Radiation Protection Program

Occupational Radiation Exposure Study

HMC Grants Reclamation Project

Cibola County, New Mexico

Final Report

Revision 0

Prepared for:

Homestake Mining Company of California

P.O. Box 98 /560 Anaconda Road

Grants, NM 87020

Prepared by:

ERG

Environmental Restoration Group, Inc.

8809 Washington St. NE, Suite 150

Albuquerque, NM 87113

505-298-4224

August 20, 2018

Environmental Restoration Group, Inc.
8809 Washington St NE, Suite 150
Albuquerque, NM 87113
ph: (505) 298-4224
www.ERGoffice.com

RADIATION PROTECTION REPORT	
To: Tom Wohlford (HMC)	**Date:** August 20, 2018
From: Randy Whicker (ERG)	**Project:** Grants Reclamation Project
Direct: 970-556-1174	**Task(s):** Radiation Safety Officer
Cc: Clark Burton (HMC); Brad Bingham (HMC); Chuck Farr (ERG)	
Subject: Occupational Radiation Exposures Study – Final Report	

Dear Mr. Wohlford,

The Occupational Radiation Exposures Study at the Homestake Mining Company of California (HMC) Grants Reclamation Project was completed in late May 2018. The attached Final Report provides Study results and data evaluation in a context of Study objectives.

Per discussion with Dr. Rob Evans with NRC at the spring 2018 NRC Site inspection, this document should be printed and made available for regulatory review at the upcoming Site inspection (September 10, 2018).

Please let me know if you have any questions regarding this Report.

Regards,

Randy Whicker, CHP
RSO, HMC Grants Reclamation Project
Environmental Restoration Group, Inc.
8809 Washington St. NE, Suite 150
Albuquerque, NM 87113
Email: RandyWhicker@ergoffice.com

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1. BACKGROUND

A radiological monitoring study (Study) to characterize occupational radiation exposure potential at the Homestake Mining Company of California (HMC) Grants Reclamation Project (Site) was conducted between December 2017 and May 2018 in accordance with an associated Study Plan (ERG, 2017). This Study was designed and initiated in response to observations by the U.S. Nuclear Regulatory Commission (NRC) during a September 12-14, 2017 Site inspection, as documented in the NRC Inspection Report dated December 20, 2017 (USNRC, 2017). An interim data transmittal was prepared for a NRC inspection March 26-27, 2018, and the issue was left open pending completion of the Study and final reporting as indicated in the NRC Inspection Report dated May 3, 2018 (USNRC, 2018). The intent of this Final Report is to provide monitoring data with relevance to occupational exposures and provide technical justification for current and future occupational radiation monitoring practices at the Site.

2. STUDY ELEMENTS AND OBJECTIVES

As detailed in the Study Plan (ERG, 2017), the objectives of this special monitoring program were as follows:

1. Characterize potential occupational exposures of workers to internal and external sources of ionizing radiation associated with historic uranium milling activities.
2. Provide sufficient data to evaluate the need for routine radiological exposure monitoring relative to regulatory thresholds that require such monitoring as specified in 10 CFR 20.1502:
    a. >10% of the annual limits on intake (ALI) given in 10 CFR 20, Appendix B, and/or
    b. >10% of the annual limit for total radiation dose to radiation workers from both internal and external sources (amounting to 500 mrem/yr).
3. Provide additional data on the levels of outdoor radon gas, radon progeny, and radon progeny/gas equilibrium ratios on top of the Large Tailings Pile (LTP), at hydrologically upgradient air monitoring station "1-OFF", and at two downgradient air monitoring stations relative to the LTP (Station HMC-5 and a temporary Study location about half way between the LTP and HMC-5).

Objective 3 is relevant to occupational exposures as well as radiological dose to the nearest member of the public (near air monitoring stations HMC-4 and HMC-5). Objectives 1 and 2 are intended to address the "Unresolved Item" regarding regulatory requirements for occupational monitoring (10 CFR 20.1201 and 20.1502). Study data with relevance to occupational radiation dose are evaluated and discussed in this Report. Study data with relevance to public dose estimation will be evaluated separately from this Report as needed to address regulatory requirements related to public dose limits (10 CFR 20.1301 and 20.1302).

Site locations with relevance to this Study (Figure 1) include the Large Tailings Pile (LTP), Small Tailings Pile (STP), the Reverse Osmosis (RO) Building and environmental monitoring locations HMC-5, HMC-1OFF, and a temporary station identified as "Between", which is situated about half way between the STP and HMC-5 (Figure 1). The Study design and monitoring program elements are detailed in the Study Plan (ERG, 2017). Portions of the Study Plan that specifically pertain to occupational radiation exposures are summarized in Table 1 below.

