Determination of the Origin of Elevated Uranium at a Former Air Force Landfill Using Non-Parametric Statistics Analysis and Uranium Isotope Ratio Analysis

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ABSTRACT

Lowry Air Force Base (Lowry) was closed in September 1994 as part of the Base Realignment and Closure (BRAC) program and the base was transferred to the Lowry Redevelopment Authority in 1995. As part of the due diligence activities conducted by the Air Force, a series of remedial investigations were conducted across the base. A closed waste landfill, designated Operable Unit 2 (OU 2), was initially assessed in a 1990 Remedial Investigation (RI; [1]). A Supplemental Remedial Investigation was conducted in 1995 [2] and additional studies were conducted in a 1998 Focused Feasibility Study. [3] The three studies indicated that gross alpha, gross beta, and uranium concentrations were consistently above regulatory standards and that there were detections of low concentrations other radionuclides. Results from previous investigations at OU 2 have shown elevated gross alpha, gross beta, and uranium concentrations in groundwater, surface water, and sediments. The US Air Force has sought to understand the provenance of these radionuclides in order to determine if they could be due to leachates from buried radioactive materials within the landfill or whether they are naturally-occurring. The Air Force and regulators agreed to use a one-year monitoring and sampling program to seek to explain the origins of the radionuclides.

Over the course of the one-year program, dissolved uranium levels greater than the 30 µg/L Maximum Contaminant Level (MCL) were consistently found in both upgradient and downgradient wells at OU 2. Elevated Gross Alpha and Gross Beta measurements that were observed during prior investigations and confirmed during the LTM were found to correlate with high dissolved uranium content in groundwater. If Gross Alpha values are corrected to exclude uranium and radon contributions in accordance with US EPA guidance, then the 15 pCi/L gross alpha level is not exceeded. The large dataset also allowed development of gross alpha to total uranium correlation factors so that gross alpha action levels can be applied to future long-term landfill monitoring to track radiological conditions at lower cost.

Ratios of isotopic uranium results were calculated to test whether the elevated uranium displayed signatures indicative of military use. Results of all ratio testing strongly supports the conclusion that the uranium found in groundwater, surface water, and sediment at OU 2 is naturally-occurring and has not undergone anthropogenic enrichment or processing. U-234:U-238 ratios also show that a disequilibrium state, i.e., ratio greater than 1, exists throughout OU 2 which is indicative of long-term aqueous transport in aged aquifers. These results all support the conclusion that the elevated uranium observed at OU 2 is due to the high concentrations in the regional watershed.

Based on the results of this monitoring program, we concluded that the elevated uranium concentrations measured in OU 2 groundwater, surface water, and sediment are due to the naturally-occurring uranium content of the regional watershed and are not the result of waste burials in the former landfill. Several lines of evidence indicate that natural uranium has been naturally concentrated beneath OU 2 in the geologic past and the higher of uranium concentrations in downgradient wells is the result of

geochemical processes and not the result of a uranium ore disposal. These results therefore provide the data necessary to support radiological closure of OU 2.

INTRODUCTION

Lowry Air Force Base (Lowry) was closed in September 1994 as part of the Base Realignment and Closure (BRAC) program and the base was transferred to the Lowry Redevelopment Authority in 1995. As part of the due diligence activities conducted by the Air Force, a series of remedial investigations were conducted across the base. A closed waste landfill, designated Operable Unit 2 (OU 2), was initially assessed in a 1990 (RI; [1]). A Supplemental Remedial Investigation was conducted in 1995 [2] and additional studies were conducted in a 1998 Focused Feasibility Study. [3] The three studies indicated that gross alpha, gross beta, and uranium concentrations were consistently above regulatory standards and that there were detections of low concentrations other radionuclides. Gross alpha and gross beta concentrations measured in groundwater consistently exceeded regulatory limits at various locations in the landfill. The highest gross alpha activity was 11.7 Bq/L and the highest gross beta activity was 23.3 Bq/L. The Air Force and regulators agreed to use a one-year monitoring and sampling program to seek to explain the origins of the radionuclides that were detected and to determine if radionuclides potentially buried within OU 2 are leaching into groundwater or surface water.

OU2 is a 30 hectare parcel located in the south-central portion of the former Lowry Air Force base, shown in Figure 1. The landfill was used from 1948 until 1986 for disposal of general base-related waste. The volume of waste has been estimated to be approximately 1.4 million cubic meters. Some drums were disposed in the 1950s and 1960s. Historical documents indicate that a drum containing electron tubes was disposed at the site sometime during the 1950s. [4] Follow-up investigations by the USAF also have been unsuccessful in locating this burial.

Fig. 1. Site map of Former Lowry AFB, including locations of OU 2 investigation area and background monitoring wells.

