is generally adequate for most installations. Screens created by cutting slots into solid casing with saws or other tools is not acceptable.
5. Before the well screen and casings are placed on the bottom of the borehole, at least 6 in of filter material should be placed at the bottom of the borehole to serve as a firm footing. If geologic conditions warrant and as approved by the appropriate regulatory agency, a 0.5- to 3-ft length of blank casing may also be placed beneath each well screen to act as a sump or reservoir for fine material (**Section 7.1**). All sections of casing and screen will be assembled on site to allow inspection immediately before installation.
6. As applicable, stainless–steel centralizers may be required and are attached to the screen or casing to help center the well in each boring and facilitate the subsequent placement of the filter pack, the bentonite seal, and the grout in the annulus. Monitoring wells with a TD of less than 50 ft generally do not require centralizers. If centralizers are used, however, they should be placed below the well screen and above the bentonite pellet seal. Specific placement intervals shall be determined based on site-specific conditions.
7. A filter pack (most commonly 16/30 or 20/40 silica sand, yet is dependent on the grain size of the geologic material), is placed in the annulus between the boring wall and the well screen. The purpose of the filter pack is to provide aquifer formation stability, minimize the entry of fine-grained material into the screen, and increase the effective well diameter and water collection zone. Recommended filter pack characteristics for common screen slot sizes is listed in **Attachment 2**.

- Whenever possible, the filter pack will extend above the top of the screen for a distance equal to 10% of the screen length, or a minimum of 2 ft, to allow for settlement of the filter pack and prevent the migration of the overlying seal material into the intake zone.
- The filter pack will be placed in such a manner that bridging of the material in the annulus is prevented. For wells deeper than 30 ft, the filter pack must be emplaced by a tremie pipe. Care should be taken not to damage the well screen or casing during placement of the filter pack using either agitation or the tremie pipe.
- The well should be surged or bailed to settle the filter pack and additional sand added, if necessary, before the bentonite seal is emplaced. If necessary, the filter pack material may be washed into the annular space with potable water to help prevent bridging.

8. A bentonite seal must be constructed immediately above the filter pack by emplacing bentonite chips or pellets (3/8-inch in size or smaller) with no added polymers in a manner that prevents bridging of the chips/pellets in the annular space. This seal is used to isolate the aquifer interval from the upper zones. The bentonite seal must be a minimum of 3 ft thick and hydrated with clean water. Adequate time should be allowed for expansion of the bentonite seal before installation of the annular space seal. One way of determining the appropriate amount of time for the pellets to hydrate, is to fill a clear jar half full with a sample of the pellets delivered to the site. The remaining headspace in the jar will then be filled with potable water. The time required to hydrate the pellets will be recorded. At a minimum, this will be the amount of time that the pellets in the borehole will be allowed to hydrate prior to grouting.
9. The annular space above the bentonite seal will be filled with an approved bentonite-based grout. Annular space seals must extend from the top of the bentonite seal to ground surface (for wells completed above grade) or to a level 3 to 6 in below the top of casing (for wells completed below grade) The grout will approximate Type I Portland cement (95–97%) and powdered bentonite (3–5%). One 94–cubic–pound sack of grout is typically mixed with 7 gallons of potable water. The grout mixture will be placed into the boring via the use of a tremie pipe, tubing, or direct pouring from the surface when appropriate. A tremie pipe must be used when placing sealing materials at depths greater than 20 ft bgs. Pumps may be used to facilitate mixing of the grout and to fill the borehole with grout.

7.4 Procedure – Surface Completion

Depending on site conditions, groundwater monitor wells may be completed either above or below grade. The appropriate surface completion required shall be established in the SAP or equivalent.

For monitor wells finished above grade:

1. A protective steel casing (shroud) and removable locking cap will be installed over the casing. The shroud must be large enough in diameter to allow easy access for removal of the cap.
2. As needed, vent holes may be placed in the shroud and in the riser pipe to allow the boring to communicate with the atmosphere. For the shroud, an approximately ¼–inch hole near the ground surface is recommended to facilitate gas venting and to prevent the accumulation of fluids in the annulus between the well casing and the shroud. The well riser pipe may be vented with an approximately ¼–inch hole near the top of the pipe below the bottom of the protective cap.
3. A concrete pad (2-foot minimum radius, 4-inch minimum thickness) shall be poured around the shroud and wellhead. The concrete and surrounding soil must be sloped to direct rainfall and runoff away from the wellhead (at approximately 2%). The installation of steel posts around the well shroud and wellhead is recommended for monitoring wells finished above grade to protect the wellhead from damage by vehicles or equipment.

Alternatively, monitoring wells may be completed below grade.

1. A manhole cover or well box/vault shall be installed around the well casing and a lockable expandable well cap shall be placed in the top of the casing. The well vault shall be flush-mounted and watertight and, as appropriate, rated to withstand traffic loads.
2. The cover must be secured with at least one bolt and shall indicate that the wellhead of a monitoring well is contained within the vault.
3. A concrete pad (2-foot minimum radius, 4-inch minimum thickness) shall be constructed at the base of the protective casing. The concrete and surrounding soil must be sloped to direct rainfall and runoff away from the wellhead (at approximately 2%).

7.5 References

ASTM International (ASTM), 2010. Standard Practice for Design and Installation of Ground Water Monitoring Wells. D5092-04 (Reapproved 2010)e1.

New Mexico Environment Department (NMED). 2011. New Mexico Environment Department Ground Water Quality Bureau Monitoring Well Construction and Abandonment Guidelines. Revision 1.1. March.

7.6 Other Sources

Environmental Protection Agency. 1991. Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitor Wells. USEPA Office of Research and Development. EPA160014-891034. March

———. 2013. Design and Installation of Monitoring Wells. SESDGUID-101-R1. USEPA Science and Ecosystem Support Division Region 4. Revision 1. January 29.

Texas Commission on Environmental Quality. 2001. Standard Operating Procedure No. 5.5 Monitoring Well Installation And Completion. Revision 1. April 29.

