THESIS

OFF SITE AND BOUNDARY EXTERNAL RADIATION EXPOSURES FROM THE COTTER URANIUM MILL LOCATED IN CAÑON CITY, COLORADO

Submitted by

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ABSTRACT

OFF SITE AND BOUNDARY EXTERNAL RADIATION EXPOSURES FROM THE COTTER URANIUM MILL LOCATED IN CAÑON CITY, COLORADO

Although many of the uranium mills in the United States have been decommissioned, the mill tailings remain and can pose health threats to those living nearby. Many studies have been done showing the relationship between radon exposure and lung cancer development for those living near a uranium mill, but it seems that little attention has been paid to the possible threat posed by exposure to gamma radiation from these tailings piles. Since 1979 the Cotter Uranium Mill in Cañon City, Colorado has been measuring external gamma exposure rates at the fence line, and at several offsite locations including the closest residence and the Shadow Hills Golf Course. These exposure rate measurements were tested against background and it has been shown that exposure rates above background exist at all locations except for the nearest residence. Assuming full time occupancy, the excess dose received by members of the public from these exposure rates do not exceed regulatory limits of 100 mrem/yr except at the entrance road of the mill, which was remediated in 2009. For a hypothetical person living in the area of highest exposure rate above background, their risk of developing a fatal cancer is only increased by 0.43%. These exposure rates were compared against the background values measured by the Cotter Corporation and published in their 2010 Environmental and Occupational Performance Report, ALARA Review and Annual Report on Remedial Action Plan Activities. It was later discovered that the background values published in this report were read from a dosimeter that was kept in lead shielding at an offsite location. This means that the background values are only transit values, and are not

representative of the actual background. As such, a discussion of what justifies an appropriate background measurement as well as its effect on the results of this study are outlined. Lastly, correlation analysis was performed on the exposure rate data to determine if there was an underlying factor effecting all the exposure rates. It was found that a single factor is responsible for 60.28% of the variation in the exposure rates, but the factor affecting the data could not be determined. It was suspected that either precipitation values, cosmic radiation fluctuations, or radium-226 air concentrations may have affected the exposure rates, and, as such, correlation analysis was conducted. It was determined that no correlation exists between any of these variables and the exposure rates measured. The inability to determine the factor contributing to the fluctuation in exposure rates over the years provides opportunity for continued research.

ACKNOWLEDGEMENTS

Special thanks to the employees of the Cotter Corporation for providing me with invaluable information regarding this study and for their diligent responses to my many, many questions. I also owe a debt of gratitude to all those within my department who have supported me and encouraged me throughout this entire process.

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INTRODUCTION

Little published information is available regarding external gamma ray exposures at the boundaries of uranium mills, especially in the USA, as many mills were decommissioned or demolished in the 1970's and 1980's. Prior to 1968 (the year that Colorado became an Agreement State) few, if any, regulations existed that limited external radiation exposures from uranium mills [1]. Consequently, published information on measurements of external radiation exposures at early uranium mill boundaries is not available.

Although uranium is certainly found in the highest concentrations of any other orebody constituents at a uranium mill, it is not the primary contributor to the exposures received from living near such a mill. It is true that uranium is a radioactive element, but the health concerns associated with oral and dermal exposure to uranium appear to be primarily chemical, and not radiological [2]. If appropriate precautions are taken to control concentrations of uranium in the air and water, the main contributors to exposure are radon-222 and radium-226 which are found primarily as milling waste, or tailings.

The proximity of residential and recreational areas to the Cotter Uranium Mill in Cañon City, CO raises concern about the types of exposures people may be receiving. The mill began decommissioning in 2006, but the tailings piles remain on site. Exposure pathways for those living near the mill include ingestion, inhalation and external gamma exposure. While the pathways of ingestion and inhalation contribute much of the dose that people receive from living near the mill, they have been studied in many cases and the health effects of such pathways are known [3] [4] [5]. However, a comprehensive analysis of the potential excess dose that people receive from the mill must also consider the pathway of external gamma exposure.

As such, the Cotter Corporation set up a dosimetry program at the uranium mill to monitor external gamma exposures along the site boundary and at several off-site recreational and residential areas. The results of this dosimetry program are available to the public through the Colorado Department of Public Health and the Environment's website [6]. The objective of this study was to perform further analysis on these results and provide some perspective to the outcome.

Since regulations require operations at the uranium mill to maintain exposures ALARA, it was believed that the exposure rates measured along the site boundary, and in surrounding off site locations, would not exceed background. Since the primary contributor to dose from living near a uranium mill is through the pathways of ingestion and inhalation, it was believed that doses, and excess cancer risk from gamma exposure from the mill would be low.

MATERIALS AND METHODS

Employees of the Cotter Uranium Mill placed dysprosium doped calcium sulfate ($CaSO_4$:Dy) Thermoluminescent Dosimeters (TLD's) at multiple locations around the facility and in several off-site residential and recreational areas. These locations are depicted in Figure 1. The northern boundary of the mill is represented by AS-206, the eastern boundary is represented by AS-202, the southern boundary by AS-203, and the western boundary by AS-204. The entrance road to the mill is represented by AS-209. The offsite areas include the neighborhood of Oro Verde represented by OV, the town of Lincoln Park represented by LP, the nearest residence represented by AS-212, the Shadow Hills golf course represented by AS-210, and the background location represented by CCB.

$CaSO_4$:Dy dosimeters are used for environmental monitoring of gamma exposures and have a sensitivity of 1 μGy to 100 μGy with a typical fade of 8% in 6 months [7] Each dosimeter was double bagged in clear plastic packaging then stapled to a wooden post placed 1 m above the ground. This geometry was intended to help avoid shielding complications. Landauer (Gleenwood, IL) read each dosimeter annually. Table 1 shows the exposure rates measured at each location.

The annual average exposure rates at each location were compared to Cañon City background using a one-tailed (the values are presumed higher than background), heteroscedastic, students t-test [8]. The background values used for the t-test were only considered for the years in which exposure data were collected for the specific location.

An in-depth analysis of the risks associated with these exposures and how they compare to regulatory limits is outlined in the Discussion section of this report.

Next, correlation analysis was used to determine if some underlying factor was affecting all the exposure rates through the years. The correlation analysis was done using the Factor Analysis Procedure in Statistical Analysis Software (SAS) [9]. The input for SAS requires that all variables contain the same number of samples. Since AS-209, AS-210 and AS-212 have significantly fewer samples, they were omitted from the analysis. The data for years prior to 1982 were also omitted so that AS-206 and Oro Verde could be included in the analysis.

Several possible influences on the data were tested against the exposure rates to determine if a specific correlation existed. Variation in exposure rate was compared against precipitation values, cosmic radiation variations, and radium air concentrations. To determine if a correlation exists, exposure rates were plotted against the variable in question and regression lines were fit to the data. The R-squared value of the regression line was used to determine if a correlation between the variable in question and exposure rates existed.