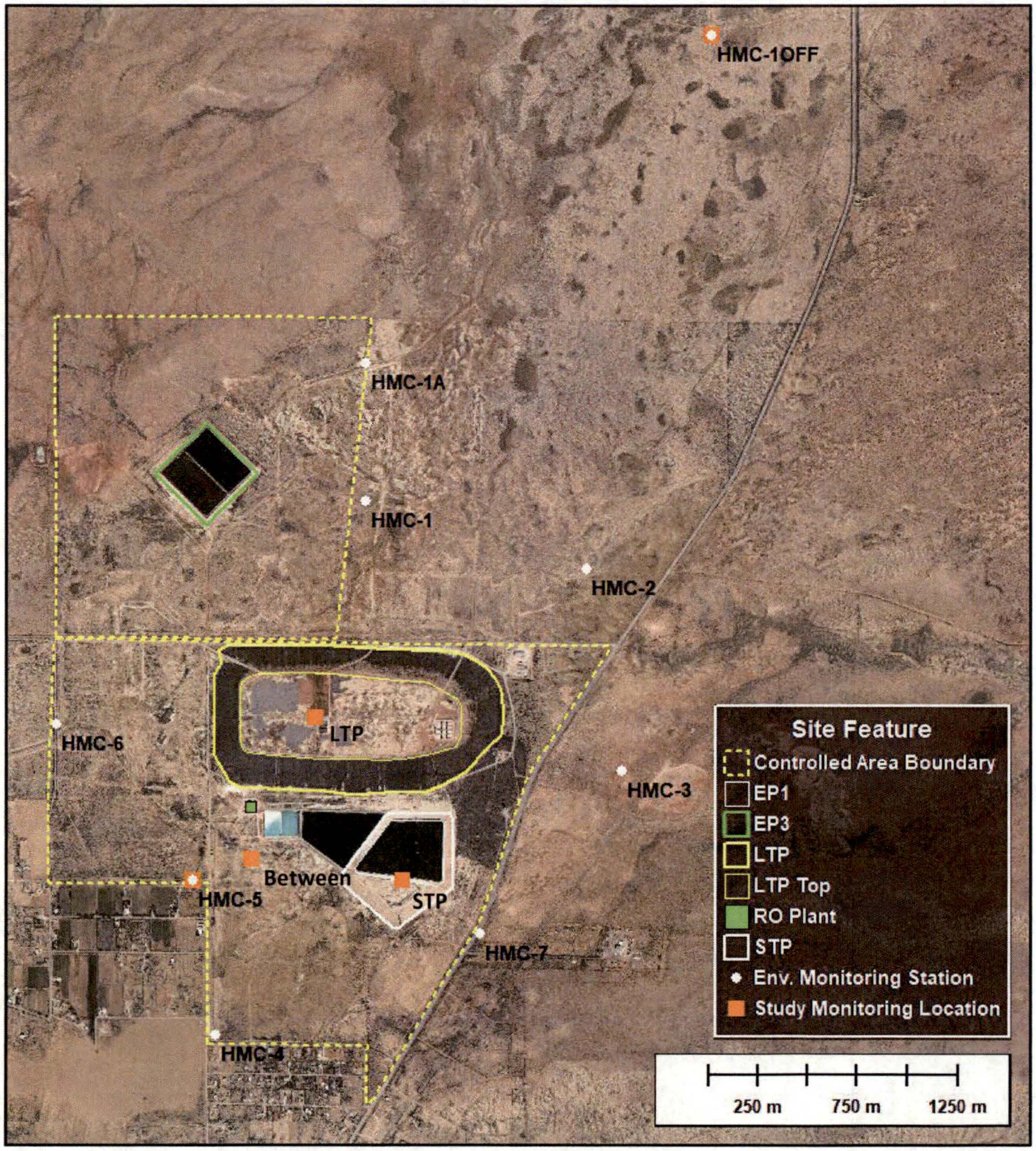


Figure 1: Routine environmental monitoring stations and occupational monitoring Study locations.

Table 1: Outline of Occupational Radiation Exposure Study parameters, sampling design and objectives.

Occupational Exposure Study Element*	Radiological Parameter(s)	Monitoring Frequency	Monitoring Objective(s)
3.1. Hi-volume general work area air particulate monitoring on top of the LTP and STP.	Radionuclide concentrations in airborne particulate matter, including U-nat, Th-230, Ra-226 and Pb-210.	Continuous air particulate sampling, filters collected weekly and composited monthly for laboratory analysis of radionuclide concentrations in air.	Characterize temporal (monthly) variability in occupational exposures and determine the need for continued routine monitoring.
3.2. Lapel-type personal BZ air monitoring for non-routine work projects.	Gross alpha concentrations in airborne particulate matter.	As needed to support non-routine work activities that have the potential for significant airborne exposures (e.g. under a RWP at the discretion of the RSO).	Characterize non-routine occupational exposures and internal dose from the inhalation pathway.
3.3. Passive radon track-etch monitoring on the LTP, STP, 1-OFF, and mid-way between the tailings piles and HMC-5.	Time-integrated average radon gas concentrations in ambient outdoor air.	Monthly exchange of high-sensitivity "Rapidos" track-etch detectors.	Characterize long-term average occupational exposures and determine the need for continued monitoring on a routine basis.
3.4. Passive monitoring of external dose rates with OSL dosimeters on the LTP, STP, 1-OFF, and mid-way between the tailings piles and HMC-5.	Time-integrated average external radiation dose rates.	Monthly exchange of OSL dosimeters from Landauer.	Characterize long-term average external dose rates and potential influence of gamma-emitting radon progeny.
3.5. Durridge RAD7 radon gas monitoring on top of the LTP and at air station HMC-5.	Radon gas concentrations in ambient outdoor air.	Continuous, with 1-hour measurement intervals.	Characterize diurnal variability in ambient radon gas on top of the LTP and at downgradient air station HMC-5.
3.6. Outdoor radon progeny measurements with the modified Kusnetz method.	Short-lived radon decay product concentrations in ambient outdoor air [in units of "working level" (WL)].	Twice daily (early morning/late afternoon), at least 3 days per week on top of the LTP, at One-off, and at HMC-5.	Characterize temporal variations in outdoor radon progeny levels upgradient, on top of, and downgradient from, the LTP.
3.7. Indoor radon progeny measurements with the modified Kusnetz method.	Short-lived radon decay product concentrations in ambient indoor air [in units of "working level" (WL)].	At least once per week within the Reverse Osmosis (RO) plant for several months, preferably in the early morning hours.	Characterize indoor radon progeny levels and potential worker exposures in the RO building.
3.8. Gamma radiation scans of routinely accessed work areas, including areas around roads, tailings piles and evaporation ponds.	True external radiation exposure rate based on cross-calibration against a high-pressure ionization chamber (HPIC).	One-time survey (terrestrial sources of gamma radiation not expected to change significantly over time)	Provide information on the spatial distribution of gamma exposure rates in areas near tailings piles, RO Plant and ponds where reclamation work routinely occurs.

*Study elements are numbered in accordance with the Section of this Report in which associated results are presented.

3. RESULTS

Occupational monitoring Study results are presented in the following numbered sections corresponding to the numbered Study elements shown in Table 1.

3.1 HIGH-VOLUME AIR SAMPLING

High-volume air samplers are stationed in the approximate centers of the Large Tailings Pile (LTP) and Small Tailings Pile (STP). Respective monitoring results for the Study are presented in Tables 2 and 3. Air monitoring filters were collected weekly, composited and sent to the analytical laboratory for analysis of U-nat, Th-230, and Ra-226 in accordance with the Study Plan. It can reasonably be assumed that continuous high-volume air monitoring results are representative of routine worker exposures to long-lived radionuclides associated with airborne particulate matter.

Results (Tables 2 and 3) are compared to the Derived Air Concentration (DAC) values given in 10 CFR 20 Appendix B, as follows: 2E-11 µCi/mL for U-nat (most conservative solubility class Y), 6E-12 µCi/mL for Th-230 (solubility class Y), and 3E-10 µCi/mL for Ra-226 (solubility class W). Estimates of the maximum possible annual inhalation doses from these radionuclides were calculated by multiplying the average fraction of the DAC for each radionuclide by 5,000 mrem/year under an assumption of light work and full-time occupational occupancy (2,000 hours/year). The maximum annual inhalation dose from airborne particulate radionuclides to an occupational worker on top of the LTP is estimated to be 0.2 mrem. For the STP, the maximum annual occupational dose from this exposure pathway is estimated to be 1.2 mrem. If we assume a typical routine worker spends 50% of their time on each of the two impoundments, the maximum annual occupational dose from this pathway would be on the order of 0.7 mrem.

Table 2: High-volume air monitoring results for LTP.