Regional Watershed Information

A search of regional groundwater quality information resulted in uranium analysis results from samples collected from an approximate 10-mile radius of former Lowry AFB. [5] As shown in Figure 2, a dissolved-phase plume of natural uranium trends from southeast to northwest, directly up-gradient of OU2. Dissolved uranium concentrations in the water-table aquifer are as high as 147 micrograms per liter (µg/L) up-gradient of OU2. [6]

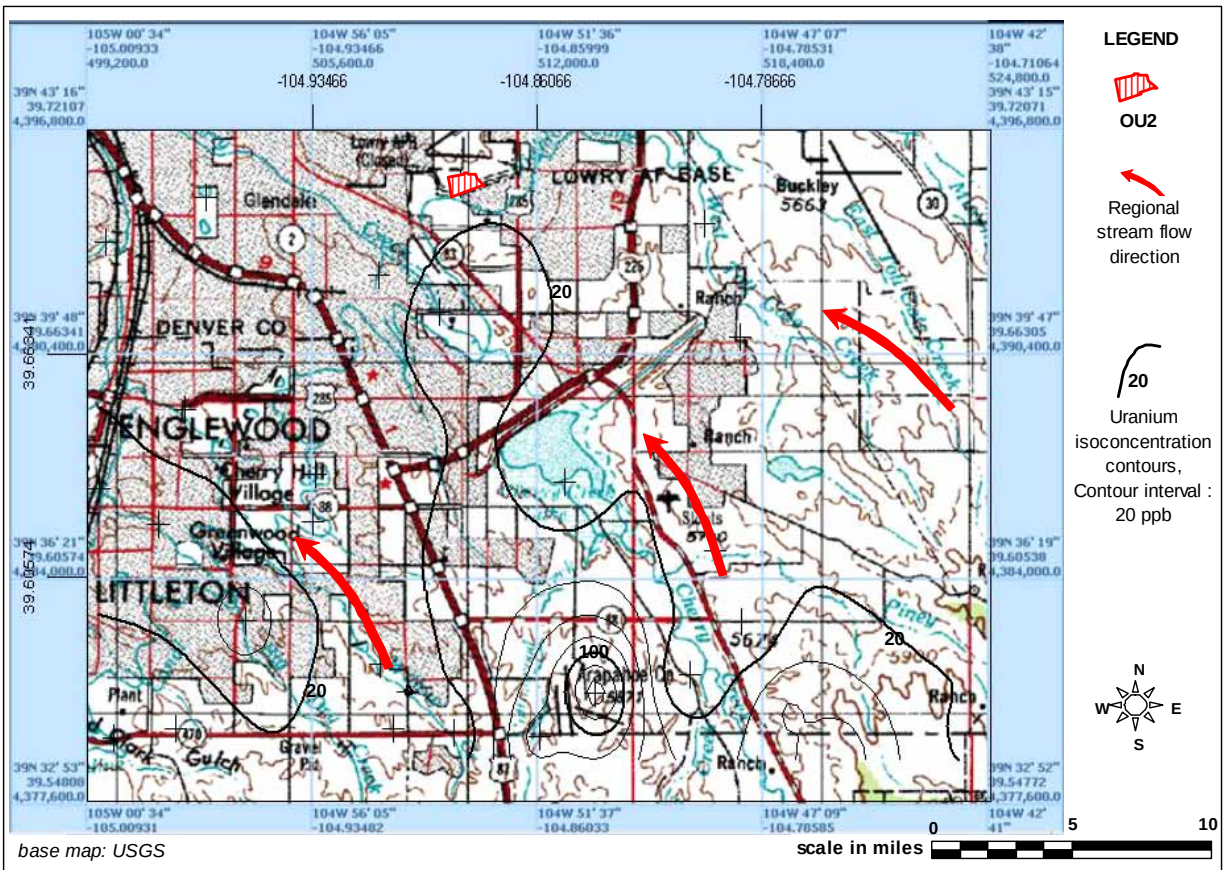

Fig. 2. USGS map showing contours of uranium concentrations and regional stream flow direction upstream of OU 2

Three background wells (shown on Fig. 1) installed around OU 2 during the Installation Restoration Program RI in 1990 (1) confirm the high regional radioactivity levels. Gross alpha, gross beta, and radium concentrations measured in these wells in shown in Table I. This data shows that there are sources of elevated dissolved radioactivity in the upgradient alluvial acquifer, as reflected in the gross aloha and gross beta data. The bedrock well (BW-1) does not show elevated activity levels.

