ARCADIS

Infrastructure · Water · Environment · Buildings

Imagine the result

uraniumone™

investing in our energy

Uranium One USA, Inc.

Willow Creek ISR Project - Christensen Ranch, Mine Units 2 – 6

Response to Comments from U.S. Nuclear Regulatory Commission Staff Technical Evaluation Report

September 2015

ARCADIS

Stephen J. Cohen
Project Manager

Patsy Moran, Ph.D.
Sr. Geochemist

Michael Kladias
Technical Expert - Hydrogeology

Willow Creek ISR Project - Christensen Ranch, Mine Units 2 – 6

Response to Comments from U.S. Nuclear Regulatory Commission Staff Technical Evaluation Report

Prepared for:
Uranium One USA, Inc.

Prepared by:
ARCADIS U.S., Inc.
1114 Benfield Boulevard
Suite A
Millersville
Maryland 21108
Tel 410 987 0032
Fax 410 987 4392

Our Ref.:
MD001216.0002

Date:
September 2015

Figures

Appendices

ABBREVIATIONS AND ACRONYMS

α - Mass Transfer Coefficient
ACL - Alternate Concentration Limit
COC - Constituent of Concern
DL - Detection Limit
DOC - Dissolved Organic Carbon
EA - Environmental Assessment
EPA - Environmental Protection Agency
ft/dy - feet per day
ft/ft - feet per foot
ft/yr - feet per year
K_D - Distribution Coefficient
KM - Kaplan-Meier
MCL - Maximum Contaminant Level
M-K - Mann-Kendall Statistical Test
m^2/g - square meters per gram
mg/L - milligrams per liter
MU - Mine Unit
ND - Nondetect Observation
NRC – U.S. Nuclear Regulatory Commission
PLE - Product Line Estimation
PRB - Powder River Basin
ROS - Regression-on-Order Statistics
SCM - Surface Complexation Model
SI - Saturation Index
s.u. - pH Standard Units
TER – Technical Evaluation Report
TRV - Target Restoration Value
UCL - Upper Confidence Limit
WDEQ - Wyoming Department of Environmental Quality
WSR - Wilcoxan Signed Rank

1.0 Introduction

Uranium One USA, Inc. (Uranium One) contracted ARCADIS US, Inc. (ARCADIS) to review groundwater quality, hydrogeologic, and geochemical data collected from Uranium One's Christensen Ranch Mine Units 2 through 6. The purpose of this review was to address issues raised by the U.S. Nuclear Regulatory Commission (NRC) staff resulting from its review of Uranium One's groundwater restoration report for the aforementioned wellfields, dated March 5, 2008 (Uranium One, 2008). The NRC staff's issues are presented in its Technical Evaluation Report (TER), dated October 23, 2012, in which the staff denied its approval of Uranium One's Christensen Ranch Restoration Report, dated March 5, 2008 (NRC, 2012). NRC staff's basis for denying its approval range from matters of statistics to matters of restoration completeness.

ARCADIS completed certain analyses to address comments raised by the NRC staff including:

- Review of Target Restoration Values (TRVs). This activity involved recalculating TRVs using ProUCL, which is recommended by the NRC staff for calculating remediation standards. Resulting TRVs values were compared to restoration data to assess restoration completeness.

- Review Water Quality, Geochemical, and Hydrogeologic Data - The NRC staff questions, in its TER, certain aspects of Uranium One's restoration effort, such as: quality of the restoration data, downgradient geochemistry (presence of reducing environment), historical excursions, and trends in stabilization data. To address these concerns, ARCADIS reviewed water quality, geochemical, and hydrogeologic data to determine data gaps or any anomalous conditions. ARCADIS also developed a geochemical conceptual site model to guide further analyses.

- Hydrogeologic and Geochemical Analyses/Modeling - Issues of excursions and completeness of restoration require an understanding of groundwater dynamics within the wellfields at Christensen Ranch. Toward that end, ARCADIS reviewed groundwater flow and fate and transport models previously developed by Uranium One and the NRC staff. ARCADIS then created its own improved geochemical models to better understand constituent fate and transport.

This report compiles the information reviewed, data generated, and responses to the NRC staff's issues in its TER. ARCADIS notes that while some analyses for MU-5 were undertaken and are presented in this report, the staff's comments regarding MU-5 are not being addressed, herein, because Uranium One is currently producing uranium from a portion of this wellfield.

2.0 Review of Target Restoration Value

2.1 Procedure

Uranium One seeks to address specific NRC staff comments regarding computation of TRVs for specific wellfields and calculation of the TRVs in an internally consistent manner. The NRC staff, has promoted the use of ProUCL, to calculate various types of restoration standards (EPA 2013). ARCADIS, therefore, used ProUCL, Version 5.0, to recalculate Uranium One's TRVs. This analysis utilized upper confidence limits (UCLs), which are preferable to mean values because they provide a more reasonable cleanup standard, and ProUCL can utilize various statistical distributions to calculate UCLs.

2.2 TRV Analysis

2.2.1 TRV Computation

Uranium One sought to address the NRC staff's comments in its TER regarding Uranium One's TRVs in MU-2 and MU-6. Specifically, the NRC staff stated the following regarding MU-2:

> *In the Restoration Report (Cogema 2008c), the licensee compares the groundwater quality after restoration shown in Tables 5 and 6 to the established TRVs. However, the staff finds the TRVs may not be statistically representative of the range in baseline data as committed to by the licensee (see general comment (2)). Furthermore, for several parameters, the TRV values in that table were calculated incorrectly.* (NRC 2012)

Regarding MU-6, the staff stated the following:

> *Based upon the above, the staff cannot concur that the restoration of MU- 6 is protective of human health and safety and the environment until the licensee: Provides the staff with data used to define baseline ...* (NRC 2012)

Because the staff questioned the methods for calculating baseline for MU-2 and MU-6, ARCADIS recalculated TRVs for wellfields MU-2 through MU-6 to maintain consistency in its analyses and conclusions. As previously stated, UCLs were used as the TRVs because ProUCL recommends this metric for relatively large data sets (EPA 2013a, pg. 18). Baseline data provided for each wellfield were considered sufficiently large data sets for the purpose of calculated UCLs.

For each wellfield, ARCADIS first determined the particular distribution that fit the data for each parameter for each wellfield. ProUCL uses normal, lognormal, and gamma

distributions. If none of these distributions fit a data set, then nonparametric methods were used for UCL development. Nonparametric methods used by ProUCL include the Chebyshev or bootstrap methods (EPA 2013, pg. 6).

Although, ProUCL calculates UCLs using each of these methods, the Chebyshev method tends to be more stable over a wider range of skews. Bootstrap methods are generally stable for mildly skewed data sets (EPA 2013, pg. 6). Since most of the datasets were considered moderately skewed, at least, the Chebyshev method was primarily relied upon for UCL calculations.

2.2.2 Treatment of Nondetect Observations

Before starting the computations, ARCADIS separated the parameters into those that contained no nondetects observations (NDs) and those for which NDs were present in the data. UCLs were then computed separately for those parameters with no NDs and those with NDs. ProUCL recommends certain methods for addressing NDs; however replacement of an ND with a value of half the detection limit (DL) is no longer an acceptable practice (EPA 2013, pg. 111).

ProUCL incorporates methods for estimating values for NDs in a dataset including the Kaplan-Meier (KM) (also known as Product Line Estimation (PLE)) and regression on order statistics (ROS) approximations. The KM method was used for ND datasets, which estimates the mean, standard error, and variance of a data set with ND, because, the KM results appeared more stable than ROS results for the data in this project. It is important to note that some data sets contained too few detections (<4) for any statistical method to work. In these cases, ProUCL's output file stated that too few detections were available to compute any statistics. Consequently, ARCADIS used the maximum DL as the UCL, which is an acceptable practice (EPA 2013, pg. 28).

2.2.3 Results

Results of the UCL analyses are presented in Table 2-1.

Table 2-1: Target Restoration Values (UCLs)

Parameter	Units	MU-2 North	Dis.[1]	MU-2 South	Dis.	MU-3	Dis.	MU-4	Dis.	MU-5	Dis.	MU-6	Dis.
Calcium	mg/L	8.44	N	9.56	NP	8.46	NP	8.55	NP	11.76	NP	29.46	NP
Magnesium	mg/L	0.59	N	1.04	NP	24.44	NP	0.81	G	1.63	NP	5.26	NP
Sodium	mg/L	137.1	N	145.2	N	135.8	N	134.9	NP	151.4	NP	241.6	G
Potassium	mg/L	3.98	N	3.32	N	3.79	NP	3.25	G	4.92	LN	7.89	NP

Table 2-1 (cont'd.)

Parameter	Units	MU-2 North	Dis.[1]	MU-2 South	Dis.	MU-3	Dis.	MU-4	Dis.	MU-5	Dis.	MU-6	Dis.
Sulfate	mg/L	215.7	N	222.3	NP	199.1	N	200.4	N	230.2	NP	537.9	N
Chloride	mg/L	9.14	N	9.64	N	9.15	N	8.90	N	8.19	NP	4.92	NP
Fluoride	mg/L	0.33	NP	0.25	NP	0.22	LN	0.20	N	0.20	NP	0.18	NP
Silica	mg/L	8.71	N	6.45	NP	9.25	NP	8.74	N	8.62	N	5.31	NP
TDS	mg/L	433.1	N	447.5	N	427.6	N	432.3	G	467.1	NP	893	NP
Conductivity	µmho/cm	715.9	N	668	NP	689.5	N	714.7	NP	788.6	NP	1294	NP
Alkalinity	mg/L	101.6	N	102.1	N	102.1	NP	102.7	NP	112.5	NP	73.91	NP
pH	(s.u.)[2]	9.23	N	8.99	NP	8.92	N	9.06	N	8.91	NP	8.89	NP
Carbonate	mg/L	13.03	N	6.72	G	7.12	G	7.72	N	15.23	NP	6.41	NP
Bicarbonate	mg/L	106.4	N	116.1	N	120.7	NP	112.5	N	137.1	NP	82.15	NP
Ammonia	mg/L	0.20	NP	0.22	NP	0.07	NP	0.07	N	0.07	N	0.08	NP
Nitrite	mg/L	0.1	ID	0.1	ID	0.013	NP	0.1	ID	0.1	ID	0.1	ID
Nitrate	mg/L	0.1	ID	0.20	ID	0.06	NP	0.1	ID	0.1	ID	0.06	G
Aluminum	mg/L	0.1	ID	0.1	ID	0.1	ID	0.1	ID	0.1	ID	0.08	G
Arsenic	mg/L	0.004	NP	0.002	NP	0.003	NP	0.002	NP	0.002	NP	0.004	NP
Barium	mg/L	0.1	ID	0.1	ID	0.1	ID	0.1	ID	0.1	ID	0.1	ID
Boron	mg/L	0.1	ID	0.1	ID	0.1	ID	0.1	ID	0.1	ID	0.1	ID
Cadmium	mg/L	0.01	ID	0.01	ID	0.01	ID	0.01	ID	0.1	ID	0.05	ID
Chromium	mg/L	0.05	ID	0.05	ID	0.05	ID	0.05	ID	0.05	ID	0.05	ID
Copper	mg/L	0.01	ID	0.01	ID	0.011	NP	0.01	ID	0.01	ID	0.1	ID
Iron	mg/L	0.05	ID	0.05	ID	0.092	G	0.05	ID	0.05	ID	0.06	N
Lead	mg/L	0.05	ID	0.05	ID	0.05	ID	0.05	ID	0.05	ID	0.05	ID
Manganese	mg/L	0.01	ID	0.01	NP	0.01	ID	0.01	ID	0.01	ID	0.03	N
Mercury	mg/L	0.001	ID	0.002	NP	0.001	ID	0.001	ID	0.001	ID	0.0002	N
Molybdenum	mg/L	0.1	ID	0.1	ID	0.1	ID	0.01	ID	0.1	ID	0.051	N
Nickel	mg/L	0.05	ID	0.05	ID	0.05	ID	0.05	ID	0.01	ID	0.054	N
Selenium	mg/L	0.024	NP	0.003	NP	0.003	NP	0.001	N	0.001	NP	0.001	NP
Vanadium	mg/L	0.1	ID	0.1	ID	0.1	ID	0.1	ID	0.1	ID	0.022	NP
Zinc	mg/L	0.01	ID	0.013	NP	0.015	N	0.01	ID	0.01	ID	0.012	NP
Uranium	mg/L	0.068	NP	0.03	G	0.11	NP	0.09	NP	0.03	NP	0.015	NP
Radium-226	pCi/L	26.95	N	25.45	NP	75.22	G	23.16	G	78.36	G	117.0	G

1. Data Distribution: N = Normal, NP = Nonparametric, ID = Insufficient data for analysis (TRV = highest detection limit), G = Gamma, LN = Log Normal

2. Standard Units

It is important to note that because the NRC's regulations at 10 CFR 40, Appendix A, discuss various groundwater protection standards, stability data were not only compared to TRVs, but also drinking water standards and Wyoming Department of

Environmental Quality (WDEQ) class-of-use standards. These other standards are presented below.

2.3 Determination of Restoration Completion and Stability

2.3.1 Utilization of Groundwater Protection Standards

To determine the degree to which Uranium One completed restoration and residual constituent concentrations remained stable, means tests were performed on wellfield stability data to determine if residual constituent concentrations are below the groundwater protection standards. As previously stated, per Criterion 5B(5) of 10 CFR 40, Appendix A, groundwater protections standards are Commission-approved background (TRVs in this case) or Table 5C concentrations, whichever is higher, or alternate concentration limits (ACLs). However, LC 16 of Uranium One's license stated that, prior to 2009, the secondary standard is class-of-use (NRC 2012). Therefore, Uranium One performed the data comparison using TRVs first, drinking water standards (on which Table 5C is based), and class-of-use.

Regarding class-of-use, pre-extraction groundwater in the restored wellfields is considered Class IV(A) (see Appendix A). The Wyoming Department of Environmental Quality (WDEQ), in its "Quality Standards for Wyoming groundwaters, Chapter 8, imposes the following regulations on Class IV(A) waters:

> *Class IV Groundwater of the State - This water is suitable for industry. The quality requirements for industrial water supplies range widely and almost every industrial application has its own standards.*
>
> *(A) Class IV (A) Groundwater of the State has a total dissolved solids concentration not in excess of 10,000 mg/L.*
>
> *(B) Class IV (B) Groundwater of the State has a total dissolved solids concentration in excess of 10,000 mg/L.*
>
> *(C) A discharge into an aquifer containing Class IV (A) or IV (B) Groundwater of the State shall not result in the water being unfit for its intended use.*
>
> *(D) A discharge into an aquifer with Class IV (A) or IV (B) Groundwater of the State shall not result in oil and grease concentrations in excess of 10 mg/L or a lesser amount if a concentration in excess of the lesser amount is determined to be toxic; or oil and grease in excess of background concentrations of the underground water, whichever is greater, at any place or places of withdrawal or natural flow to the surface.*

> *(E) A discharge into an aquifer with Class IV (A) or IV (B) Groundwater of the State shall not result in radioactivity concentrations or amounts which exceed the standards for Class I through III and Special (A) Groundwaters of the State; or in concentrations or amounts which exceed background concentrations of the underground water, whichever is greater, at any place or places of withdrawal or natural flow to the surface.*

However, in its analysis the NRC staff erred when considering which standards to use for wellfield restoration comparisons. The NRC staff stated the following:

> *According to this regulation, the NRC staff concludes that the Class IV restoration standards for all mine units for the radionuclide radium-226 are the Class I, II and III standard of 5 pCi/L or the baseline mean value, whichever is higher. For the radionuclide uranium, Wyoming lists no Class I, II, or III standards, so the NRC staff concludes that the class-of-use standard for uranium is the baseline mean for each mine unit.* (NRC 2012)

The NRC staff incorrectly states that no class-of-use standard exists for uranium because it only considered Classes I – III. Because the WDEQ has stated that the groundwater is classified as IV(A), paragraph E of the Class IV definition applies. This paragraph explicitly states that radioactivity discharges shall not exceed Classes I through III and Special (A) Groundwaters. Therefore, the uranium standard of 0.3 to 1.4 milligrams per liter (mg/L) based on hardness applies to MU 2 – MU 6. Considering that the groundwater is hard based on groundwater quality data, the final uranium class-of-use standard is 1.4 mg/L.