Large Tailings Pile									
Month	Filters		Total Volume	U-nat		Th-230		Ra-226	
	From	To	(Liters)	µCi/ml	Fraction of DAC	µCi/ml	Fraction of DAC	µCi/ml	Fraction of DAC
2017 DEC	12/12/2017	12/21/2017	3.06E+06	1.0E-16	5.0E-06	1.0E-16	1.7E-05	5.0E-16	1.7E-06
	12/21/2017	12/27/2017							
	12/27/2017	1/4/2018							
	1/4/2018	1/11/2018							
2018 JAN	1/11/2018	1/18/2018	2.06E+06	1.0E-16	5.0E-06	2.0E-16	3.3E-05	5.0E-16	1.7E-06
	No Filter	Lost in wind							
	1/25/2018	2/1/2018							
	2/1/2018	2/8/2018							
2018 FEB	2/8/2018	2/15/2018	2.10E+06	1.0E-16	5.0E-06	2.0E-16	3.3E-05	6.0E-16	2.0E-06
	No Filter	No Power							
	2/22/2018	3/2/2018							
	3/2/2018	3/8/2018							
2018 MAR	3/8/2018	3/15/2018	2.53E+06	1.0E-16	5.0E-06	7.0E-17	1.2E-05	9.0E-16	3.0E-06
	3/15/2018	3/22/2018							
	3/22/2018	3/28/2018							
	3/28/2018	4/5/2018							
2018 APR	4/5/2018	4/15/2018	2.72E+06	4.0E-16	2.0E-05	5.0E-17	8.3E-06	7.0E-16	2.3E-06
	4/15/2018	4/19/2018							
	4/19/2018	4/29/2018							
	4/29/2018	5/3/2018							
2018 MAY	5/3/2018	5/11/2018	1.90E+06	4.0E-16	2.0E-05	7.0E-18	1.2E-06	8.0E-16	2.7E-06
	5/11/2018	5/17/2018							
	5/17/2018	5/22/2018							
Average				2.0E-16	1.0E-05	1.0E-16	1.7E-05	6.7E-16	2.2E-06
Annual Dose Estimate (mrem)				0.05		0.09		0.01	

Table 3: High-volume air monitoring results for STP.

Small Tailings Pile									
Month	Filters		Total Volume	U-nat		Th-230		Ra-226	
	From	To	(Liters)	µCi/ml	Fraction of DAC	µCi/ml	Fraction of DAC	µCi/ml	Fraction of DAC
2017 DEC	12/12/2017	12/21/2017	3.00E+06	8.0E-16	4.0E-05	2.0E-16	3.3E-05	7.0E-16	2.3E-06
	12/21/2017	12/27/2017							
	12/27/2017	1/4/2018							
	1/4/2018	1/11/2018							
2018 JAN	1/11/2018	1/18/2018	2.50E+06	7.0E-16	3.5E-05	2.0E-16	3.3E-05	2.0E-16	6.7E-07
	1/18/2018	1/25/2018							
	1/25/2018	2/1/2018							
	2/1/2018	2/8/2018							
2018 FEB	2/8/2018	2/15/2018	2.42E+06	4.0E-16	2.0E-05	1.0E-16	1.7E-05	6.0E-16	2.0E-06
	2/15/2018	2/22/2018							
	2/22/2018	3/2/2018							
	3/2/2018	3/8/2018							
2018 MAR	3/8/2018	3/15/2018	2.47E+06	9.0E-16	4.5E-05	2.0E-16	3.3E-05	8.0E-16	2.7E-06
	3/15/2018	3/22/2018							
	3/22/2018	3/28/2018							
	3/28/2018	4/5/2018							
2018 APR	4/5/2018	4/15/2018	2.59E+06	8.2E-15	4.1E-04	6.0E-16	1.0E-04	1.0E-15	3.3E-06
	4/15/2018	4/19/2018							
	4/19/2018	4/29/2018							
	4/29/2018	5/3/2018							
2018 MAY	5/3/2018	5/11/2018	1.46E+06	1.3E-14	6.5E-04	3.0E-16	5.0E-05	9.0E-16	3.0E-06
	5/11/2018	5/17/2018							
	5/17/2018	5/22/2018 End flow zero							
Average				4.0E-15	2.0E-04	2.7E-16	4.4E-05	7.0E-16	2.3E-06
Annual Dose Estimate (mrem)				1.0		0.22		0.01	

3.2 LAPEL-TYPE PERSONAL BREATHING ZONE AIR SAMPLING

As previously reported (ERG, 2017), some personal breathing zone (BZ) air sampling was conducted in 2017. Since then, two radiation work permits issued in June 2018 (including RWP 18-6 and 18-7) have included BZ air monitoring. The June 2018 RWPs involved work with the potential to mobilize airborne particulates containing elevated levels of radionuclides (zeolite plant maintenance and drilling work in contact with buried tailings). All BZ air sampling results since the inception of this Study are provided in Table 4.

Table 4: Personal BZ air monitoring data.

Date	BZ Air Sampling		Date	BZ Air Sampling	
	U-nat (µCi/mL)	Percent of DAC (%)		U-nat (µCi/mL)	Percent of DAC (%)
10/24/2017	2.5E-12	12.4	6/14/2018	1.7E-12	8.6
10/25/2017	3.6E-12	18.2	6/14/2018	1.3E-12	6.7
10/26/2017	2.1E-12	10.5	6/15/2018	1.2E-12	5.9
10/30/2017	3.6E-12	17.9	6/15/2018	0.0E+00	0.0
10/31/2017	1.7E-12	8.3	6/17/2018	2.8E-13	1.4
11/2/2017	0.0E+00	0.0	6/18/2018	0.0E+00	0.0
11/6/2017	2.9E-13	1.5	6/18/2018	1.4E-13	0.7
11/7/2017	8.2E-13	4.1	6/19/2018	3.8E-13	1.9
11/8/2017	0.0E+00	0.0	6/19/2018	5.7E-13	2.8
6/5/2018	0.0E+00	0.0	6/20/2018	9.7E-13	4.9
6/6/2018	0.0E+00	0.0	6/20/2018	1.2E-12	6.2
6/7/2018	6.1E-13	3.1	6/21/2018	1.5E-12	7.4
6/8/2018	6.1E-13	3.0	6/21/2018	3.3E-13	1.6
6/11/2018	4.1E-13	2.0	6/22/2018	0.0E+00	0.0
6/12/2018	1.5E-12	7.3	6/22/2018	3.0E-13	1.5
6/13/2018	0.0E+00	0.0	6/25/2018	1.2E-12	6.2
6/13/2018	0.0E+00	0.0	6/26/2018	2.0E-13	1.0

Statistic	U-nat (µCi/mL)	%DAC	DAC-hrs	CEDE (mrem)
Mean	8.5E-13	4.3	11.6	29
Median	4.9E-13	2.4	6.6	17

Given the short-term potential for higher radiological exposures to air particulates associated with some RWPs, it is reasonable to estimate non-routine "RWP dose" separately from that of routine work at the Site. The maximum possible committed effective dose equivalent (CEDE) associated with RWP activities during the course of this Study was estimated by hypothetically assuming a single individual was exposed to the measured fraction of the DAC for 8 hours per day of BZ air sampling under each RWP (a total of 34 RWP workdays) as shown in Table 4. The average or median DAC fraction was multiplied by the total number of hours (272 hours) to determine the DAC-hours of exposure and estimate the maximum possible CEDE for any RWP worker (Table 4). In a typical year of reclamation operations at the Site, RWP activities that warrant BZ air sampling are not expected to exceed the number of days of BZ monitoring reflected in Table 4 (34 days), and these estimates thus provide a conservative indication of the maximum non-routine inhalation dose to any RWP worker from air particulates in any given year.