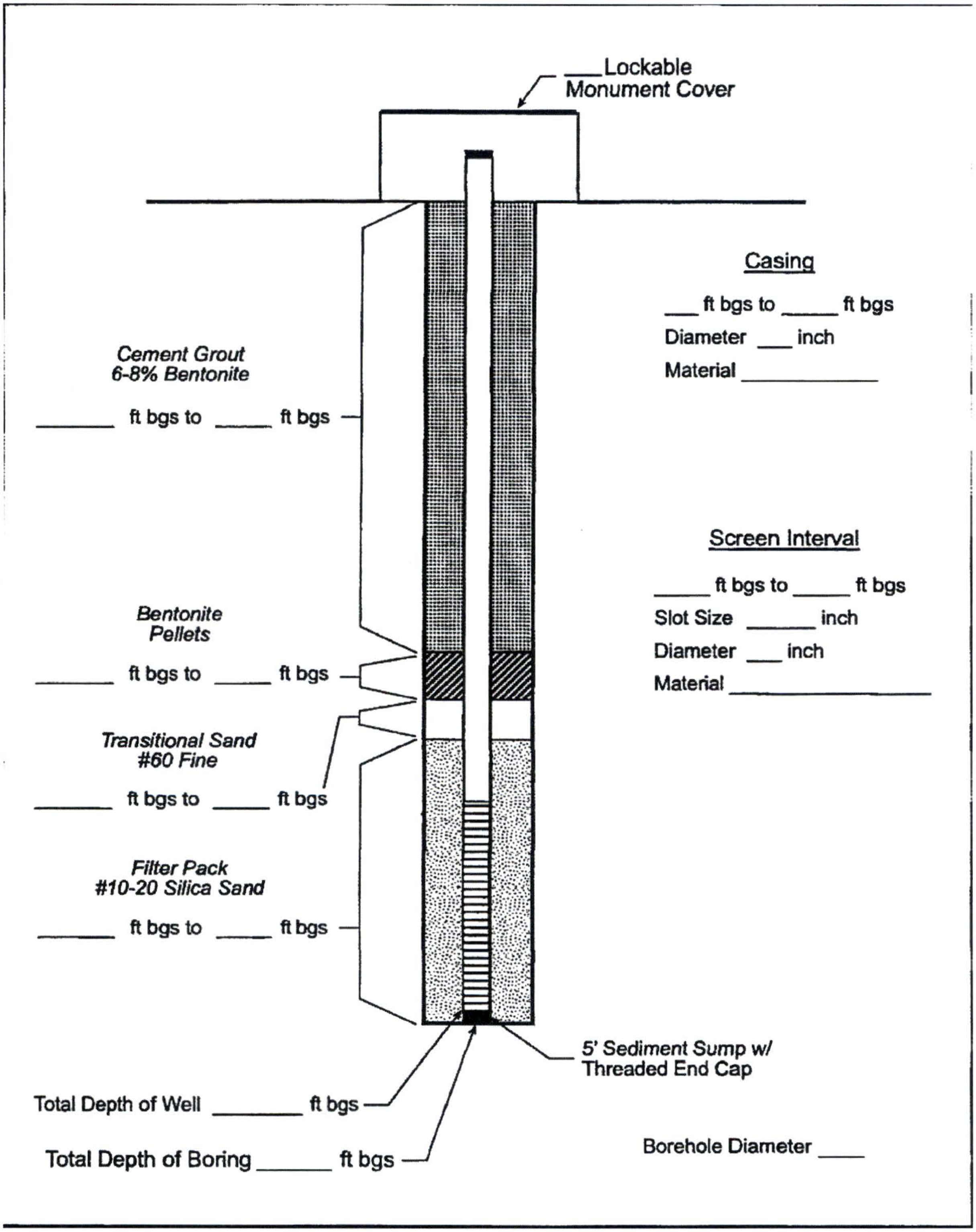
7.7 Forms or Attachments

Form A: INTERA General Well Construction Schematic – Type 1
Form B: INTERA General Well Construction Schematic – Type 2
Form C: INTERA General Well Construction Schematic – Type 3
Form D: INTERA General Well Construction Schematic – Type 4
Form E: INTERA General Well Construction Schematic – Type 5

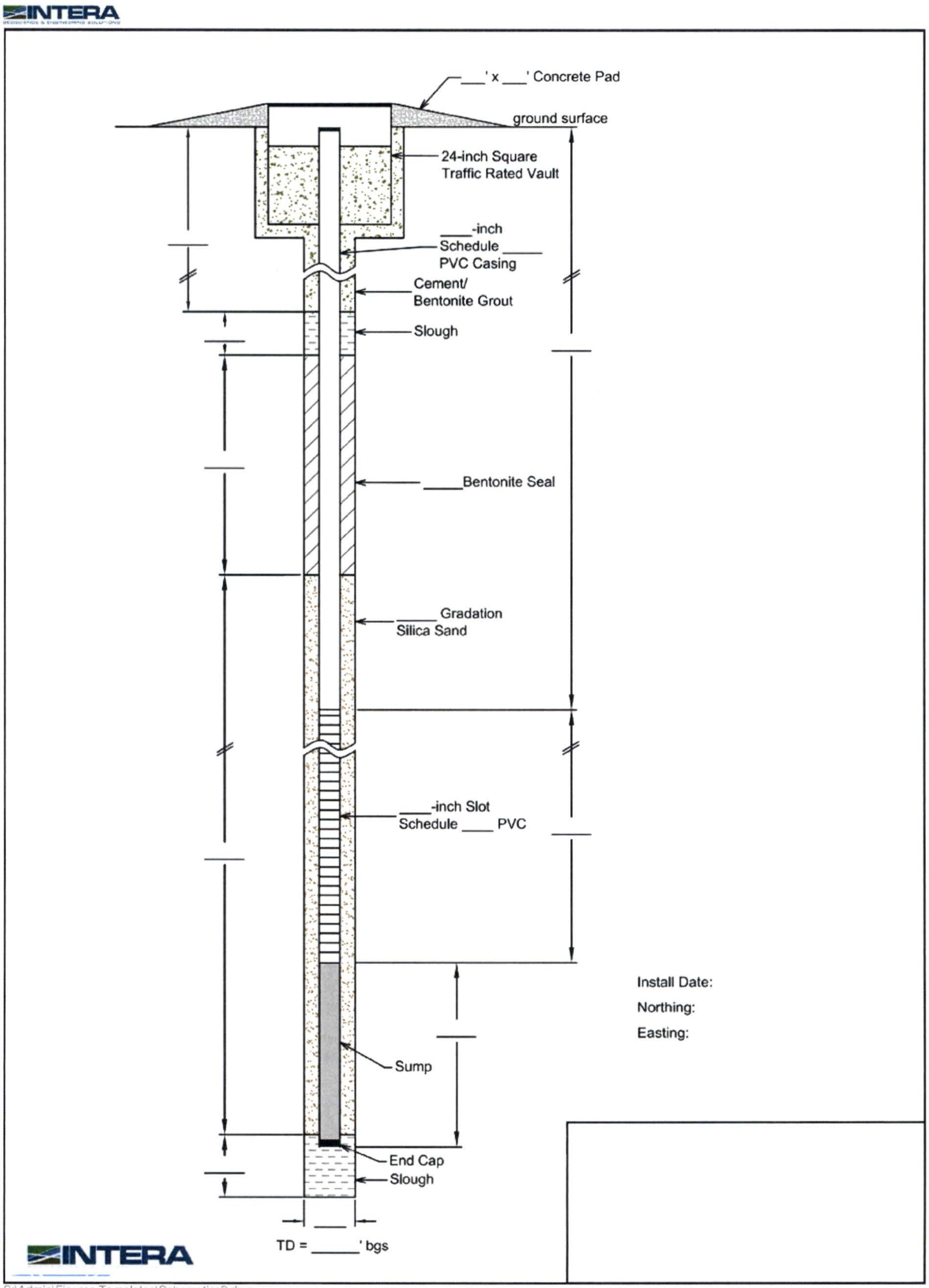
Attachment 1: Groundwater Monitor Well Construction Requirements
Attachment 2: Recommended Filter Pack Characteristics for Common Screen Slot Sizes

7.8 Document History

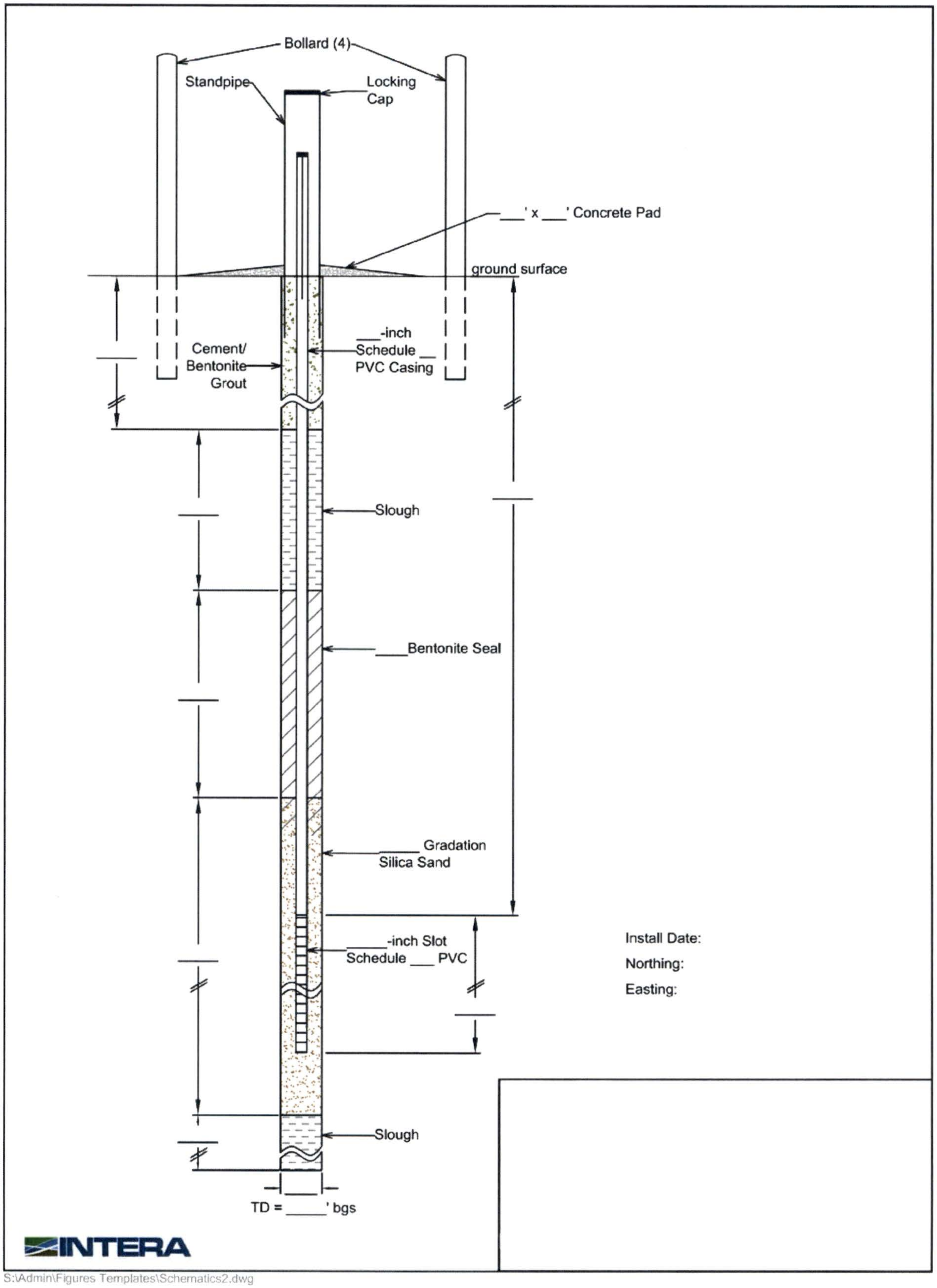
Revision	Effective Date	Lead Author	Summary of Changes
00	4/2004	Taimur Malik	Original version
01	2/2015	Kate Herrell	Revised for inclusion in COA Brownfields QAPP