2.3.2 Means Testing

According to ProUCL, when sufficient data exists, means tests are the proper method for assessing restoration and comparison to UCLs due to the size of the data sets (EPA 2013, pg. 18). For the stability data, means tests were accomplished using one of two tests depending on distribution and the presence of NDs. For those parameters with no NDs and exhibiting normal distributions, the Students t-test was used. For those parameters with NDs and/or not exhibiting a normal distribution, the Wilcoxan Signed Rank (WSR) test was used. Means tests were performed at the 95% confidence level. In some cases, the absence or an insufficient number of detections prevented the use of any statistics; therefore, the maximum detection limit was used and the parameter was assumed to be restored. Appendix B contains the ProUCL means test results. Table 2-2 presents a summary of the means test results.

One point regarding Table 2.2 is the determination of whether or not a constituent is listed in 10 CFR 40, Appendix A, Criterion 13 – Hazardous Constituents. This is

important because of the definition of a hazardous constituent, as the staff states on page 4 of its TER (NRC 2012):

> *The constituents to be monitored at the point of compliance are hazardous constituents as defined in Criterion 5B(2). Criterion 5B(2) defines a hazardous constituent as follows:*
>
> *A constituent becomes a hazardous constituent subject to paragraph 5B(5) only when the constituent meets all three of the following tests:*
>
> *(a) The constituent is reasonably expected to be in or derived from the byproduct material in the disposal area;*
>
> *(b) The constituent has been detected in the ground water in the uppermost aquifer; and*
>
> *(c) The constituent is listed in Criterion 13 of 10 CFR Part 40 Appendix A.*

If the constituent is not listed in Criterion 13, then it is not considered hazardous and the groundwater protection standards in Criterion 5B(5) do not apply.

Table 2-2: Stability Data Comparison Results

Parameter	Units	MU-2 North	MU-2 South	MU-3	MU-4	MU-5	MU-6	Listed in Criterion 13 (Y or N)
Calcium	mg/L	8.44	9.56	8.46	8.55	11.76	29.46	N
Magnesium	mg/L	0.59	1.04	24.44	0.81	1.63	5.26	N
Sodium	mg/L	137.1	145.2	135.8	134.9	151.4	241.6	N
Potassium	mg/L	3.98	3.32	3.79	3.25	4.92	7.89	N
Sulfate	mg/L	250	250	199.1	250	250	537.9	N
Chloride	mg/L	250	9.64	9.15	250	250	250	N
Fluoride	mg/L	0.1	0.1	0.1	0.20	0.20	0.18	N
Silica	mg/L	8.71	6.45	9.25	8.74	8.62	5.31	N
TDS	mg/L	500	500	500	500	500	893	N
Conductivity	µmho/cm	715.9	668	689.5	714.7	788.6	1294	N
Alkalinity	mg/L	101.6	102.1	102.1	102.7	112.5	73.91	N
pH	s.u.	9.23	8.99	8.92	9.06	8.91	8.89	N
Carbonate	mg/L	1	1	5	5	15.23	5	N
Bicarbonate	mg/L	106.4	116.1	120.7	112.5	137.1	82.15	N

Table 2-2: Stability Data Comparison Results

Parameter	Units	MU-2 North	MU-2 South	MU-3	MU-4	MU-5	MU-6	Listed in Criterion 13 (Y or N)
Ammonia	mg/L	0.20	0.22	0.5	0.5	0.5	0.08	N
Nitrite	mg/L	0.1	0.1	1	0.01	0.1	0.01	N
Nitrate	mg/L	0.1	0.20	0.1	10	0.1	0.06	N
Aluminum	mg/L	0.1	0.1	0.1	0.2	0.1	0.1	N
Boron	mg/L	0.1	0.1	0.1	0.1	0.1	0.1	N
Copper	mg/L	0.02	0.02	0.01	0.01	0.01	0.01	N
Iron	mg/L	5	5	5	5	0.3	5	N
Manganese	mg/L	0.2	0.2	0.2	0.2	0.2	0.2	N
Vanadium	mg/L	0.1	0.1	0.1	0.1	0.1	0.1	N
Zinc	mg/L	0.01	0.01	0.01	0.01	0.01	0.01	N
Arsenic	mg/L	0.2	0.01	0.01	0.01	0.2	0.01	Y
Barium	mg/L	0.5	0.5	0.5	0.5	0.5	0.5	Y
Cadmium	mg/L	0.002	0.002	0.002	0.002	0.002	0.002	Y
Chromium	mg/L	0.01	0.01	0.01	0.01	0.1	0.1	Y
Lead	mg/L	0.02	0.02	0.02	0.02	0.02	0.02	Y
Mercury	mg/L	0.001	0.001	0.001	0.001	0.001	0.001	Y
Molybdenum	mg/L	0.02	0.02	0.02	0.02	0.02	0.02	Y
Nickel	mg/L	0.01	0.01	0.01	0.01	0.01	0.056	Y
Selenium	mg/L	0.05	0.05	0.05	0.05	0.05	0.05	Y
Uranium	mg/L	1.4	1.4	1.4	1.4	1.4	1.4	Y
Radium-226	pCi/L	26.95	25.45	75.22	23.16	78.36	116.9	Y

Legend:

- Meets TRV (refer back to Table 2-1)
- Meets MCL
- Meets Class-of-Use
- Exceeds all Criterion 5B(5) groundwater protection standards or licensed secondary standards
- Nondetect – Meets standards by definition

A review of Table 2-2 indicates that Uranium One has restored 8 of the 11 hazardous constituents to TRVs, MCLs, or class of use, for each wellfield. Only selenium, uranium, and radium-226 exceed various limits for certain wellfields. Selenium exceeds the MCL in MU-4 and -5, uranium exceeds the class-of-use standard in MU-4 and -5, and radium-226 exceeds the TRV in all wellfields.

2.3.3 Wellfield Trend Analyses

ARCADIS assessed stability of the hazardous constituents that exceeded standards by determining the trends for radium-226, selenium, and uranium for each particular wellfield. Stability data were first combined for all ore zone monitoring wells for each wellfield and UCLs were calculated for each round for each parameter. Results of those UCLs are presented Table 2-3, and were used for trend analyses.

Table 2-3: Stability Data UCL Results

	Round 1 (mg/L)	Round 2 (mg/L)	Round 3 (mg/L)	Round 4 (mg/L)
MU-2 North				
Uranium	1.20	1.16	1.14	3.18
Radium-226	856.5	669.1	1264	836.6
MU-2 South				
Uranium	0.15	0.16	0.27	0.27
Radium-226	235.3	364.8	247	210
MU-3				
Uranium	0.79	0.21	0.24	0.27
Radium-226	262.2	281.2	257	235.5
MU-4				
Uranium	8.26	4.959	7.783	8.384
Radium-226	181.6	316	245.5	200.7
Selenium	0.429	0.432	0.336	0.498
MU-6				
Uranium	1.29	1.48	1.61	1.80
Radium-226	227.3	235.2	222.5	222.2

This type of trend analysis differs from that of the NRC staff. The NRC staff reviews constituent trends in individual wells; however, this strategy is inappropriate and actually represents a biased review of the available data. Because the groundwater protection standards are calculated on a wellfield basis, trend analyses must be calculated on a wellfield basis. Otherwise, comparisons between individual well trends and groundwater protection standards are not statistically valid.

ARCADIS used the Mann-Kendall (M-K) trend analyses method to assess trends in uranium, radium-226, and selenium (MU-4 only) (EPA 2013, pg. 230). The M-K test is a non-parametric test that compares consecutive pairs of chronological data and assigns a 1, -1, or 0 according to whether or not the later data is higher, lower, or the same as the previous data. The test value is the sum of all the assigned values and is

a non-parametric test that compares consecutive pairs of chronological data and assigns a 1, -1, or 0 according to whether or not the later data is higher, lower, or the same as the previous data. The test value is the sum of all the assigned values and is either positive, negative, or close to zero. Positive values indicate a positive trend, negative values indicate a negative trend, and values close to zero indicate no trend.

Significance of the test value is based on a comparison of a tabulated p-value with the level of significance (e.g., 0.05). If the tabulated p-value is greater than the level of significance, then the trend is significant at the 0.05 level. If the tabulated value is less than the level of significance, then the trend is not significant. Note that in the case that M-K test values are close to 0, no tabulated p-value is calculated.

Table 2-4 presents the results of the trend analyses, and individual trend results are presented in Appendix C.

Table 2-4: Trend Analysis Results

Mine Unit	Uranium	Radium-226	Selenium
MU-2 North	No trend	No trend	NA
MU-2 South	Increasing trend	No trend	NA
MU-3	No trend	No trend	NA
MU-4	No trend	No trend	No trend
MU-5*	NA	NA	NA
MU-6	Increasing trend	No trend	NA

*Not computed for MU-5, as Uranium One is still extracting from portions of this wellfield
NA = not applicable

A review of Table 2-4 indicates that SSI trends only exist for uranium in MU-2 South and MU-6. Although M-K test indicated increasing or decreasing uranium, radium-226, and selenium trends in the other wellfields, no other trends were statistically significant. Appendix C contains the trend test analyses.

2.4 Conclusions

Based on the information presented in this section, Uranium One determines the following:

- Uranium One restored 8 of the 11 hazardous constituents in all of its wellfields.
- Only uranium, radium-226, and selenium exceed all groundwater protection standards.
- SSI trends were only identified for uranium and only in wellfields MU-2 South and MU-6.

3.0 Geology and Hydrogeology

Sections 3 and 4 discuss various information that was used to review and construct geochemical models to assess the long-term stability of MU-2 through MU-6. Hydrogeologic information was reviewed for all wellfields except MU-5, due to the current extraction at Module 5-2. The following sections briefly describe the evaluation of hydrogeology for various wellfields.

3.1 Site Geology

The Christensen Ranch facility geology is detailed in Malapai (1988), Cogema (2008), and the associated Mine Unit Restoration Data Packages. Descriptions of the regional and site geology are presented below.

3.1.1 Regional Geology

Christensen Ranch is located within the Great Plains Physiographic Province, which is characterized by broad river plains and low plateaus on stratified sedimentary rocks. On a regional basis, the surface of the Basin sediments dips gently (1 to 2 degrees) to the north-northwest. Specifically, the Christensen Ranch facility is located in the west-central portion of the Powder River Basin (PRB), a large, gently down-warped asymmetrical syncline. The facility is located east of the axis of the PRB, which is open to the north, bounded on the west by the Big Horn Mountains, on the east by the Black Hills, and by the Laramie Range, and Hartville Uplift on the south. Basin orientation and plunge generally are south to north.

3.1.2 Stratigraphy – Wasatch Formation

The geologic section beneath MU-2 through MU-6 from the surface through the production zone, including the underlying confining unit and underlying aquifer is all within the Eocene age Wasatch Formation. No major structural features appear within the Wasatch at MU-2 through MU-6. A generalized stratigraphic section for the project area is shown in Figure 3-1. The Wasatch Formation is comprised of claystone and lenticular sandstone of fluvial origin, as well as minor coal deposits. In the vicinity of Christensen Ranch, the Wasatch varies from 650 to 1,000 feet thick, and is divided into three units at the facility:

- The "J" Fluvial System is the uppermost stratigraphic interval from the base of the Upper Aquitard above the "K" Fluvial System to the ground surface. The interval is dominated by siltstones and mudstones with thin sandstone units deposited. Total thickness of the "J" Fluvial System varies from 300 to 450 feet.

The Upper Aquitard is composed of a shale/claystone interval with a thickness from 90 to 100 feet.

- The "K" Fluvial System is defined as the stratigraphic interval from the top of the Lower Aquitard that overlies the "L" Fluvial System to the base of the Upper Aquitard. Thicknesses typically ranges from 150 to 200 feet thick at the facility. The "K" Fluvial System contains three major sandstone units that are the primary uranium host, the "K1", "K2", and "K3" sandstones, which are separated by thin shaley lenses that are limited both vertically and laterally. The "K" Sandstone is predominately clean, fine to coarse grained, moderately sorted, well cemented, arkosic sand. The "K" Sandstone is locally carbonaceous and pyritic with interbedded clay stringers.

- The "L" Fluvial System is the lowest stratigraphic interval, between the Fort Union/Wasatch Formation contact and the base of the lowest uranium mineralized host sandstone. The "L" fluvial system is approximately 200-230 feet thick and consists of one to two continuous sandstone aquifers separated from each other and from the overlying and underlying units by shales, mudstones and siltstones. The uppermost portion of the "L" Fluvial System is a 60 to 70 foot thick shale/mudstone confining layer that separates aquifers of the "L" and "K" fluvial systems.

3.2 Mineralogy

Uranium mineralization at Christensen Ranch occurs as a typical roll-front with uranium and lesser amounts of selenium and vanadium deposited at the interface between the oxidized and reduced zones (Malapai 1988). Uranium minerals occur as sand grain coatings and interstitial fillings. The most common uranium minerals are uraninite, UO_2, and coffinite, $U(SiO_4)(OH)_4$, with minor quantities of tyuyamunite, $Ca(UO_2)_2(VO_4)\cdot nH_2O$, possibly carnotite, $K_2(UO_2)_2(VO_4)_2\cdot nH_2O$, and brannerite, UTi_2O_6 (Swapp, 2012). In addition, roscoelite (vanadium), and gerroselite (selenium) have been identified in varying quantities within the ore zones (Malapai 1988).

The mineralogical investigation of MU-7 conducted by Swapp (2012) provides additional insight about the wellfield mineralogy (Table 3-1). Specifically, in order of general abundance: quartz, K-feldspar, ferromagnesian minerals (primarily biotite and chlorite), clay minerals (dominantly smectite, with minor amounts of illite and kaolinite), and pyrite. Clays are important to the fate and transport of metals. On average, Swapp (2012) found that clay minerals make up approximately 3 to 4% of the minerals identified in the ore zone following extraction. These findings are consistent with the findings presented in Sharp and Gibbons (1964), which identified montmorillonite (a member of the smectite group) as the primary clay mineral in the Wasatch Formation, with minor amounts kaolinite and sericite. Montmorillonite and kaolinite clays were also identified

by Uranerz (2007) in the oxidized sandstones in the nearby Nichols Ranch and Hank Unit.

Mineralogy presented in the Wellfield Restoration Report (Cogema 2008) based on (Harshman 1972, Goldhaber et al. 1978, Reynolds and Goldhaber 1983), suggests that approximately half of the iron present in the ore zone and downgradient into the unaltered sandstone is in the form of pyrite and marcasite, with the total iron contents in the ore zone generally ranging from 1 to 2% compared to about 0.8 to 1% in the altered and unaltered sandstone. Ore zone samples collected from MU-7 following extraction have highly variable pyrite content ranging from 0.2 to 39.9% (as volume, model abundance), including an average of 0.3% associated with one core compared to an average of 8.6% associated with a second core (Swapp 2012). The sands in the reduced zones of the nearby Nichols Ranch and Hank Unit (6 miles and 4 miles from the Christensen Ranch facility, respectively) also contain pyrite (Uranerz 2007).

Table 3-1: Mineral Abundance associated with MU-7 Core Samples

Abundance	MU-7 Core 1						MU-7 Core 2					
Depth (feet)	593.0	593.8	594.6	595.2	596.0	Avg.	579.0	581.3	584.0	586.0	588.5	Avg.
Pyrite (in vol. %)	0.6	0.5	1.5	39.9	0.3	8.6	0.3	0.4	0.5	0.2	0.2	0.3
Albite (in vol. %)	12.1	15.9	16.4	11.8	15.1	14.3	29.2	25.1	21.4	24.7	21.0	24.3
Quartz (in vol. %)	34.5	28.3	30.4	21.6	17.6	26.5	32.1	32.9	41.6	39.1	39.3	37.0
K-Feldspar (in vol. %)	26.8	27.3	24.8	18.8	30.2	25.6	26.3	23.2	17.1	19.5	18.6	20.9
Fe-Mg (in vol. %)	26.1	28.0	26.9	7.9	36.8	25.1	12.2	18.5	19.4	16.6	20.8	17.5
Clay (in weight %)	4.0	3.7	3.9	2.8	5.5	4.0	3.9	4.0	3.4	2.4	2.8	3.3

Fe-Mg includes ferromagnesian minerals primarily biotite and chlorite.
Abundance reported as volume percentage (model abundance), normalized to 100%, except clay minerals are reported as weight percent.