3.3 PASSIVE RADON TRACK-ETCH MONITORING

Passive radon track-etch monitoring was conducted from December 2017 through May 2018 with Rapidos High-Sensitivity Alpha-Track Detectors from Radonova. Results (Table 5) are well below the DAC for radon in equilibrium with progeny as given in 10 CFR 20 Appendix B (equivalent to 30 pCi/L). Unusually high results at HMC-1OFF were recorded in February and March, and at the "Between" station in March. The reason for these high results is unknown but could be due to sampling and/or analytical error based on a lack of similarly high radon gas measurements at other locations during March and April of 2018 (see also Section 3.5). With respect to potential occupational dose from radon, this is evaluated based on direct measurement of radon progeny (see Section 3.6) since most of the dose from radon is due to its decay products.

Table 5: Radon track etch monitoring results, locations are listed from upgradient to downgradient.

Month	Dates		Days	Radon Concentration (pCi/L)				
	From	To		HMC-1OFF	LTP	STP	Between	HMC-5
2017 DEC	12/6/2017	1/8/2018	33	1.8	2.7	2.2		1.9
2018 JAN	1/8/2018	2/6/2018	29	1.4	1.8	1.5	1.3	1.5
2018 FEB	2/6/2018	3/7/2018	29	3.6*	1.4	0.81	0.89	0.73
2018 MAR	3/7/2018	4/5/2018	29	2.7*	1.5	1.1	2.8*	0.89
2018 APR	4/5/2018	5/3/2018	28	0.89	1.1	1.1	0.59	0.57
2018 MAY**	5/3/2018	5/24/2018	21	1.5	2.1	1.5	1.5	1.5
			Average	2.0	1.8	1.4	1.4	1.2

*Unexpectedly high result, roughly 3 times higher than typical quarterly radon monitoring results at the Site.

** May 2018 values are from re-analysis as requested of Radonova due to a possible systemic bias in original results.

3.4 LONG-TERM EXTERNAL DOSE MONITORING

Passive monitoring of external dose rates with optically stimulated luminescent (OSL) dosimeters from Landauer was conducted on the LTP, STP, HMC-1OFF, HMC-5 and midway "Between" the tailings piles and HMC-5 (Table 6). The control badge was stored in the office. Ambient outdoor dose rates at most field locations are similar to background as measured at the indoor control badge storage location. The dose rate on the STP is slightly elevated due to higher external gamma radiation near the edges of Evaporation Pond EP-1 (see Section 3.8 for corresponding gamma survey data). Slightly elevated dose rates are also apparent between the tailings piles and HMC-5 (at station "Between"), possibly due to the influence of radon progeny associated with radon gas emissions from the tailings piles. Despite some elevated gamma radiation at certain locations, workers are only occasionally present in these areas, and personal dosimetry results for workers routinely show no measurable external dose from overall work activities at the Site (this is documented in annual ALARA Audit Reports). Nevertheless, net occupational external doses for hypothetical continuous exposures at each Study monitoring location (in excess of the control badge location) are provided in Table 6. The intent is to provide a conservative indication of locations where long-term occupancy could result in small but potentially measurable external doses to workers in excess of background levels.

Table 6: Ambient external dose rate data

Month	Dates		Days	Gross Dose (mrem)					
	From	To		CONTROL	HMC-1OFF	LTP	STP	Between	HMC-5
2017 DEC	12/6/2017	1/8/2018	33	13.8	14.9	15.6	19.9	n/a	14.8
2018 JAN	1/8/2018	2/8/2018	31	15.2	29.1	27.1	33.4	30.7	27.3
2018 FEB	2/8/2018	3/7/2018	27	20.8	20.1	21.0	25.1	20.5	22.2
2018 MAR	3/7/2018	4/5/2018	29	21.2	18.3	19.4	23.9	20.0	19.2
2018 APR	4/5/2018	5/3/2018	28	17.7	18.3	19.0	21.2	19.9	18.0
2018 MAY	5/3/2018	5/24/2018	21	19.0	18.4	16.9	21.8	18.9	19.4
Weighted Average 30 Day Gross Dose				19.7	21.5	21.4	26.1	24.3	21.9
Net Occupational External Dose by Location				-	**1.8**	**1.7**	**6.4**	**4.6**	**2.2**

3.5 CONTINUOUS RADON GAS MONITORING

Continuous monitoring of ambient airborne radon gas levels with a powered Durridge RAD7 radon gas monitoring instrument was conducted at three locations: upgradient from the LTP at air station HMC-1OFF, on top of the LTP, and downgradient from the LTP at air station HMC-5. There were some technical difficulties keeping these RAD7 instruments running continuously at all three location as intended due to malfunctions, apparently associated with extreme cold temperatures during the winter months in the Grants, NM area. Radon gas concentration data (pCi/L) collected at each monitoring station are shown in Figures 2-4.

This monitoring was conducted from late November 2017 through late May 2018. However, due to the technical difficulties noted above, temporally paired (contemporaneous) data for all three monitoring locations (three-way paired data) are only available for intermittent periods over the course of the Study (Figures 2-4). Average monthly results for the three-way paired data are presented in Table 7. Results are well below the DAC for radon in equilibrium with progeny as given in 10 CFR 20 Appendix B (equivalent to 30 pCi/L).

Despite temporal gaps in three-way paired data, there is a considerable amount of contemporaneous radon data among all three locations, and these paired data sets were used to perform temporally unbiased statistical comparisons to evaluate differences in radon levels between the three locations (Figure 5). Average ambient outdoor radon gas is highest on top of the LTP (Table 7). Differences in mean and median values between the LTP and other locations (Figure 5) are statistically significant under both parametric and nonparametric testing (p-values < 0.001). Statistical differences between HMC 1-OFF and HMC-5 cannot be inferred by parametric T-test at the 95% confidence level, but non-parametric Wilcoxon Rank Sum (WRS) testing indicates a significant difference in median values.

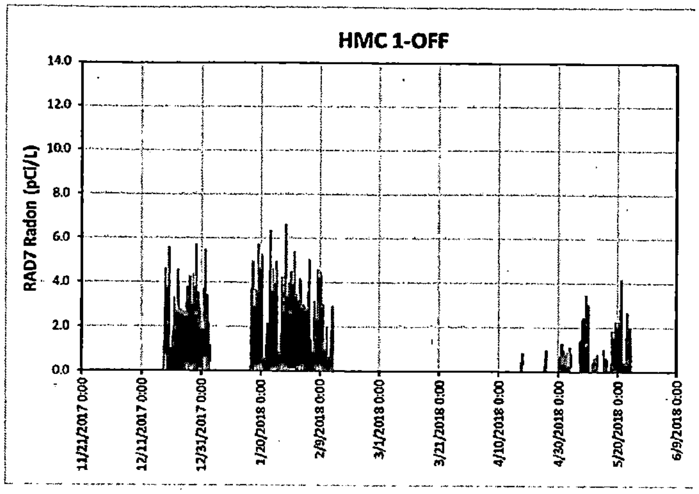


Figure 2: Continuous radon gas monitoring data at HMC-1OFF (upgradient).