The annual precipitation values for Cañon City were drawn from the Colorado Climate Center database [10]. The weather monitoring station is also identified on the map in Figure 1.

Since some of the weather data were unavailable for certain years during the study, only the years in which definite values of precipitation were measured were used for the comparison. The data set used for this analysis only considered the exposure rates from years for which there were credible precipitation data.

Cosmic radiation fluctuations were drawn from the University of Oulu's On-line Database of Cosmic Ray Intensities [11]. The monitoring station for this data is located in Finland, so the magnitude of the values is not necessarily representative for Colorado, rather it is representative of the relative variability in cosmic ray intensity for Colorado.

Lastly, radium-226 air concentration values are from Cotter's Environmental and Occupational Performance Report, ALARA Review, and Annual Report on Remedial Action Plan Activities for Calendar Year 2010 available from the Colorado Department of Public Health and Environment's website [6].

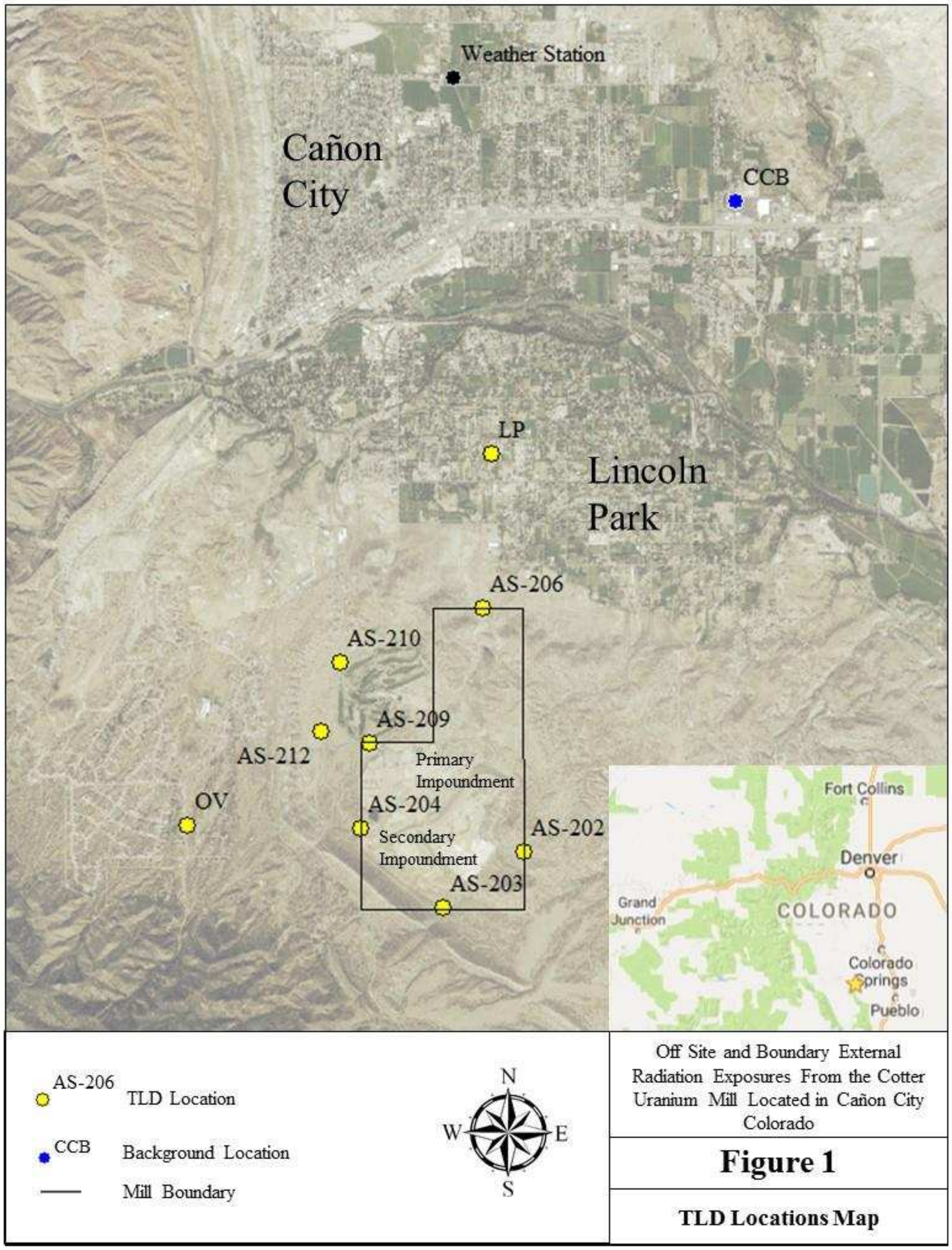

Figure 1: Cotter Uranium Mill area map showing locations of external gamma measurements. The northern boundary of the mill is represented by AS-206, the eastern boundary is represented by AS-202, the southern boundary by AS-203, and the western boundary by AS-204. The entrance road to the mill is represented by AS-209. The offsite areas include the neighborhood of Oro Verde represented by OV, the town of Lincoln Park represented by LP, the nearest residence represented by AS-212, the Shadow Hills golf course represented by AS-210, and the background location represented by CCB.

RESULTS

The results of the dosimetry surveys conducted by the Cotter Corporation are outlined in Table 1 [6]. The highest recorded exposure rate of 30.3 μR/hr was measured at AS-209 in 2002. The lowest recorded exposure rate (excluding background values) of 9.1 μR/hr was measured at AS-212 in 1999.

The p-values produced from the t-test, are outlined in Table 2. All p-values, with the exception of the result for AS-212, resulted in rejection of the null hypothesis

Table 3 and Table 4 show the results of the Factor Analysis amongst the exposure rates at all applicable locations output by SAS. The factor analysis shows that a single factor is responsible for 60.28% of the variability amongst the samples, and that a second factor determines 18.07% of the variability.

The annual precipitation data for Cañon City is outlined in Table 5. The linear relationship between exposure rates and annual precipitation values at the various locations is shown in Figure 2. The strongest correlation between exposure rates and precipitation demonstrated a regression value of 0.19.

Cosmic ray data from Oulu's online database is shown in Table 6. The linear relationship between exposure rates and cosmic radiation variability at the various locations is shown in Figure 3. The strongest correlation between exposure rates and cosmic radiation variability demonstrated a regression value of 0.43.

Air sample data from Cotter's Environmental and Occupational Performance Report, ALARA Review, and Annual Report on Remedial Action Plan Activities for Calendar Year 2010 is shown in Table 7. The linear relationship between exposure rates and radium air concentrations at the various locations is shown in Figure 4. The strongest correlation between exposure rates and air concentrations demonstrated a regression value of 0.36.