Table I. Radioactivity in Background Wells

Radioactivity (Bq/L)	**BW-1** (bedrock)	**BW-2** (alluvium)	**BW-3** (alluvium)
Gross Alpha	< 0.07	5.0±2.2	3.6±1.3
Gross Beta	< 0.11	4.4±1.1	1.7±0.5
Radium-226	< 0.02	< 0.02	< 0.02
Radium-228	0.14	0.14	0.14

Source of data: SAIC, 1990, Table J-2 (1)

It should be noted that all historically reported gross alpha results at OU 2 included contributions from uranium isotopes. Guidance in the Environmental Protection Agency's (EPA) *Primary Drinking Water Regulations, Radionuclides; Final Rule* [7] says that gross alpha measurements should be corrected for potential contributions from uranium and radon. All gross alpha results reported during the LTM are thus shown as 'raw,' and 'corrected,' meaning that contributions from uranium have been subtracted. Entrained radon was not a concern at OU 2 and thus no correction for radon was attempted.

Investigation Methods

An extended sampling an analysis protocol was designed over four consecutive quarters in an attempt to ascertain whether the elevated concentrations were due to natural conditions or from landfill leachate. This was performed in a step-wise fashion as shown in the project decision statements below.

1. Determine whether ROPC concentrations in groundwater, surface water, and sediment downgradient of OU 2 burials statistically exceed concentrations sampled from upgradient groundwater, surface water, and sediment locations.
2. Determine whether ROPC concentrations in groundwater, surface water, and sediment upgradient and downgradient of OU 2 burials exceed applicable regulatory guidelines. A summary of the applicable regulatory standards and required detection limits for the ROPCs is provided in Table II.
3. Determine whether ROPC concentrations in groundwater, surface water, and sediment upgradient and downgradient of OU 2 burials represent naturally-occurring and/or anthropogenic radionuclides. If so, can the origin of the radionuclides be deduced?

No new wells were installed as part of this investigation since OU 2 already had a clay cap installed. Therefore, only existing wells located hydraulically upgradient, downgradient, and crossgradient were used. A total of 18 wells were utilized (8 upgradient, 2 crossgradient, 8 downgradient). For the purposes of well group comparisons, the crossgradient wells were assigned to the upgradient group. The groundwater samples were collected in compliance with the US EPA's low-flow sampling method. Field filtering of sampling was shown to be unnecessary due to the effectiveness of low-flow sampling in controlling turbidity.

Due to the lack of extensive information regarding potential radioactive material burials within OU 2, a comprehensive list of 23 radionuclides of potential concern (ROPC) was developed based historical information and review of the Air Force Radioactive Material Database, administered at Wright Patterson AFB. The list of ROPCS and their reason for inclusion are shown in Table II.

Table II. Radionuclides of Potential Concern and Applicable Groundwater Standards

ROPC[1]	Name	Regulatory Standard [pCi/L]	Regulatory Standard [Bq/L]	Reason for Inclusion
Gross Alpha	Gross Alpha	15[2]	0.56	Historically detected at OU2
Gross Beta	Gross Beta	50[3]	1.85	Historically detected at OU2
Ra-226	Radium-226	5[4]	0.19	Most widely used radionuclide in Air Force instruments
Ra-228	Radium-228	5[4]	0.19	
U_{total}	Total Uranium	30 μg/L[5]	1.11	Widely used as weight for various purposes and as mockup for special weapons
U-234	Uranium-234	≈ 9.5[5]	0.35	
U-235	Uranium-235	≈ 1.1[6]	0.04	
U-238	Uranium-238	≈ 9.5[5]	0.35	
Pu-238	Plutonium-238	15[2]	0.56	Not used at Lowry except as various types of calibration and check sources
Pu-239/240	Plutonium-239/240	0.15[6]	0.01	
Pu-241	Thorium-232	15[2]	0.56	Second most widely used radionuclide in Air Force components
Th-228	Thorium-228	15[2]	0.56	
Th-230	Thorium-230	15[2]	0.56	
Am-241	Americium-241	0.15[6,7]	0.01	Widely used in Air Force Components
H-3	Tritium	20,000[8]	740	Widely used luminous radionuclide in Air Force
C-14	Carbon-14	2,000[9]	74	Used in electron tubes
Ni-63	Nickel-63	50[9]	1.85	Used in electron tubes
Sr-90	Strontium-90	8[8]	0.30	Limited use in Air Force
Pm-147	Promethium-147	600[10]	22.2	Used in electron tubes
Re-187	Rhenium-187	9,000[9]	333	Used in electron tubes
K-40	Potassium-40	Not listed	Not listed	Not a ROPC but measured to help with interpretation of gross beta analysis
Co-60	Cobalt-60	100[9]	3.70	Used in electron tubes
Cs-137	Cesium-137	200[9]	7.40	Used in electron tubes

Notes:

1. As determined by historical investigation of radioisotope use at the former Lowry AFB.
2. Stated in 40 Code of Federal Regulations (CFR) 141.66(c), the MCL for gross alpha particle activity, including radium-226 but excluding radon and uranium
3. Stated in 40 CFR 141.26. For community water systems designated as vulnerable, the screening level for gross beta particle activity minus the naturally-occurring K-40 beta is 1.85 Bq/L (50 pCi/L). For community water systems contaminated by effluents from nuclear facilities, the screening level for gross beta particle activity minus the naturally-occurring K-40 beta is 0.56 Bq/L (15 pCi/L)
4. Stated in 40 CFR 141.66(b), the MCL for combined Ra-226 and Ra-228 is 0.18 Bq/L (5 pCi/L).
5. Stated in 40 CFR 141.66(e). Apportioning the 30 micrograms per liter [μg/L] limit to the uranium isotopes assumed 0.67 pCi/μg and uranium activity fractions of 0.473 for U-234 and U-238 and 0.054 for U-235.
6. Stated in Regulation 41, Section 41.5.C.2, Basic Standards for Groundwater, CDPHE, Water Quality Control Commission.
7. Non-descript americium standard in CDPHE Regulation 41.5.C.2 applied to Am-241.
8. Stated in 40 CFR 141.66, Table A
9. Stated in 40 CFR 141.66(d). 4 mrem/yr limit as specified in Table IV-2A and IV-2B of EPA76 and in Table 3-3 of EPA00
10. Stated in 40 CFR 141.66(d) calculated from NBS Handbook 69.

Analytical data collected during the project was reduced using USEPA's *Interim Guidance on Statistical Analysis of Groundwater Monitoring Data at Resource Conservation and Recovery Act (RCRA) Facilities* [8] as well as the *Addendum to the Interim Final Guidance* [9]. The two-sample non-

parametric Wilcoxon Rank Sum (WRS) statistical test was used to test distinguishability of the upgradient and downgradient well groups. The WRS test was set up to test the well groups against a null hypothesis of equal means, in that if the mean values of the upgradient and downgradient populations were shown to be statistically different at the 95^{th} percent confidence level, the null hypothesis would be rejected. The alternate hypothesis for this study included the application of the regulatory limits to the downgradient well group for each ROPC, if the means were found to statistically distinguishable.

RESULTS

Well Group Distinguishability

A total of 68 groundwater samples from OU 2 wells were collected over the course of the LTM. Thirty-six (36) were collected from upgradient wells while 32 were collected from downgradient wells. Data from the upgradient and downgradient groundwater well groups were analyzed for differentiation using the 2-sample non-parametric Wilcoxon Rank Sum (WRS) test. Each quarter's data were analyzed individually, then analyzed again after being added to the cumulative data pool. This practice was repeated each quarter as new data was collected. One upgradient well, LFPOC05, was found to be dry during each of the LTM sample periods. After obtaining four full quarters of data from OU 2, it has been established that uranium (Total U, U-238, and U-234), gross alpha, gross beta, nickel-63 (Ni-63) and promethium-147 (Pm-147) were shown to be statistically distinguishable via the WRS test. The Ni-63 and Pm-147 test results were shown to be false positives attributable either to having concentrations at method detection levels (Ni-63) or from laboratory lanthanide method interferences (Pm-147).

An example of the uranium behavior across OU2 is shown on Figure 3, which plots the average total dissolved uranium for all groundwater wells during the LTM. Uranium concentrations are clearly shown to trend higher along the eastern side of OU2, with increases trending up from both the east and west. These increases coincide with the axis of an ancient hydrogeologic formation identified as a paleochannel in this area.

