Project Summary Report

Pre- and Post-Rehabilitation Source Reduction Modeling and Radiometric Surveys

U.S. Department of Energy Office of Legacy Management
GRAND JUNCTION REGIONAL AIRPORT
CALIBRATION PADS REHABILITATION PROJECT

Revision 0

December 2017

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U.S. Department of Energy Office of Legacy Management

GRAND JUNCTION REGIONAL AIRPORT CALIBRATION PADS REHABILITATION PROJECT

Prepared for:

Navarro Research and Engineering, Inc

Contractor to the U.S. Department of Energy
Office of Legacy Management
2597 Legacy Way
Grand Junction, CO 81503

Prepared by:

Amec Foster Wheeler Environment & Infrastructure, Inc.

Radiological Services & Engineering
2275 Logos Court, Suite A
Grand Junction, Colorado, 81505

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Signature Page

Written by:

Robert G. Posner, Manager
Advanced Measurement Technology Group
Radiological Services & Engineering
Amec Foster Wheeler Environment & Infrastructure, Americas

Digitally signed by Robert.Posner
Date: 2017.12.04 18:01:59 -07'00'

Reviewed by:

Jeffrey W. Lively
Program Manager | Chief Scientist
Radiological Services & Engineering
Amec Foster Wheeler Environment & Infrastructure, Americas

Jeffrey.Lively
I have reviewed this document
2017.12.04 18:04:17 -07'00'

Issued by:

Jeffrey W. Lively
Program Manager | Chief Scientist
Radiological Services & Engineering
Amec Foster Wheeler Environment & Infrastructure, Americas

Jeffrey.Lively
This report is approved for issue as FINAL Report
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Acronyms and Abbreviations

Cal Pads ... Calibration Pads
cc .... cubic centimeter
Ci .... Curie
cm .... centimeter
cps .... counts per second
Cs .... cesium
DOE .... U. S. Department of Energy
g................ gram
GPS .... Global Positioning System
HPIC .... highly pressurized ionization chamber
K .... potassium
keV............ kiloelectron-volt
m............... meter
MeV .... megaelectron-volt
m/s............ meters per second
NaI .... sodium iodide
pCi .... pico-Curie
Ra .... radium
ROI .... region of interest
SRCs .... Series Response Checks
Th.............. thorium
U .... uranium
μR/h .... microRoentgen per hour

1. EXECUTIVE SUMMARY

The Grand Junction Regional Airport Calibration Pads (Cal Pads) are a collection of five 30'x40' concrete monoliths, 18" thick, each containing known and uniform concentrations of naturally occurring radioactive materials. The Cal Pads were designed and constructed to provide traceable reference calibration standards for aerial radiation measurements. Over time, the surfaces of the Cal Pads have weathered and deteriorated to various degrees, causing spalling of the concrete at the surfaces. The degree of deterioration that had occurred prompted the DOE to initiate the *Grand Junction Regional Airport Calibration Pads Rehabilitation Project*. The surface rehabilitation project removed approximately 4-5 cm of active source material from the surfaces of the Cal Pads. This project summary report details the impacts of the completed rehabilitation process on the radiometric characteristics of the Cal Pads.

Due to the large magnitude of the observed uncertainties in radiometric measurements collected on the Cal Pads relative to the minor impacts of the rehabilitation process on the Cal Pads, both empirical and theoretical (calculated) methodologies were implemented to quantify the impacts of the rehabilitation process on the radiometric characteristics of the Cal Pads. The calculated method involved utilizing gamma radiation transport modeling software to produce a mathematical model which estimated the effects of the rehabilitation process on the gamma ray fluxes produced directly above the Cal Pads. The empirical method involved collecting a robust suite of radiometric measurements on each of the Cal Pads and the surrounding area, both prior to, and upon completion of, the rehabilitation process.

The calculated reduction in the gamma fluxes due to the surface rehabilitation process on the Cal Pads is negligible given the depth of the surface veneer removed. The greatest calculated reduction in the gamma fluxes up to 1 m directly above any of the Cal Pads is less than 1% (~0.6%). Such minute variations in gamma fluxes would be extremely difficult to measure confidently, even in highly controlled laboratory conditions.