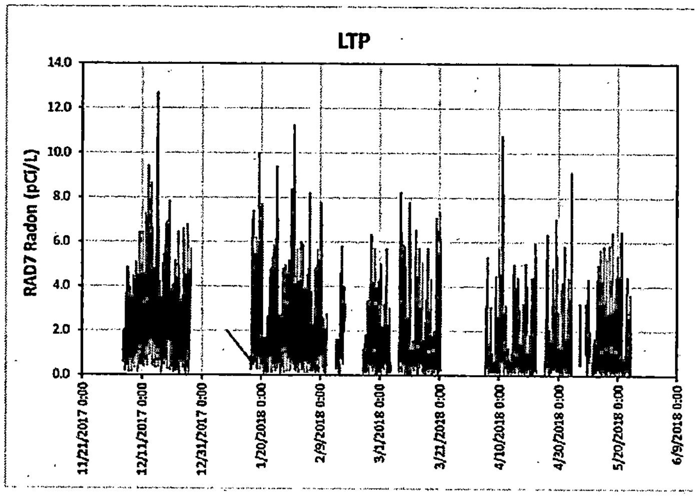


Figure 3: Continuous radon gas monitoring data at LTP.

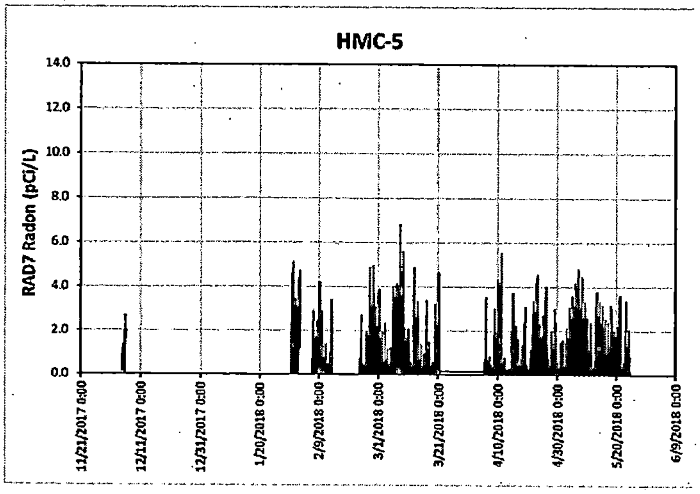
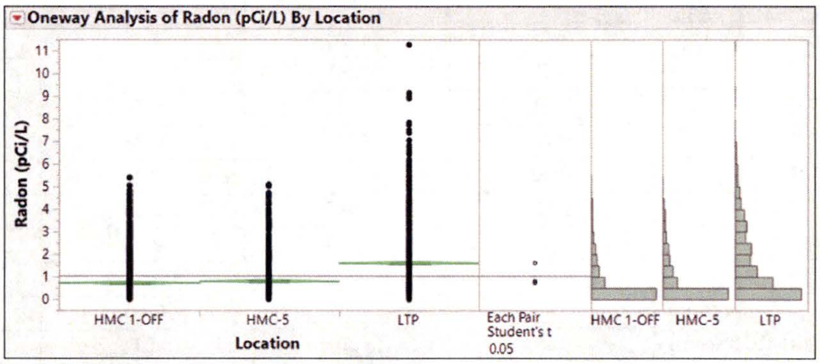


Figure 4: Continuous radon gas monitoring data at HMC-5 (downgradient).

Table 7: Three-way paired continuous radon gas monitoring data.

Month	Dates		Number of Data Points	Radon Concentration (pCi/L)		
	From	To		HMC-1OFF	LTP	HMC-5
2018 JAN	1/30/2018	1/31/2018	70	1.8	3.1	1.8
2018 FEB	2/1/2018	2/11/2018	268	1.2	2.1	1.3
2018 APR	4/17/2018	4/30/2018	89	2.2	1.1	0.4
2018 MAY	5/1/2018	5/24/2018	659	0.5	1.3	0.6
			Average	**0.7**	**1.6**	**0.8**



Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
HMC 1-OFF	1086	0.72164	0.03764	0.6478	0.7954
HMC-5	1088	0.79738	0.03761	0.7236	0.8711
LTP	1086	1.60677	0.03764	1.5330	1.6806

Std Error uses a pooled estimate of error variance

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
LTP	HMC 1-OFF	0.8851281	0.0532371	0.780747	0.9895098	<.0001*
LTP	HMC-5	0.8093855	0.0532127	0.705052	0.9137192	<.0001*
HMC-5	HMC 1-OFF	0.0757426	0.0532127	-0.028591	0.1800763	0.1547

Nonparametric Wilcoxon Comparisons

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value
LTP	HMC 1-OFF	500.9015	26.90815	18.61523	<.0001*
LTP	HMC-5	462.6839	26.91865	17.18823	<.0001*
HMC-5	HMC 1-OFF	63.4508	26.89029	2.35962	0.0183*

Figure 5: Statistical comparisons for three-way paired continuous radon gas monitoring data.

3.6 AIRBORNE RADON PROGENY MONITORING

It is well known that solid-phase, short-lived decay products of radon gas (radon "progeny") are responsible for most of the radiological dose associated with radon. Monitoring of solid-phase airborne radon progeny was conducted with routine grab samples of air collected with a lapel-type BZ air sampler and analysis of respective air sampling filters with the modified Kusnetz method. Progeny measurements were collected twice per day, three days per week at the same locations as the continuous radon gas monitors (RAD7 instruments).

Results, initially expressed in units of Working Level, were converted to the same units of measure as Rn-222 gas (pCi/L) (Table 8). This conversion is known as the radon equilibrium-equivalent concentration (EEC), defined as the concentration of radon in air, in equilibrium with its short-lived decay products, which would have the same potential alpha energy per unit volume as the existing non-equilibrium mixture: 1 Working Level = 100 pCi/L EEC (NCRP, 1987). Estimates of the maximum possible annual inhalation doses from radon progeny at each location were calculated by multiplying the average fraction of the radon progeny DAC (equivalent to 30 pCi/L radon EEC) by 5,000 mrem/year under an assumption of light work and full-time occupational occupancy (2,000 hours/year).

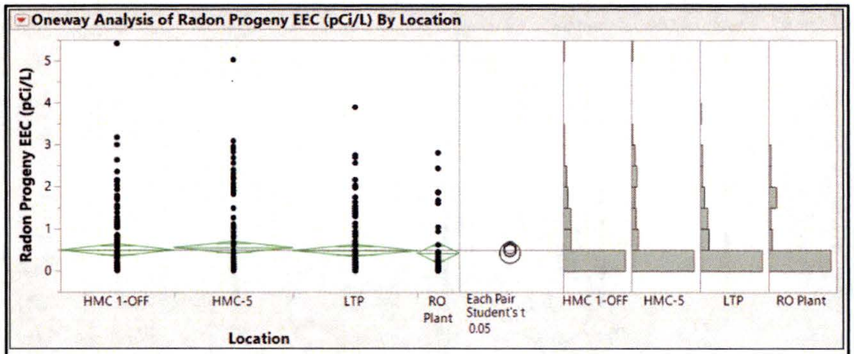
Table 8: Radon progeny equilibrium-equivalent concentration monitoring results.