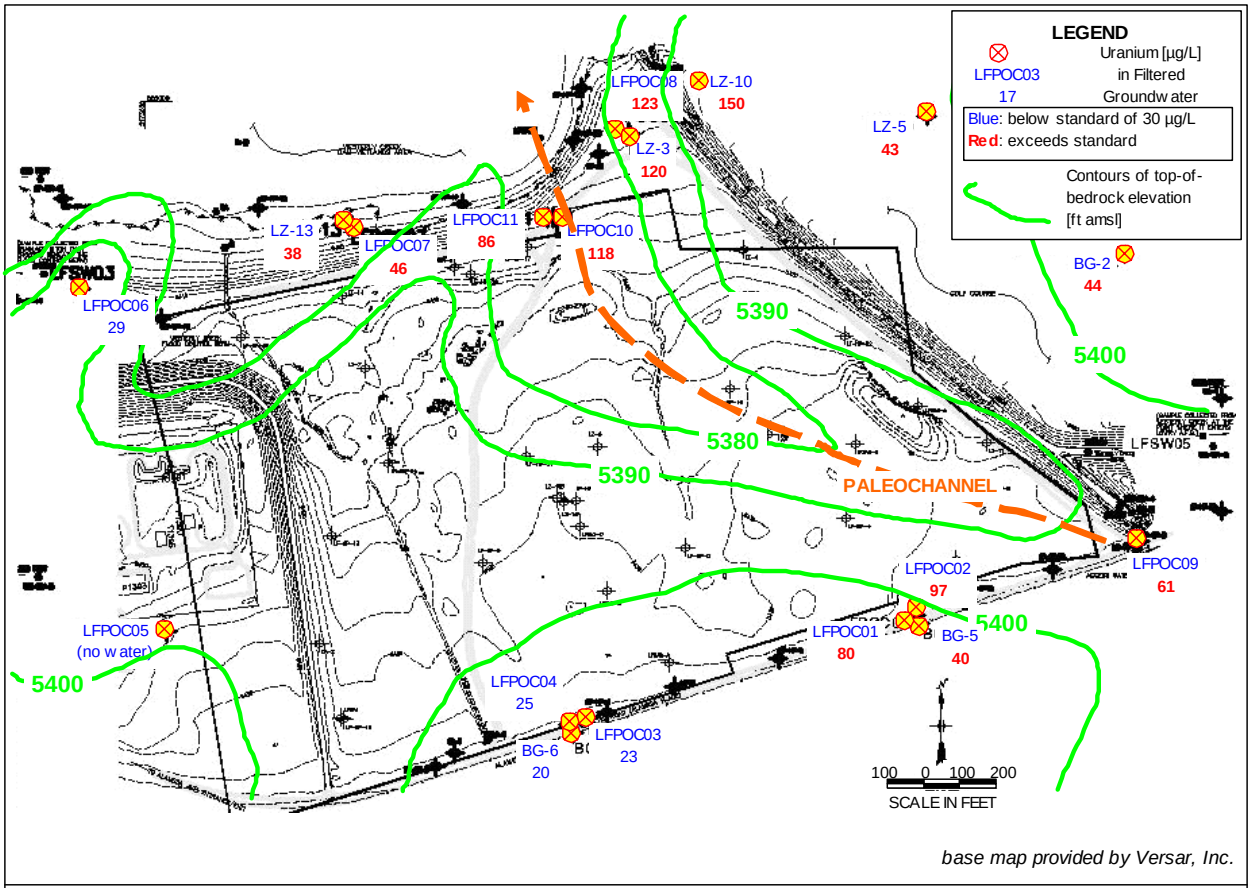

Fig. 3. Plot of average total dissolved uranium at OU2 at each groundwater monitoring well.

The WRS Test was also run on surface water and sediment samples collected at OU 2. Seven upstream and 5 downstream surface water and sediment samples, from three locations were tested. The results of the WRS test on the surface water and sediment data sets showed the same general behavior as the groundwater results. Uranium (total and isotopic), gross alpha, and gross beta were shown to be statistically distinguishable.

Comparison of ROPC Levels to Applicable Regulatory Standards

The second Decision Statement focused on the levels of measured ROPC concentrations measured at OU2. The intent was to assess where and how many ROPCs were found to exceed their applicable regulatory limit. All ROPC analysis results were directly compared to their applicable regulatory standards provided in Table 2. Each quarter's result and the cumulative mean for each ROPC, as well as the cumulative mean for each ROPC, was compared to its applicable standard.

ROPC levels in all wells were found to be fairly consistent throughout the LTM, regardless of well location or screen interval. The only ROPCs shown to exceed their applicable regulatory standards during every sampling event were raw gross alpha, total uranium, U-238, and U-234. Thorium-230 (Th-230) was found to exceed the 0.56 Bq/L MCL only once, at well location LZ-10 during the second quarter. The 2Q results also showed detectable Th-228 and Th-232 results, albeit below MCL levels, both at LZ-10 and in LZ-13. These results were not seen during any other sampling event during the LTM. The gross alpha results, after correction for uranium, were all less than the MCL.

Relationship of Gross Alpha and Gross Beta to Uranium at OU 2

Data from the gross alpha and gross beta analyses performed during the LTM were compared to the isotopic and total uranium results to ascertain their direct influence. The LTM data shows that both gross alpha and gross beta results track very closely with high dissolved uranium content in groundwater in and around OU 2. Gross alpha was shown to have a closer direct relationship due to the increased number of alpha decays in the uranium decay chain, all of which contribute to the gross alpha result. For example, there are 18 alpha decays from the parent U-238 down to daughter Ra-226, and 42 alpha decays total down to stable lead-206 (Pb-206). As a comparison, there are an equivalent 1 and 2 beta decays for those same two scenarios, respectively.