___Lockable
Monument Cover
Casing
___ ft bgs to _____ ft bgs
Diameter ___ inch
Material ___________
Cement Grout
6-8% Bentonite
_______ ft bgs to _____ ft bgs
Screen Interval
_____ ft bgs to _____ ft bgs
Slot Size ______ inch
Diameter ___ inch
Material ______________
Bentonite
Pellets
_______ ft bgs to _____ ft bgs
Transitional Sand
#60 Fine
_______ ft bgs to _____ ft bgs
Filter Pack
#10-20 Silica Sand
_______ ft bgs to _____ ft bgs
5' Sediment Sump w/
Threaded End Cap
Total Depth of Well ________ ft bgs
Total Depth of Boring ______ ft bgs
Borehole Diameter ____

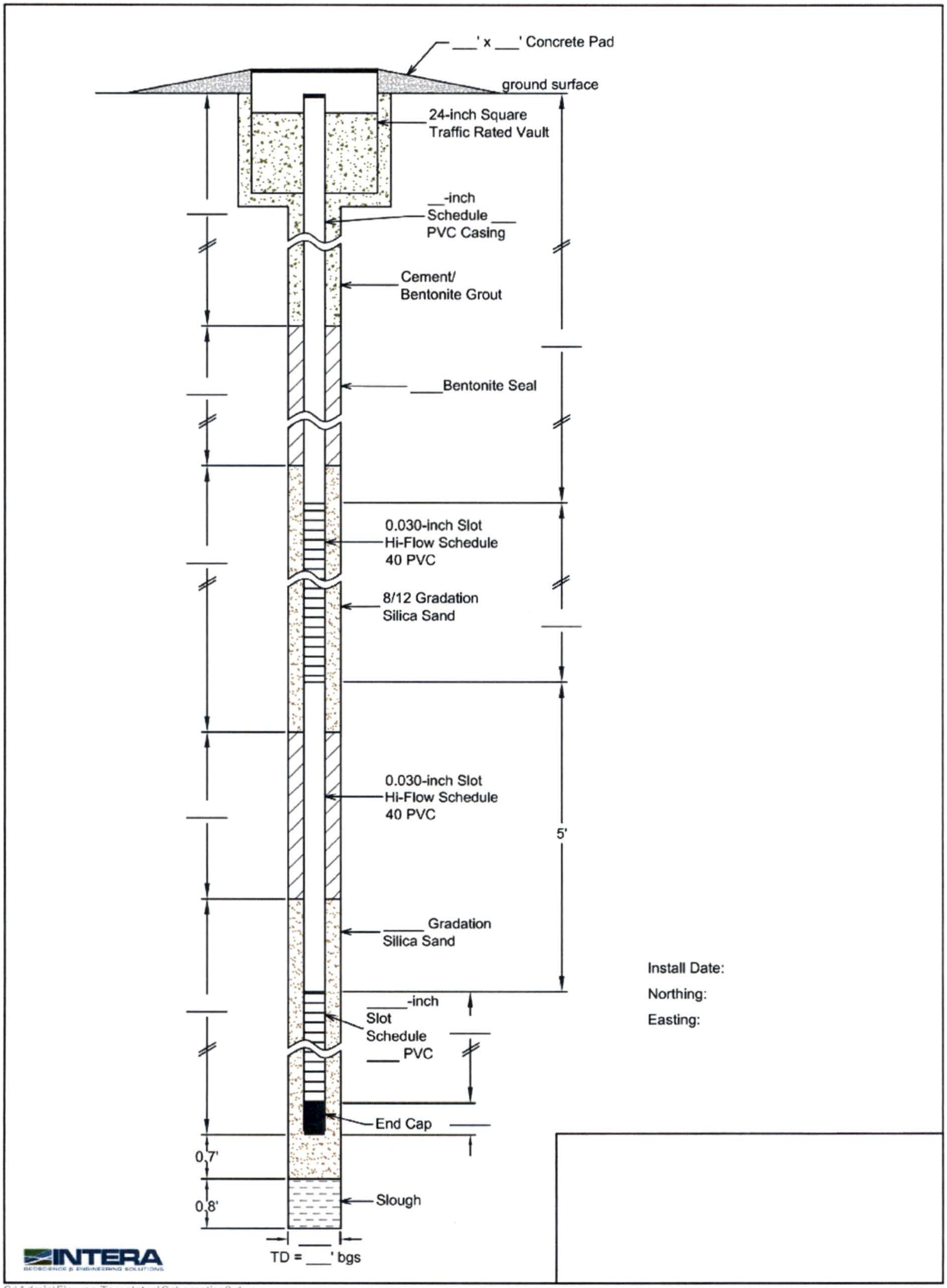
Form A


___' x ___' Concrete Pad
ground surface
24-inch Square
Traffic Rated Vault
___-inch
Schedule ___
PVC Casing
Cement/
Bentonite Grout
Slough
___Bentonite Seal
___ Gradation
Silica Sand
___-inch Slot
Schedule ___ PVC
Sump
End Cap
Slough
TD = ______' bgs
Install Date:
Northing:
Easting:
S:\Admin\Figures Templates\Schematics2.dwg

Form B


Bollard (4)
Standpipe
Locking Cap
___' x ___' Concrete Pad
ground surface
Cement/ Bentonite Grout
___-inch Schedule ___ PVC Casing
Slough
___ Bentonite Seal
_____ Gradation Silica Sand
_____-inch Slot Schedule ___ PVC
Slough
TD = _____' bgs
Install Date:
Northing:
Easting:
INTERA
S:\Admin\Figures Templates\Schematics2.dwg