3.3 Hydrogeology

3.3.1 Mine Unit-2

ARCADIS analyzed water level elevation data for MU-2 collected between February 1993 and April 2014 covering various operational periods including production, groundwater sweep, reverse osmosis, hydrogen sulfide (H_2S) application, and stability. Evaluation of the water level data suggested that the hydraulic gradient and groundwater flow direction varied across MU-2 during its operational periods. Estimated hydraulic gradients across MU-2 ranged approximately from 0.00057 feet per foot (ft/ft) to 0.012 ft/ft, with an average of approximately 0.007 ft/ft. Analysis of the

water level data also suggested that groundwater flow direction fluctuated from northwest to southwest across MU-2 during the operational periods.

Additionally, baseline water level data was evaluated between December 1992 and January 1993, which suggested that under natural hydrogeologic condition, the average hydraulic gradient is approximately 0.007 ft/ft across MU-2, which is the same as the overall average during the operational period. Utilizing an average hydraulic conductivity of approximately 0.52 feet per day (ft/day) (Cogema 2008), estimated average hydraulic gradient of 0.007 ft/ft, and reported effective porosity of 0.26 (Cogema 2008), the average groundwater velocity across MU-2 was found to be approximately 5.1 feet per year (ft/yr). However, since the hydraulic gradients appeared to vary widely during MU-2 operational periods, the groundwater velocity likely also varied from time to time during the last two decades.

3.3.2 Mine Unit-3

Similar to MU-2, ARACDIS evaluated water level elevation data from various operational periods at MU-3 between December 1990 and April 2014. Evaluation of the water level data suggested an average hydraulic gradient of approximately 0.005 ft/ft and an overall northwest flow direction across MU-3. Utilizing an average hydraulic conductivity of 0.34 ft/day (Cogema 2008), estimated average hydraulic gradient of 0.005 ft/ft, and reported effective porosity of 0.26 (Cogema 2008), the average groundwater velocity across MU-3 was estimated to be approximately 2.4 ft/yr. However, it should be noted that since the hydraulic gradient appeared to vary during MU-3 operational periods, the groundwater velocity likely also varied from time to time during the last two decades.

3.3.3 Mine Unit-4

Based on reported (Cogema 2008) hydraulic parameter values – average hydraulic conductivity of 0.51 ft/day, average hydraulic gradient of 0.0075 ft/ft, and effective porosity of 0.26 – the average groundwater velocity across MU-4 was estimated to be approximately 5.4 ft/yr. However, it is expected that similar to MU-2 and MU-3, the hydraulic gradient at MU-4 had likely varied during its operational periods, and hence, the groundwater velocity also varied from time to time during the last two decades.

3.3.4 Mine Unit-6

ARCADIS reviewed water level elevation data at MU-6 between January 2000 and May 2013. Evaluation of the water level data suggested an average hydraulic gradient of approximately 0.00733 ft/ft and an overall northwest flow direction across MU-6. Utilizing an average hydraulic conductivity of 1.58 ft/day (Cogema 2008), estimated average hydraulic gradient of 0.00733 ft/ft, and reported effective porosity of 0.26

(Cogema 2008), the average groundwater velocity across MU-6 was estimated to be approximately 16.3 ft/yr. However, it should be noted that the average hydraulic conductivity of 1.58 ft/day at MU-6 was estimated using an ore-zone thickness of 10 ft. Considering the thickness of 70 ft for the entire K zone aquifer, the hydraulic conductivity estimate would be 0.51 ft/day and the corresponding groundwater velocity would be 5.3 ft/yr, which is comparable to other mine units (i.e. 5.1 ft/yr, 2.4 ft/yr, and 5.4 ft/yr at MU-2, MU-3, and MU-4, respectively).

4.0 Geochemistry

ARCADIS investigated the geochemistry at the Christensen Ranch facility to assess the subsurface processes that affect the rate of contaminant migration for various constituents. This discussion focuses on the primary constituents driving restoration approval: uranium, selenium, and radium-226.

4.1 Background

Uranium One's Restoration Report identified iron (Fe), manganese (Mn), selenium (Se), total dissolved solids (TDS), uranium (U) and radium-226 (Ra-226) exceedances of the TRVs and either WDEQ or EPA standards in at least one wellfield (Cogema 2008). The associated hydrological and geochemical assessment, in combination with stability monitoring completed in 2006 did not indicate statistically significant increasing concentration trends, suggesting that residual constituent concentrations for MU-2 through MU-6 did not pose a threat to human health or the environment. However, the subsequent NRC staff evaluation, as detailed in its TER (NRC 2012) stressed the need for a more quantitative analysis of the fate and transport of constituents of concern (COCs) before reclamation would be approved.

A geochemical conceptual site model was prepared, along with an associated fate and transport model to support Uranium One's determination that the wellfield chemistry was stable. The analysis does not focus on MU-5, however, due to uranium recovery currently being conducted in Module 52 within this wellfield.

4.2 Uranium Geochemistry

Fate and transport of uranium is largely controlled by precipitation and dissolution, complexation, adsorption, and oxidation-reduction (redox) reactions. Uranium exists in numerous oxidation states (+3, +4, +5, +6, and +7) but is generally found as uranium (IV) and uranium (VI) in environmental systems. Under oxidizing conditions, uranium (VI) exists as the uranyl ion which undergoes extensive hydrolysis at higher pH values and forms aqueous complexes with carbonate and other anions (Grenthe et al. 2004). Increased Alkalinity enhances uranium (VI) mobility due to the formation of both aqueous phase complexes with carbonate and adsorbed uranium (VI) carbonate complexes.

Numerous studies have demonstrated that uranium (VI) adsorption to mineral surfaces is dependent on pH and the dissolved concentration of carbonate and other complexing agents (ligands) such as dissolved organic matter (e.g., Hsi and Langmuir 1985, Payne et al. 1998, Arai et al. 2006). Adsorption of uranium is low under acidic pH (approximately pH < 4) and increases with pH, concurrent with an increase in the fraction of uranium (VI) hydrolysis species. Uranium(VI) adsorption on metal oxides

typically increases up to approximately pH 8, and decreases in the pH 8 to 10 range consistent with formation of more weakly adsorbing uranyl carbonate complexes and competition with carbonate for sorption sites.

In waters containing calcium and carbonate (typical of alkaline waters in near-equilibrium with calcite), the dominant uranium species in solution comprise ternary calcium-uranyl-carbonate complexes such as $Ca_2UO_2(CO_3)_3^0$; this complexation further decreases uranium adsorption affinity (Fox et al. 2006). The PHREEQC geochemical model (discussed in detail in Sections 4.6 and 4.7) confirms that the uranium species in production zone groundwater comprise approximately 80% $Ca_2UO_2 (CO_3)_3^0$ and approximately 20% $CaUO_2(CO_3)_3^{2-}$, with minor amounts (less than 1%) of other uranyl species. In contrast, under reducing conditions uranium (IV) can form low-solubility phases, which limits its mobility (Langmuir 1997).

4.3 Selenium Geochemistry

The primary inorganic selenium species include selenide (selenium (-II)), elemental selenium (selenium (0)), and two oxyanions: selenite (selenium (IV)) and selenate (selenium (VI)). Sorption is an important control on selenite and selenate with both species sorbing to common iron, manganese, and aluminum minerals (e.g., goethite, hematite, kaolinite, respectively) (Rovira et al. 2008, USEPA 2007). However, in general, selenite sorbs more strongly to minerals than selenate (Zachara et al. 1994). Similar to uranium, selenium sorption is greatly influenced by pH, dissolved organic carbon (DOC) and the presence of competing anions (e.g., CO_3^{2-}, PO_4^{3-}). Biotic and abiotic reduction of selenite and selenate to form elemental Se(0) can be a major sink of soluble selenium in the environment (Oremland et al. 1989, Tokunaga et al. 1994, Zawislanski and Zavarin 1996).

4.4 Radium-226 Geochemistry

Radium-226 occurs in the environment in the +II oxidation state, and, therefore, attenuation is not directly dependent on redox conditions. Radium-226 has a low affinity to form aqueous complexes and primarily exists as cationic radium (II) from pH 3 to 10. Sorption to clays, sorption to iron and manganese hydrous oxides, and coprecipitation with iron and manganese hydrous oxides are strong radium attenuation mechanisms particularly at neutral to alkaline pH (EPA 2004). Sorption is also dependent on ionic strength and competing cation concentrations. Coprecipitation with barite ($BaSO_4$) represents an important radium-226 attenuation mechanism particularly in water containing moderate to high sulfate concentrations (EPA 2004, Landa 2004).

4.5 Wellfield Water Quality

Each wellfield was subjected to water quality monitoring to establish baseline conditions prior to extraction, pursuant to SUA-1341, LC 10.3. Water quality monitoring was also conducted following extraction and during restoration to track restoration effectiveness and demonstrate stability. An overview of the production zone water quality for each wellfield is provided below, with a focus on baseline and stability water quality. Baseline perimeter well water quality (surrounding aquifer) and more recent monitoring (e.g., 2013 through 2015) to address the NRC TER comments and also conduct excursion monitoring are presented in Section 4.6 - Reactive Transport Modeling Overview.

4.5.1 Data Sources

The following data sources were used in this geochemical evaluation:

- Wellfield data packages (wellfield reports) for each wellfield (Cogema 1994a, 1994b, 1995, 1996, TMC 1993a, 1993b). Uranium One also provided water quality data in excel format.
- Tabulated data from samples collected in 2013 and 2014 for select MU-3 production zone wells.
- Tabulated data from samples collected in 2015 from the production zone and the downgradient perimeter wells for each wellfield.

4.5.2 Water Quality Analysis

Production zone baseline water quality in each wellfield was characterized as sodium-sulfate type as illustrated in the trilinear diagram shown in Figure 4-1. MU-2 (North and South), MU-3, and MU-4 plot together on the trilinear diagram whereas MU-6 is characterized by higher sulfate and lower alkalinity (Figure 4-2). Although pyrite is expected in the ore zone within each wellfield, these results suggest that MU-6 ore contains more pyrite (or more readily accessible pyrite) than the other wellfields. Specifically, pyrite oxidation releases sulfate and acidity, and the acidity is neutralized by alkaline mineral dissolution. Therefore, more pyrite oxidation is consistent with higher sulfate concentrations and lower alkalinity. The lower alkalinity observed for MU-6 also correlates with lower baseline concentrations of uranium (Table 4-2), consistent with a lesser amount of uranyl-carbonate aqueous complex formation within MU-6 and/or higher content of reduced uranium (IV) mineral phases.

Round 4 stability water quality is also illustrated in the trilinear diagrams provided in Figure 4-1. The water quality data shows a transition from sodium-sulfate to sodium-bicarbonate type water with the exception of MU-3 and MU-6, which were still characterized as sodium-sulfate type water following stability monitoring. Wellfield

production zones are characterized by increases in alkalinity (primarily as bicarbonate), As described above, the increase in alkalinity appears to be stabilizing uranium as aqueous carbonate complexes thereby hindering reduction to less soluble uranium (IV) mineral phases and sorption of uranium (VI) to mineral surfaces during restoration and stability monitoring. The interplay between pH, alkalinity, and calcium concentration will also have a strong effect on the adsorption affinity of uranium; this is described in more detail below.

At least two production zone and two perimeter wells were sampled from each mine unit in May 2015 with key water quality parameters illustrated in Figure 4-3 (total uranium selenium, and radium-226), Figure 4-4 (pH and electrical conductivity), and Figure 4-5 (dissolved oxygen and oxidation reduction potential). The 2015 water quality illustrates the heterogeneous nature of water quality across the wellfields within the production zone, and the perimeter wells. The 2015 water quality at the perimeter well rings is consistent with baseline perimeter well water quality.

4.6 Reactive Transport Modeling Overview

Fate and transport modeling was conducted to assess the effectiveness of the MU-2 through MU-6 wellfield restoration and is summarized in the following subsections. Models were developed following review of the initial geochemical model developed by Uranium One (Cogema 2008) and the subsequent modeling conducted by NRC staff (NRC 2012).

4.6.1 Procedures

Geochemical reactive transport modeling was performed to evaluate the transport of dissolved reactive constituents migrating in the facility groundwater. Model calculations were performed using PHREEQC version 2.17 with the WATEQ4F database (Parkhurst and Appelo 1999), supplemented with stability constants for the ternary calcium and magnesium uranyl-carbonate aqueous complexes (Dong and Brooks 2006, 2008) as well as updated formation constants for other uranyl complexes from Guillaumont (2003). These additions to the database are included in Appendix D.

4.6.2 Model Domain

Separate one-dimensional transects following the direction of groundwater flow were constructed for MU-2 North, MU-2 South, MU-3, MU-4, and MU-6. For each wellfield, the one-dimensional model domain included four zones, as illustrated in Figure 4-6: upgradient of the production zone (Zone 1), the production zone (Zone 2), the 300-ft region between the production zone and perimeter well ring (Zone 3), and the region downgradient of Zone 3 (Zone 4). Distances for Zones 1 and 4 were arbitrarily set at 400 and 200 ft, respectively; Zone 3 was fixed at 300 ft (distance to the perimeter well

ring from the wellfield); and Zone 2 was fixed at 400 ft for the wellfields, except MU-6, for which a production zone length of 500 ft was assumed. Hydraulic parameters were estimated immediately for each wellfield (Section 3.0) and are included in Table 4-3. Initial water quality conditions assumed for each zone in the modeling transect are presented in Figure 4.6, based on the average water quality determined for each wellfield as described above (Section 4.5). Flux-type boundary conditions were used at the ends of the modeling domain, with the influent solution water quality matching the initial water quality in Zone 1.

Table 4-2: Reactive Transport Model Water Quality Data

Parameter	Units	MU-2 South			MU-2 North			MU-3			MU-4			MU-6		
		Surrounding Aquifer	Production Zone		Surrounding Aquifer	Production Zone		Surrounding Aquifer	Production Zone		Surrounding Aquifer	Production Zone		Surrounding Aquifer	Production Zone	
			2005 Stability Round 4	May 2015 (2AG31-1)		2005 Stability Round 4	May 2015 (2S88-1)		2005 Stability Round 4	May 2015 (3U45-1)		2005 Stability Round 4	May 2015 (4S106-2)		2005 Stability Round 4	May 2015 (6S29-1)
pH (field)	s.u.	8.90	7.74	ND	9.36	7.80	7.40	8.88	7.67	7.75	8.84	8.01	7.74	8.55	7.98	7.08
pH (lab)	s.u.	—	—	7.60	—	—	8.50	—	—	8.30	—	—	8.20	—	—	7.90
Temperature	°C	12.5[a]	—	—	13.2[a]	—	16.8	13.9[a]	—	14.3	14.0[a]	—	14.6	15.2[a]	—	15.70
Alkalinity	mg/L $CaCO_3$	98.1	202.4	435.0	92.4	270.5	557.0	96.7	182.2	468.0	97.4	366.4	484.0	65.7	227.1	181.0
Ca	mg/L	9.1	58.4	45.0	7.5	73.6	96.0	7.6	46.6	36.0	7.8	42.7	61.0	28.7	54.8	49.0
Mg	mg/L	1.0	8.1	9.0	0.5	7.6	11.0	2.8	6.2	6.0	0.9	9.1	14.0	5.1	12.0	12.0
Na	mg/L	142.9	108.9	208.0	135.8	109.8	198.0	134.4	109.0	228.0	130.5	226.6	293.0	240.2	188.5	199.0
K	mg/L	2.7	1.5	3.0	3.3	1.4	3.0	2.7	1.6	3.0	0.9	3.6	6.0	4.4	4.0	3.0
SO4	mg/L	214.3	185.7	162.0	204.7	154.4	173.0	198.4	174.8	88.0	201.8	210.5	236.0	528.7	296.1	367.0
NO_3(N)	mg/L	0.11	0.10	0.10	0.10	0.10	0.10	0.04	0.05	0.10	0.26	0.12	0.10	0.47	0.06	0.10
F	mg/L	0.18	0.11	0.10	0.81	0.10	0.10	0.21	0.10	0.10	0.18	0.12	0.10	0.15	0.10	0.10
Cl	mg/L	9.5	8.2	16.0	9.1	7.2	15.0	8.9	5.6	10.0	8.5	19.3	34.0	5.0	10.4	13.0
U	mg/L	0.008	0.13	1.71	0.016	0.330	2.690	0.045	0.120	3.260	0.017	3.830	8.180	0.008	1.180	0.531
Se	mg/L	0.002	0.010	0.002	0.008	0.010	0.001	0.008	0.010	0.005	0.001	0.210	0.429	0.001	0.080	0.105
Ba	mg/L	0.016[b]	0.5[c]	0.039	0.016[b]	0.5[c]	0.045	0.015[b]	0.5[c]	0.037	0.0125[b]	0.5[c]	0.041	0.012[b]	0.5[c]	0.161
Ra226	pCi/L	2.7	164.3	0.2	0.86	243.0	0.2	31.0	195.6	127.0	2.3	114.1	0.2	6.7	181.0	0.2
Ra226	mg/L	2.70E-09	1.64E-07	2.00E-10	8.61E-10	2.43E-07	2.00E-10	3.10E-08	1.96E-07	1.27E-07	2.26E-09	1.14E-07	2.00E-10	6.73E-09	1.81E-07	2.00E-10

--- Not determined

[a] Temperature values correspond to surrounding aquifer results collected in 2015.