Table 1: External gamma exposure rates (in μR/hr) at locations near the Cotter Uranium Mill. Table drawn from Cotter's *Environmental and Occupational Performance Report, ALARA Review, and Annual Report on Remedial Action Plan Activities for Calendar Year 2010*.

Year	AS-202	AS-203	AS-204	AS-206	AS-209	AS-210	AS-212	CCB	LP	OV
1979	14.0	12.6	12.7					11.8	11.4	
1980	13.4	11.7	12.9					10.4	11.4	
1981	14.3	12.8	12.7					10.6	12.3	12.3
1982	13.7	12.6	14.7	20.4				9.9	11.2	12.7
1983	13.6	12.6	14.2	15.6				10.6	11.6	12.0
1984	14.5	14.3	14.6	14.8				12.3	11.2	13.2
1985	14.3	13.5	14.5	14.8				10.5	11.2	12.3
1986	13.9	13.7	14.5	14.2				11.0	10.7	11.8
1987	12.9	12.5	12.6	12.6				9.6	9.7	10.4
1988	15.0	13.6	12.8	13.4				9.3	11.6	10.2
1989	14.7	14.9	15.3	15.9				10.6	13.7	11.9
1990	13.2	13.1	14.8	15.2				9.6	11.5	11.7
1991	14.1	13.2	15.7	17.5				10.0	12.9	12.4
1992	13.7	13.2	16.0	18.3				9.6	12.1	11.3
1993	12.5	12.6	14.4	15.6				8.6	10.7	10.9
1994	14.3	13.8	15.9	16.2	27.8			10.8	12.1	12.3
1995	12.5	13.7	14.0	15.4	23.0			9.2	10.3	11.3
1996	13.1	13.2	14.5	16.2	27.2	13.0		9.7	10.9	11.4
1997	12.6	13.1	13.8	15.7	29.1	12.3		9.1	10.2	11.1
1998	12.3	12.0	13.4	15.9	28.0	12.0		9.0	10.3	11.5
1999	12.7	12.0	13.8	16.0	29.6	12.2	9.1	9.3	10.6	10.9
2000	12.7	12.6	14.7	16.6	27.7	12.5	9.3	9.5	10.7	11.4
2001	13.7	14.3	15.4	18.6	26.2	13.9	9.7	10.4	12.0	12.2
2002	14.0	14.4	15.9	17.7	30.3	14.3	10.5	10.5	12.3	12.6
2003	12.8	13.3	14.8	15.5	27.7	13.3	10.0	10.0	11.7	11.8
2004	13.6	14.1	15.5	14.7	25.5	14.2	10.9	10.5	12.2	12.5
2005	12.8	13.5	14.8	13.8	22.9	12.9	9.9	10.1	11.5	11.5
2006	12.7	13.4	14.6	14.2	21.5	12.6	9.5	10.1	11.5	11.7
2007	12.9	13.2	14.6	14.1	17.8	12.7	9.5	10.1	11.5	11.6
2008	13.9	13.5	15.5	14.9	18.7	13.3	10.2	10.8	12.2	12.6
2009	14.2	14.3	16.1	15.9	19.5	13.7	10.5	11.1	12.7	13.2
2010	14.3	14.6	16.3	15.4	18.9	13.9	10.3	12.2	12.7	13.5

Table 2: Results of statistical tests performed on exposure rate values from Table 1.

Location	Location average (μR/hr)	Background average (μR/hr)	T-test p-value	Reject Null Hypothesis? (H_0: $\mu_1 = \mu_2$)
AS-202	13.5	10.2	4.14 E -24	YES
AS-203	13.3	10.2	2.73 E -22	YES
AS-204	14.6	10.2	6.48 E -26	YES
AS-206	15.7	10.1	5.09 E -20	YES
AS-209	24.8	10.1	3.40 E -11	YES
AS-210	13.1	10.2	3.06 E -11	YES
AS-212	10.0	10.4	0.06	NO
LP	11.5	10.2	7.01 E -08	YES
OV	11.9	10.2	2.30 E -11	YES

Note: p-value tested against $\alpha = 0.05$, at a 95% confidence interval.

Table 3: Pearson Correlation Coefficients; $N = 29$, Prob > |r| under H_0: Rho = 0. The bolded numbers represent the correlation between the location indicated in the column versus the location indicated in the row. The second value represents the probability that the correlation between the two locations is due to chance.

	Year	AS-202	AS-203	AS-204	AS-206	CC Bkgd	LP	OV
Year	1.00000	**-0.26563** 0.1637	0.22940 0.2313	0.40721 0.0283	-0.10126 0.6012	0.10959 0.5714	0.25777 0.1770	0.21680 0.2586
AS-202	-0.26563 0.1637	1.00000	**0.66013** <0.0001	0.40628 0.0287	0.09129 0.6376	0.65407 0.0001	0.67063 <0.0001	0.49444 0.0064
AS-203	0.22940 0.2313	0.66013 <0.0001	1.00000	**0.59797** 0.0006	-0.01918 0.9214	0.69196 <0.0001	0.68186 <0.0001	0.57211 0.0012
AS-204	0.40721 0.0283	0.40628 0.0287	0.59797 0.0006	1.00000	**0.46232** 0.0116	0.55878 0.0016	0.78362 <0.0001	0.75182 <0.0001
AS-206	-0.10126 0.6012	0.09129 0.6376	-0.01918 0.9214	0.46232 0.0116	1.00000	**-0.06400** 0.7415	0.26214 0.1695	0.33115 0.0793
CCB	0.10959 0.5714	0.65407 0.0001	0.69196 <0.0001	0.55878 0.0016	-0.06400 0.7415	1.00000	**0.53138** 0.0030	0.82053 <0.0001
LP	0.25777 0.1770	0.67063 <0.0001	0.68186 <0.0001	0.78362 <0.0001	0.26214 0.1695	0.53138 0.0030	1.00000	**0.59090** 0.0007
OV	0.21680 0.2586	0.49444 0.0064	0.57211 0.0012	0.75182 <0.0001	0.33115 0.0793	0.82053 <0.0001	0.59090 0.0007	1.00000

Table 4: Communality estimates for variation among the exposure data. The bolded values represent the communality among all the data due to a certain, unknown contributing factor.