Form C



S:\Admin\Figures Templates\Schematics2.dwg

Form D

Borehole Materials

Well S

____

____

____

Well M

____

____

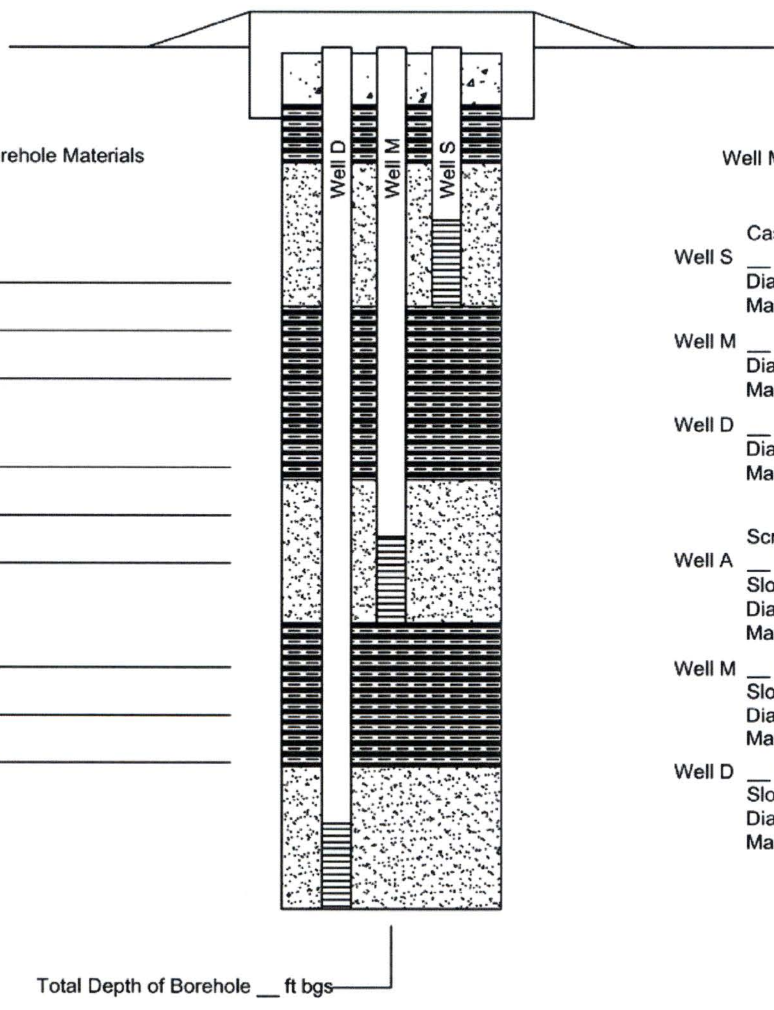
____

Well D

____

____

____



Well Materials

Casing

Well S __ ft bgs to __ ft bgs
Diameter ___"
Material: __________

Well M __ ft bgs to __ ft bgs
Diameter ___"
Material: __________

Well D __ ft bgs to __ ft bgs
Diameter ___"
Material: __________

Screen Interval

Well A __ ft bgs to __ ft bgs
Slot Size: ___"
Diameter ___"
Material: __________

Well M __ ft bgs to __ ft bgs
Slot Size: ___"
Diameter ___"
Material: __________

Well D __ ft bgs to __ ft bgs
Slot Size: ___"
Diameter ___"
Material: __________

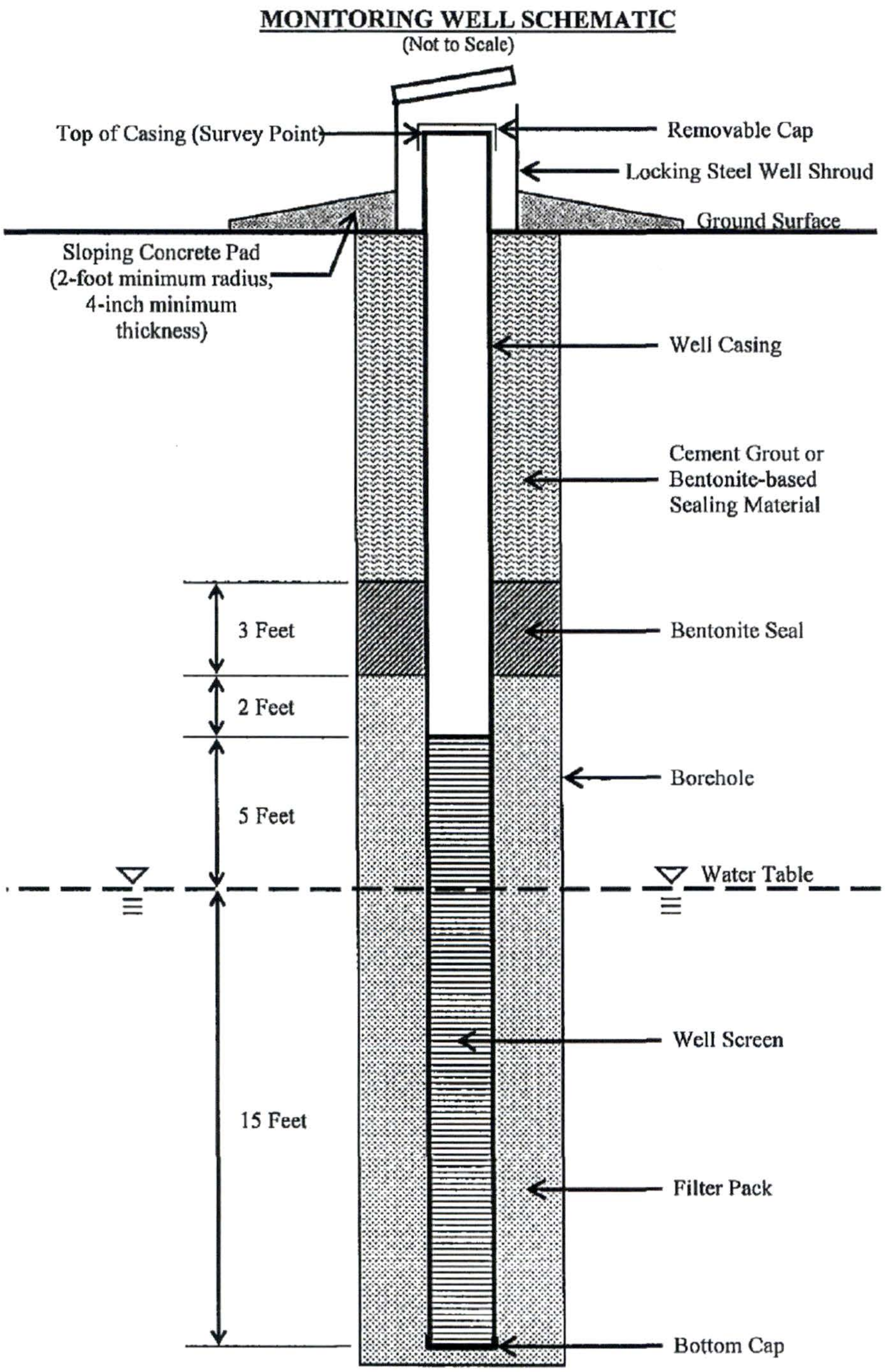
Note(s):

Well
Completion Diagram

S:\Admin\Figures Templates\Schematics2.dwg

Form E

Attachment 1: Groundwater Monitor Well Construction Requirements



Excerpted from (NMED, 2011)

Attachment 2: Recommended Filter Pack Characteristics for Common Screen Slot Sizes

Size of Screen Opening, mm (in.)	Slot No.	Sand Pack Mesh Size Name(s)	1 % Passing Size (D-1), mm	Effective Size, (D-10), mm	30 % Passing Size (D-30), mm	Range of Uniformity Coefficient	Roundness (Powers Scale)
0.125 (0.005)	5[A]	100	0.09 to 0.12	0.14 to 0.17	0.17 to 0.21	1.3 to 2.0	2 to 5
0.25 (0.010)	10	20 to 40	0.25 to 0.35	0.4 to 0.5	0.5 to 0.6	1.1 to 1.6	3 to 5
0.50 (0.020)	20	10 to 20	0.7 to 0.9	1.0 to 1.2	1.2 to 1.5	1.1 to 1.6	3 to 6
0.75 (0.030)	30	10 to 20	0.7 to 0.9	1.0 to 1.2	1.2 to 1.5	1.1 to 1.6	3 to 6
1.0 (0.040)	40	8 to 12	1.2 to 1.4	1.6 to 1.8	1.7 to 2.0	1.1 to 1.6	4 to 6
1.5 (0.060)	60	6 to 9	1.5 to 1.8	2.3 to 2.8	2.5 to 3.0	1.1 to 1.7	4 to 6
2.0 (0.080)	80	4 to 8	2.0 to 2.4	2.4 to 3.0	2.6 to 3.1	1.1 to 1.7	4 to 6

[A] A 5-slot (0.152-mm) opening is not currently available in slotted PVC but is available in Vee wire PVC and Stainless; 6-slot opening may be substituted in these cases.

Excerpted from (ASTM, 2004)

8.0 SCOPE AND APPLICABILITY

This Standard Operating Procedure (SOP) covers common development methods of a groundwater monitor well that may be implemented by INTERA field personnel during characterization, remediation, or monitoring of environmental sites as follows:

- Mechanical Surging (**Section 8.1.1**);
- Air Surging or Jetting (**Section 8.1.2**);
- Pumping (**Section 8.1.3**); and
- Bailing (**Section 8.1.4**).

The intent of well development is to:

- Reduce compaction and intermixing of grain sizes produced during drilling;
- Increase porosity and permeability of the artificial filter pack via removal of any fines introduced near the screen during drilling/well installation; and
- Remove any residual drilling fluids/foreign material from the borehole or the adjacent natural formation.

Common well development methods as outlined in this SOP, used solely or in conjunction, facilitate the movement of water through a well screen thereby moving any residual fines (silt and clay particles) trapped in the filter pack around the well screen into aqueous suspension within the well casing. The sediment-laden water is then removed from the well casing using a pump, bailer, or air compressor.