The radiometric measurements collected before and after the removal of the incompetent surfaces of the calibration pads confirm that the measurable radiometric characteristics of the Cal Pads remain essentially unchanged. The uncertainty in the radiometric measurements, resulting from the diurnal and seasonal variability in uncontrollable environmental factors, is evident in the controlled radiometric field measurements, and is considerably larger than the calculated difference.

Strong temporal correlations between variances in measured radiometric results and variances in barometric pressure and relative humidity were observed. While environmental factors clearly have an obvious impact on the measured results, such correlations are simply not mathematically consistent and cannot, therefore, be used to “normalize” results to account for the inherent, uncontrollable diurnal and seasonal variability of environmental parameters.

The impact of the rehabilitation process on the radiometric characteristics of the calibration pads is so small that it cannot be reliably detected or measured. The existing DOE document, *Field Calibration Facilities for Environmental Measurement of Radium, Thorium, and Potassium* (DOE 2013), will be revised in the following manner:

“The Grand Junction Airport Calibration Pads underwent a rehabilitation process in 2017 which removed the top 4-5 cm of source material from each pad. The loss of gamma signal that resulted from this process is negligible (less than1%). This loss of signal is insignificant given the variances observed due to atmospheric conditions (up to 16%). Consideration should be given to the environmental and atmospheric conditions when utilizing the Calibration Pads.”

2. INTRODUCTION

The Grand Junction Regional Airport Calibration Pads (Cal Pads) are a collection of five 30’x40’ concrete monoliths, 18” thick, each containing known and uniform concentrations of naturally occurring radioactive materials (Figure 2-1).

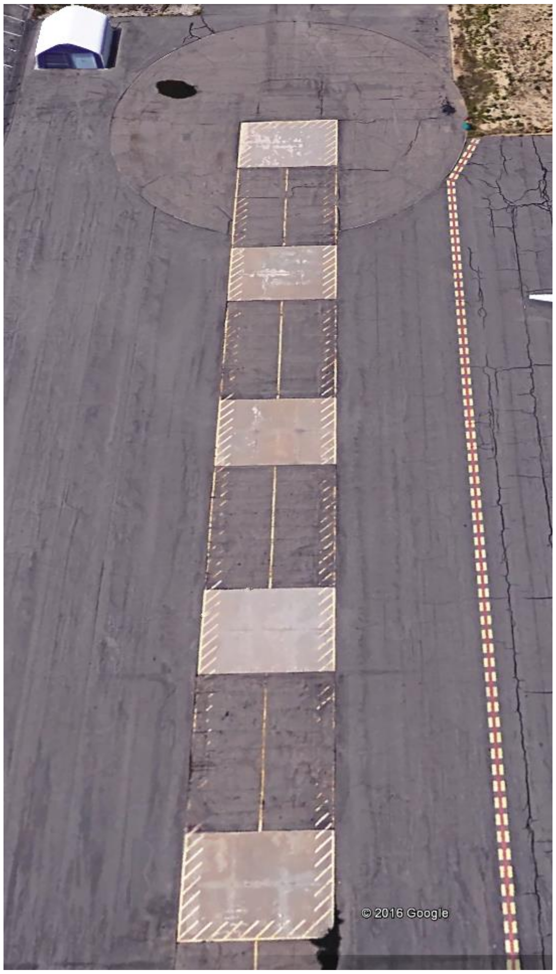

Figure 2-1. Grand Junction Regional Airport Calibration Pads, Before Rehabilitation

The Cal Pads were constructed in 1976 as a resource to calibrate airborne gamma spectrometer systems. The Cal Pads are maintained by the U.S. Department of Energy’s (DOE) Office of Legacy Management and are located at the Grand Junction Regional Airport in Grand Junction, Colorado (Figure 2-2).