	Eigenvalue	Difference	Proportion	Cumulative
1	4.21964	2.95485	**0.6028**	**0.6028**
2	1.26478	0.63087	**0.1807**	**0.7835**
3	0.63391	0.16662	0.0906	0.8740
4	0.46729	0.20713	0.0668	0.9408
5	0.26016	0.16569	0.0372	0.9780
6	0.09446	0.03473	0.0135	0.9915
7	0.05972		0.0085	1.0000

Table 5: Annual precipitation data for Cañon City in inches.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1979	0.20I	0	1.19	0.1	1.13I	1.40	0.94	2.28	1.64	0.44	M	M	--
1980	M	M	M	0I	6.57	0	0.19	0.99	1.65	0.60	1.03I	0	--
1981	0.01	0.10	0.99	0	1.13	0.58	3.45	3.19	0.43	0.74	0.10	0.38	11.1
1982	3.5	M	M	M	3.51	2.36	1.96	1.66	2.54	0.31	0.65	0.20	--
1983	0.06	0.12	1.83	0.69	2.09	1.95	1.36	4.32	0.18	0.03	1.53	0.87	15.02
1984	0.20	0.15	1.65	2.88	0.05	1.23	1.78	4.17	M	M	M	0.24	--
1985	0.47	0.74	1.90	2.13	2.36	0	2.08	0.55	2.23	0.62	2.00	0.99	16.07
1986	0.06	0.42	0.69	0.61	0.63	1.76	1.41	1.50	1.66	1.09	1.13	0.56	11.52
1987	0.94	1.45	M	M	2.13I	1.88	0.44	2.11	0.61	0.30	0.47	0.60	--
1988	0.48	0.46	0.68	0.59	1.10	2.37	0.59	0.66	0.70	0.06	0.30	0.69	8.68
1989	0.57	0.96	0.18	0.58	1.04	1.04	1.19	1.35	1.80	0.23	0.02	1.13	10.09
1990	0.43	0.70	1.34	2.34	2.17	0.03	3.84	1.69	1.75	2.12	0.92	0.38	17.71
1991	0.05	0.01	0.16	0.41	0.58	1.36	2.54	3.24	0.57	0.77	1.87	0.28	11.84
1992	0.04	0.01I	1.76	1.06	0.68	1.18	1.58	4.82	0.04	0.12	1.20	0.21	12.7
1993	0.15	0.23	1.05	0.78	2.27	1.47	0.53	1.94	1.24	0.68	0.91	0.23	11.48
1994	0.63	0.06	1.10	1.96	M	M	M	M	M	M	M	M	--
1995	M	M	M	M	M	M	M	M	M	M	0.25	0.06	--
1996	0.61	0.18	0.69I	0.96	1.39	1.06	2.31	4.10	2.02	1.11	0.77	0.39	15.59
1997	0.60	1.82I	0.80	3.06	0.60I	1.59	3.16I	4.44	1.31	1.39	0.87	0.22I	19.86
1998	T	0.69	2.35	1.97	0.14	0.27	2.47	1.77	0.58	1.37	0.66	0.50	12.77
1999	0.09	0.01	0.16	6.44	2.90	0.87	3.96	2.64	0.67	1.06	0.54	0.34	19.68
2000	0.59	0.23	2.67	1.18	1.16	1.07	0.76	T	M	M	M	M	--
2001	M	M	1.09	0.97	2.91	0.14	1.60	2.26	0.80	0.33	0.78	0.14	--
2002	0.77	0.33I	0.57	0.17	0.39	0.49	2.13	0.53	1.26	1.02	0.12	0.20	7.98
2003	0.04	1.28	1.77	0.77	0.84	1.47	1.22	1.24	0.78	0.11	0.35	0.24	10.11
2004	0.94	0.78	0.40	6.83	0.27	1.25	1.88	1.10	1.22	1.18	1.27	0.47	17.59
2005	2.03	0.36I	1.20	0.44	0.42	0.87	0.44	3.09	0.88	0.73	0.20	0.62	11.28
2006	0.56	0.19	0.87	0.80	0.50	0.71	5.99	2.69	M	1.89	0.41	1.16	--
2007	1.12	0.48	0.71	2.33	2.73	0.68	2.74	1.66	0.53	0.27	0.22	1.17	14.64
2008	0.63	0.31	1.05	0.51	0.49	0.78	0.82	2.22	0.12	0.21	0.13	1.29	8.56
2009	0.62	0.07	0.83	1.37	1.50	1.68	3.10	1.92	1.76	1.88	0.62	0.64	15.99
2010	0.19	0.91	2.18	0.59	0.51	0.36	2.13	2.61	0.23	0.27	0.03	0.22	10.23

Key: M: Missing
T: Trace
I: Incomplete (at least 1 days' worth of precipitation data is unavailable)

Table 6: Cosmic radiation data from the University of Oulu's On-line Cosmic Ray Database.

Date (Year.Month.Day)	Time	Fractional Date	Uncorrected Count Rate (counts per minute)	Corrected Count Rate (counts per minute)	Barometric Pressure (mbar)
1979.01.01	0:00:00	1979	5583	5945	1009.08
1980.01.01	0:00:00	1980	5386	5794	1010.3
1981.01.01	0:00:00	1981	5346	5638	1007.82
1982.01.01	0:00:00	1982	5294	5583	1007.68
1983.01.01	0:00:00	1983	5586	5771	1004.96
1984.01.01	0:00:00	1984	5399	5868	1011.99
1985.01.01	0:00:00	1985	5771	6152	1009.01
1986.01.01	0:00:00	1986	5977	6384	1008.55
1987.01.01	0:00:00	1987	5944	6431	1010.25
1988.01.01	0:00:00	1988	5719	6053	1007.21
1989.01.01	0:00:00	1989	5247	5480	1005.52
1990.01.01	0:00:00	1990	5192	5416	1005.43
1991.01.01	0:00:00	1991	5097	5432	1008.32
1992.01.01	0:00:00	1992	5634	5922	1006.32
1993.01.01	0:00:00	1993	5818	6203	1008.61
1994.01.01	0:00:00	1994	5967	6280	1006.61
1995.01.01	0:00:00	1995	6055	6387	1006.41
1996.01.01	0:00:00	1996	5893	6502	1012.34
1997.01.01	0:00:00	1997	6146	6545	1007.57
1998.01.01	0:00:00	1998	6030	6399	1007.11
1999.01.01	0:00:00	1999	5844	6209	1007.15
2000.01.01	0:00:00	2000	5495	5784	1006.32
2001.01.01	0:00:00	2001	5486	5879	1008.56
2002.01.01	0:00:00	2002	5377	5806	1009.89
2003.01.01	0:00:00	2003	5358	5759	1009.15
2004.01.01	0:00:00	2004	5757	6093	1007.1
2005.01.01	0:00:00	2005	5746	6157	1008.68
2006.01.01	0:00:00	2006	6021	6479	1009.31
2007.01.01	0:00:00	2007	6328	6633	1005.9
2008.01.01	0:00:00	2008	6328	6662	1006.85
2009.01.01	0:00:00	2009	6346	6804	1009.51
2010.01.01	0:00:00	2010	6153	6623	1010.19

Note: Corrected count rate refers to raw count data that have been corrected to account for pressure and detector efficiency [11].

Table 7: Radium-226 air concentrations from Cotter's Environmental and Occupational Performance Report, ALARA Review, and Annual Report on Remedial Action Plan Activities for Calendar Year 2010.