A groundwater monitor well is determined to be effectively developed upon achievement of one or more of the following criteria, as applicable:

1. At least 3 well casing volumes have been removed and water quality parameters for pH, temperature, and conductivity, as appropriate, have stabilized as defined in **Section 8.3** of this SOP; or
2. Five well casing volumes have been removed.

Development of a groundwater monitor well should occur no earlier than **24 hours** after initial installation to allow enough time for (1) the well's annular seal and grout to properly set and (2) to maximize the hydraulic connection between the well and surrounding aquifer material (TCEQ, 2001). Settling periods longer than 24 hours may be required by different state or federal agencies (EPA, 2001). Settling periods longer than 24 hours may also be required for wells where a more vigorous well development method (e.g. surging) was used to minimize the potential for well development procedures to compromise the annular seal. Site-specific development criteria will be specified in the SAP/FSP/WP.

With the exception of some self-contained drive point samplers as discussed in INTERA SOP 6, *Direct Push Drilling*, a typical groundwater monitor well requires development **prior** to obtaining any necessary water level measurements or water quality samples.

NOTE: The process of well development should not be confused with well purging, the purpose of which is to remove from the well casing stagnant or "old" groundwater not representative of aquifer conditions immediately prior to a sampling event. Wells, if installed, should be developed; alternatively, well purging, as detailed in INTERA SOP 10, *Monitor Well Sampling for Groundwater*, is commonly performed only prior to the collection of a representative groundwater sample.

The methods outline in this SOP also apply to monitor wells in which excessive siltation has occurred. During a well's operation (ranging from months to years), fines may accumulate in the bottom of the well casing and impact the effective hydraulic connectivity of the well with the surrounding aquifer. In this case, well redevelopment may be selected as an attempt to re-establish a complete hydraulic connection.

Methods outlined in this SOP comply with the following ASTM Standard:

- D5521/D5521M-13, *Standard Guide for Development of Groundwater Monitoring Wells in Granular Aquifers* (ASTM, 2013).

This SOP should be used in conjunction with procedures presented in the INTERA Site-Specific Health and Safety Plan (SSHASP) and in site-specific investigation planning documents such as a Sampling and Analysis Plan (SAP), Field Sampling Plan (FSP), or Work Plan (WP). This SOP will also be commonly used with and is referenced in the following INTERA SOPs:

- 2, *Decontamination;*
- 9, *Water Level Gauging; and*
- 10, *Monitor Well Sampling for Groundwater.*

8.1 Common Well Development Methods

The intent of this section is to provide a brief description of the four common well development methods that may be utilized by INTERA field personnel during characterization, or monitoring of environmental sites. These methods as well as other less common methods are available for well development and application considerations are summarized in **Attachment 2**.

Which method(s) is most appropriate for a site/well is dependent on site conditions (e.g., subsurface geology, level of contamination, depth to water (DTW)), equipment limitations (well construction), and any state-specific requirements (e.g., introduction of foreign material, particularly water, or use of vigorous methods with a higher risk of damage to well/formation); however, the chosen method of well development should be selected foremost on its relative success of attaining site data quality objectives, which for most environmental investigations, is obtaining a representative sample of

groundwater conditions. For each site, the well development method selected shall be documented in the SAP/FSP/WP.

General field implementation of well development for a site corresponding to one or more of the common well development methods listed below is further detailed in **Section 8.4**.

8.1.1 Mechanical Surging

Mechanical surging is one of the more commonly applied methods of well development and involves forcefully moving water into and out of the well screen, thereby increasing the porosity in the immediate vicinity of the well. Mechanical surging is typically completed using a fitted surge block or, in some cases, a bailer (**Section 8.1.4**) may also be used. A surge block consists of one or more flat rubber rings that fit closely inside the well and seals the well casing interior and is operated like a plunger beneath the water level. Because it seals closely to the casing, it has a very direct positive action on water movement within the well; as such, it is critical that the diameter of the flexible rings chosen for the surge block are sufficient to generate a tight seal within the well casing. For wells where only the casing will be surged, the seal should be sized to be within $^1/_8$ of an inch or ¼ of an inch of the casing inner diameter. For wells where the screen will be surged, it may be appropriate to utilize a less tight block to avoid sandlocking (ASTM, 2013).

To initiate well development via use of a surge block, the block is attached to a rod or pipe of sufficient length to reach the bottom of the well. The block is then sequentially raised and lowered inside the well casing at a predetermined rate and depth, beginning slowly at the top of the well screen, proceeding through the well screen interval, and ending at the base of the well (**Section 8.4**). This repetitive motion forces water through the screen and into the formation, which loosens trapped fines. A pump or bailer may then be used to remove the sediment-laden water in the well casing and the process is repeated until well development criteria, as defined in **Section 8.2** and **Section 8.3** of this SOP and detailed in the SAP/FSP/WP, are achieved.

The process of "swabbing" is similar in effect to mechanical surging but relies mostly on the upward movement of the swab in the well casing so that water is only being pulled into the well and out of the formation. Swabbing is less dependent on applying a "backwash" effect (**Section 8.1.3**) on the well screen/filter pack and care should be taken to avoid pushing water through the screen and into the formation. Swabbing is achieved by slowly advancing the swabbing equipment down the well casing followed by the application of a vacuum/suction on the well screen and surrounding formation with the upstroke.

Some considerations when choosing whether to apply mechanical surging for well development include:

1. Surging via block is best applied for wells screened in formations exhibiting medium to high porosity and hydraulic conductivity, and are relatively uniform in lithology. Also, good and consistent recharge in the well minimizes the potential for damage to the surrounding aquifer as a result of surging actions.
2. Surging may be performed manually for smaller diameter wells that are less than 50 ft deep. For larger and deeper wells, mechanical surging will typically require assistance via a block and tackle or pulley system constructed over the well or a drill rig.
3. Surging via block is not recommended for wells screened in formations exhibiting a high percentage of fines (i.e., low permeability) as plugging of the well screen may result; alternatively, in these instances, use of a bailer should be considered.
4. Sandlocking with the block may occur. Sediments must be removed from the well with a sand bailer. This may cause the sand filter pack around the screen to become displaced to such a degree as to compromise its future ability as a filtering medium. Channels or voids may form near the screen if the filter pack sloughs away during surging.
5. Forcing water through a filter/screen, in general, can be quite vigorous and care should be taken not to damage the well head or screen. In addition, this process may dislodge fines from more impermeable lithological units encountered during drilling and force them into more permeable layers. If applicable, this potential impact may be minimized by completing fewer surging cycles, using a block that is looser fitting, and/or increasing the purge volume or time of development.

8.1.2 Compressed Gas

Compressed gas, generally nitrogen, or filtered air can be used both to surge and to purge a monitor well. Surging via compressed air or gas is implemented by injecting a sudden charge of compressed air into the well with an airline attached to a tank that forces water back through the well screen. Periodically, the air/gas source is turned off to allow for the water column to return into the well casing and to correct any bridging that may have resulted during application. This process is then repeated. Periodically, the airline is pulled up into a pipe string (educator) and the water is pumped from the well using air as the lifting medium (air-lift pumping). The process continues until well development criteria as defined in **Section 8.2** and **Section 8.3** of this SOP. Method variations include leaving the air line in the pipe string or using the well casing as the educator pipe

Compressed gas can also be used for "Jetting," a process by which air is directed at the slots in the well screen to cause turbulence (thereby disturbing fines in the adjacent filter pack). Jetting may be performed in conjunction with air-lift pumping and begins below the well screen of interest and proceeds by slowly moving the nozzle upward along the length of the screen. The hose or pipe installed for Jetting should be equipped with a

horizontal (side) discharge nozzle and one or more small holes in the bottom of the hose to enhance the lifting of sediment during jetting.

NOTE: Jetting may also be performed using water as the medium; however, this is often objectionable to many state regulatory agencies as the introduction of non-formation water too often compromises achievement of data quality objectives typical of an environmental site.

Since the compressed gas will be used to "lift" water from the monitor wells, provisions must be made for controlling the discharge from contaminated wells. This is generally accomplished by attaching a "tee" discharge to the top of the casing to control the overflow and providing the necessary containment for discharged water as defined in the SAP or equivalent. Air-lift pumping in contaminated wells must never be applied unless a discharge control apparatus (e.g., educator) and proper containment is identified and provided in advance.