Ratios of the gross alpha to total uranium (by ICP/MS) activities each ground water sample analyzed during the LTM are shown in Fig. 4. This plot includes all samples, regardless of time period or OU 2 location. The mean ratio is 0.46 ± 0.08, excluding the outlier from an upgradient well during the 3Q. The high calculated ratio was due to a very low total uranium result. Understanding the correlation between gross alpha and total uranium allowed for development of gross alpha 'control limits' that can be used reliably to track the behavior of uranium as part of the OU 2 long-term landfill closure monitoring program. An 'investigate' limit was calculated based the mean plus two standard deviations of the gross alpha to total uranium ratios observed at each well, while the follow-up limit corresponds to the mean three standard deviations. The well-specific ratios are provided in Table III.

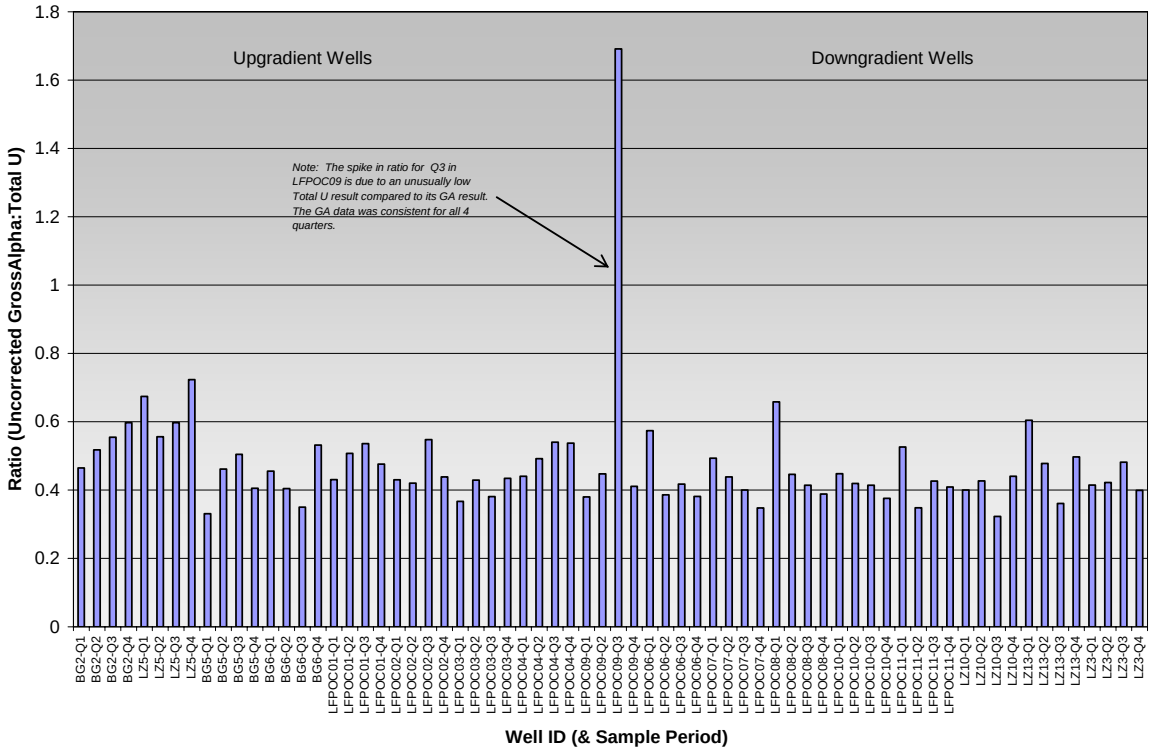

Fig. 4. Plot of calculated gross alpha to total dissolved uranium at OU 2.

Table III. Well-Specific Raw Gross Alpha Control Limit Concentrations (in pCi/L) for Future OU 2 Use.

Well ID	Well Group	Gross Alpha Investigate Control Limit Bq/L	Gross Alpha Follow-Up Control Limit Bq/L (pCi/L)
BG-2	Upgradient	1.26	1.44
LZ-5	Upgradient	1.44	1.63
BG-5	Upgradient	0.89	1.04
BG-6	Upgradient	0.48	0.56
LFPOC01	Upgradient	2.0	2.29
LFPOC02	Upgradient	2.29	2.63
LFPOC03	Upgradient	0.52	0.60
LFPOC04	Upgradient	0.67	0.74
LFPOC09	Upgradient	1.70	1.96
LFPOC06	Downgradient	0.70	0.81
LFPOC07	Downgradient	1.04	1.18
LFPOC08	Downgradient	3.0	3.40
LFPOC10	Downgradient	2.48	2.85
LFPOC11	Downgradient	1.89	2.15
LZ-10	Downgradient	3.07	3.52
LZ-13	Downgradient	0.96	1.11
LZ-3	Downgradient	2.63	3.0

Gross beta also displays a modest increase downgradient of OU2, although zero samples collected during the LTM were observed to be greater than the MCL value of 50 pCi/L. Analysis of the 4

quarters' worth of ROPC data at OU2 indicate that Pa-234m, Ni-63, K-40, Cs-37, H-3, and C-14 are all likely contributors to the Gross Beta measurements, albeit not all in equal amounts. The largest contributor is likely Pa-234m, which is a very short-lived (half life = 1.17 min) decay daughter of U-238 (given an intermediary decay of Th-234 (half-life = 24.1 days). Since Pa-234m occurs in the uranium decay chain between U-238 and U-234, it can be assumed to have the same activity as the parent U-238 since the later decay daughter U-234 has been shown to have the show same behavior.