[b] Barium results correspond to surrounding aquifer results collected in 2015. Barium was typically non-detect in the original analysis due to excessively high detection limits of between 0.1 and 0.5 mg/L.

[c] Barium was generally at or below the detection limit of 0.5 mg/L in the production zone in 2005.

Table 4-3: Average Hydraulic Parameters Used in Reactive Transport Modeling

Parameter	MU-2	MU-3	MU-4	MU-6
Effective Porosity	0.26	0.26	0.26	0.26
Hydraulic Conductivity (ft/day)	0.52	0.34	0.51	1.58
Hydraulic Gradient (ft/ft)	0.007	0.005	0.0075	0.007
Groundwater Velocity (ft/yr)	5.11	2.39	5.37	15.5

4.6.3 Geochemical Model

The geochemical reactive transport model was used to evaluate two limiting scenarios; one in which no redox reactions occur, and one in which redox reactions run to complete thermodynamic equilibrium. Although not necessarily realistic, ARCADIS ran the "no redox" model to illustrate this bounding condition and its effect on constituent transport. The following geochemical reactions were considered in the reactive transport model:

- Equilibrium speciation reactions for all dissolved constituents included in Table 4-2.
- Mineral dissolution/precipitation equilibria for calcite, pyrite, elemental selenium, and uraninite (crystalline UO_2).
    - Calcite supersaturation was assumed with saturation index maintained at 0.35, based on the calculated level of calcite supersaturation in the surrounding aquifer.
    - Although barite saturation was evaluated in the model, it was not allowed to precipitate.
- Redox equilibria for the following constituents:
    - U(IV)/U(VI), Se(0)/Se(IV)/Se(VI), S(-II)/S(VI), Fe(II)/Fe(III), O(-II)/O(0)
- Uranium sorption via a surface complexation model (SCM) approach, with effective K_D values calculated for comparison.

In model scenarios where redox was not considered, uranium was assumed to be present exclusively as uranium (VI), and selenium was assumed to be present as selenium (VI). Due to the relatively weak adsorption of selenate on most mineral surfaces compared to other anions (e.g., Balistrieri and Chao 1990), adsorption of selenium was not considered in the model. Concentrations of solid phases and uranium surface complexation sites for PHREEQC input were calculated assuming a bulk density

of 1.7 kg/L and a total porosity of 0.35 (note that this is higher than the effective porosity of 0.26, which represents the "mobile" fraction of the total porosity).

Uranium and selenium reduction were considered in the geochemical model by addition of pyrite within Zones 3 and 4. Based on mineralogy presented in Section 3.2, a pyrite content of 1% by weight was assumed within the aquifer downgradient of the production zone (pyrite was not included in the upgradient and production zones). Pyrite was allowed to dissolve to equilibrium, releasing Fe(II) and S(-II), which then reacts with dissolved oxygen, uranium, and selenium in the aqueous phase. In practice, abiotic selenium and uranium reduction typically proceed via sorption to reduced mineral phases, followed by electron transfer at the mineral surface (Myneni et. al. 1997 and Breynaert et. al. 2008). However, the aqueous phase reactions in the geochemical model adequately capture the overall thermodynamic process.

Uranium adsorption in the transport model was captured using a SCM approach. The primary advantage of a SCM over a constant distribution coefficient (K_D) approach is that the SCM is a thermodynamic model that accounts for changes in uranium adsorption strength as a function of the system geochemistry. It is important to note that the SCM was used to estimate K_Ds in different geochemical modeling zones, as identified in Figure 4-6. It's these zone-specific K_D values that were used in the fate and transport models.

Uranium adsorption strength depends primarily on solution pH, alkalinity, and calcium content. As described in Section 4.2, uranium adsorption strength changes with pH and ion concentrations. In particular, the dominant aqueous species in groundwater at Christensen Ranch include $Ca_2UO_2(CO_3)_3^0$ and $CaUO_2(CO_3)_3^{2-}$; formation of these species tends to stabilize uranium in solution, keeping it from adsorbing. The relative proportions of these and other aqueous phase uranium species are most dependent on the concentrations of calcium and carbonate, with carbonate concentrations dependent on pH and alkalinity. Mineral surface charge is also controlled by pH and ion concentrations.

The generalized-composite SCM of Bond et al. (2008) was chosen for use in the reactive transport model. The SCM consists of a non-electrostatic, single-site, two-reaction model with the following reactions:

$$SOH + UO_2^{2+} + H_2O = SOUO_2OH + 2H^+ \qquad Log(K_f) = -5.152 \quad (1)$$

$$SOH + UO_2^{2+} + H_2CO_3^0 = SOHUO_2CO_3 + 2H^+ \qquad Log(K_f) = -0.833 \quad (2)$$

where, SOH is the surface site for binding and K_f is the formation constant for the reaction. Because $H_2CO_3^0$ is not included as a species in the WATEC database for

PHREEQC by default, Equation 2 was converted to a bicarbonate basis according to the following:

$$HCO_3^- + H^+ = H_2CO_3^0 \qquad Log(K_f) = 6.351 \quad (3)$$

$$SOH + UO_2^{2+} + HCO_3^- = SOHUO_2CO_3 + H^+ \qquad Log(K_f) = 5.518 \quad (4)$$

This model was developed for the shallow sediment at the Hanford site (300 Area), but has reasonable applicability to the Christensen Ranch wellfields for the following reasons:

- Many of the phases responsible for uranium adsorption in the shallow alluvium at Hanford, including quartz sand/silica and aluminosilicate clay minerals, are also present in the Wasatch Formation sandstone.

- Although some mineralogy is likely different at the two sites (e.g., potential greater abundance of oxic phases in Hanford alluvium, vs. a greater abundance of reduced phases at Christensen Ranch), differences in mineralogy, grain sizes/reactivity, and porosity can be reasonably accounted for by scaling the number of reactive surface sites in the model, as described below.

- The aqueous chemistry of the Hanford 300 Area is very similar to the chemistry at Christensen Ranch, particularly with respect to pH, calcium content, and alkalinity. Specifically, the Hanford SCM was calibrated using synthetic groundwater with pH between 7.85 and 8.65, a calcium concentration of 24 mg/L, and alkalinity between 25 and 500 mg/L as $CaCO_3$.

The surface site concentration in the model (entered into PHREEQC on a per-liter basis) was estimated using a site density of 3.84 micromoles per square meter of mineral surface area (the concentration assumed in development of the SCM; Bond et al. 2008), a total porosity of 0.35, and a specific surface area of 3 square meters per gram (m^2/g). This results in a surface site concentration of 5.6×10^{-2} moles/L. The actual surface area of the solid phase in the formation is unknown, making this choice arbitrary (for comparison, the sediments used to develop the Hanford SCM exhibited surface areas of 15 to 27 m^2/g for the < 2mm size fraction; Bond et al. 2008). However, to verify that the resulting uranium adsorption strength achieved with this estimate is realistic, effective K_D values were calculated for the surrounding aquifer and compared to the value assumed by the NRC staff in previous modeling efforts for Christensen Ranch (NRC 2012). These results are described in the next section.

4.6.4 Reactive Transport Model Scenarios

The reactive transport model for each well field was run for three production zone water quality scenarios, with each scenario alternately run assuming that no redox reactions occur, and then assuming that redox reactions run completely to thermodynamic equilibrium. The various model scenarios are summarized in Table 4-4 below (see Table 4-2 for production zone and surrounding aquifer water quality).

Table 4-4: Geochemical Model Scenarios

Scenario	Description	Equilibrium Redox	No Redox
1	Production zone chemistry represented by the 2005 Round 4 Stability well-average values	X	X
2	Similar to Scenario 1, but with uranium concentration increased to 50 mg/L to evaluate protectiveness at the perimeter	X	X
3	Production zone chemistry represented by May 2015 values	X	X

The May 2015 production zone chemistry was based on the well in each wellfield exhibiting the highest uranium and selenium concentrations. Only the uranium concentration was adjusted between Scenarios 1 and 2, making the scenarios equivalent with respect to all other constituents, including selenium and radium.

The "Equilibrium Redox" and "No Redox" scenarios likely represent the extreme ends of a more realistic scenario in which reduction of uranium and selenium proceeds, but with a kinetic limitation (i.e., the redox reactions proceed at a slow rate due to the time required for constituents to come into contact and react). The effect of kinetic limitations on the achievement of redox equilibrium is investigated in Section 4.7.4.

Uranium adsorption in the "No Redox" models was alternately simulated using the SCM model and an "effective K_D" approach. In the effective K_D approach, K_D values for each well field production zone and surrounding aquifer were calculated using the SCM. As demonstrated below, these different approaches yield different results because the K_D approach does not account for the transport of water quality.

4.7 Modeling Results and Discussion

The geochemical modeling results are presented in the following subsections.

4.7.1 Uranium Distribution Coefficient Estimation

Distribution coefficient (K_D) values for adsorption were calculated using the SCM approach described above, with unique K_D values calculated separately for the production zones and surrounding aquifer in each MU. The calculated surrounding-aquifer K_D values (Table 4-5) varied between 1.1 and 2.7 L/kg, which are lower than the K_D value of 10 L/kg suggested in the NRC staff's modeling report, but slightly above the value of 0.5 L/kg initially assumed in the staff's model based on references cited therein (NRC 2012). Based on this comparison, the level of uranium adsorption observed with the SCM (using an assumed mineral surface area of 3 m^2/g) is believed to be reasonable. However, considering the high degree of uncertainty in the surface site concentration, Uranium One performed a sensitivity analysis for this parameter, the results of which are described below.

Production zone K_D values estimated using the 2005 Round 4 Stability water quality varied between 0.08 and 1.1 L/kg, in some cases approximately one order of magnitude less than the corresponding surrounding aquifer value for each wellfield. K_D values calculated using May 2015 water quality were typically similar to the 2005 Round 4 Stability values, with the exception of MU-6 which exhibited a much higher K_D value of 14 L/kg. Although alkalinity and calcium concentrations were similar to the 2005 water quality values, the calculated K_D value was higher for the 2015 water chemistry due to the much lower field pH.

Table 4-5: SCM-Based Uranium Effective K_D Values

Mine Unit	Surrounding Aquifer K_D (L/kg)	Production Zone K_D (L/kg)	
		2005 Stability Round 4	May 2015
MU-2 South	1.41	0.39	0.22
MU-2 North	1.02	0.11	0.11
MU-3	1.62	1.07	0.16
MU-4	1.69	0.082	0.088
MU-6	2.56	0.17	14.4

4.7.2 Uranium Transport

As mentioned above, the "Equilibrium Redox" and "No Redox" scenarios likely represent the extreme ends of a more realistic scenario, in which reduction of uranium and selenium proceeds, but with a kinetic limitation. Therefore, it is useful to understand the

implications of uranium transport in the absence of redox reactions. The results of these two modeling cases are described below.

4.7.2.1 Uranium Transport with No Redox Reactions

The predicted uranium concentrations at the 300-ft perimeter wells as a function of time are shown in Figures 4-7 through 4-11 for MU-2 South, MU-2 North, MU-3, MU-4, and MU-6, respectively. The predicted perimeter well uranium concentrations (gray and blue) are shown against the production zone uranium concentrations (red line) and the EPA groundwater maximum contaminant level (MCL) for uranium of 30 µg/l. Without uranium redox in the model, uranium transport was separately predicted using the SCM (blue curves) and the effective K_D values provided in Table 4-5 above (including separate K_D values for the surrounding aquifer and wellfield-specific production zone). These approaches yield different results due to the migration of production zone water quality. In other words, the SCM approach accounts for the fact that the uranium adsorption affinity in the aquifer downgradient of the production zone changes as the production zone water quality moves through (i.e., uranium adsorption strength changes as pH, calcium content, and alkalinity changes in the surrounding aquifer). In contrast, the effective K_D approach does not account for this effect; the assigned surrounding aquifer K_D does not change over time regardless of changes in water chemistry.

Overall, the model prediction results are similar among the wellfields, with general observations described below. The following observations were noted for the non-redox case, which, again, is not considered reasonable:

- Sorptive retardation combined with dispersion results in a spreading of the uranium plume as it is transported downgradient from the production zone, resulting in a decrease in the maximum uranium concentration observed at the perimeter relative to the production zone.

- The effective K_D approach results in delayed arrival times relative to the SCM approach, with predicted peak arrival times of the maximum concentration occurring between 50 and over 100 years based on the SCM, and between 250 and 1100 years or later based on the effective K_D model (MU-6 and MU-3, respectively).

- Increases in uranium concentration above the MCL at the perimeter wells occur on arrival of the front face of the plume, within approximately 20 to 50 years or later (note that the MU-3 baseline surrounding aquifer uranium concentration is already above the MCL).

- Although sorption and dispersion result in a decrease in the peak uranium concentration, the peak concentration remains above the MCL in each case.

- Uranium behavior is similar in the three scenarios considered for each wellfield, scaling with uranium concentration. The exception is the 2015 MU-6 model, which exhibits a much longer time to arrival of the uranium peak, with excursions of uranium above the current production zone value for the SCM run. This is a result of the high level of adsorption in the production zone (as demonstrated by the high K_D value in Table 4-5), which predicts an excessively high quantity of adsorbed uranium that subsequently desorbs.

The SCM results predict a more rapid time of arrival of the uranium peak relative to the effective K_D approach. As described above, uranium adsorption strength is controlled most strongly by the aqueous pH, alkalinity, and calcium content of the solution. In the model, the uranium adsorption affinity in the downgradient aquifer changes as the production zone chemistry (particularly, pH, alkalinity, and calcium content) travels downgradient. Since the production zone adsorption affinity is lower than in the downgradient aquifer (as illustrated by the calculated effective K_D values in Table 4-5), migration of the production zone water quality results in less retardation of uranium. Although the SCM does not account for all of the processes that may retard water chemistry (e.g., pH buffering and ion exchange for calcium and alkalinity), the SCM approach is more realistic than the effective K_D approach, which does not account for the effect of water quality transport.

Although the no-redox case provides a useful conservative bookend for assessing uranium transport, ARCADIS considers this scenario to be unreasonable, considering the presence of sulfide minerals and the reducing environment downgradient. The following section examines the level of uranium removal that can occur with uranium reduction coupled to pyrite oxidation.

4.7.2.2 Uranium Transport with Redox Reactions

This model scenario includes redox reactions, which Uranium One considers to be more reasonable than the model scenario with no redox reactions (Figures 4-7 through 4-11). With equilibrium redox considered in the model (uranium reduction and precipitation as crystalline uraninite, coupled to pyrite oxidative dissolution), effectively all of the dissolved uranium is removed from solution, resulting in uranium concentrations below the MCL at the well ring. Note that the final predicted aqueous uranium concentration is independent of the starting concentration of uranium, so long as there is sufficient pyrite mass to completely reduce uranium. The model results demonstrate that sufficient pyrite mass is present to achieve uranium reduction throughout the modeled timeframe. Potential kinetic limitations on redox, as well as the effect of the assumed U(IV) mineral product, are described in more detail below.

4.7.3 Selenium Transport

Selenium concentrations at the perimeter wells were also predicted in the reactive transport model with and without selenium reduction coupled to pyrite oxidation. Selenium results are only shown for the "Scenario 1" runs described above, since the predictions for the May 2015 results are similar. These model predictions are provided in Figures 4-12 and 4-13. The following observations were noted:

- Selenium is transported in the model without retardation, with peak arrival occurring between 50 and 200 years. In the absence of redox, the maximum concentration is similar to the production zone concentration; this result is similar for the 2005 production zone chemistry (results not shown).

- In the absence of redox reactions, production zone selenium concentrations are below the groundwater MCL of 50 µg/L in MU-2 (North and South) and in MU-3, whereas production zone selenium concentrations are above the MCL in MU-4 and MU-6. In the absence of redox, dispersion is insufficient to decrease selenium concentrations below the MCL.