Some considerations to using compressed air/gas for well development include:

1. Highly accommodating - no limitations regarding well diameter or depth to static water, and can be used to develop both shallow and deep wells;
2. Surging via air is best applied for wells screened in relatively uniform formations exhibiting high hydraulic conductivities and is not recommended for wells screened in permeable formations interbedded with clays;
3. In some cases, introduction of external air or gas to the formation/aquifer system may alter the hydrochemistry of the aquifer; this is of special concern in formations exhibiting high permeability; and
4. Surging with air may produce “air locking” in some formations, preventing water from flowing into the well.

8.1.3 Pumping

Pumping may be used either solely or in conjunction with another well development method; however, in most instances, a pump is typically applied as an aid to mechanical surging or bailing unless the pump is dedicated (e.g., permanently installed in the well). Pumping as the sole method of development is typically used at wells completed at depths where other development methods are too cumbersome to implement and/or at wells that contain a large volume of water where a continuous supply of water is expected for proper development.

When developing a well via pumping, pumping must be performed at a rate that is greater than the recharge rate of the well. When the pumping rate exceeds the design capacity of the well, this is referred to as “over pumping”. The well drawdown should be monitored to prevent the well from going dry. Effective development cannot be accomplished if the pump must be shut off to allow the well to recharge. A pump intake hose, placed in the center or towards the top of the well screen, generates suction that

effectively acts as a plunger on the well screen, drawing water from the formation, through the filter pack (as applied) and well screen (thereby dislodging trapped fines), into the well casing and up to the surface. The process continues until well development criteria as defined in **Section 8.2** and **Section 8.3** of this SOP are achieved.

Where appropriate, extracted development water from a well may also be redirected back into the well casing to assist with correcting any potential bridging of material that may have occurred over the well area as a result of unidirectional groundwater flow via extraction during pumping. This process is referred to a "backwashing." Once the well casing is filled to the surface via backwashing, the pump is shut off, and groundwater is allowed to re-equilibrate to static level thus forcing water to re-enter the surrounding formation through the well screen and filter pack. However, it is important to note that suspended sediment must be removed from the extracted groundwater prior to reintroduction into the well. This can be achieved by allowing groundwater to pass through appropriate filtering media or by allowing sediment to settle in an appropriate container (e.g., steel drum) prior to backwashing.

Rawhiding may also be performed during well development via pumping. Rawhiding refers to starting and stopping the pump quickly to produce a rapid change in the water column (pressure head) in the well thereby producing movement similar to surging. If rawhiding is selected, the pump utilized must be able to pump at a rate of at least 5 to 10 gal/min, and the pump should be monitored for excessive damage/wear.

There are many varieties of pumps that can be used for well development including suction lift pumps, electric submersible pumps, and positive displacement pumps. Suction lift pumps include peristaltic pumps, surface centrifugal pumps, and vacuum pumps. Electric submersible pumps include centrifugal submersible pumps, helical rotor (progressing cavity) pumps, and gear pumps. Positive displacement pumps include gas-drive pumps, piston pumps, inertial-lift pumps, and bladder pumps. Electric submersible pumps are the most commonly applied pumps for development of groundwater monitor wells.

Regardless of which type of pump is used, the pumping rate should be low enough to avoid turbulent flow that causes entrainment of fines in the sand pack. In addition, the pump must be capable of moving some solids without damage. Inertial-lift pumps are often preferred for small diameter wells (i.e. <2 inches) due to the surging action of the pumps and their low well yield requirements.

Some considerations to using a pump for well development include:

1. Best applied for deep wells or wells with a high well yield and in combination with backwashing;
2. Limited to the size of the well casing; many pumps necessary to perform effective development may not fit in small diameter wells;

3. Can generate a large volume of investigation derived waste (IDW) that may not be desirable if the IDW requires special disposal and/or treatment;
4. Can cause wear or significant damage to equipment;
5. Development solely via pumping is considered passive development and often will not sufficiently stabilize the formation or surrounding filter pack, remove fine-grained material, or rectify damage done to the formation during drilling/well installation (ASTM, 2013);
6. Not recommended for wells screened in heterogeneous formations consisting of both high and low permeable lithology. Pumping often preferentially develops the most permeable zone(s) and/or zones closest to the top of the well screen thereby resulting in a low well-yield; and
7. Pumping may compact finer sediments in formations with low permeability thus restricting flow into the well.

8.1.4 Bailing

Bailing is typically the preferred method of well development for shallow wells completed in heterogeneous formation(s) and for wells that contain a high volume of suspended sediment that cannot be accommodated by most positive–displacement pumps. Bailing is not as vigorous a well development technique as surging via a surge block but can attain a similar effect and result in less damage/clogging to the well screen in well(s) completed in formations exhibiting a high percentage of fines.

Bailing includes the use of a simple check-valve bailer to remove water from the well. Like other methods, the process of bailing continues until well development criteria as defined in **Section 8.2 and Section 8.3** of this SOP are attained.

Some considerations to using a bailer for well development include:

1. As bailing is a purely manual effort, this method is not recommended for deep wells or wells with a high well yield; and
2. Ideal for developing well(s) screened in low permeable formations as bailing generally will not produce pressures great enough to cause well damage.

8.2 Procedure - Calculations

One of the criteria to achieve proper well development (**Section 8.0**) is defined by the removal (purge) of a minimum of three well casing volumes or up to five well casing volumes. The well casing volume can be defined as the volume of groundwater observed in the well casing under static conditions and can be calculated as follows:

<u>Equation 1:</u>

$$V_{WC} = \frac{\pi D^2 h}{4}$$

Where:

V_{WC} (ft^3) = well casing volume
D (ft) = inner diameter of well casing
h (ft) = height of the water column in the well casing.

The inner diameter of the well casing (D) is a known parameter that can be established by reviewing the well installation documentation for the well. The height of the water column in the well casing (h) is calculated by subtracting the depth to groundwater as measured (in feet) prior to development from the known total depth of the well (in feet) as determined prior to development.

This equation can be modified to reflect common-sized monitor wells as follows:

Equation 2:

$$V_{WC} = h \times a$$

Where:

V_{WC} (gal) = well casing volume
h (ft) = height of the water column in the well casing
a (gal/ft) = the corresponding standard volume calculated per linear foot for a monitor well based on the inner well diameter as given below in **Table 1**.

Table 1: Well Casing Diameter versus Volume of Water

Conversion: 1 ft^3 = 7.48 gal; 1 gal = 0.134 ft^3

Well Casing Diameter	Gallons/Linear Foot of Water Column
1	0.041
2	0.163
3	0.367
4	0.653
5	1.02
6	1.469
7	1.999
8	2.611
9	3.305
10	4.08

Consequently the minimum purge volume (V_P) required to be removed from the well during well development can be calculated as follows:

Equation 3:

$$V_P = V_{WC} \times 3$$

Where:

V_P (gal/ft) = minimum required purge volume for well development
V_{WC} (gal/ft) = well casing volume as calculated by **Equation 1** or **Equation 2**.

In some instances, volume of the filter pack may also be of interest and need to be calculated. The volume of the filter pack can be estimated by calculating the volume of the borehole filter pack less the casing volume.

Filter pack volume is calculated using the following equation:

<u>Equation 4:</u>

$$V_{FP} = \left[\frac{\pi D^2 h}{4} - V_{WC}\right](n)$$

Where:

V_{FP} (ft^3) = filter pack volume
D (ft) = diameter of the borehole
h (ft) = lesser of (a) length of filter pack, or (b) length of water column in well casing
n = filter pack porosity (assume 30%)
V_{WC} (ft^3) = well casing volume (as defined in **Equation 1**)
Well Volume Total = $V_{FP} + V_{WC}$.
Conversion: 1 ft^3 = 7.48 gal; 1 gal = 0.134 ft^3

8.3 Procedure – Measurement of Water Quality Parameters

The other primary criteria for defining the achievement of proper well development (**Section 8.0**) is stabilization of certain water quality parameters as measured in the field. For well development conducted as part of most environmental investigations, this specifically applies to the parameters of pH, specific conductivity, turbidity, and less so, temperature (EPA, 2001).

The intent of utilizing these field parameters in well development is to identify when the physical and/or chemical characteristics of groundwater entering the well begin to reflect that of the surrounding aquifer system. This process also helps establish a baseline to guide further sampling efforts to collect representative groundwater samples.

Numerous instruments are commercially available for measuring water quality parameters. As such, setup and implementation of instruments should follow a basic format that applies consistency of use. Regardless of the brand of meter used, meters should be properly maintained, calibrated, and operated in accordance with the manufacturer's instructions. Calibrations should be checked prior to each use.