Month	Average Radon Progeny EEC (pCi/L)			
	HMC-1OFF	LTP	HMC-5	RO Plant
2017 OCT	-	0.49	-	-
2017 NOV	-	0.74	1.76	-
2017 DEC	0.60	0.81	0.57	0.43
2018 JAN	0.71	0.58	0.78	0.88
2018 FEB	0.71	0.66	0.73	0.59
2018 MAR	0.40	0.27	0.29	0.11
2018 APR	0.15	0.17	0.13	0.11
2018 MAY	0.19	0.20	0.24	0.24
Average	0.49	0.48	0.55	0.42
Annual Dose Estimate (mrem)	**82**	**80**	**91**	**70**

The results of radon progeny measurements at HMC-1OFF, the LTP, and at HMC-5, along with indoor progeny levels in the Reverse Osmosis (RO) Plant and relevant statistical comparisons between data sets are shown in Figure 6. Statistical comparison of radon progeny by diurnal sampling period is shown in Figure 7.

Because this Study included continuous monitoring of radon gas with the RAD7 instrument, it is possible to determine the relationship between radon gas and radon progeny (progeny/gas "equilibrium ratios") at paired locations and measurement times. While technical difficulties with RAD7 instruments resulted in temporal data gaps for each monitoring station, there is considerable overlap between available radon gas measurements and radon progeny sampling results, and 190 "paired" radon progeny/gas measurements were identified and used to calculate and statistically compare equilibrium ratios among the three outdoor radon monitoring locations.

Figure 8 shows statistical comparisons for calculated radon equilibrium ratios by location. Figure 9 shows comparisons of radon equilibrium ratios by diurnal sampling period (morning or afternoon). As might be expected, equilibrium ratios of airborne radon progeny on top of the LTP are lower than the other two locations because radon gas from the tailings is "fresh" and free of radon progeny when it is first released to the atmosphere from the soil surface (progeny from the radioactive decay process have not yet "grown in"). Radon equilibrium ratios at HMC-1OFF tend to be significantly higher than the other two monitoring locations, but average values at all stations are relatively low (ranging from 0.17 for the LTP to 0.34 at HMC-5). Across all locations, average equilibrium ratios tend to be significantly higher in the morning hours versus afternoon hours (P-values <0.001).



Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
HMC 1-OFF	120	0.491552	0.07519	0.34376	0.63935
HMC-5	126	0.551773	0.07338	0.40754	0.69601
LTP	133	0.482394	0.07142	0.34201	0.62278
RO Plant	44	0.422806	0.12417	0.17873	0.66688

Std Error uses a pooled estimate of error variance

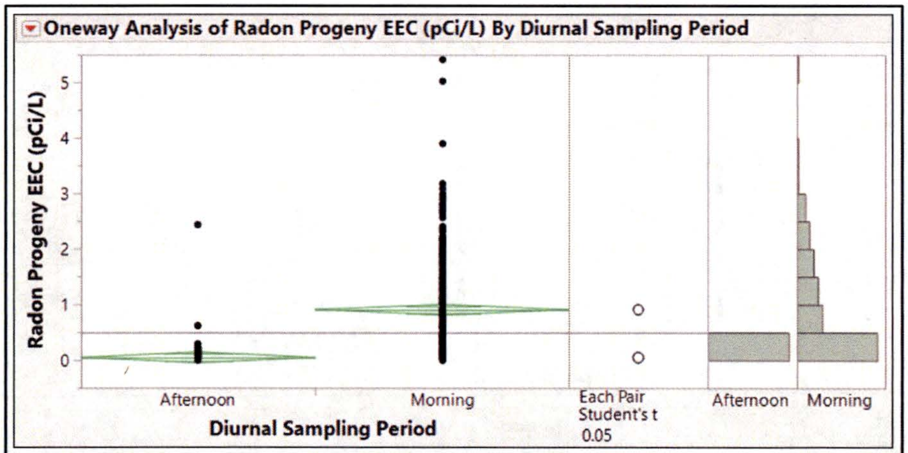
Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
HMC-5	RO Plant	0.1289672	0.1442311	-0.154540	0.4124738	0.3717
HMC-5	LTP	0.0693797	0.1023964	-0.131895	0.2706544	0.4984
HMC 1-OFF	RO Plant	0.0687456	0.1451614	-0.216590	0.3540808	0.6360
HMC-5	HMC 1-OFF	0.0602215	0.1050601	-0.146289	0.2667320	0.5668
LTP	RO Plant	0.0595875	0.1432453	-0.221982	0.3411565	0.6776
HMC 1-OFF	LTP	0.0091581	0.1037027	-0.194684	0.2130004	0.9297

Nonparametric Wilcoxon Comparisons

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value
LTP	HMC 1-OFF	2.599749	9.055433	0.2870928	0.7740
RO Plant	HMC 1-OFF	2.562500	8.249697	0.3106175	0.7561
RO Plant	HMC-5	2.192460	8.514979	0.2574828	0.7968
HMC-5	HMC 1-OFF	1.277183	8.924927	0.1431029	0.8862
RO Plant	LTP	0.680537	8.797622	0.0773546	0.9383
LTP	HMC-5	0.579574	9.169373	0.0632076	0.9496

Figure 6: Statistical comparisons for radon progeny by location.



t Test

Morning-Afternoon

Assuming equal variances

Difference	0.856729	t Ratio	12.5383
Std Err Dif	0.068329	DF	421
Upper CL Dif	0.991037	Prob > |t|	<.0001*
Lower CL Dif	0.722420	Prob > t	<.0001*
Confidence	0.95	Prob < t	1.0000

Nonparametric Wilcoxon Comparisons

q*	Alpha
1.95996	0.05

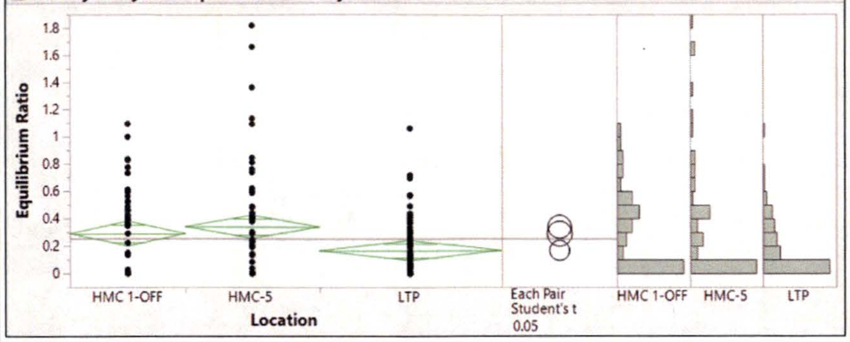
Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value
Morning	Afternoon	162.6355	11.72232	13.87400	<.0001*

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Afternoon	202	0.051855	0.04939	-0.0452	0.1489
Morning	221	0.908583	0.04722	0.8158	1.0014

Figure 7:Statistical comparisons for radon progeny by diurnal sampling period.