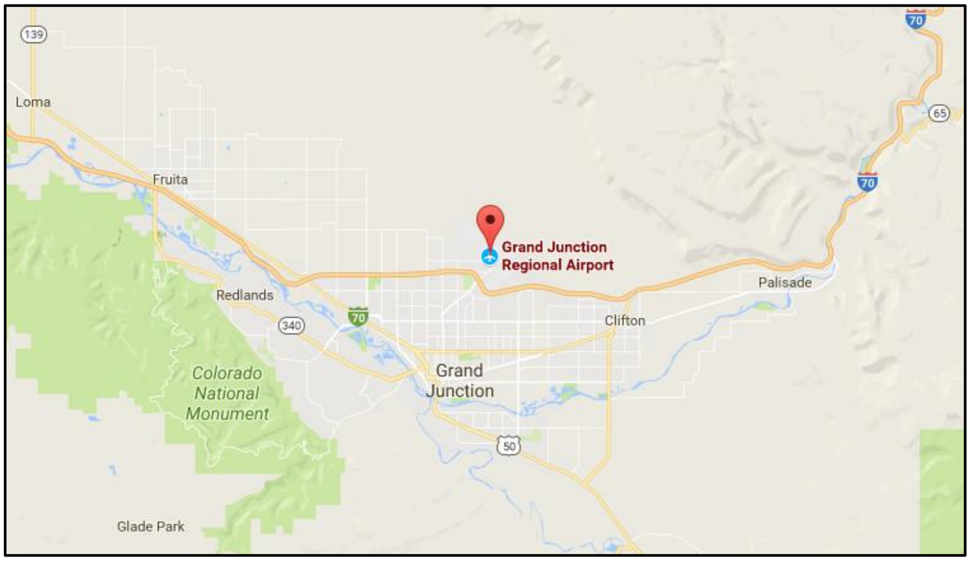

Figure 2-2. Grand Junction Regional Airport Location

Over time, the surfaces of the Cal Pads have weathered and deteriorated to various degrees, causing spalling of the concrete at the surface of the monoliths. The spalling of the surfaces is visually evident in Figure 2-3. The concrete chips that have spalled are a potential hazard to aircraft that utilize this portion of the airfield, and the voids left behind have led to a (slightly) non-uniform geometry of the surface of the Cal Pads.

Figure 2-3. Spalling at Surface of Cal Pads

The degree of deterioration that had occurred prompted the DOE to initiate the *Grand Junction Regional Airport Calibration Pads Rehabilitation Project*. This project summary report details the impacts of the completed rehabilitation process on the radiometric characteristics of the Cal Pads.

3. CALIBRATION PAD REHABILITATION PROCESS

Each Cal Pad was ground and milled to remove the spalled surface, leaving mechanically competent concrete at the new surface. The depths of surfaces removed are presented in Table 3-1. The rehabilitated surface of Pad W5 is shown in Figure 3-1.

Pad #	Thickness Removed [cm]
W1	3.8
W2	4.1
W3	4.6
W4	3.8
W5	3.8

Table 3-1. Depth of Surfaces Removed from the Cal Pads

Figure 3-1. Rehabilitated Surface of Cal Pad W5

In addition to the rehabilitation of the Cal Pads themselves, the asphalt surrounding the Cal Pads was also the surface of the asphalt was milled and replaced. Localized areas that were not directly adjacent to the Cal Pads required full-depth replacement of the asphalt due to the degree of deterioration that had occurred.

4. CONCEPTUAL APPROACH

Ideally, an entirely empirical approach could be developed to quantify the impacts of the rehabilitation process on the Cal Pads. However, due to the large magnitude of the observed uncertainties relative to the [presumed] minor impacts of the rehabilitation process on the Cal Pads discussed in Section 0, both empirical and theoretical methodologies were implemented. The calculated (theoretical) method allows the impact to be assessed in a way that isolates the changes to those strictly limited to the changes in the depth of the surface of the Cal Pad removed, controlling for all other variables. The calculated method produces precise and reproducible quantifications of the changes in gamma fluxes directly above the Cal Pads due to the reduction of source term (removal of surface). The empirical method is used to corroborate the calculated method; however, it is susceptible to confoundment from the uncontrollable environmental factors.

The calculated method involved utilizing software to produce a mathematical model which estimated the effects of the rehabilitation process on the gamma ray fluxes produced directly above the Cal Pads. Each of the Cal Pads was modeled with the appropriate concentrations of the radionuclides of interest to the as built depth of 18”, and the theoretical gamma flux at various heights above the surface was calculated. The depth of the source term (i.e. depth of the Cal Pad) was reduced incrementally, and the resulting gamma fluxes were calculated and compared to the as-built condition.

The empirical method involved collecting a robust suite of radiometric measurements on each of the Cal Pads and the surrounding area, both prior to, and upon completion of, the rehabilitation process. These measurements were collected utilizing the same instruments and methods in the pre- and post-rehabilitation surveys and are detailed in Section 0. Additionally, environmental factors that have the potential to influence sensitive radiometric measurements were recorded simultaneously in order to analyze the influences of these factors on the resulting measurements.