Year	AS-202	AS-203	AS-204	AS-206	AS-209	AS-210	AS-212	CCB	LP	OV
1979	1.55E-15	3.75E-16	7.89E-15					3.07E-16		
1980	3.61E-15	7.81E-16	1.62E-15					1.58E-15	2.78E-16	
1981	4.19E-15	2.35E-15	2.94E-15	2.96E-15				4.59E-16	3.79E-16	6.30E-16
1982	6.53E-15	6.92E-15	3.81E-15	3.82E-15				4.02E-16	6.07E-16	1.25E-15
1983	2.00E-15	5.08E-15	4.95E-15	2.85E-15				1.76E-16	9.42E-17	5.30E-16
1984	1.11E-15	1.84E-15	3.63E-15	2.20E-15				1.67E-16	1.18E-16	1.87E-16
1985	9.63E-15	1.11E-15	1.78E-15	1.97E-15				1.88E-16	1.69E-16	1.89E-16
1986	1.47E-15	1.98E-15	1.61E-15	2.60E-15				3.45E-16	1.43E-16	2.22E-16
1987	5.91E-16	7.52E-16	1.19E-15	4.74E-16				1.15E-16	1.83E-16	1.89E-16
1988	1.29E-15	2.05E-15	2.53E-15	3.60E-16				5.09E-17	1.24E-16	1.09E-16
1989	2.72E-16	1.81E-16	3.30E-16	4.79E-17				8.89E-17	1.02E-16	7.77E-17
1990	1.75E-16	1.68E-16	1.92E-16	4.36E-17				8.36E-17	6.69E-17	7.82E-17
1991	1.19E-16	1.25E-16	2.68E-16	6.17E-17				**6.63E-17**	**5.59E-17**	1.37E-16
1992	8.46E-17	7.30E-17	1.50E-15	3.71E-17				**5.27E-17**	**4.85E-17**	1.17E-16
1993	9.11E-17	1.14E-16	2.49E-16	5.99E-17				6.72E-17	6.14E-17	2.20E-16
1994	1.03E-16	7.57E-17	1.69E-16	4.96E-17	1.55E-16			8.68E-17	7.80E-17	2.64E-16
1995	1.21E-16	1.14E-16	2.07E-16	7.46E-17	2.06E-16			1.05E-16	6.88E-17	3.99E-16
1996	1.78E-16	1.02E-16	2.08E-16	5.33E-17	2.11E-16	5.82E-17		6.67E-17	5.22E-17	3.59E-17
1997	1.29E-16	7.55E-17	2.01E-16	5.66E-17	9.45E-16	1.06E-16		5.40E-17	5.09E-17	4.84E-17
1998	2.89E-16	8.22E-17	2.95E-16	9.43E-17	1.34E-15	1.21E-16		6.71E-17	6.21E-17	4.24E-17
1999	4.18E-16	1.29E-16	3.81E-16	1.02E-16	1.26E-15	1.46E-16	2.13E-16	9.21E-17	8.27E-17	5.90E-17
2000	3.37E-16	1.53E-16	4.64E-16	1.40E-16	2.38E-15	2.21E-16	4.60E-16	4.64E-17	7.41E-17	5.10E-17
2001	2.15E-16	2.09E-16	4.36E-16	1.38E-16	1.92E-15	1.51E-16	1.99E-16	6.82E-17	7.01E-17	5.16E-17
2002	1.55E-16	1.17E-16	2.34E-16	7.51E-17	3.83E-16	1.05E-16	1.14E-16	6.07E-17	8.41E-17	6.72E-17
2003	1.45E-16	1.10E-16	1.75E-16	8.02E-17	2.96E-16	1.23E-16	9.65E-17	8.40E-17	9.70E-17	8.93E-17
2004	7.81E-17	7.35E-17	1.41E-16	6.14E-17	3.30E-16	9.05E-17	8.14E-17	6.26E-17	5.79E-17	4.95E-17
2005	1.78E-16	1.56E-16	1.75E-16	1.97E-16	2.29E-15	2.49E-16	2.95E-16	1.22E-16	1.08E-16	9.58E-17
2006	4.10E-16	1.40E-16	2.17E-16	1.34E-16	7.52E-16	1.69E-16	1.42E-16	1.03E-16	1.20E-16	1.15E-16
2007	8.67E-16	1.11E-16	2.07E-16	1.00E-16	2.31E-16	1.16E-16	9.11E-17	9.66E-17	1.09E-16	1.11E-16
2008	7.92E-16	7.36E-17	2.00E-16	5.16E-17	1.78E-16	7.33E-17	5.71E-17	5.91E-17	6.21E-17	3.28E-17
2009	2.68E-16	8.08E-17	1.38E-16	5.48E-17	9.63E-17	6.62E-17	5.34E-17	6.63E-17	6.05E-17	3.32E-17
2010	1.45E-16	7.21E-17	2.51E-16	4.26E-17	1.11E-16	4.21E-17	7.28E-17	4.10E-17	4.00E-17	2.70E-17

Note: Bolded values represent the average of two values for the same location during a single year.