Although the presence of uranium at OU 2 was shown to have an impact on both gross alpha and gross beta results, development of specific gross beta control limits was deemed unnecessary since gross alpha was shown to be a more reliable indicator of uranium.

Investigation of the Origin of Elevated ROPCs at OU 2

The third Decision Statement investigated the potential origin of those ROPCs that met any of the following criteria:

- Downgradient well pool mean values were found to be statistically distinguishable from their upgradient counterpart; and
- ROPC levels were found to exceed their applicable regulatory limit.

The four quarters of data collected over the course of the LTM resulted in five ROPCs requiring provenance analysis. These include gross alpha, gross beta, total uranium, U-234, U-235, and U-238. These results created the need to assess whether concentrations present in OU 2 groundwater were indicative of natural sources or potentially anthropogenic means.

The primary means for addressing the origin of the elevated uranium was through calculation of isotopic ratios for the three isotopes of uranium measured during the LTM. Differences in the ratios of U-234:U-238 and U-238:U-235 from theoretical values may be used to predict whether man may have processed the uranium into a state that is different from what is found geologically as 'natural uranium.'

For example, U-234:U-238 was calculated to test whether the uranium may have undergone separation processing while U-238:U-235 was calculated to test whether the uranium had undergone enrichment or depletion processing. In addition to these fundamental tests, a total activity to total mass ratio was also calculated to test against published ratios for natural uranium in the US EPA's *Primary Drinking Water Regulations, Radionuclides; Final Rule.* [7]

The ratio results from each quarter were directly compared against calculated U-234:U-238 and U-238:U-235 ratios from natural uranium in equilibrium, depleted uranium (DU), commercially enriched nuclear reactor fuel, and weapons-grade uranium. The isotopic breakdowns of the uranium and the theoretical isotopic ratios are shown in Table IV. The results of the ratio analyses over the course of the LTM are shown in Table V. All ratios have been found to be consistent with a natural uranium source term, even when considering the measurement uncertainties included in the ratios.

Table IV. Characteristics of Uranium in Various Isotopic Mixtures

	Natural Uranium (in equilibrium)		Depleted Uranium		Commercial Reactor Fuel (~3% U-235)		Weapons-grade Uranium (>95% U-235)	
Isotope	**Weight %**	**Activity % (approx)**	**Weight %**	**Activity % (approx)**	**Weight %**	**Activity % (approx)**	**Weight %**	**Activity % (approx)**
^{234}U	0.006	48.8	0.0007	28	0.03	79	1.2	97.4
^{235}U	0.72	2.3	0.2	1	3	4	95	2.6
^{238}U	99.2	48.8	99.8	71	97	17	3.3	0.01
U-234:U-238 Ratio		***1***		***0.4***		***4.6***		***9740***
U-238:U-235 Ratio		***21.1***		***71.0***		***4.3***		***0.004***

Table V. Results of uranium isotope analysis at OU 2

LTM Period	Theoretical Value*	Groundwater	Surface Water	Sediment
U-234:U-238 Ratios				
1Q	1	1.17 ± 0.02	1.14 ± 0.06	1.18 ± 0.08
2Q	1	1.16 ± 0.04	1.22 ± 0.11	1.18 ± 0.13
3Q	1	1.18 ± 0.02	1.21 ± 0.11	1.02 ± 0.11
4Q	1	1.19 ± 0.04	1.21 ± 0.09	1.03 ± 0.11
U-238:U-235 Ratios				
1Q	21.6	19.7 ± 6.4	20.1 ± 7.6	28.9 ± 26.0
2Q	21.6	20.0 ± 4.8	18.1 ± 6.8	23.9 ± 23.6
3Q	21.6	22.0 ± 6.0	20.6 ± 9.9	23.0 ± 21.8
4Q	21.6	16.6 ± 8.5	19.1 ± 10.8	20.4 ± 22.3

* Theoretical uranium ratio values were based on the following natural abundance assumption: 48.8% ^{238}U, 48.8% ^{234}U, and 2.3% ^{235}U, by activity.