Oneway Analysis of Equilibrium Ratio By Location



Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
HMC 1-OFF	51	0.288134	0.04619	0.19701	0.37926
HMC-5	59	0.338937	0.04295	0.25422	0.42366
LTP	80	0.165836	0.03688	0.09308	0.23859

Ordered Differences Report

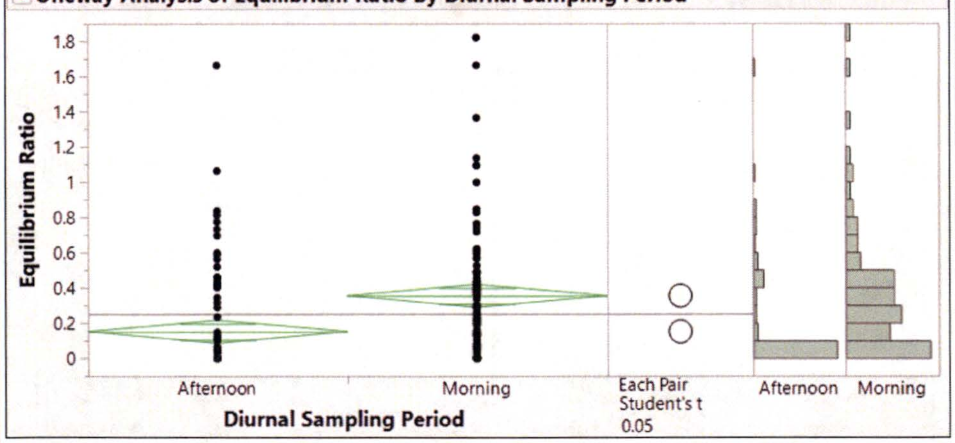
Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
HMC-5	LTP	0.1731004	0.0566086	0.061427	0.2847739	0.0026*
HMC 1-OFF	LTP	0.1222980	0.0591087	0.005692	0.2389036	0.0399*
HMC-5	HMC 1-OFF	0.0508024	0.0630712	-0.073620	0.1752250	0.4216

Nonparametric Wilcoxon Comparisons

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value
HMC-5	HMC 1-OFF	-0.5301	5.871764	-0.09028	0.9281
LTP	HMC-5	-8.0985	6.727344	-1.20382	0.2287
LTP	HMC 1-OFF	-10.1140	6.632661	-1.52487	0.1273

Figure 8: Statistical summary/analysis for radon equilibrium ratios by location.

Oneway Analysis of Equilibrium Ratio By Diurnal Sampling Period



t Test

Morning-Afternoon

Assuming equal variances

Difference	0.202610	t Ratio	4.335239
Std Err Dif	0.046736	DF	188
Upper CL Dif	0.294804	Prob > |t|	<.0001*
Lower CL Dif	0.110416	Prob > t	<.0001*
Confidence	0.95	Prob < t	1.0000

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Afternoon	95	0.151111	0.03305	0.08592	0.21630
Morning	95	0.353721	0.03305	0.28853	0.41891

Nonparametric Wilcoxon Comparisons

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value
Morning	Afternoon	46.80000	7.749600	6.039021	<.0001*

Figure 9: Statistical summary/analysis for radon equilibrium ratios by sampling time.

3.7 INDOOR RADON PROGENY MONITORING

Indoor radon progeny measurements in the RO Plant show that values are low, averaging 0.42 pCi/L radon EEC (see Table 9 and Figure 6 in the previous section). Assuming full-time occupational occupancy of 2000 hours/year in the RO building, this average progeny concentration would result in a dose of about 70 mrem/year, inclusive of natural indoor progeny levels not attributable to RO water treatment operations. This gross radon progeny dose is below the 100 mrem/yr annual dose limit for members of the public and far below the 5,000 mrem/yr occupational dose limit for Site workers.

3.8 GAMMA RADIATION LEVELS ACROSS ROUTINE WORK AREAS

A comprehensive gamma radiation survey was conducted across routine operational work areas at the Site. The results are shown in Figure 10. Significantly elevated gamma radiation fields primarily occur near the edges of Evaporation Pond EP-1 on the STP. There are also small pockets of elevated gamma radiation on top of the LTP.

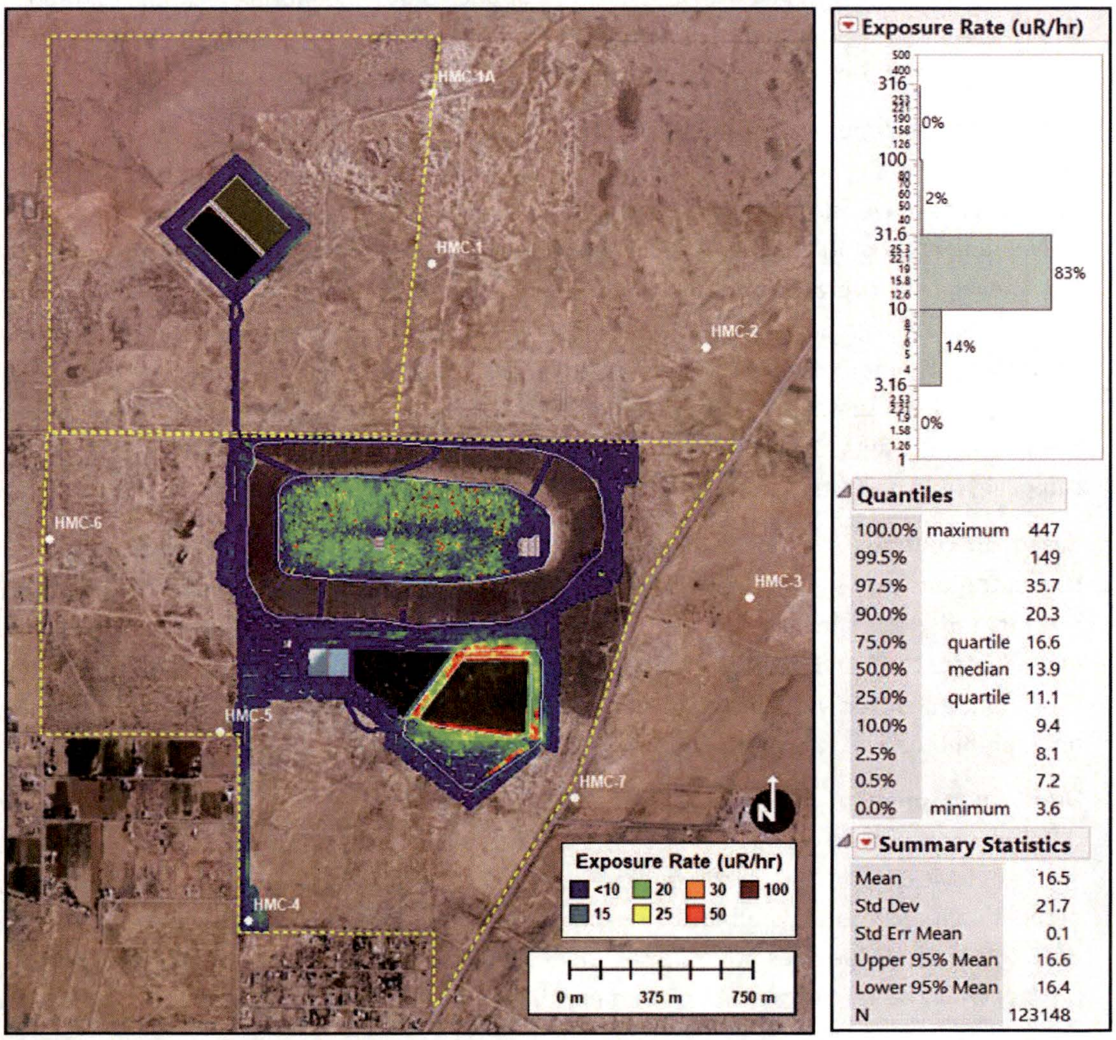


Figure 10: Gamma radiation exposure rates across operational areas of the Site.