For well development, water quality parameters are considered stable when three consecutive readings are achieved as follows:

- pH: ± 0.2

- Temperature: ±1°C
- Specific conductivity: ±10% (microSiemens per centimeter [μS/cm])
- Turbidity (if measured): ±10% nephelometric turbidity units (NTUs)

NOTE: In assessing acceptable turbidity levels for well development, visual observation is often considered sufficient for most sites. However, depending on the regulatory authority for a project, there may be specific qualitative constraints on achieving clear, formation water during well development. RCRA regulations cite the need to achieve purge water that is at or less than 5 NTUs (EPA, 1992a and b) as observed on a turbidity meter; however, EPA also states that turbidity of 5 NTUs or less is often not attainable for marginal aquifers with high lithological heterogeneity (e.g. interbedded sand and clay) (EPA, 1992a). A more realistic parameter for stabilized turbidity is obtaining consistent readings at or below 50 NTUs (EPA, 2001). If the well cannot yield groundwater within the specified turbidity requirements for that site upon completion of well development, then proper well development must be demonstrated and documented to verify that the observed turbidity is inherent in the aquifer being sampled and not a result of improper well construction or insufficient well development.

Standard practice for measuring water quality parameters in the field are presented in INTERA SOP 10, *Monitor Well Sampling for Groundwater*. Measurement and documentation of water quality parameters during well development should be conducted in accordance with SOP 10, Section 10.4, procedures for high-volume purging.

8.4 Procedure - Well Development

The most effective well development for a groundwater monitor well is often a combination of pumping, over-pumping, or bailing alternated with one or more cycles of surging/backwashing. The exact combination, the total number, and the appropriate timing relationships needed for each cycle to achieve proper well development at a particular site is usually either determined through initial field testing or from previous field experience obtained at sites exhibiting similar hydrogeologic conditions. If applicable, the SAP/FSP/WP developed for the site shall specify the appropriate well development cycles or the need for field testing.

In general, upon determination/selection of an appropriate well development procedure for a site/well, the following steps shall be completed by INTERA staff:

1. Verify equipment required for the selected well development procedure is available, cleaned, and in good working order prior to initiating field efforts. Exact equipment needs will be well specific and will depend on the diameter of the well, the depth to the static water level, and other factors. Some equipment may be provided by the contracted driller responsible for well installation; these items

should be coordinated by INTERA with the contracted driller prior to mobilization. Equipment taken to the site by INTERA field staff may include:

- Personal Protection Equipment (PPE) as specified in the SSHASP;
- Site map, well completion diagrams, and a copy of the SAP/FSP/WP;
- Field logbook, waterproof pens, appropriate water level indicator, time-keeping device, camera, and applicable field forms;
- Well development equipment as designated in the SAP/FSP/WP. Equipment may include: plastic sheeting, disposable tubing, bailer (s), pump, rope, pump controller, flow meter, air compressor/generator, surge block, and pump fittings;
- Water quality meter(s) as specified in the SAP/FSP/WP;
- Waste storage containers (e.g., drums, 5-gallon buckets) for temporary or permanent containment of extracted well water and/or sediment as identified in the SAP/FSP/WP; Include labels and marking pens/tools for proper labeling of waste storage containers.
- Tools for opening well vaults (e.g., socket wrench, screwdriver) and/or managing IDW storage containers (e.g., steel 55-gallon drum[s], 5-gallon bucket[s]); and
- Appropriate personnel and equipment decontamination supplies (INTERA SOP 2, *Decontamination*).

2. Verify/define work zones and IDW storage and containment area(s) for the site as established in the SAP/FSP/WP.
3. Calibrate required field screening or monitoring equipment per the manufacturer's instructions. Calibrate instrumentation required to ascertain water quality parameters.

NOTE: If a site requires additional field screening or personnel monitoring during well development (i.e., high levels of VOCs), this requirement shall be outlined in the SAP/FSP/WP or SSHASP, respectively.

4. As applicable, determine sequence of wells to be developed. If multiple wells are to be developed sequentially at a contaminated site, develop wells in order of least contaminated to most contaminated to minimize the potential for cross contamination and use disposable well development equipment as reasonably achievable.
5. Verify well is appropriately marked (well location ID) and confirm that grout seal has properly set. Stage appropriate sampling equipment. Per the SAP/FSP/WP, obtain and stage the appropriate number and type of IDW container(s). Apply

ground cloth or plastic sheeting around location prior to well development initiation, as applicable.

6. Don appropriate PPE. At a minimum this should include gloves, foot, and eye protection. If development is to proceed in close proximity to the drill rig or any other overhead hazards, a hard hat shall also be required and sound-generating equipment, such as a generator, will require hearing protection. Refer to the SSHASP for additional specifics regarding required PPE at a site.
7. Obtain a well TD and DTW measurement from the marked datum point of the well using the appropriate method(s) defined in INTERA SOP 9, *Water Level Gauging*. If appropriate, the thickness of settled sediment may also be measured/calculated. If more than 10% of the well screen is plugged by sediment, staff may consider the use of a bailer to remove sediment prior to continuing development.
8. Calculate the appropriate minimum purge volume (typically 3 well casing volumes) to achieve proper well development using the equations provided in **Section 8.2** of this SOP. Take into consideration any site-specific information such as whether foreign fluids were introduced into the well (i.e., during construction). If fluids were utilized, at least three times the volume of the fluid introduced needs to be removed from the well (in addition to the minimum purge requirement). If an alternate site/well-specific minimum purge volume is required due to known or anticipated site conditions, this variation in the well development requirement shall be identified in the SAP/FSP/WP. Document well casing and purge volume requirements in the field logbook and/or on the appropriate field form (**Attachment 1**).
9. Begin well development using the development procedure selected in the SAP. General implementation of each method detailed in this SOP are discussed below. If an alternate well development method is selected for a site, a discussion on the procedure shall be included in the SAP/FSP/WP.

    - **<u>Mechanical Surging</u>**
        - Bail or pump well to verify that the well will yield water. If water does not enter the well, surging should not be performed as it may cause the well screen to collapse.
        - Insert surge apparatus (block or bailer) into well and lower slowly to the level of static water.
        - Start surging well slowly and gently above well screen using plunger strokes of 3 to 5 feet, using the water column to transmit the surge action to the screened interval.

- After approximately 5 to 10 surges, remove block and purge well using a pump or bailer.
- Reinsert block and repeat process slowly increasing both depth and speed of surging.

NOTE: The required velocity of the surge block motion will depend on the tightness of the formation in which the well is installed.

- For wells equipped with long screens (greater than 10 feet), surging should be undertaken along the entire screen length in short intervals (2 to 3 feet) at a time.

- **Compressed Gas**
  - Lower the gas/air line from the cylinder into the well, and place near the bottom of the screened interval.
  - Install discharge control equipment at the well head and set gas/air flow rate to allow continuous discharge from well into the appropriated container (if required).
  - When discharge begins to clear of suspended material, terminate gas/air flow and allow groundwater to flow back into the well casing through the screened interval.
  - Re-establish gas/air flow when the water level in the well has recovered to at or near static level.
  - Occasionally, raise the discharge nozzle into the cased portion of the well to enhance sediment lifting.
- **Pumping**
  - Select pump and pump accessories of appropriate size and required pumping rate.
  - Insert pump and/or pump intake hose into well and place as close to the center of the well screen as possible. Verify that the intake is completely submerged. To minimize sediment clogging, care should be taken not to place pump or intake hose at the base of the well.
  - Initiate pumping at a rate that is greater than the highest rate anticipated for future purging and sampling.
- **Bailing**
  - Select bailer and bailing string of appropriate size, strength, and volume. Use disposable equipment when possible.
  - Lower bailer into the screened interval of the well.

- Using long slow strokes, raise and lower the bailer in the screened interval, simulating the action of a surge block.
- Periodically bail standing water from the well to remove silt and clay particles drawn into the well via the surging motion. To avoid potential introduction of contaminants into the well, do not allow the bailing string to contact the ground or other potentially-contaminated surface/material.

10. Upon development initiation, measure initial pH, temperature, turbidity, and specific conductivity of the purge water, as required by the SAP/FSP/WP, in accordance with the procedure outlined in **Section 8.3** of this SOP. Note color, clarity, and odor of the water. Document findings on the appropriate field form or in the field logbook.
11. Continue development procedure and periodically measure required parameters until the minimum purge volume has been achieved (three well casing volumes) and the well parameters have stabilized or the equivalent of five well casing volumes have been removed.