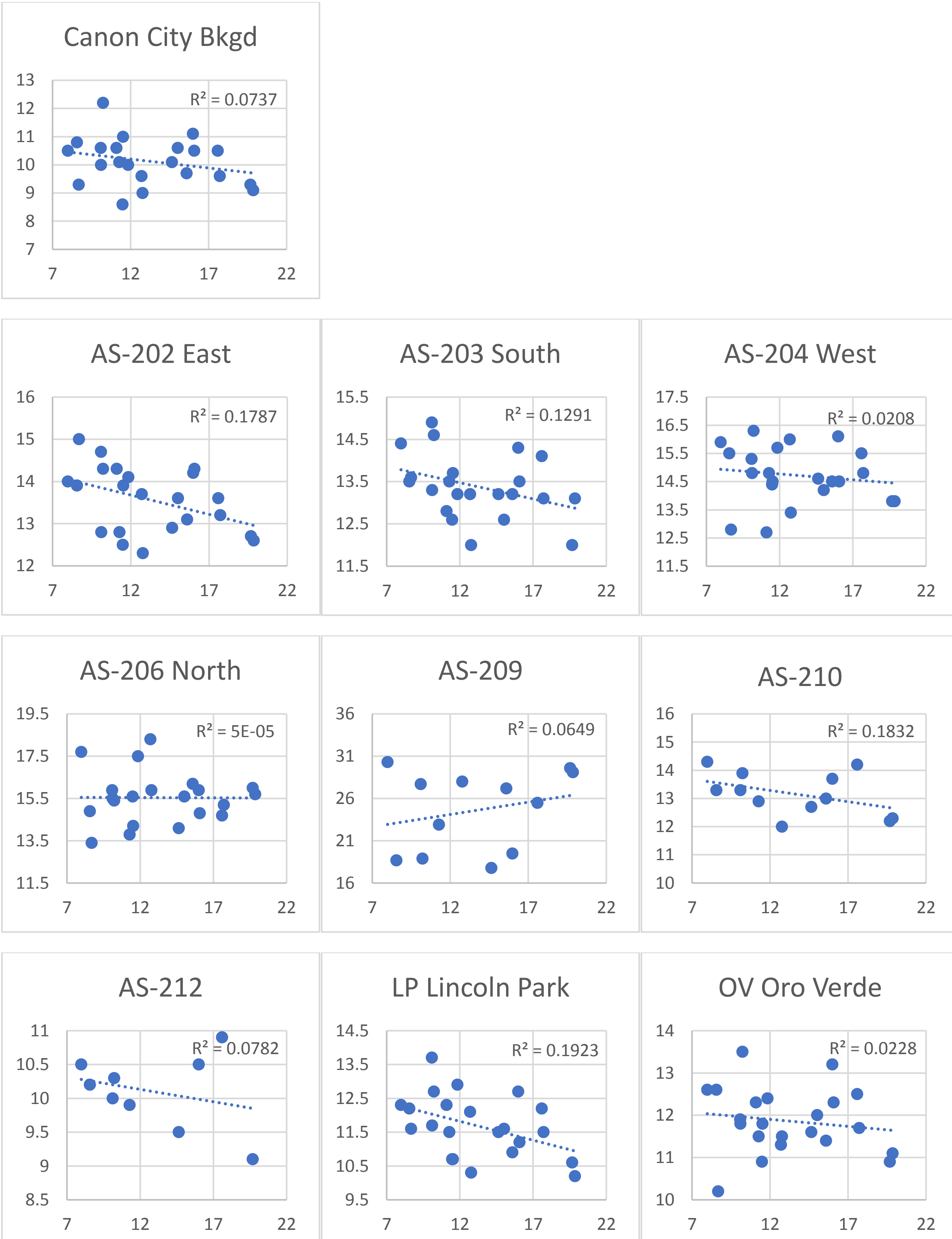

Figure 2: Correlation analysis for exposure rates against precipitation. Exposure rates are plotted along the y-axis in units of μR/hr and precipitation is plotted along the x-axis in units of inches. R-squared values are determined for a linear fit.

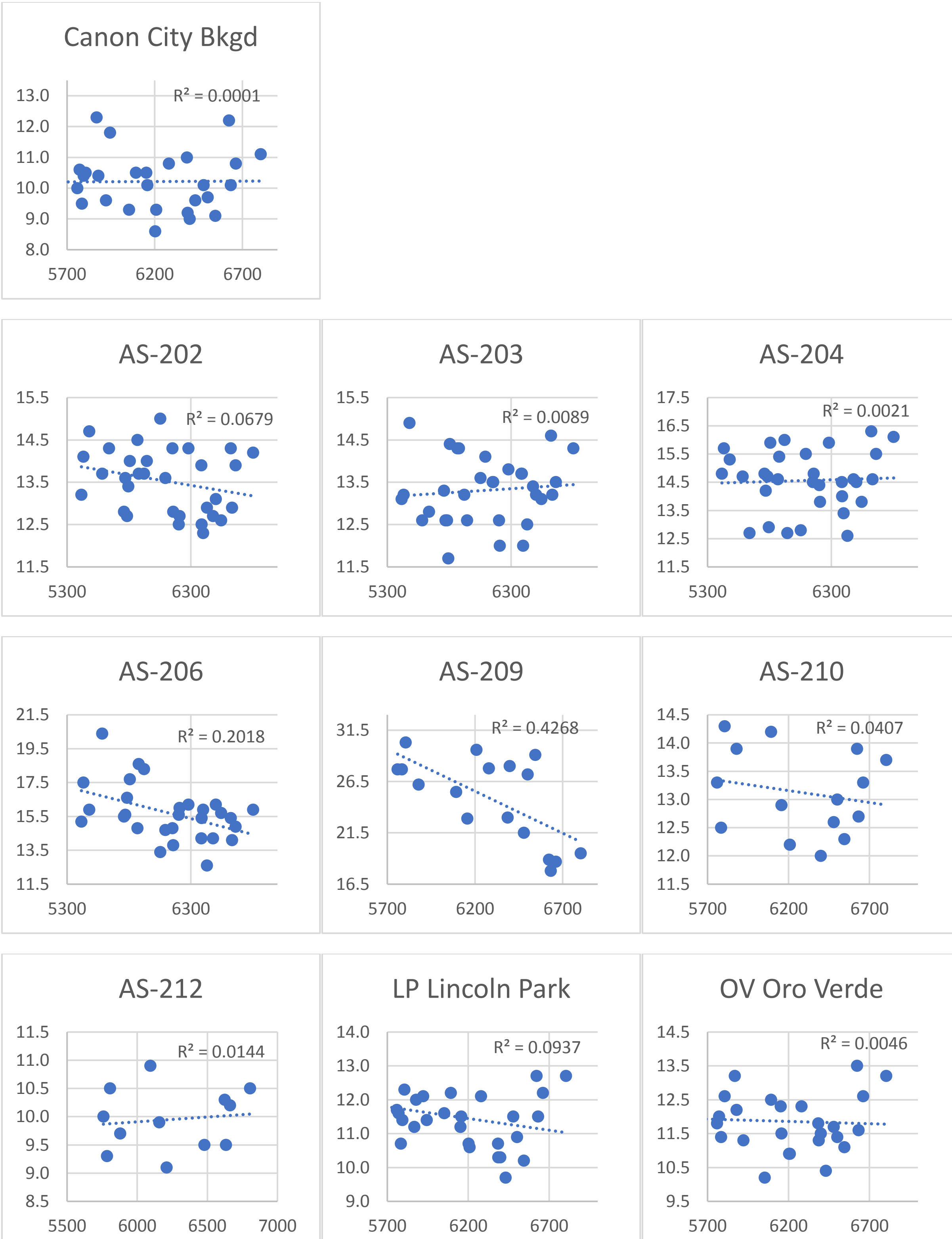

Figure 3: Correlation analysis for exposure rates against cosmic radiation values. Exposure rates are plotted along the y-axis in units of µR/hr and pressure and efficiency corrected cosmic radiation count rates are plotted along the x-axis in units of counts per minute.