The natural uranium assertion holds true across all OU 2 samples, including groundwater, surface water and sediment. These ratios strongly support the conclusion that elevated concentrations of uranium found in groundwater, surface water, and sediment samples are the result of naturally-occurring uranium species.

The increase in observed U-234:U-238 ratios was not unexpected. The theoretical activity ratio for these isotopes is 1; assuming secular equilibrium conditions are present. However, it is not uncommon for uranium in groundwater to actually be in a "disequilibrium" condition due to geochemical processes. Examples of these processes include preferential leaching of certain radioisotopes during water/rock interactions in old aquifers and separation of U-234 atoms from U-238 atoms due to breakdown in the crystalline structure from alpha decay and recoil. Geologists frequently cite disequilibrium conditions as a tracer for determining the age of groundwater aquifers. The reader is referred to the following sources for detailed information regarding disequilibrium. [10, 11] The U-238:U-235 ratios for groundwater and surface water agree favorably with the theoretical values for natural uranium.

Given the ratio evidence that the uranium at OU 2 is naturally occurring, the next step is to attempt to ascertain the reason for the downgradient increases. Two hypotheses were investigated to potentially explain this condition. The first is the concept the eastern edge of OU 2 was the location of one of an ancient 'paleochannel,' which is contributing additional dissolved uranium into downgradient groundwater from formerly deposited sediments. The alternate hypothesis involves the burial of uranium ores within OU 2. Evidence supporting and/or refuting each hypothesis is provided below.

- Paleochannel sediments have been shown to be eroded into bedrock beneath OU 2, based on the bedrock contour mapping performed during the 1995 SRI. [2]
- Uranium concentrations in OU 2 wells correlate fairly well with their proximity to the paleochannel.
- There is evidence of elevated uranium concentrations in the upstream watershed as shown in the increases in the background wells, and
- Isotopic ratio evidence indicates that the uranium has been transported in water.

Evidence supporting the alternate hypothesis are:

- Documentation that some 300 pounds of uranium ore was stored at the former LAFB;
- Higher concentrations of natural uranium are found in downgradient groundwater than in upgradient groundwater.

Evidence contradicting the ore-disposal hypothesis includes:

- There is no evidence that uranium ore was ever disposed in the landfill;
- Levels of radioactive radium or thorium in OU 2 groundwater have consistently been shown to be at method detection levels (with the exception of the two thorium anomalies during 2Q). This is significant due to the fact that some 85% of the total radioactivity in uranium ores is due to the presence of its radium and thorium daughters. Our research indicates that all mined uranium ores are Eocene-aged or older (older than 33 million years), while the Piney Creek alluvium of the OU 2 water-table aquifer is Holocene-aged (less than 11,000 years old). The observed levels of uranium at OU 2 versus their later-appearing radium and thorium daughters supports our assertion that OU 2 groundwater is too young to have reached an equilibrium state;
- U-234:U-238 isotopic ratios at OU 2 do not support a uranium ore burial hypothesis. All calculated U-234:U-238 activity ratios indicate that the uranium has undergone aqueous transport. Conversely, these ratios would be expected to be closer to unity due to dissolution of the uranium under the ore-disposal hypothesis;
- Uranium ore contains gangue minerals rich in aluminum, manganese, nitrate, iron and selenium, yet these elements are not present in OU 2 groundwater in any significant quantities.

CONCLUSIONS

Dissolved uranium levels greater than the 30 µg/L MCL were consistently found in both upgradient and downgradient wells at OU 2. Elevated gross alpha and gross beta measurements, observed during prior investigations and confirmed during the LTM, were found to correlate with high dissolved uranium content in groundwater, surface water, and sediment. If the gross alpha values are corrected to exclude uranium and radon contributions in accordance with US EPA guidance, then the 0.56 Bq/L (15 pCi/L) gross alpha level is not exceeded.

The behavior of the elevated ROPCs at OU 2, particularly uranium, gross alpha, and gross beta were found to be stable over the course of the LTM, regardless of well location or screening interval. No statistically noticeable seasonal variations were observed in either of the well groups, nor is there any indication of a migrating local plume of any kind relative to OU 2.

The isotopic ratio analysis indicates that despite the observed increases in the downgradient well group, all samples appear to be from a natural uranium source. Based on the results of this monitoring program, it was concluded that the elevated uranium concentrations measured in OU 2 groundwater,

surface water, and sediment are due to the naturally-occurring uranium content of the regional watershed and are not the result of waste burials in the former landfill. Several lines of evidence indicate that natural uranium has been naturally concentrated beneath OU 2 in the geologic past and the higher of uranium concentrations in downgradient wells is the result of geochemical processes and not the result of a uranium ore disposal. These results therefore provide the data necessary to support radiological closure of OU 2.

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