- When redox reactions are considered (selenate reduction coupled to pyrite oxidation), predicted aqueous selenium concentrations are reduced to well below 1 µg/L in each case.

These results demonstrate that, in the absence of strong kinetic limitations on redox (discussed in the next section), reaction with pyrite would attenuate selenium concentrations to below the MCL. As it currently stands, production zone selenium concentrations in MU-2 and MU-3 are currently below the groundwater MCL. However, the equilibrium model does predict lower concentrations of selenium in the downgradient aquifer that are actually currently present, indicating a level of redox non-equilibrium between sulfide minerals and dissolved selenium. This further points to the importance of kinetic limitations on selenium reduction, which will be further described in the next section.

4.7.4 Uranium and Selenium Transport Sensitivity Analysis (Example: MU-2 North)

4.7.4.1 Uranium Adsorption Site Concentration

The SCM was run using a surface cite concentration of 0.056 moles per liter, based on an assumed mineral surface area of 3 m^2/g. Due to the high degree of uncertainty in the actual reactive surface area, a sensitivity analysis was run in which the surface site concentration was increased and decreased by a factor of five; down to 0.0112 moles/L and up to 0.28 moles/L. The results of this analysis using MU-2 North with the 2005

production zone water quality are shown in Figure 4-14. Decreasing the sorption site density (reducing the overall adsorption strength) results in a faster breakthrough of uranium, an increase in the peak concentration, and a closer agreement between the SCM and effective K_D approaches. Increasing the site concentration results in greater retardation (slower breakthrough and reduced peak concentration).

Varying the sorption site concentration for MU-2 North under the 2005 production zone chemistry does not change the overall observation that in the absence of redox, uranium concentrations at the well ring are predicted to exceed the uranium MCL. Therefore, the importance of redox processes in helping to achieve uranium attenuation at the perimeter well ring is evident in spite of the high degree of uncertainty in adsorption parameters.

4.7.4.2 Uranium and Selenium Reduction Kinetics

The results above indicate that if reaction of dissolved uranium and selenium with pyrite dissolution products is allowed to proceed, then reductive precipitation of uranium and selenium is thermodynamically favorable and will be sufficient to provide attenuation to levels below concern at the perimeter boundary. However, the degree of uranium and selenium reduction that is actually realized in the field will be dependent on kinetic limitations. Specifically, although it is known that sulfide minerals are present within the aquifer downgradient of the production zone, the extent of reaction between uranium and selenium and these sulfide minerals will be dependent on the accessibility and availability of sulfide mineral surfaces. For example, it is possible that pyrite present within the aquifer is present within pore spaces that are not within the direct groundwater flow-path, such that reaction between dissolved constituents is controlled by diffusion kinetics into immobile pore spaces. Another possibility is that sulfide mineral surfaces are passivated by oxidation byproducts or other mineral coatings, limiting the ability of uranium and selenium to come into direct contact with the surface, and/or limiting dissolution of the mineral.

Ultimately, the importance and extent of these processes are highly aquifer-specific, and direct solids characterization or field testing is required to define these processes. However, as an illustration of the potential consequences of these processes, kinetic limitations have been included in the Scenario 1 MU-2 North model runs as an example.

Limitations on redox reaction extent were studied in the model via two mechanisms:

1) A mass transfer limitation on reaction was established by including dual-domain processes in the model (schematic in Figure 4-15). Uranium and selenium were present in the mobile domain, while pyrite was placed in the immobile domain. Aqueous-phase redox reactions were, therefore, limited by diffusion of uranium and selenium into the immobile domain and/or diffusion of ferrous iron

and sulfide into the mobile domain. The rate of this diffusion is controlled by the mass transfer coefficient, α (with units of inverse time).

2) A constraint on the extent of equilibrium pyrite dissolution was established by varying the saturation index (SI) of pyrite, where a SI of zero represents thermodynamic equilibrium solubility. Adjusting this value to values below zero decreases the concentration of ferrous iron and sulfide in solution. This scenario effectively represents a situation where pyrite accessibility is limited by surface passivation.

The results of these evaluations are shown in Figures 4-15 and 4-16. In the mass transfer limitation scenario, decreasing the mass transfer coefficient from a value of 1.0 $years^{-1}$ to a value of 0.001 $years^{-1}$ decreases the rate at which redox reactants come into contact, ultimately decreasing the extent to which uranium and selenium are reduced. Consequently, elevated concentrations of uranium and selenium reach the perimeter wells. Note that a similar effect is exhibited for uranium and selenium, since the mass transfer rate in the model is not constituent-specific.

A similar effect on the extent of uranium reduction is observed when the pyrite saturation index is decreased. Decreasing the SI from zero (SI = -25, -30, and -40 investigated) results in lower concentrations of sulfide and ferrous iron in solution, which shifts the redox balance such that higher concentrations of U(VI) remain in solution. In this case, very different results are observed between uranium and selenium, since the redox potentials of these two constituents are very different; even at the low pyrite saturation indices, complete reduction of selenate to elemental selenium is observed (Figure 4-16).

These results illustrate that, although the actual level of decrease achieved by redox processes may be strongly controlled by kinetic factors, achievement of substantial uranium and selenium decreases are still achievable with kinetic limitations in place. These results suggest that a combination of sorptive retardation, dispersion, and reduction greatly reduce the risk of concentration exceedances at the well ring.

4.7.5 Radium Transport

Radium chemistry and transport were also investigated in the batch-scale and reactive transport models. Adsorption of radium, although likely, was not considered in the model. The two processes considered in the model that could potentially attenuate radium include precipitation of radium sulfate and precipitation of barium sulfate (barite). Barite dissolution/precipitation does not directly affect radium concentration in the model; rather, it is assumed that if geochemical conditions support precipitation of barite, then attenuation of radium via coprecipitation within barite is highly likely. The saturation index of barite was calculated in the geochemical model using the surrounding aquifer

and 2005 stability production zone chemistry, updated with barium concentrations measured in 2015 as described above.

In all cases, radium sulfate was found to be undersaturated, suggesting that direct precipitation of radium as a sulfate mineral is not likely. However, the modeling results do indicate that barite is very close to saturation in the surrounding aquifer (SI values of zero +/- 0.1) and supersaturated in the production zone (SI values between 0.3 and greater than 1; Figure 4-17). The elevated concentrations of barium in the production zone and the fact that the surrounding aquifer is at saturation suggest that barite is present in the formation and barite was liberated during production. Supersaturation of barite in the production zone is expected to lead to barite precipitation within and downgradient of the production zone, which is expected to result in the attenuation of radium.

4.8 Modeling Summary

One-dimensional reactive transport models were constructed for the wellfields to predict the behavior of uranium, selenium, and radium within the production zone, with the goal of predicting anticipated concentrations at perimeter wells through time. Uranium adsorption was simulated using an SCM approach, which represents a more rigorous and technically defensible approach, as it accounts for variations in water quality between the production zone and the surrounding aquifer. Uranium predictions, that exclude redox reactions, indicate that sorption and dispersion processes will act to both retard the arrival and decrease the maximum concentrations of uranium observed at the perimeter wells, consistent with the modeling results obtained by NRC (2012). However, these concentration decreases are not sufficient to attenuate uranium to below the MCL.

However, modeling results, that include redox reactions, indicate that reductive precipitation of uranium coupled to pyrite oxidation is thermodynamically favorable and capable of decreasing concentrations to below MCL at the perimeter wells. The greatest uncertainty in this process is the extent to which site-specific kinetic limitations are hindering redox equilibrium, although the simulations suggest that even with substantial kinetic limitation, concentrations below the MCL are achievable at the well ring.

Similar results were observed for selenium. Specifically, in MU-4 and MU-6, where production zone selenium concentrations are above the MCL, dispersion alone is insufficient to reduce concentrations to below the MCL at the perimeter wells. However, reductive precipitation as elemental selenium coupled to pyrite oxidation is thermodynamically favorable. As with uranium, kinetic limitations may hinder redox equilibrium, but substantial concentration reductions are still observed even with significant kinetic limitation. Finally, based on evidence that barium sulfate is present

within and downgradient of the production zone, the mobility of radium is predicted to be limited.

4.9 MU-2 South Excursion

One aspect of kinetic limitation is the abrupt change in water level that can occur in dormant wellfields depending on activities at other nearby wellfields. Because changes in water level, and thereby hydraulic gradient, affects the rate of constituent migration, these hydraulic gradient changes alter the extent of constituent attenuation. Such a circumstance appears to have contributed to the excursion at 2MW-84.

In July 2015, Uranium One notified the NRC staff of an excursion at 2MW-84. ARCADIS reviewed the analytical data and discovered that the excursion appears to coincide with a decrease in water levels. Upon further examination, a small groundwater level depression occurs occasionally near 2MW-84. Potentiometric surface maps from July 2015 and June 2005 demonstrate this occasional groundwater drop near 2MW-84 (see Figures 4-18 and 4-19, respectively. Although the cause of this drop is unknown, such drops cause hydraulic gradients to increase, which ultimately affects contaminant transport.

5.0 Response to NRC Comments

This section contains responses to specific NRC staff comments regarding individual wellfields

5.1 Mine Unit 2 North

The NRC staff stated the following in its TER regarding the evaluation findings for MU-2 North:

> *Based upon the above, the staff concurs that the restoration of MU-2 North is protective of human health and safety and the environment provided that:*
>
> *(1) SSI trends noted for uranium and radium-226 at well 2T92-2 are shown to be reversed and stabilization is demonstrated.*
>
> *(2) The licensee provides a confirmatory analysis of the groundwater quality at well 2MW108 subsequent to corrective actions for the 2011 excursion that demonstrates impacts to the aquifer following the 2011 excursion event meet regulatory requirements (groundwater protection criteria).*
>
> *The staff cannot recommend restoration approval of MU-2 North until the above is completed.*

5.1.1 SSI Trends for Uranium and Radium-226

Regarding item 1, Uranium One demonstrated in Section 2.3.3, that MU-2 North is stable without SSI trends. The NRC staff's assessment of trends is not appropriate, as they attempted to determine trends on individual wells when all groundwater protection standards and restoration efforts are developed on a wellfield basis. This approach mine-unit based approach is supported by the ProUCL documentation, as stated in Section 10.2 of the ProUCL technical guide (EPA, 2013). Therefore, determining concentration trends in an entire wellfield is the most statistically valid and appropriate trend analysis method for this project.

5.1.2 Water Quality at 2MW-108

Regarding item 2, Table 5-1 presents monitoring data after the 2011 excursion at MW-108.

Table 5-1: 2MW-108 Monitoring Results

Parameter/ Sample Date	Chloride	Specific Conductance	Total Alkalinity	pH	Piezometric Elevation
Units	mg/L	µmho/cm	mg/L as $CaCO_3$	s.u.	Feet above mean sea level
Upper Control Limit	11.6	778	124.6		
10/24/2011	10.9	709	116.7	8.4	4546.7
10/31/2011	10.8	701	115.2	8.5	4535.7
11/07/2011	11.2	686	109.1	8.4	4536.7
11/08/2011	10.4	684	107.6	8.4	4536.7
11/14/2011	10.6	684	105.2	8.4	4542.7
11/21/2011	10.4	683	103.6	8.5	4548.7
11/28/2011	10.0	686	105.7	8.2	4549.8
12/05/2011	10.1	688	106.6	8.2	4550.4
03/19/2012	10.1	668	98.8	8.6	4537.6
05/23/2012	10.4	690	105.8	8.5	4549.3
08/16/2012	10.8	699	112.6	8.4	4549.1
12/13/2012	10.9	712	116.0	8.4	4546.4
03/11/2013	11.6	729	116.6	8.5	4532.7
05/07/2013	11.6	730	111.0	8.3	4540.2

A review of Table 5-1 indicates that the excursion at monitoring well MW-108 is no longer an issue. Based on the information presented in the aforementioned responses, restoration MU 2 North should be approved.

5.2 Mine Unit 2 South

The NRC staff stated the following in its TER regarding the evaluation findings for MU-2 South:

> *The staff cannot recommend restoration approval of MU-2 South until:*

(1) The licensee demonstrates the overlying and production aquifers between MU 2 South and MU 3 are not impacted; and –

(2) The licensee demonstrates the SSI trend noted in the uranium concentrations at well 2AF34-1 is reversed and stable.

5.2.1 Impacts to Overlying and Production Aquifers

The NRC staff expressed concerns that the area between MU-2 and MU-3 was not sufficiently characterized and was a source of excursions (NRC, 2012, pages 22 and 23). ARCADIS reviewed data that demonstrates excursions are not an issue with the wells cited by the NRC staff. Tables 5-2 through 5-6 show monitoring data for the monitoring well ring between MU-2 South and MU-3. Data shown is from the beginning of 2009 into 2013.

Table 5-2: 2MW-28 Monitoring Results (Production Aquifer)

Parameter/ Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	11.6	778	124.6
01/06/2009	9.9	710	95.4
04/22/2009	10.1	713	94.2
07/21/2009	10.6	714	94.9
10/06/2009	11.5	704	93.3
01/05/2010	12.7*	718	96.4
04/05/2010	11.0	708	97.4
07/13/2010	10.9	699	92.2
10/26/2010	11.7*	709	94.6
01/11/2011	9.9	706	84.3
04/04/2011	9.4	705	96.8
07/12/2011	9.7	703	94.5
10/06/2011	9.9	701	97.2

Table 5-2 (cont'd.)

Parameter/ Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	11.6	778	124.6
01/09/2012	9.4	703	97.5
05/01/2012	9.7	699	98.3
08/16/2012	10.4	694	97.8
11/02/2012	10.0	674	93.2
01/15/2013	10.5	695	95.6
05/02/2013	9.8	705	92.4

*Exceeds Upper Control Limit

Table 5-3: 2MW-73 Monitoring Results (Production Aquifer)

Parameter/ Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	13.6	823	121.3
03/02/2009	10.5	664	96.6
06/22/2009	10.8	662	90.1
09/14/2009	9.9	669	96.7
12/16/2009	9.4	666	93.9
03/08/2010	9.4	659	87.1
06/07/2010	9.0	665	89.3
09/27/2010	8.7	664	88.6
12/13/2010	9.2	656	83.4
03/08/2011	9.5	666	89.4
06/15/2011	8.8	667	92.8

Table 5-3 (cont'd)

Parameter/ Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	13.6	823	121.3
08/22/2011	9.4	665	95.6
11/09/2011	9.0	671	98.2
03/20/2012	9.3	664	91.9
05/22/2012	9.5	666	98.1
08/16/2012	9.3	658	91.3
12/20/2012	9.6	654	91.5
03/21/2013	9.6	678	92.1
06/13/2013	9.9	663	95.6

Table 5-4: 2MW-87 Monitoring Results (Production Aquifer)

Parameter/ Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	13.6	823	121.3
03/02/2009	9.6	664	96.6
06/16/2009	10.4	665	100.6
09/15/2009	9.9	665	94.6
12/16/2009	9.7	661	94.1
03/08/2010	9.5	663	81.4
06/07/2010	9.7	666	98.5
09/28/2010	9.1	664	93.0
12/08/2010	9.0	663	89.0
03/07/2011	9.8	666	96.8

Table 5-4 (cont'd)

Parameter/ Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	13.6	823	121.3
06/15/2011	9.4	665	93.1
08/22/2011	9.6	662	96.2
11/08/2011	9.3	664	99.3
03/21/2012	9.2	665	96.1
05/22/2012	9.8	663	99.5
08/21/2012	9.6	663	97.0
12/19/2012	9.5	664	95.5
03/20/2013	9.5	682	96.8
06/13/2013	10.3	685	101.5

Table 5-5: MW-88 Monitoring Results (Production Aquifer)

Parameter/ Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	13.6	823	121.3
04/30/2009	9.8	646	91.6
06/23/2009	9.8	650	94.4
09/15/2009	9.8	666	97.0
12/15/2009	9.5	662	96.0
03/08/2010	9.5	665	91.9
06/07/2010	8.9	664	92.0
09/28/2010	8.9	666	95.2
12/08/2010	8.8	665	89.3

Table 5-5 (cont'd)

Parameter/ Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	13.6	823	121.3
03/07/2011	9.3	664	98.9
06/15/2011	9.2	664	94.3
08/22/2011	9.5	665	96.0
11/08/2011	9.2	665	99.3
03/21/2012	9.1	667	96.3
05/22/2012	9.6	673	100.1
08/21/2012	9.5	666	95.7
12/19/2012	9.3	663	95.0
03/21/2013	9.3	678	95.0
06/13/2013	9.8	683	99.3