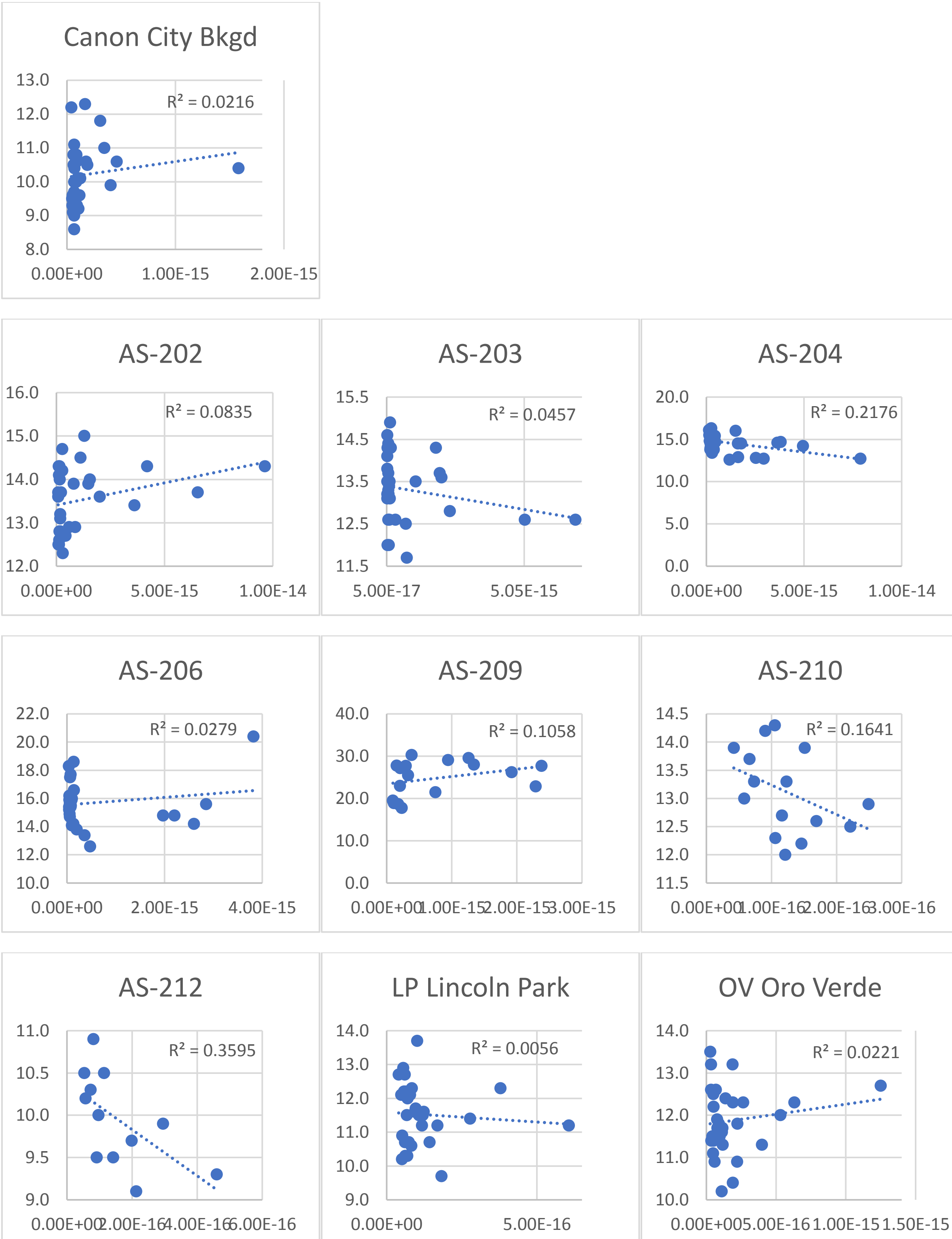

Figure 4: Correlation analysis for exposure rates against radium-226 air concentrations. Exposure rates are plotted along the y-axis in units of µR/hr and the average annual radium-226 air concentration is plotted along the x-axis in units of µCi/ml.

DISCUSSION

Background

Background plays an important role in any/all health physics studies. It is a measure of the ambient radiation present due to naturally occurring radioactive materials, cosmic radiation, or anthropogenic sources [12]. This study aims to compare ambient gamma exposures at several locations near the Cotter Uranium Mill to background. The monitoring locations and background reference for this study were selected by employees at the Cotter Uranium Mill in 1979. Upon recent consultation with Cotter employees, it was discovered that the TLD used to determine the values for Cañon City Background, presented in Table 1, was kept in lead shielding at an offsite location. This means that the background exposure rates provided in Table 1 are only transit values (representing the exposure that they received as they traveled through the postal service to the site) and are not representative of the background for Cañon City. A more appropriate background reference would need to consider the local geology, weather patterns, and mill production rates and activities.

The location of a uranium mill is typically dictated by proximity to a uranium ore deposit which, naturally, would cause a higher background measurement for the area [13]. Additionally, Colorado front range ores typically localize in narrow sections making it possible to observe dramatic changes in short distances [14]. It's possible that each TLD is placed above a different soil type or soil composition and to accurately represent the background a different measurement would need to be considered for each sample location. Having several different background references based on the specific present soil types would greatly increase the validity of the background comparison.

Wind patterns could also help determine the location of a suitable background reference. A TLD placed upwind and out of range of the sample set could sufficiently illustrate the background exposures without being affected by the presence of the mill. This is the case for the location of the background measurement, but since the TLD was held in shielding it cannot be considered representative of background.

Ideally, the background measurements would have been taken before the installation of the mill, or soil sampling could have allowed for proper characterization of the local geology and background locations could have been selected based on the results of such samples. Even though the background values reported by Cotter do not provide much location specific information about the background exposures, they were published as background exposure rates and the objective of this study is to perform further analysis on the information provided to the public by the Cotter corporation. While it is not believed that these background values are representative, they were presented as such by the Cotter Corporation, so for the following analysis the exposure rates were compared against these values.

Data Analysis

Exposures Against Background

As shown in Table 2, there is no statistically significant difference between the background exposure rates and the exposure rates observed at AS-212 (the nearest residence). There were, however, statistically significant differences between the background exposure rates and the exposure rates measured at all other locations.

The exposure rates at the nearest resident may not show statistically significant differences from background for several reasons. It is possible that the nearest residence could be located on a different geologic unit from the other samples. If, for example, the residence is built on the bedrock or in an area with different soil types from the surrounding locations, it is possible that the readings could be lower in this location.

Additionally, the lower exposures could be caused by wind patterns in this area. Figure 5 displays wind data for the Cañon City area for 2010 [6]. It is shown that winds for 2010 were predominantly westerly (51% of the time) which could explain the difference in exposure rate at the nearest residence assuming the wind pattern for 2010 is representative of wind patterns for all years of the study [6] [15]. Winds may have prevented dust from the tailings from migrating to this location and effectively reduced exposure. However, wind patterns do not explain how exposure rates at