NOTE: if the well is experiencing poor recharge and begins to go dry prior to development completion, reduce the extraction rate and remove any sediments (as applicable) prior to continuing to attempt development. If development cannot be continued, the well will need to re-equilibrate with formation water and a subsequent development period shall be required.

12. Containerize, label, and temporarily store IDW as described in the SAP/FSP/WP until final disposition can be determined.
13. Decontaminate equipment, as necessary, prior to advancing to another location in accordance with INTERA SOP 2, *Decontamination*.
14. Document well development and purge information on the appropriate field form (**Attachment 1**) and/or in the field logbook, taking care to cite any problems or unusual conditions encountered. Make sure the following information is noted:
    - Well location ID and date(s) of well installation;
    - Date(s) and duration of well development;
    - Water level before and after development and, if possible, 24 hours after well development;
    - TD of well from the marked datum point and any presence of sediment in the well before, during, and after development;
    - Type(s) and quantity of drilling fluids introduced during drilling or development (if any);

- Field water quality parameters before, during, and after well development;
- Total volume and physical characteristics of purged water;
- Type and capacity of pump or bailer used and pumping rates (if applicable); and
- Description of development method(s) used.

15. Allow groundwater to stabilize at least 24 hours prior to obtaining a final well DTW measurement from the marked datum point of the well using the appropriate method(s) defined in INTERA SOP 9, *Water Level Gauging*.

8.5 References

ASTM International (ASTM), 2013. Standard Guide for Development of Groundwater Monitoring Wells in Granular Aquifers. D5521/D5521M-13.

Environmental Protection Agency (EPA), 1991. Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells. USEPA Office of Research and Development. EPA160014-891034. March.

EPA, 1992a. Monitoring Well Development Guidelines for Superfund Project Managers. Office of Solid Waste and Emergency Response. Ground Water Forum Issue Paper. April.

EPA, 1992b. RCRA Ground-Water Monitoring: Draft Technical Guidance. USEPA Office of Solid Waste. USEPA. November.

EPA, 2001. Standard Operating Procedure 2044. Monitor Well Development. Environmental Response Team. Revision 1. October 23.

Texas Commission on Environmental Quality (TCEQ), 2001. TCEQ Remediation Division Superfund Section Field Standard Operating Procedures (SOPs), SOP 5.6 - Monitoring Well Development/Abandonment. Revision 0. December 3.

8.6 Forms or Attachments

Attachment 1: Well Development and General Data Form

Attachment 2: Application of Well Development Techniques

8.7 Document History

Revision	Effective Date	Lead Author	Summary of Changes
00	4/2004	Taimur Malik	Original version
01	2/2015	Kate Herrell	Revised for inclusion in COA Brownfields QAPP
02	10/2015	Noreen Baker	Minor text revisions for clarification

Attachment 1: Well Development and General Data Form

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WELL DEVELOPMENT AND GENERAL WELL DATA

PROJECT NAME: ____________________ WELL NO.: __________

PROJECT NO.: __________ DATE: __________ FORM COMPLETED BY: __________

WELL CONSTRUCTION

TOTAL DEPTH BELOW MEASURING POINT (BMP) (FT): ________ BOREHOLE DIAMETER (IN): __________

TOTAL DEPTH BELOW LAND SURFACE (BLS) (FT): ________ WELL DIAMETER INSIDE (IN): __________

WELL PROTECTOR: ☐ YES ☐ NO PADLOCK NO.: ________ WELL DIAMETER OUTSIDE (IN): __________

SAND PACK INTERVAL (BLS) (FT): __________ SCREEN INTERVAL (BLS) (FT): __________

WATER VOLUME CALCULATION

DATE/TIME OF MEASUREMENT: __________

MEASURING POINT: __________ ELEV.: __________

WATER LEVEL INSTRUMENT USED: __________

INITIAL WATER LEVEL (BMP) (FT): __________

LINEAR FEET OF WATER: __________

LINEAR FEET SATURATED GRAVEL PACK: __________

NOTE: Quantities are to be calculated prior to development

ITEM	WATER VOLUME	
	FT³	GAL
Well Casing		
Sand Pack		
Drilling Fluids		
TOTAL		

DEVELOPMENT CRITERIA

METHOD OF DEVELOPMENT: ____________________

WATER VOLUME TO BE REMOVED (GAL): ________ WATER VOLUME ACTUALLY REMOVED (GAL): ________

TIME DEVELOPMENT STARTED: ________ TIME DEVELOPMENT COMPLETED: ________

NOTE: Development is to be performed in accordance with Standard Operating Procedure

WATER QUALITY INSTRUMENTS

DATE/TIME	INSTRUMENT	SERIAL NO.	CALIBRATION PERFORMED	TECH	COMMENTS

WATER QUALITY READINGS DURING DEVELOPMENT*

DATE/TIME	TOTAL WATER PURGED (gal)	TEMP ☐°C ☐°F	SPECIFIC CONDUCTANCE (µS/cm)	TURB (NTU)**	pH	TECH	COMMENTS

*Stabilization = Temp ±1°C, pH ±0.2 units, Sp. Cond. ±10%, Turb. ±10%.

**If measured.

COMMENTS: ______________________________

Attachment 2: Application of Well Development Techniques

Application of Well Development Techniques

Reference	Overpumping	Backwashing	Surge Block*	Bailer	Jetting	Airlift Pumping	Air Surging
gass (1966)	Works best in clean coarse formations and some consolidated rock; problems of water disposal and bridging	Breaks up bridging, low cost & simple; preferentially develops	Can be effective; size made for≥2"-well; preferential development where screen >5'; surge inside screen		Consolidated and uncon-solidated application; opens fractures, develops discrete zones; disadvantage is external water needed	Replaces air surg ing; filter air	Perhaps most widely used; can entrain air in form-ation so as to reduce per-meability, affect water qualify; avoid if possible,
United States Environmental Protection Agency (1966)	Effective develop-ment requires flow reversal or surges to avoid bridges	Indirectly indicates method applicable; formation water should be used	Applicable; forma-tion water should be used; in low-yield formation, outside water source can be used if analyzed to evaluate impact	Applicable		Air should not be used	Air should not be used
Barcelona et al. ** (1963)	Productive wells; surging by alternat-ting pumping and allowing to equili-brate; hard to create must be sufficient entrance velocities; often use with airlift		Productive walk; use care to avoid casing and screen damage	Productive walk; more common than surge blocks but not as effective			Effectiveness depends on geometry of device; air filtered; crew may be exposed to contaminated water; per-turbed Eh in sand and gravel not persistent for more than a few weeks
Staff et al. (1901)		Suitable; periodic removal of fines	Suitable; common with cable to of; not easily used on other rigs	Suitable; use sufficiently heavy bailer; advantage of removing fines; may be custom made for small diameters		Suitable	Suitable; avoid injecting air into intake; chemical interference; air pipe never inside screen
National Council of the Paper Industry for Air and Stream Im-provement (1961)	Applicable drawback of flow in one direction; smaller wells hard to pump if water level below suction		Applicable; caution against collapse of intake or plugging screen with clay		Methods introducing foreign materials should be avoided (i.e., compressed air or water jets)		

Reference	Overpumping	Beckwashing	Surge Block*	Bailer	Jetting	Airlift Pumping	Air Surging
Everett (1960)	Development operation must cause flow reversal to avoid bridging; can alternate pump oft and on'		Suitable; periodic bailing to remove fines		High velocity jets of water generally most effective; discret zones of development		
Keely and Boateng (1987 a and b)	Probably most desirable when surged; second series of evacuation/ recovery cycles is recommended after resting the well for 24 hours; settlement and loosening of fines ocurs after the first development attempt; not as vigorous as backwashing	Vigorous surging action may not be desirable due to disturbance of gravel pack	Method quite effective in loosening fines but may be inadvisable in that filter pack and fluids may be displaced to degree that damages value as a filtering media		Popular but less desirable; method different from water wells; water displaced by short downward bursts of high-pressure injection; important not to jet air or water across screen because fines driven into screen cause irreversible blockage; may subsatantiafly displace native fluids	Air can become entrained behind screen and reduce permeability	

* Schalla and Landick (1986) report on special 2"- valved block
** For low hydraulic conductivity wells, flush water up annulus prior to sealing; afterwards pump

Excerpted from (EPA, 1991)