5. GAMMA RADIATION SOURCE REDUCTION MODEL

To assess the potential impact of reducing the thickness of the source of the Cal Pads on the resulting gamma radiation signal, a gamma radiation attenuation model was used to perform a series of calculations. The MicroShield® gamma transport and radiation shielding software was used to perform the calculations (Grove 2014). For each of the Cal Pads, a series of modeling runs (termed "cases") were created holding all parameters other than the parameter of interest (thickness of the Cal Pad) constant. In this way, by comparing each case to a baseline case (no surface removal), the impact of the depth of Cal Pad removed on the gamma radiation signal was evaluated.

A. MODEL CONFIGURATION

The MicroShield® modeling case was set up with the following key parameters:

Pad Designation		Initial Concentration* (pCi/g)		
		Ra-226	Th-232	K-40
Background Pad	W1	0.82	0.67	12.67
Potassium Pad	W2	1.92	0.87	45.58
Thorium Pad	W3	1.7	4.92	17.07
Radium Pad	W4	12.07	1.04	17.56
Mixed Pad	W5	8.36	1.91	34.68

*Initial concentrations decayed for 40 years to produce the current radionuclide concentrations in the Cal Pads

Table 5-1. Source Reduction Modeling Radionuclide Parameters

- Initial Source Geometry – 30'x40', 18" thick, uniform radioactivity distribution.
- Radioactivity
  - As built source radioactivity decayed for 40 years
  - Gamma data library: Grove (default)
  - Group method: Standard Indices
  - Photons less than 0.015 MeV included
  - Buildup included
  - Radioactivity concentrations in the Cal Pads remained fixed while the total radioactivity in the Cal Pads diminished incrementally as the thickness of the pad was reduced.

- Shield material
  - Air
  - Infinite slab (covers entire survey area with a uniform thickness)
  - Density = 0.00122 g/cc.
- Dose Points – 3, 15, 30, 100 cm above the surface of the Cal Pad. The dose point heights remained at fixed distances above the surface of the Cal Pads regardless of the thickness of the pad. That is, the distance from the dose points to the top of the Cal Pads remained constant while the distances from the dose points to the bottom of the pads was incrementally diminished.
- The depth of Cal Pad removed was varied from no removal (0 cm) to a depth of 10 cm (-10 cm), in increments of 1 cm.

B. RESULTS OF MODELING

The modeling results, when compared to the baseline case (no surface removed) produce results that show the magnitude of gamma radiation signal loss as well as the remaining signal as thickness of the Cal Pad decreases. The results of this modeling are presented tabularly in Table 5-2 through Table 5-6 and graphically in Figure 5-1 through Figure 5-5, with the actual depths removed from each pad (rounded up to the nearest centimeter) emphasized for clarity.

MicroShield Model Summary, Pad W1	Source Thickness	Dose Point #1 3 cm Above Surface			Dose Point #2 15 cm Above Surface			Dose Point #3 30 cm Above Surface			Dose Point #4 100 cm Above Surface		
Case Description	cm	Gamma Signal	% Signal Reduction	% Signal Remaining	Gamma Signal	% Signal Reduction	% Signal Remaining	Gamma Signal	% Signal Reduction	% Signal Remaining	Gamma Signal	% Signal Reduction	% Signal Remaining
As Built	48.72	5.904E-03	0.00%	100.00%	5.614E-03	0.00%	100.00%	5.423E-03	0.00%	100.00%	4.699E-03	0.00%	100.00%
1-cm removed	47.72	5.902E-03	0.03%	99.97%	5.609E-03	0.09%	99.91%	5.418E-03	0.09%	99.91%	4.694E-03	0.11%	99.89%
2-cm removed	46.72	5.898E-03	0.10%	99.90%	5.604E-03	0.18%	99.82%	5.413E-03	0.18%	99.82%	4.689E-03	0.21%	99.79%
3-cm removed	45.72	5.895E-03	0.15%	99.85%	5.599E-03	0.27%	99.73%	5.407E-03	0.30%	99.70%	4.684E-03	0.32%	99.68%
4-cm removed	**44.72**	**5.890E-03**	**0.24%**	**99.76%**	**5.593E-03**	**0.37%**	**99.63%**	**5.400E-03**	**0.42%**	**99.58%**	**4.678E-03**	**0.45%**	**99.55%**
5-cm removed	43.72	5.886E-03	0.30%	99.70%	5.586E-03	0.50%	99.50%	5.394E-03	0.53%	99.47%	4.671E-03	0.60%	99.40%
6-cm removed	42.72	5.880E-03	0.41%	99.59%	5.579E-03	0.62%	99.38%	5.386E-03	0.68%	99.32%	4.664E-03	0.74%	99.26%
7-cm removed	41.72	5.874E-03	0.51%	99.49%	5.571E-03	0.77%	99.23%	5.378E-03	0.83%	99.17%	4.656E-03	0.92%	99.08%
8-cm removed	40.72	5.867E-03	0.63%	99.37%	5.562E-03	0.93%	99.07%	5.369E-03	1.00%	99.00%	4.647E-03	1.11%	98.89%
9-cm removed	39.72	5.860E-03	0.75%	99.25%	5.552E-03	1.10%	98.90%	5.359E-03	1.18%	98.82%	4.638E-03	1.30%	98.70%
10-cm removed	38.72	5.851E-03	0.90%	99.10%	5.541E-03	1.30%	98.70%	5.348E-03	1.38%	98.62%	4.627E-03	1.53%	98.47%