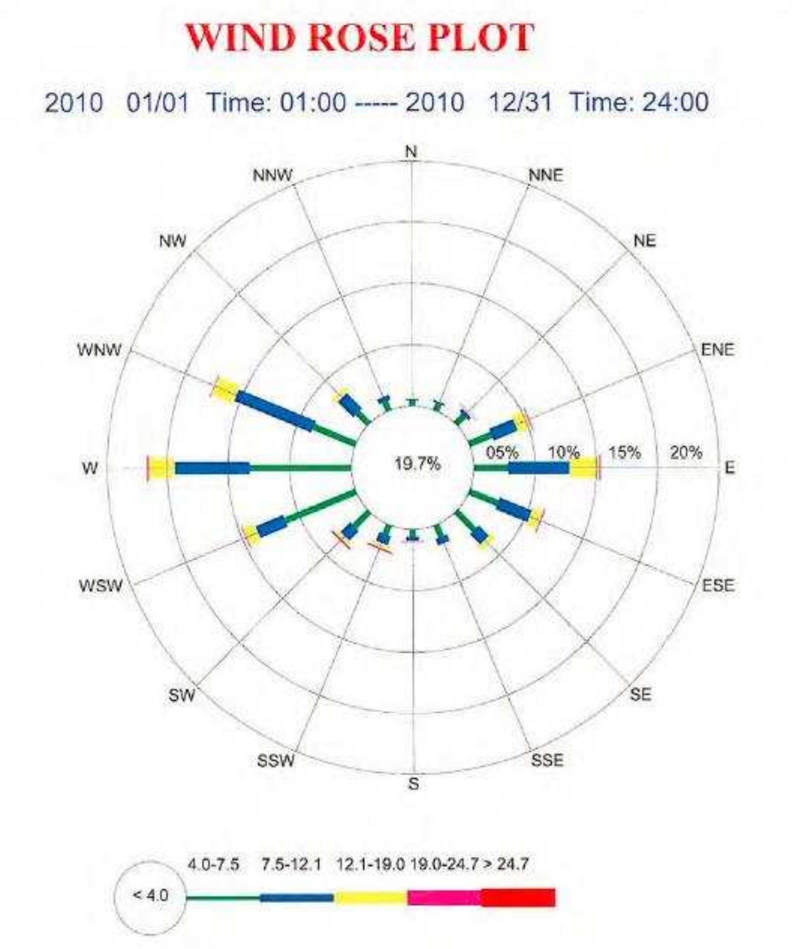

Figure 5: Cañon City wind rose for 2010 [6].

AS-210 and OV, which are also located west of the facility, were measured above background while exposure rates at AS-212 showed no significant difference from background.

Dose Analysis

Following the comparison to background, it seemed appropriate to convert these exposure rate measurements to dose to continue with different forms of analysis. For analysis of gamma measurements, the roentgen and the rem are considered equal for safety purposes [12] [16]. Table 8 shows the excess dose received at the measurement locations assuming full-time occupancy for a year.

Table 8: Excess dose received at locations with exposure rates different from background.

Location	Average excess exposure rate observed (μR/hr) (Exposure Rate- Background)	Excess annual dose from full time occupancy (mrem/yr)
AS-202	3.3	29.04
AS-203	3.1	27.12
AS-204	4.4	38.10
AS-206	5.6	49.05
AS-209	14.7	128.77
AS-210	2.9	25.40
LP-1	1.3	11.38
OV-3	1.7	14.89

Note: For gamma measurements, μR and μrem were considered equal [16].

Although the exposure rates measured did exceed background, all, except AS-209, were below regulatory excess dose limits for members of the public (100 mrem/year or 11.4 μR/hr). The regulatory dose limit of 100 mrem/yr for general public exposure applies to all exposure pathways, including ingestion, inhalation, and external gamma. AS-209 exceeds the regulatory limit when considering only external gamma doses prior to decontamination (assuming full time residence).

AS-209 is the entrance road to the Cotter Uranium Mill. Exposure rates measured at this location are elevated due to spilled ore material from historical activities at the site. The entrance road to the mill was remediated in 2009 even though extensive studies showed no impact on public health or lack of regulatory compliance [17]. It is important to remember that the excess dose was calculated assuming full time occupancy, so even if a member of the public found themselves in this area for a short period, it was not likely that they would meet the dose limit for members of the public.

Considering that these doses are excess, it seemed prudent to determine the excess cancer risk imposed on a hypothetical person occupying an area with such an exposure rate for 24 hours a day, 7 days a week for 50 years (lifetime commitment period from ICRP 103) [18]. To illustrate the best and the worst-case scenario, the lowest and the highest exposure rates were used to determine an associated excess fatal cancer risk.

The lowest exposure rate observed in this study was 9.1 μR/hr found at AS-212. Since this value is below the background value, the best-case scenario regarding excess fatal cancer risk is that the increase in risk from this exposure is 0%, or that there is no excess risk of developing a fatal cancer.

The highest exposure rates observed in this study were found at AS-209, the north entrance road to the mill, at 19.8 μR/hr above background. Over the course of 50 years (assuming full-time occupancy), 19.8 μR/hr equates to 8.672 rem. According to the Health Physics Society, risk assessments for doses less than 10 rem, should be considered cautiously, because in some cases at this level the lower bound of the uncertainty of such estimates extends to zero, meaning that there is possibly no risk associated with such doses [19]. However, to proceed with the analysis, the nominal probability coefficient for developing a fatal cancer is 5.0 x 10^{-2} Sv^{-1} or 5.0 x 10^{-4} rem^{-1} [12]. This means that a person who is exposed to 8.672 rem has an increased chance of developing cancer of 0.43%.

Correlation Analysis

The correlation analysis revealed that 60.28% of the variation in the data was caused by a single factor. However, the correlation analysis could not reveal the underlying factor affecting the data. Several factors considered to have a possible effect on the exposure rates were precipitation values, cosmic radiation fluctuations, and radium air concentrations. Correlation analysis was performed for each variable, and the outcomes of the analysis are shown in Figures Figure ***2***-Figure ***4***. Each set of data was fit with a linear trendline, and the strongest coefficient of determination for each set of data was 0.19 for precipitation values, 0.43 for cosmic radiation fluctuations, and 0.36 for radium air concentrations, indicating that no significant relationship between the factors and the exposure rates exists.

Other factors may be influencing the exposure rates read by the dosimeters, including the impact of fading, but it is not currently possible to identify the exact cause of this correlation. Future research might focus on comparing the amount of ore processed during a given year to the exposure rates. However, the Cotter Corporation was unable to provide this information for this study.

CONCLUSION

Since regulations require operations at uranium mills to maintain exposures ALARA it was believed that the exposure rates measured at the boundary of the mill, and at surrounding off site locations, would not exceed background. Exposure rates were found to be greater than background at all locations other than the nearest residence. Even though the exposure rates were measured above background, only one unoccupied location ever exceeded the regulatory dose limit (assuming full time occupancy) of 100 mrem/year for general public exposure and has since been remediated. The excess cancer risk from external gamma exposure for someone living near the mill is <1%. However, the Health Physics Society advises that this risk assessment be considered cautiously because the dose is small (less than 10 rem).

It was discovered that 60% of the variability in the data could be explained by a single factor. In attempting to identify this factor, it was realized that precipitation values, cosmic radiation fluctuation, and radium air concentrations do not have a strong relationship with the exposure rate measurements. Correlation analysis revealed that 60% of the variation among the tested locations was due to a single factor, but that factor has yet been identified, providing opportunity for further research.

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