Table 5-6: MW-89 Monitoring Results (Production Aquifer)

Parameter/ Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	13.6	823	121.3
03/09/2009	15.8 *	787	136 *
03/11/2009	15.2 *	777	140.5 *
03/17/2009	15.4 *	769	142.2 *
03/26/2009	16.1 *	786	147.6 *
03/31/2009	15.5 *	782	142 *
04/08/2009	16.1 *	793	145.6 *
04/15/2009	16.2 *	783	140.5 *

Table 5-6 (cont'd)

Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	13.6	823	121.3
04/22/2009	15.5 *	781	141.4 *
04/29/2009	15.8 *	773	146.3 *
05/06/2009	15.9 *	769	139 *
05/14/2009	15.4 *	763	135.6 *
05/20/2009	15.4 *	758	131.4 *
05/27/2009	15.5 *	753	130.1 *
06/03/2009	14.2 *	751	131.4 *
06/10/2009	13.9 *	751	126.5 *
06/17/2009	14.2 *	752	129.6 *
06/25/2009	14.4 *	745	126.9 *
07/01/2009	14.4 *	744	122.1 *
07/08/2009	14.5 *	751	121.1
07/15/2009	15.5 *	740	117.2
07/22/2009	13.6	737	121.3
07/27/2009	13.4	735	121.2
09/15/2009	12.6	755	126.9 *
12/15/2009	15.4 *	765	135.3 *
12/16/2009	15.3 *	764	136.6 *
12/21/2009	16.3 *	772	142.1 *
12/28/2009	15.1 *	775	158.4 *
01/04/2010	15.3 *	777	157.9 *
01/11/2010	16.1 *	771	157.4 *

Table 5-6 (cont'd)

Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	13.6	823	121.3
01/18/2010	15.1 *	758	135.9 *
01/25/2010	13.9 *	755	125.6 *
02/01/2010	13.6	726	110.0
02/08/2010	13.3	720	112.8
02/16/2010	13.6	711	99.9
03/08/2010	13.3	716	95.6
06/07/2010	12.8	732	118.4
09/28/2010	13.3	750	120.0
12/08/2010	13.7 *	760	118.4
03/08/2011	15 *	765	142 *
03/09/2011	14.5 *	763	137.8 *
03/14/2011	14.4 *	759	137.5 *
03/21/2011	15.5 *	760	148.2 *
03/28/2011	14.7 *	763	147.9 *
04/04/2011	14.5 *	762	145.8 *
04/11/2011	14.5 *	748	130.9 *
04/18/2011	14.5 *	738	127.4 *
04/25/2011	14.9 *	729	123.2 *
05/09/2011	14.7 *	727	114.8
05/16/2011	14.7 *	716	112.0
05/23/2011	14.5 *	712	105.7
05/31/2011	14.2 *	713	106.9
06/06/2011	14.5 *	714	108.5

Table 5-6 (cont'd)

Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	13.6	823	121.3
06/13/2011	12.6	711	107.0
06/15/2011	13.0	708	109.9
06/20/2011	12.9	712	109.9
06/27/2011	12.5	708	112.5
08/22/2011	13.5	713	112.8
11/08/2011	13.2	732	123.2 *
03/27/2012	14 *	743	128.3 *
03/28/2012	13.9 *	742	127.4 *
04/02/2012	13.6	739	124.2 *
04/09/2012	13.6	728	122.1 *
04/16/2012	13.4	720	117.8
04/23/2012	14.9 *	715	112.7
04/30/2012	13.6	719	118.7
05/07/2012	12.6	715	111.1
05/14/2012	13.5	713	104.8
05/23/2012	13.3	706	107.7
08/21/2012	13.3	713	111.9
12/13/2012	13.5	729	123.4 *
03/28/2013	13.5	749	119.7
06/18/2013	12.7	742	118.2

*Exceeds Upper Control Limit

A review of Tables 5-2 through 5-6 indicates that none of these monitoring wells exhibited excursions, except well 2MW-89. Regarding 2MW-89, this well has not exhibited any excursions, per the definition of excursions in LC 11.2 since March 2012.

Therefore, Uranium One has demonstrated that the ore zone aquifer between MU-2 South and MU-3 is not impacted by activities.

Tables 5-7 through 5-11 present monitoring data for shallow monitoring wells nearest to MU-3.

Table 5-7: 2MW-92S Monitoring Results (Overlying Aquifer)

Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	23.5	3560	304
3/2/2009	11.6	2402	141.5
6/23/2009	11.5	2406	135.9
9/14/2009	11.4	2385	137.5
12/8/2009	11.9	2412	141.7
3/8/2010	11.5	2403	127.9
6/8/2010	10.6	2360	134.4
9/27/2010	10.4	2410	134.9
12/8/2010	10.6	2405	123.7
3/8/2011	10.8	2411	139.3
6/15/2011	10.7	2286	135.7
8/23/2011	11.7	2392	136.9
11/9/2011	10.8	2407	141.5
3/21/2012	11	2407	139.9
5/23/2012	11.3	2376	144.9
8/21/2012	11.7	2383	141.6
12/20/2012	11.5	2346	142.9
3/14/2013	11.5	2454	145
6/12/2013	12	2452	145.2
8/22/2013	12.6	2410	149.5
10/24/2013	10.8	2447	139.8
1/8/2014	11.1	2430	149.1
4/3/2014	10.8	2420	145.8
7/24/2014	11.1	2370	139.3

Table 5-8: 2MW-72S Monitoring Results (Overlying Aquifer)

Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	63.4	21,365	5,861.3
3/2/2009	11.9	2204	180.9
6/17/2009	11.7	2200	160.4
9/15/2009	11.9	2216	168
12/8/2009	12.3	2213	160.4
3/9/2010	11.7	2199	144.2
6/8/2010	11.3	2167	149.5
9/27/2010	10.9	2200	148.1
12/8/2010	11.1	2220	145.8
3/7/2011	11.7	2218	164.2
6/15/2011	11.8	2202	157.9
8/22/2011	12.0	2202	161
11/9/2011	11.3	2216	169.2
3/21/2012	11.6	2167	163.1
5/22/2012	11.6	2163	164.5
8/22/2012	12.7	2193	166.7
12/20/2012	12.1	2173	168.1
3/14/2013	11.7	2254	165
6/12/2013	12.1	2248	169.6
8/21/2013	12.6	2190	179.3
10/24/2013	12.6	2237	163.6
1/2/2014	12.0	2230	177.7
4/2/2014	11.3	2220	174
7/23/2014	11.8	2220	166

Table 5-9: 2MW-70S Monitoring Results (Overlying Aquifer)

Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	63.4	21,365	5,861.3
3/2/2009	11.6	1906	44.2
6/16/2009	11.1	1888	46.8
9/14/2009	11.1	1855	54.3
12/8/2009	11.0	1899	59.3
3/8/2010	11.1	1914	57
6/8/2010	10.2	1786	62.7
9/27/2010	9.8	1789	66.3
12/8/2010	10.2	1873	63.7
3/7/2011	10.9	1929	69.1
6/15/2011	10.3	1820	65.8
8/24/2011	10.2	1787	72.9
11/9/2011	11.9	1955	102.8
3/21/2012	12.4	1973	181.6
5/22/2012	12.0	1840	113.6
8/21/2012	12.1	1954	103
12/19/2012	10.8	1933	84.4
3/14/2013	11.1	2002	80.1
6/12/2013	11.1	2007	80.2
8/22/2013	12.0	1971	79.9
10/24/2013	10.5	2000	75
1/2/2014	11.1	2000	84.5
4/3/2014	10.1	2000	80.8
7/23/2014	12.3	1992	84

Table 5-10: 2MW-68S Monitoring Results (Overlying Aquifer)

Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	23.5	3560	304
3/2/2009	14.1	2434	197.4
6/17/2009	13.6	2450	200.1
9/15/2009	13.3	2436	193.4
12/8/2009	12.6	2428	179.7
3/9/2010	13.1	2441	166.1
6/8/2010	12.6	2449	188.2
9/28/2010	11.7	2446	183.4
12/8/2010	11.6	2430	179.1
3/8/2011	12.1	2436	181.7
6/16/2011	11.5	2408	168.5
8/23/2011	12.6	2431	177.2
11/10/2011	11.5	2438	185.3
3/21/2012	11.6	2423	175.7
5/23/2012	11.2	2390	170.7
8/21/2012	10.8	2402	175.2
12/19/2012	11.9	2347	170.5
3/14/2013	11.5	2466	167.2
6/12/2013	11.6	2467	166.9
8/22/2013	12.5	2390	169.8
10/24/2013	11.1	2440	159
1/2/2014	11.8	2430	172.8
4/3/2014	11.1	2410	165.5
7/24/2014	11.5	2400	161.1

Table 5-11: 3MW-48S Monitoring Results (MU-3, Overlying Aquifer)

Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	22.15	1,774.5	282.26
1/18/2000	9.4	1847*	118.4
2/14/2000	9.2	1866*	121.3
3/20/2000	9.6	1841*	122.4
4/25/2000	9.5	1831*	118.6
5/11/2000	9.8	1844*	120.5
6/12/2000	9.9	1849*	119.6
7/17/2000	9.6	1834*	117.8
8/22/2000	9.7	1878*	122.2
9/18/2000	9.4	1873*	123.3
10/16/2000	9.8	1868*	129.1
11/28/2000	9.3	1874*	120.5
12/19/2000	9.5	1853*	123.8
1/9/2001	9.4	1872*	122.1
2/13/2001	8.9	1864*	113.1
3/13/2001	9.5	1860*	126.4
4/11/2001	9.5	1853*	127.8
5/8/2001	9.8	1872*	131.4
6/12/2001	9.8	1888*	129.7
7/11/2001	9.6	1869*	126.6
8/13/2001	10.3	1905*	133.9
9/11/2001	10	1909*	130.1

Table 5-11 (cont'd)

Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	22.15	1,774.5	282.26
10/15/2001	9.6	1869*	125.6
11/12/2001	9.9	1909*	128.5
12/11/2001	9.6	1876*	128.4
1/15/2002	9.7	1871*	127.5
2/11/2002	9.9	1870*	127.2
3/12/2002	10.1	1891*	129.8
4/8/2002	9.8	1896*	128.2
5/13/2002	9.9	1906*	128.7
6/11/2002	9.9	1906*	127.9
7/28/2002	9.7	1832*	129.6
8/14/2002	10	1847*	131.3
9/9/2002	9.9	1917*	126.4
10/5/2002	9.9	1822*	131.7
11/11/2002	10	1887*	131.8
12/10/2002	10.1	1892*	129.1
1/13/2003	10.1	1911*	133
2/10/2003	10.1	1900*	131.2
3/10/2003	10.1	1886*	131.9
4/15/2003	10.1	1865*	130.7
5/12/2003	10.1	1941*	122.8
6/9/2003	9.7	1927*	118.9
7/7/2003	10	1912*	123.7
8/11/2003	9.7	1902*	120.9

Table 5-11 (cont'd.)

Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	22.15	1,774.5	282.26
9/8/2003	9.9	1915*	121.6
10/6/2003	9.7	1905*	121.2
11/10/2003	10.3	1888*	127.7
12/8/2003	9.7	1889*	129.5
1/12/2004	9.4	1885*	128.4
2/9/2004	9.8	1897*	130.1
3/15/2004	9.9	1871*	129.3
4/5/2004	9.4	1880*	123.9
5/10/2004	9.7	1868*	121.4
6/15/2004	9.9	1809*	130.8
7/12/2004	9.6	1786*	125.6
8/9/2004	9.4	1812*	126.8
9/20/2004	9.4	1821*	125.5
10/4/2004	9.4	1795*	127.1
1/3/2005	9.3	1811*	125.5
4/28/2005	9.6	1850*	122.4
7/11/2005	9.6	1828*	122.4
10/27/2005	9.5	1795*	127.9
1/24/2006	9.9	1835*	120.8
4/12/2006	9.9	1826*	132.7
7/27/2006	10.1	1833*	143.5

Table 5-11 (cont'd)

Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	22.15	1,774.5	282.26
10/16/2006	9.0	1814*	127.5
1/24/2007	9.1	1818*	125.1
4/11/2007	9.3	1812*	123.4
7/11/2007	9.0	1812*	124
10/10/2007	9.1	1802*	125.7
1/8/2008	8.7	1821*	127.3
4/8/2008	9.2	1812*	125
7/14/2008	9.9	1806*	130.4
10/6/2008	9.2	1805*	126.7
1/5/2009	9.1	1794*	131.4
4/21/2009	9.2	1809*	133
7/21/2009	8.8	1798*	129.4
10/6/2009	9.2	1791*	128.7
1/5/2010	8.3	1792*	130.1
4/5/2010	8.7	1806*	121.7
7/13/2010	8.9	1809*	126.9
10/26/2010	8.4	1800*	127.3
1/12/2011	8.9	1804*	114.4
4/4/2011	8.5	1803*	129.7
7/12/2011	8.7	1812*	128.8
10/6/2011	8.3	1753	131.5
1/10/2012	8.3	1796*	131.5

Table 5-11 (cont'd)

Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	22.15	1,774.5	282.26
5/2/2012	8.2	1816*	126.4
8/16/2012	8.9	1787*	132
11/9/2012	8.7	1719	130
1/23/2013	8.6	1766	128.3
5/9/2013	8.6	1845*	125.2
7/25/2013	8.8	1841*	128.7
10/10/2013	9.0	1840*	125.4
1/29/2014	8.5	1876*	134.1
4/2/2014	8.1	1850*	128.1

*Exceeds Upper Control Limit

Table 5-12: 3MW-46S Monitoring Results (MU-3, Overlying Aquifer)

Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	13.48	1,087.4	184.39
1/18/2000	12.6	1907*	126.8
2/14/2000	12.9	1917*	137.7
3/20/2000	13.7	1913*	138.8
3/22/2000	13.2	1858*	140.4
3/24/2000	12.9	1832*	144.6
4/25/2000	12.8	1867*	129.8
5/11/2000	13.2	1891*	131
6/12/2000	13.5	1887*	130
7/17/2000	12.3	1870*	125.8

Table 5-12 (cont'd)

Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	13.48	1,087.4	184.39
8/22/2000	12.2	1890*	127.7
9/18/2000	12.2	1892*	134.4
10/16/2000	11.8	1890*	131.8
11/28/2000	13.0	1883*	143.4
12/19/2000	13.5	1819*	149.5
1/9/2001	12.9	1801*	144
2/13/2001	12.5	1710*	142.5
3/13/2001	12.4	1731*	145.6
4/11/2001	13.0	1738*	155.4
5/8/2001	12.8	1794*	147.6
6/12/2001	12.8	1850*	151.7
7/11/2001	12.6	1875*	146.5
8/13/2001	12.6	1860*	144.3
9/11/2001	12.6	1896*	147.4
10/15/2001	12.2	1854*	143.1
11/12/2001	12.4	1881*	147.8
12/11/2001	12.2	1830*	148.9
1/15/2002	12.1	1822*	147.9
2/11/2002	12.6	1814*	153.5
3/12/2002	12.1	1800*	148.1
4/8/2002	11.8	1823*	146.6
5/13/2002	11.5	1849*	152.3

Table 5-12 (cont'd)

Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	13.48	1,087.4	184.39
6/11/2002	12.0	1849*	144.9
7/29/2002	11.0	1773*	142.3
8/14/2002	11.5	1784*	146
9/9/2002	12.1	1829*	153.1
10/5/2002	11.9	1761*	152.4
11/11/2002	11.6	1765*	147.3
12/10/2002	11.4	1734*	146.6
1/13/2003	11.4	1728*	148.9
2/10/2003	11.2	1720*	146.3
3/10/2003	11.2	1709*	149.5
4/15/2003	11.4	1726*	146.7
5/12/2003	11.3	1783*	138.7
6/9/2003	10.9	1757*	135.7
7/7/2003	10.7	1741*	133.6
8/11/2003	10.7	1736*	134.2
9/8/2003	11.3	1712*	139.7
10/6/2003	10.8	1725*	136.2
11/10/2003	11.4	1703*	153.4
12/8/2003	10.8	1700*	145.9
1/12/2004	10.8	1757*	144.5
2/9/2004	10.8	1776*	143.2
3/15/2004	11.0	1803*	142.4
4/5/2004	11.2	1819*	138.4

Table 5-12 (cont'd)

Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	13.48	1,087.4	184.39
5/3/2004	11.1	1831*	133.7
6/15/2004	11.1	1777*	135.6
7/12/2004	11.4	1713*	145.3
8/9/2004	10.8	1713*	142.7
9/20/2004	10.7	1695*	141.6
10/4/2004	10.8	1667*	144.2
1/3/2005	10.2	1536*	128.7
4/5/2005	10.6	1440*	144.7
7/11/2005	10.5	1417*	145.5
10/27/2005	9.9	1399*	141.6
1/24/2006	10.7	1269*	136.1
4/12/2006	9.9	1208*	149.7
7/31/2006	10.2	1182*	154.7
10/16/2006	9.2	1192*	143.1
1/24/2007	9.2	1177*	141.2
4/9/2007	9.2	1176*	137.4
7/11/2007	9.7	1181*	149.9
10/10/2007	8.8	1177*	138.3
1/8/2008	8.8	1183*	141.6
4/8/2008	9.1	1183*	137
7/14/2008	9.4	1191*	139.5
10/6/2008	9.7	1190*	137.6

Table 5-12 (cont'd)

Sample Date	Chloride	Specific Conductance	Total Alkalinity
Units	mg/L	µmho/cm	mg/L as $CaCO_3$
Upper Control Limit	13.48	1,087.4	184.39
1/5/2009	8.9	1184*	146.9
4/21/2009	9.2	1190*	140
7/21/2009	8.8	1190*	132.5
10/6/2009	9.1	1199*	134.9
1/5/2010	8.5	1190*	136.5
4/5/2010	8.6	1195*	130.7
7/13/2010	8.8	1203*	130.1
10/26/2010	8.2	1250*	131.8
1/12/2011	9.0	1210*	120
4/5/2011	8.6	1218*	136.6
7/12/2011	8.8	1272*	133.1
10/6/2011	8.4	1215*	137.7
1/9/2012	8.8	1230*	140.1
5/2/2012	8.5	1252*	135.3
8/16/2012	9.2	1237*	137.3
11/9/2012	8.9	1185*	137.1
1/23/2013	9.1	1208*	136.5
5/9/2013	8.9	1314*	132.9
7/25/2013	9.0	1398*	136.1
10/10/2013	9.5	1445*	130.3
1/29/2014	8.5	1364*	142.3
4/2/2014	8.8	1301*	144.3

*Exceeds Upper Control Limit

A review of Tables 5-7 through 5-12 indicates that the monitored parameters in the overlying monitoring wells in MU-2 South and near MU-3 exhibit concentrations below the respective limits, except specific conductance in MW-48S and specific conductance in MW-46S.