4. DISCUSSION

Study results and findings for each of the three Study objectives can be summarized as follows:

1. Characterize potential occupational exposures of workers to internal and external sources of ionizing radiation associated with historic uranium milling activities.

    - The maximum annual occupational dose to workers due to routine reclamation operations at the HMC Grants Site from long-lived radionuclides in airborne particulate matter via the inhalation pathway is on the order of 0.7 mrem CEDE.
    - For non-routine RWP's with higher than normal potential to release airborne particulates, the maximum number of DAC-hours of exposure in any given year is estimated to contribute an additional occupational dose on the order of 29 mrem/yr.
    - The net above-background occupational external dose (in excess of the control badge location) for hypothetical continuous worker exposures at each Study monitoring location, extrapolated to an annualized dose based on 6 months of monitoring data, ranges from 3.4 mrem/yr on top of the LTP to a maximum of 12.8 mrem/yr on top of the STP near the southern edge of EP-1.
    - Radon track-etch monitoring data indicate that the average monthly radon gas concentration on top of the LTP (1.8 pCi/L) is slightly higher than that on top of the STP (1.4 pCi/L), and both tailings piles have slightly higher average monthly concentrations than that measured at downgradient air station HMC-5. Although the data suggest that upgradient station HMC-1OFF has the highest average monthly radon level of all Study locations (2 pCi/L), this result is believed biased high due to two unusually high results at this location. Because the high results at HMC-1OFF were not also reflected in track-etch data at other locations during the same two months, and the same is true for continuous radon gas monitoring with the RAD7 instrument, the two high results at HMC-1OFF are believed attributable to analytical error associated with sampling, transport, storage and/or lab analysis.
    - Based on continuous radon gas monitoring with the RAD7 instrument, ambient radon gas concentrations vary significantly on a diurnal basis (higher levels in the morning hours). Average ambient radon gas concentrations on top of the LTP are slightly higher relative to upgradient air station HMC-1OFF and downgradient air station HMC-5. Average radon gas concentrations at these upgradient/downgradient monitoring locations are not statistically different from one another, but median values are.
    - Direct monitoring of radon progeny over the course of the Study indicate no statistical differences in progeny levels between the LTP, upgradient location HMC-1OFF, downgradient location HMC-5, and inside the reverse osmosis (RO) building. The estimated maximum occupational dose to a hypothetical receptor from radon progeny is 91 mrem/yr at air station HMC-5, but this value does not represent net occupational dose in excess of background, which is expected to be on the order of 82 mrem/yr based on results for station HMC-1OFF. Based on

radon progeny measurement data during this Study, the maximum net occupational dose due to radon progeny at the Site is estimated to be on the order of 10 mrem/yr.

- The average radon progeny/gas equilibrium ratio is lowest on top of the LTP (0.17). This is consistent with expectations for "fresh" radon exhaled from soil cover that serves as an interim radon barrier. The average radon equilibrium ratio is highest at air station HMC-5 (0.34), and the difference in these average values is statistically significant (P-value 0.003). Equilibrium ratios are also significantly higher in the morning hours versus afternoon hours (P-value <0.0001).

2. Provide sufficient data to evaluate the need for routine radiological exposure monitoring relative to regulatory thresholds that require such monitoring as specified in 10 CFR 20.1502.

   - Estimated maximum potential occupational doses at the HMC Grants Site, summarized in Table 9, indicate that routine occupational radiation monitoring is not required a under 10 CFR 20.1502 criteria, amounting to roughly 10% of the 500 mrem/yr threshold that necessitates monitoring of occupational radiation exposures at a NRC-licensed facility. The results of BZ air monitoring indicate that non-routine activities with significant potential for release of airborne particulates represents the largest potential for above-background radiation exposures at the Site, though this potential remains very low relative to occupational dose limits given in 10 CFR 20.1201. Consistent with ALARA principles and associated regulatory requirements, the RSO should continue to evaluate non-routine activities to determine the need for BZ air monitoring under RWP's issued for such work (e.g. contact with tailings, pond residues, zeolite media, etc.).

Table 9: Estimated maximum potential occupational doses based on monitoring Study results.

Dose Pathway	Source	Exposure Type	Dosimetric Quantity	Maximum Annual Dose (mrem)
Inhalation	Air Particulates	Routine Operations	CEDE	1
Inhalation	Air Particulates	Non-Routine RWPs	CEDE	29
Inhalation	Radon Progeny	Routine Operations	CEDE	10*
External Exposure	Gamma Radiation	Routine Operations	EDE	13*

Total Effective Dose Equivalent (TEDE): **53**

*Estimated net (above-background) value attributable to Site operations.

3. Provide additional data on the levels of outdoor radon gas, radon progeny, and radon progeny/gas equilibrium ratios on top of the LTP, at hydrologically upgradient air monitoring station "1-OFF", and at two downgradient air monitoring stations relative to the LTP (Station HMC-5 and a new location "Between" established between the LTP and HMC-5).

   Because routine environmental air monitoring stations do not include a location on top of the LTP, this Study provides valuable information with respect to occupational exposure airborne radiation associated with the tailings piles, including radon gas and progeny levels on the LTP relative to the upgradient station (HMC-1OFF) and downgradient stations (HMC-5 and "Between"). As might be expected, average radon gas levels are slightly higher on top of the LTP relative to upgradient (HMC-1OFF) and downgradient (HMC-5) monitoring locations. Conversely, average radon progeny levels are lower on the LTP as exhaled radon from covered tailings is relatively fresh and progeny have not had time to "grow in" due to the radioactive decay of radon gas. The Study data generally indicate that average radon gas and progeny levels upgradient (HMC-1OFF) and downgradient (HMC-5) from the LTP are statistically indistinguishable from one another, suggesting that radon gas emissions from the LTP have little or no influence on doses from radon progeny near or beyond the boundaries of Controlled Areas of the Site (see Figure 1).

5. CONCLUSIONS

This Study provides direct analytical evidence, based on radiological monitoring over a six-month period, that occupational radiation exposures at the HMC Grants Site are minimal, and the potential for radiological doses to workers is well below the 500 mrem/yr threshold that requires occupational radiation monitoring under 10 CFR 20.1502. Although Study results verify that no activities at the Site warrant occupational radiation monitoring under 10 CFR 20.1502 criteria, higher potential for inhalation exposures was observed for non-routine activities involving work with tailings or zeolite water treatment media. Consistent with ALARA regulatory requirements, the RSO should continue to evaluate the need for personal BZ monitoring for workers involved with RWP's that include exposures to potentially elevated airborne radionuclide levels associated with certain sources (e.g. dry tailings, pond residues, zeolite media, etc.).

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