Table 5-2. Pad W1 Source Reduction Modeling Tabular Results

MicroShield Model Summary, Pad W2	Source Thickness	Dose Point #1 3 cm Above Surface			Dose Point #2 15 cm Above Surface			Dose Point #3 30 cm Above Surface			Dose Point #4 100 cm Above Surface		
Case Description	cm	Gamma Signal	% Signal Reduction	% Signal Remaining	Gamma Signal	% Signal Reduction	% Signal Remaining	Gamma Signal	% Signal Reduction	% Signal Remaining	Gamma Signal	% Signal Reduction	% Signal Remaining
As Built	48.72	1.539E-02	0.00%	100.00%	1.464E-02	0.00%	100.00%	1.414E-02	0.00%	100.00%	1.226E-02	0.00%	100.00%
1-cm removed	47.72	1.539E-02	0.00%	100.00%	1.463E-02	0.07%	99.93%	1.413E-02	0.07%	99.93%	1.225E-02	0.08%	99.92%
2-cm removed	46.72	1.538E-02	0.06%	99.94%	1.462E-02	0.14%	99.86%	1.412E-02	0.14%	99.86%	1.223E-02	0.24%	99.76%
3-cm removed	45.72	1.537E-02	0.13%	99.87%	1.460E-02	0.27%	99.73%	1.410E-02	0.28%	99.72%	1.222E-02	0.33%	99.67%
4-cm removed	44.72	1.536E-02	0.19%	99.81%	1.459E-02	0.34%	99.66%	1.409E-02	0.35%	99.65%	1.221E-02	0.41%	99.59%
5-cm removed	**43.72**	**1.535E-02**	**0.26%**	**99.74%**	**1.457E-02**	**0.48%**	**99.52%**	**1.407E-02**	**0.50%**	**99.50%**	**1.219E-02**	**0.57%**	**99.43%**
6-cm removed	42.72	1.533E-02	0.39%	99.61%	1.455E-02	0.61%	99.39%	1.405E-02	0.64%	99.36%	1.217E-02	0.73%	99.27%
7-cm removed	41.72	1.532E-02	0.45%	99.55%	1.453E-02	0.75%	99.25%	1.403E-02	0.78%	99.22%	1.215E-02	0.90%	99.10%
8-cm removed	40.72	1.530E-02	0.58%	99.42%	1.451E-02	0.89%	99.11%	1.401E-02	0.92%	99.08%	1.213E-02	1.06%	98.94%
9-cm removed	39.72	1.528E-02	0.71%	99.29%	1.448E-02	1.09%	98.91%	1.398E-02	1.13%	98.87%	1.210E-02	1.31%	98.69%
10-cm removed	38.72	1.526E-02	0.84%	99.16%	1.446E-02	1.23%	98.77%	1.395E-02	1.34%	98.66%	1.208E-02	1.47%	98.53%