Regarding the overlying wells in MU-3, MW-46S and -48S, specific conductance measurements exceed the limit since 2000 while neither alkalinity nor chloride exceed the respective limits. Because both chloride and alkalinity have remained stable since 2000, the data does not represent an excursion. According to LC 11.2 in Materials License SUA-1341, wells MW-46S and -48S have not been on excursion status since 2000.

ARCADIS' examination of Tables 5-2 through 5-12 demonstrates that the overlying and production aquifers between MU-2 South and MU-3 are stable. Furthermore, although, NRC staff expressed concerns that upper control limits in MW-70S and -72S are high and may not be useful, a review of the actual data indicates that no anomalous results appear. Therefore, parameter concentrations remained stable, and, thus, the overlying **aquifer has not been impacted by Uranium One's operations**, pursuant to LC 11.2.

5.2.2 SSI Trends for Uranium

Regarding item 2, ARCADIS reassessed the stability data for the entire MU-2 South wellfield, the discussion and results of which are presented in Section 2.3.3 and Table 2-4. A review of the data indicates that uranium concentrations meet the class-of-use standard and concentrations in MU-2 South exhibit a SSI trend. However, as reported in Section 4.0 of this report, geochemical modeling indicates that concentrations of uranium in MU-2 will not result in an exceedance of the MCL at the monitoring well ring. Although concentrations may exhibit an increasing trend, modeling results, which are conservative in nature, indicate that public health and safety, and the environment are protected. Therefore, considering that the class-of-use standard is met and the residual constituent concentrations will not affect water quality at the perimeter well ring. As a result, the NRC staff should approve the restoration of MU-2 South. Although an SSI trend is an interesting statistic, in this case ARCADIS notes that 10 CFR Appendix A, Criterion 5B(5) does not have provisions for approving a restoration based on an SSI trend. Therefore, from a regulatory perspective, the staff cannot rely on SSI trends alone for approving a wellfield restoration.

5.3 Mine Unit 3

5.3.1 Expansions

Uranium One's current license contains separate information for MU-3 and its expansions, Module 2 and Module 4A. Consequently, the NRC staff analyzed the restoration of MU-3 by segregating Module 4A from the rest of MU-3. Although, the

staff's position is understandable, it is functionally incorrect for the following reasons. First, Uranium One operated MU-3 as one single wellfield not separate modules. Because Module 4A is directly connected to MU-3, it is impossible to separate the effects of one on the other.

Second, Uranium One had every intention of operating MU-3 as one unit, not separate areas. This is demonstrated by the amended wellfield package that was submitted to the WDEQ in April 1994 (Cogema 1994). This package combined MU-3 and its expansions into one package. While this package was submitted to the WDEQ, it was never submitted to the NRC staff, resulting in the confusion that was expressed in the NRC staff's TER. Therefore, the NRC staff should issue an administrative amendment to combine MU-3 and its expansions as one wellfield during further analyses.

5.3.2 Wells 3T37-1 and 3T27-2

In its TER, the NRC staff state the following in its evaluation findings:

> *The elevated conductivity noted in the 2009 sampling and levels of all constituents of concern in wells 3T37-2 and 3T27-2 are adequately demonstrated to be below Class IV standards.*

In this discussion, Uranium One assumes the staff means well 3T37-1 rather than 3T37-2. Tables 5-13 and 5-14 present post-stability monitoring data collected by Uranium One from these wells.

Table 5-13: Post-Stability Monitoring at Well 3T37-1

Sample Date	Chloride	Specific Conductance	Total Alkalinity	Uranium	Radium-226
Units	mg/L	µmho/cm	mg/L as $CaCO_3$	mg/L	pCi/L
Standards	250*	689.5	102.1	1.4	75.22
12/19/12	64.2	2539	951.7	34.85	
02/26/13	75.0	2672	971.0	36.30	
03/06/13	71.2	2652	1016.0	35.70	
03/06/13	59.8	2659	1015.0	36.40	
06/04/13	74.9	2640	1039.0	36.50	
06/04/13	78.5	2600	1023.0	36.40	

Table 5-13 (cont'd)

Sample Date	Chloride	Specific Conductance	Total Alkalinity	Uranium	Radium-226
Units	mg/L	µmho/cm	mg/L as $CaCO_3$	mg/L	pCi/L
Standards	250*	689.5	102.1	1.4	75.22
06/04/13	70.1	2550	1005.0	41.30	
06/12/13	63.4	2520	978.9	37.40	
06/17/13	62.5	2355	959.2	37.60	
06/19/13	56.2	1746	873.2	28.00	
06/24/13	46.8	1692	771.0	22.20	
06/26/13	46.2	1946	757.7	20.60	
07/01/13	43.3	1891	699.0	16.70	
07/08/13	43.6	1761	657.0	14.00	
07/15/13	40.7	1751	613.5	13.10	
07/22/13	38.6	1682	609.0	11.70	
07/29/13	39.5	1700	603.0	12.60	
08/12/13	40.0	1743	638.0	8.40	
08/19/13	39.3	1743	601.0	9.30	
08/26/13	37.4	1692	598.1	7.70	
08/28/13	38.0	1626	617.0	8.40	
08/28/13	40		651	6.82	225
09/03/13	39.5	1752	651.0	9.10	
09/09/13	39.0	1711	657.0	8.00	
09/16/13	38.6	1704	654.0	9.20	
09/23/13	38.2	1721	625.0	8.30	
09/30/13	38.1	1709	618.0	7.90	
10/09/13	37.8	1702	610.9	8.40	

Table 5-13 (cont'd)

Sample Date	Chloride	Specific Conductance	Total Alkalinity	Uranium	Radium-226
Units	mg/L	µmho/cm	mg/L as $CaCO_3$	mg/L	pCi/L
Standards	250*	689.5	102.1	1.4	75.22
10/15/13	36.1	1720	602.3	7.50	
10/21/13	36.9	1713	607.0	8.50	
10/24/13	38.0	1722	622.4	9.30	
10/28/13	34.0		620.0	6.03	192.0
11/06/13	35.0		632.0	6.98	207.0

* Yellow = MCL, Green = TRV, Blue = Class-of-Use

Table 5-14: Post-Stability Monitoring at Well 3T27-2

Parameter/ Sample Date	Chloride	Specific Conductance	Total Alkalinity	Uranium	Radium-226
Units	mg/L	µmho/cm	mg/L as $CaCO_3$	mg/L	pCi/L
Standards	250*	689.5	102.1	1.4	75.22
12/19/12	33	1795	666	9.49	
02/26/13	42	1854	654	9.20	
03/06/13	31	1809	694	8.30	
03/06/13	32	1819	680	8.10	
08/28/13	40	1747	698	8.10	
08/28/13	42		716	5.98	242
02/26/14	47	1901	662	13.90	
	46.1	1936	667	10.50	
	46.3	1982	677	9.30	

* Yellow = MCL, Green = TRV, Blue = Class-of-Use

A review of Tables 5-13 and 5-14 indicate that contaminant concentrations have rebounded since the stability monitoring period. However, the effect of these increased concentrations on long-term stability in this wellfield and water quality at the aquifer exemption boundary is negligible. As demonstrated by the modeling discussed in

Section 4.0, residual concentrations of constituents are not expected to exceed drinking water standards at the aquifer exemption boundary. Therefore, the restoration effort was successful.

5.3.3 Other Issues

In its evaluation findings, the NRC staff stated the following:

> *The licensee demonstrates the SSI trend noted in the uranium concentrations at well 3V58-2 is reversed and stable.*

Regarding SSI trends, ARCADIS reassessed the stability data for the entire MU-3 wellfield, the discussion and results of which are presented in Section 2.3.3 and Table 2-4. A review of the stability data indicates that uranium concentrations in MU-3 exhibit no SSI trends, and are therefore, stable.

Regarding wells 3W75-1 and 3Z87-1, the NRC staff stated that it could not approve the restoration of Module 4A until the licensee:

> *(1) Provides a statistical evaluation of the restoration data including rationale for outliers and stability analyses.*
>
> *(2) Demonstrates the SSI trend in uranium and radium-226 in wells 3W75-1 and 3Z87-1 is reversed and stable.*

Regarding item 1, the statistical analyses and comparisons to TRVs and other groundwater protection standards are discussed in Section 2.3.2. ARCADIS considered all of MU-3 and the expansions as one wellfield. As stated in Section 2.3.2 and presented in Table 2-2, only radium exceeds the groundwater protection standard. Section 4.0 discusses the geochemical modeling effort, which indicates that residual radium concentrations in the production zone will not exceed the MCL at the monitoring well ring. Regarding Item 2, SSI trends, as discussed above, uranium and radium-226 do not exhibit SSI trends as a function of the entire wellfield, which is the appropriate manner in which to analyze the trends. Therefore, the restoration at MU-3 is considered complete and protective of public health and safety, and the environment, and the NRC staff should approve this restoration.

The NRC staff raised one more issue in its evaluation findings:

> *The licensee confirms that well 3D12-2 used in the restoration, but not in the baseline, was needed to replace a well that has been abandoned.*

Regarding this well, based on information provided by Uranium One, ARCADIS believes that 3D12-2 was used as a baseline and restoration well, and that 3D12-1 was

drilled but never completed. Therefore, the correct well designation for both baseline and restoration is 3D12-2.

5.4 Mine Unit 4

5.4.1 Best Practice Technology

Regarding the restoration of MU- 4, the NRC staff stated the following in its evaluation findings:

> *Demonstrates that its restoration effort results in parameter levels approaching asymptotic trends using BPT.*

To support its conclusions, the NRC staff stated the following:

> *The licensee reports the parameter average concentrations post-RO but not the average concentrations post-reductant addition (as was reported in the MU-2 and MU-3 reports). The stability monitoring data are significantly higher than the concentrations reported post-RO and a significant percentage of the post-mining concentrations. Furthermore, though the uranium level at well 4T114-1 has diminished to 6.66 mg/L from the concentration of 16 mg/L during stabilization (2004-2005), the levels of most parameters have remained relatively constant at elevated levels. In addition, the concentration during stability monitoring of 16 mg/L was approximately equal to the post-mining concentration of 17.55 mg/L. Consequently, the staff concludes that the licensee has not adequately demonstrated that its restoration effort at MU4 is consistent with the application of BPT.*

ARCADIS disagrees with the NRC staff. Restoration and stability data and standards are all based on wellfield averages or variations thereof (i.e., UCLs). For the staff to focus on specific data is inappropriate, as with any kind of statistical averaging or analysis, a few data points will not fit a certain model or meet a certain standard. However, a review of restoration and stability data, as calculated using ProUCL, clearly demonstrates that uranium exists in MU-4 at concentrations well below the post-extraction value (17.55 vs. 3.75 average stability).

Regarding restoration and stability data, Table 5-15 contains data for hazardous constituents.

Table 5-15: MU-4 Restoration and Stability Data, Hazardous Constituents

Parameter	Post-Extraction	Post Sweep	Post RO	Stability			
				R1	R2	R3	R4
As	0.011	0.059	0.013	0.006	0.005	0.006	0.006
Ba	0.10	0.10	0.10	*0.50*	*0.50*	*0.50*	*0.50*
Cd	0.01	0.01	0.01	0.002	0.002	0.002	0.002
Cr	0.05	0.05	0.05	0.01	0.01	0.01	0.01
Pb	0.05	0.05	0.05	0.02	0.02	0.02	0.02
Hg	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Mo	0.10	0.10	0.10	0.02	0.02	0.02	0.02
Ni	0.05	0.05	0.05	0.01	0.01	0.01	0.01
Se	3.04	2.12	0.30	0.28	0.26	0.21	0.21
Radiometric							
U (mg/L)	17.55	13.19	2.85	3.71	3.53	3.91	3.83
Ra 226 (pCi/L)	286.2	198.7	71.2	107.8	170.2	141.3	114.1

Note: *Italics* means non-detect results.

A review of this table clearly shows that the stability concentrations for MU-4 are below the post-extraction concentrations which is a demonstration that BPT was utilized and achieved. Again, **the staff's focus on** individual wells is statistically inappropriate when wellfield groundwater standards are based on averages or variations of averages.

5.4.2 Monitoring Well 4MW-15

Regarding uranium concentrations at 4MW-15, the NRC staff stated the following:

Provides confirmatory analyses on the uranium concentrations at monitoring well 4MW-15 that demonstrate the levels are within regulatory requirements (groundwater protection criteria).

Latest analytical data collected in September of 2013 indicates a uranium concentration of 0.14 mg/L, whereas baseline (mean + 2 standard deviations) is 0.037 mg/L. Furthermore, all upper control limit parameters except alkalinity meet the respective upper control limit standards.

5.4.3 Monitoring Well 4MW-1

Regarding aquifer impacts at 4MW-1, the NRC staff stated the following:

Adequately characterizes the impacts to the aquifer in the vicinity of 4MW-1 and those impacts are within regulatory requirements (groundwater protection criteria).

Water quality data collected from monitoring well 4MW-1 is presented in Table 5-16.

Table 5-16: Well 4MW-1 Water Quality Data

Sample Date	Chloride	Conductivity	Alkalinity	pH
Units	mg/L	µmhos	mg/L	s.u.
Upper Control Limit	11.08	825.2	116.9	
3/11/2009	23.3*	751	108.6	8.3
3/11/2009	23.6*	758	110	8.3
6/1/2009	37.6*	880*	134.9*	8
6/3/2009	25.9*	769	114.1	8
6/3/2009	25.5*	768	114	8
9/14/2009	31.6*	824	133.7*	8
9/15/2009	32.1*	827*	139.5*	7.9
9/24/2009	18.6*	730	108.8	8.2
10/1/2009	16.9*	703	96.4	7.9
10/8/2009	16.3*	690	99.1	8.1
10/15/2009	15.6*	687	97.5	8.2
12/1/2009	14.1*	700	98.9	8.4
3/3/2010	21.7*	740	99.6	8.2
6/9/2010	25*	809	124.9*	7.8
6/10/2010	25.8*	796	125*	7.8
6/15/2010	29.1*	857*	135*	7.4
6/21/2010	31.8*	859*	131.7*	6.6

Table 5-16 (cont'd)

Sample Date	Chloride	Conductivity	Alkalinity	pH
Units	mg/L	µmhos	mg/L	s.u.
Upper Control Limit	11.08	825.2	116.9	
6/29/2010	28*	864*	140*	6.6
7/7/2010	28.9*	857*	141.4*	7.2
7/12/2010	29.4*	851*	134.4*	7.1
7/19/2010	28.8*	855*	135.8*	7.2
7/26/2010	26.3*	848*	137.8*	7.1
8/4/2010	15.0*	697	119*	8.3
8/9/2010	12.0*	694	99.5	8.1
8/18/2010	11.1*	689	95.2	7.9
8/25/2010	10.5	691	93.2	7.7
9/20/2010	10.1	673	88.2	8.1
12/13/2010	9.8	678	86	8.4
3/22/2011	19.5*	755	118.9*	8.4
3/23/2011	19.1*	753	117.6*	8.3
3/28/2011	22.0*	787	137*	8.4
4/4/2011	19.5*	760	128.7*	8.4
4/11/2011	10.6*	676	96.6	8.5
4/18/2011	12.0*	689	101	8.1
4/25/2011	13.2*	697	103	8.4
5/4/2011	10.7	673	92	8.3
5/9/2011	11.7*	672	93.4	8.5
5/16/2011	11.9*	670	92.7	8.6
5/23/2011	12.3*	672	88.4	8.4
5/31/2011	11.6*	670	89	8.4
6/6/2011	12.1*	674	93	8.4
6/13/2011	11.8*	676	96.3	8.5
6/20/2011	12.5*	679	97.4	8.5
6/27/2011	12.4*	681	96.4	8.5
7/20/2011	12.3*	680	93	8.3
10/18/2011	11.7*	692	107.1	8.5
2/7/2012	12.1*	681	96.6	8.3
6/13/2012	12.1*	680	97.9	8.3
8/9/2012	13.3*	678	90.2	8.4
11/1/2012	11.6*	663	99.9	8.5
1/17/2013	14.8*	736	111.4	8.5
5/2/2013	13.5*	725	101.3	8
7/24/2013	14.3*	727	105.1	8.3

Table 5-16 (cont'd)

Sample Date	Chloride	Conductivity	Alkalinity	pH
Units	mg/L	µmhos	mg/L	s.u.
Upper Control Limit	11.08	825.2	116.9	
11/21/2013	15.0*	753	112.1	8.1
1/20/2014	12.3*	734	115.8	7.5
6/11/2014	15.2*	749	114.8	8.1
7/2/2014	14.6*	729	101.8	8.3

*Exceeds Upper Control Limit

A review of the analytical data presented above indicates that excursions have occurred at this well; however, this well has been off excursion status for more than three years. Furthermore, concentrations of UCL parameters have been stable since April 2011. Therefore, Uranium One has adequately characterized the aquifer near 4 MW-1, and water quality data show no excursions per LC 11.2 since April 2011.

5.4.4 SSI Trends in MU 4

Regarding the stability of COCs in MU-4, the NRC staff stated the following:

> *Demonstrates stability of contaminant concentrations by showing no SSI trends during the stability monitoring period once the restoration goals are achieved.*

Section 2.3.3 above discusses the manner in which contaminant trends were analyzed using ProUCL. Trend results are presented in Table 2-4, which shows that no SSI trends exist for uranium, selenium, or radium-226 in MU-4. Therefore, contaminant concentrations in MU-4 are stable.

In summary, Uranium One's restoration effort at MU-4 was primarily successful at stabilizing constituent concentrations in the wellfield. However, constituent levels are slightly elevated in 4MW-15; however, ARCADIS anticipates that this condition is caused by perturbations in potentiometric surface caused by ISR operations similar to the condition at MW-84. However, a review of all the data and modeling results indicates that MU-4 is stable, and the NRC staff should approve this restoration.

5.5 Mine Unit 6

The NRC staff states that it cannot concur that the restoration of MU-6 is protective of human health and safety and the environment until the licensee:

> *(1) Provides the staff with data used to define baseline; and*

(2) Demonstrates that its restoration effort is consistent with BPT and results in levels that exhibit an asymptotic trend.

Regarding baseline calculations, Section 2.2 discusses calculation of TRVs for MU-6 using ProUCL and presents the TRVs in Table 2-1. Regarding the restoration effort, Section 2.3.2 discusses testing the restoration data versus the groundwater protections standards (i.e., TRVs, MCLs, class-of-use). Results are presented in Table 2-2 and indicate that only radium-226 exceeds all standards.

An analysis of constituent trends is provided in Section 2.3.3, and the results are presented in Table 2-4. A review of the results indicates that uranium, although concentrations meet groundwater protection standards, exhibits SSI trend. Section 4.0 discusses the geochemical modeling results for MU-6, which indicate that much higher concentrations of uranium can exist in the production zone without impacting water quality at the monitoring well ring. Therefore, the restoration at MU-6 is considered successful. Similar to MU-2 South, the use of SSI trends has no basis in 10 CFR 40, Appendix A, Criterion 5B(5). Therefore, the NRC staff's reliance on this statistic, by itself, is inappropriate for determining restoration completeness.

6.0 Conclusions

The purpose of this investigation was to review the NRC TER, various data, and undertake statistical calculations and geochemical modeling to respond to the NRC staff's comments, as presented in its TER. The restoration of MU-5 was not addressed in this report because of ongoing extraction within this wellfield. To respond to the NRC staff's comments, ARCADIS completed the following tasks:

- Recalculating baseline values using ProUCL
- Reassessing SSI trends using ProUCL for entire wellfields not individual wells.
- Developing geochemical models to understand the effects of residual constituent concentrations in the production zone on downgradient water quality.
- Providing responses to specific NRC comments.

Based on the information provided, herein, ARCADIS concludes that Uranium One successfully restored wellfields MU-2 North, MU-2 South, MU-3, MU-4, and MU-6 to the point that residual concentrations in the wellfields pose no threat to human health and the environment. ARCADIS bases its conclusions on the fact that although, uranium, selenium, and radium exceed TRVs, MCLs, and Class-of-Use standards in some or all of the wellfields, ARCADIS' geochemical models indicate that constituent concentrations will remain below safety standards at the monitoring well ring. Therefore, human health and the environment will be protected.

7.0 References

Arai, Y., McBeath, M., Bargar, J.R., Joye, J. and Davis, J.A. 2006. Uranyl Adsorption and Surface Speciation at the Imogolite–Water Interface: Self-consistent Spectroscopic and Surface Complexation Models. *Geochmica et Cosmochimica Acta*, 70:2492-2509.

Balistrieri, L.S. and T.T. Chao. 1990. Adsorption of selenium by amorphous iron oxyhydroxide and manganese dioxide. *Geochimica et Cosmochimica Acta*, 54:739-751.

Breynaert, E., Bruggeman, C. and Maes, A. 2008. XANES-EXAFS Analysis of Se Solid Phase Reaction Produces formed upon contacting Se(IV) with FeS_2 and FeS. *Environmental Science and Technology*, 42(10):3595-601.

Bond, D. L. Davis, J.A., and Zachara, J.M. 2008. Uranium(VI) Release from Contaminated Vadose Zone Sediments: Estimation of Potential Contributions from Dissolution and Desorption. In *Adsorption of Metals by Geomedia II: Variables, Mechanisms, and Model Applications.* Edited by M.O. Barnett and D.B. Kent. Chapter 14, Elsevier, Amsterdam, Netherlands. Pp. 375-416. Cogema Mining Inc. (Cogema). 1994a. Wellfield Data Package (Revised and Combined), Mine Unit 3, Christensen Ranch Project, April.

Cogema. 1994b. Wellfield Data Package, Mine Unit 4, Christensen Ranch Project, April.

Cogema. 1995. Wellfield Data Package, Mine Unit 5, Christensen Ranch Project, February.

Cogema. 1996. Wellfield Data Package, Mine Unit 6, Christensen Ranch ISR Project, September 24.

Cogema. 2004. Wellfield Restoration Report Irigaray Mine, Wyoming. Prepared by Cogema Mining, Inc., Petrotek Engineering Corp. and Hydrosolutions, Inc. July.

Cogema. 2008. Wellfield Restoration Report Christensen Ranch Project, Wyoming. Prepared by Cogema Mining, Inc, and Petrotek Engineering Corp. March 5. ADAMS Accession Numbers ML081060131, ML081060132 and ML081060140.

Davis, J.A. and Curtis, G.P. 2003. Application of Surface Complexation Modeling to Describe Uranium (VI) Adsorption and Retardation at the Uranium Mill Tailings Site at Naturita, Colorado. NUREG/CR-6820. U.S. Nuclear Regulatory Commission.

Dong, W., and Brooks, S.C. 2006. Determination of the Formation Constants of Ternary Complexes of Uranyl and Carbonate with Alkaline Earth Metals (Mg^{2+}, Ca^{2+}, Sr^{2+}, and Ba^{2+}) using Anion Exchange Method. *Environmental Science and Technology*, 40(15):4689-4695.

Dong, W., and Brooks, S.C. 2008. Dong, W. and S. C. Brooks. 2008. Formation of Aqueous $MgUO_2(CO_3)_3^{2-}$ Complex and Uranium Anion Exchange Mechanism onto an Exchange Resin. *Environmental Science and Technology.* 42(6):1979-1983.

U.S. Environmental Protection Agency (EPA). 2004. Understanding Variation in Partition Coefficient, Kd, Values. Volume III: Review of Geochemistry and Available Kd Values for Americium, Arsenic, Curium, Iodine, Neptunium, Radium, and Technetium. EPA402-R-04-002C. Office of Air and Radiation. July.

EPA, 2013. ProUCL Version 5.0 Technical Guide, Environmental Protection Agency, Washington, DC. EPA/600/R-07/041.

Fox, P.M., Davis, J.A., Zachara, J.M. 2006. The Effect of Calcium on Aqueous Uranium(VI) Speciation and Adsorption to Ferrihydrite and Quartz. *Geochimica et Cosmochimica Acta*, 70:1379-1387.

Goldhaber, M.B., Reynolds, R.L., and Rye, R.O., 1983. Role of Fluid Mixing and Fault Related Sulfide in the Origin of the Ray Point Uranium District, South Texas. *Economic Geology*, 78(6):1043-1063.

Grenthe, I.H., Fuger, J., Konings, R.J.M, Lemire, R.J., Muller, A.B., and Wanner, H. 2004. *Chemical Thermodynamics of Uranium*, (Wanner, H. and Forest, I. eds.),

Guillaumont, R., T. Fanghanel, J. Fuger, I. Grenthe, V. Neck, D. Palmer, and M.H. Rand. 2003. Update on the Chemical Thermodynamics of Uranium, Neptunium, Plutonium, Americium and Technetium. Elsevier: Amsterdam.

Nuclear Energy Agency Organization for Economic Co-operation and Development (OECD).

Harshman, E.N. 1974. Distribution of Elements in Some Roll-type Uranium Deposits. In *IAEA Proceedings,* IAEA-SM-183/4, International Atomic Energy Agency, Vienna, Austria.

Hsi, C.-K.D. and Langmuir, D. 1985. Adsorption of Uranyl onto Ferric Oxyhydroxides: Application of the Surface Complexation Site-binding Model. *Geochimica et Cosmochimica Acta*, 49:1931–1941.

Landa, E.R., Miller, C.L., and Updegraff, D. M. 1986. Leaching of 226Ra from U Mill Tailings by Sulfate-Reducing Bacteria, *Health Physics*, 51:509-518.

Landa, E.R. 2004. Uranium Mill Tailings: Nuclear Waste and Natural Laboratory for Geochemical and Radioecological Investigations, *Journal of Environmental Radioactivity,* 77:1-27.

Langmuir, D. 1997. *Aqueous Environmental Chemistry*, Prentice-Hall, Upper Saddle River, New Jersey.

Malapai Resources Company (Malapai). 1988. Christensen Ranch Amendment Application to WDEQ Permit to Mine No. 478 & NRC License SUA-1341: prepared for Wyoming Department of Environmental Quality Permit to Mine No. 478 and NRC License No. SUA-1341. ML090300532.

Martin, A.J., Crusius, J., McNee, J.J., and Yanful, E.K. 2003. The Mobility of Radium-226 and Trace Metals in Pre-oxidized Subaqueous Uranium Mill Tailings, *Applied Geochemistry,* 18:1095-1110.

Moyes, A. 2013. (Thesis) Clay Mineralogy and Chemical Variation in uranium Roll-Front Deposits in the Gas Hills Uranium District, Wyoming. M.S. Thesis. Available from: University of Utah, Department of Geology and Geophysics, Utah. p. 105.

Myneni, S.C.B., Tokunaga, T.K., and Brown, G.E. 1997. Abiotic Selenium Redox Transformations in the Presence of Fe(II, III) Oxides. *Science,* 278:1106-1109

Nuclear Regulatory Commission (NRC). 2012. Technical Evaluation Report Christensen Ranch Mine Units 2 through 6 Restoration Report. October 23. ADAMS Accession Numbers ML12174A048.

Oremland, R.S., Herbel, M.J., Blum, J.S., Langley, S., Beveridge, T.J., Ajayan, P.M., Sutto, T., Ellis, A.V., Curran, S. 2004. Structural and Spectral Features of Selenium Nanoshperes Produced by Se-Respiring Bacteria. *Applied Environmental Microbiology*, 70:52.

Parkhurst, D.L. and Appelo, C.A.J. 1999. User's guide to PHREEQC (Version 2) - A Computer Program for Speciation, Batch-reaction, One-dimensional Transport, and Inverse Geochemical Calculations: United Stated Geological Survey Water-Resources Investigations Report 99-4259, 310 p.

Payne, T.E., Davis, J.A., Waite, T.D. 1998. Uranium(VI) Adsorption on Model Minerals: Controlling Factors and Surface Complexation Modeling. In: Jenne, E.A. (Ed.), *Adsorption of Metals by Geomedia.* Academic Press, New York, pp. 75–97.

Reynolds, R.L., and Goldhaber, M.B., 1978. Origin of a South Texas Roll-type Uranium Deposit-I. Alteration of Iron-Titanium Oxide Minerals, *Economic Geology*, 73:1677-1689.

Rovira, M., Gimenez, J., Martinez, M., Marinez-Llado, X., de Pablo, J., Marti, V., Duro, L. 2008. Sorption of Selenium (IV) and Selenium (VI) on to Natural Iron Oxides: Goethite and Hematite. *Journal of Hazardous Materials*, 150:279-284.

Sharp, W.N., and Gibbons, A.B. 1964. Geology and Uranium Deposits of the Southern Part of the Powder River Basin, Wyoming. U.S. Geological Survey Bulletin 1147-D.

Sharp, W.N., McKay, E.J., McKeown, F.A., and White, A.M.1964. Geology and Uranium Deposits of the Pumpkin Buttes Area of the Powder River Basin, Wyoming. U.S. Geological Survey Bulletin 1107-H.

Sharp, W.M. cited in Wellfield Restoration Report (1995), need full reference (this may not be the correct year)

Tokunaga, T.K., S.R. Sutton, and S. Bajt. 1994. Mapping of Selenium Concentrations in Soil Aggregates with Synchrotron X-ray Fluorescence Microprobe. *Soil Science*, 158:421-434.

TMC. 1993a. Wellfield Data Package, Unit 2 South, Christensen Ranch Project. March.

Total Metals Corporation (TMC). 1993b. Wellfield Data Package, Unit 2 North, Christensen Ranch Project. April.

USEPA. 2007. Monitored Natural Attenuation of Inorganic Contaminants in Ground Water, Volume 2. EPA/600/R-07/140. October.

Uranerz Energy Corporation (Uranerz). 2007. Nicholson Ranch ISR Project. U.S.NRC Source Material License Application. Technical Report and Environmental Report. November. Revisions submitted August 2008, November 2008, December 2008, February 2009, March 2009, May 2009, and September 2010. http://www.nrc.gov/info-finder/materials/uranium/licensed-facilities/nichols-ranch.html.

Zachara, J.M., Rai, D., Moore, D.A. Turner, G.D., and Felmy, A.R. 1994. Chemical Attenuation Reactions of Selenium. TR-103535, Electric Power Research Institute, Palo Alto, California.

Zawislanski, and Zavarin. (1996) Zawislanski, P.T. and M. Zavarin. 1996. Nature and Rates of Selenium Transformations: A Laboratory Study of Kesterson Reservoir Soils. *Soil Science Society of America Journal*, 60:791-800.