Table 5-3. Pad W2 Source Reduction Modeling Tabular Results

MicroShield Model Summary, Pad W3	Source Thickness	Dose Point #1 3 cm Above Surface			Dose Point #2 15 cm Above Surface			Dose Point #3 30 cm Above Surface			Dose Point #4 100 cm Above Surface		
Case Description	cm	Gamma Signal	% Signal Reduction	% Signal Remaining	Gamma Signal	% Signal Reduction	% Signal Remaining	Gamma Signal	% Signal Reduction	% Signal Remaining	Gamma Signal	% Signal Reduction	% Signal Remaining
As Built	48.72	2.085E-02	0.00%	100.00%	1.982E-02	0.00%	100.00%	1.915E-02	0.00%	100.00%	1.658E-02	0.00%	100.00%
1-cm removed	47.72	2.084E-02	0.05%	99.95%	1.980E-02	0.10%	99.90%	1.913E-02	0.10%	99.90%	1.656E-02	0.12%	99.88%
2-cm removed	46.72	2.083E-02	0.10%	99.90%	1.978E-02	0.20%	99.80%	1.911E-02	0.21%	99.79%	1.655E-02	0.18%	99.82%
3-cm removed	45.72	2.081E-02	0.19%	99.81%	1.976E-02	0.30%	99.70%	1.908E-02	0.37%	99.63%	1.652E-02	0.36%	99.64%
4-cm removed	44.72	2.080E-02	0.24%	99.76%	1.974E-02	0.40%	99.60%	1.906E-02	0.47%	99.53%	1.650E-02	0.48%	99.52%
5-cm removed	**43.72**	**2.078E-02**	**0.34%**	**99.66%**	**1.971E-02**	**0.55%**	**99.45%**	**1.903E-02**	**0.63%**	**99.37%**	**1.648E-02**	**0.60%**	**99.40%**
6-cm removed	42.72	2.076E-02	0.43%	99.57%	1.969E-02	0.66%	99.34%	1.900E-02	0.78%	99.22%	1.645E-02	0.78%	99.22%
7-cm removed	41.72	2.073E-02	0.58%	99.42%	1.966E-02	0.81%	99.19%	1.897E-02	0.94%	99.06%	1.642E-02	0.97%	99.03%
8-cm removed	40.72	2.071E-02	0.67%	99.33%	1.962E-02	1.01%	98.99%	1.894E-02	1.10%	98.90%	1.639E-02	1.15%	98.85%
9-cm removed	39.72	2.068E-02	0.82%	99.18%	1.959E-02	1.16%	98.84%	1.890E-02	1.31%	98.69%	1.635E-02	1.39%	98.61%
10-cm removed	38.72	2.064E-02	1.01%	98.99%	1.955E-02	1.36%	98.64%	1.886E-02	1.51%	98.49%	1.631E-02	1.63%	98.37%

Table 5-4. Pad W3 Source Reduction Modeling Tabular Results

MicroShield Model Summary, Pad W4	Source Thickness	Dose Point #1 3 cm Above Surface			Dose Point #2 15 cm Above Surface			Dose Point #3 30 cm Above Surface			Dose Point #4 100 cm Above Surface		
Case Description	cm	Gamma Signal	% Signal Reduction	% Signal Remaining	Gamma Signal	% Signal Reduction	% Signal Remaining	Gamma Signal	% Signal Reduction	% Signal Remaining	Gamma Signal	% Signal Reduction	% Signal Remaining
As Built	48.72	2.979E-02	0.00%	100.00%	2.827E-02	0.00%	100.00%	2.731E-02	0.00%	100.00%	2.366E-02	0.00%	100.00%
1-cm removed	47.72	2.978E-02	0.03%	99.97%	2.825E-02	0.07%	99.93%	2.729E-02	0.07%	99.93%	2.364E-02	0.08%	99.92%
2-cm removed	46.72	2.976E-02	0.10%	99.90%	2.823E-02	0.14%	99.86%	2.726E-02	0.18%	99.82%	2.362E-02	0.17%	99.83%
3-cm removed	45.72	2.975E-02	0.13%	99.87%	2.821E-02	0.21%	99.79%	2.724E-02	0.26%	99.74%	2.360E-02	0.25%	99.75%
4-cm removed	**44.72**	**2.973E-02**	**0.20%**	**99.80%**	**2.818E-02**	**0.32%**	**99.68%**	**2.721E-02**	**0.37%**	**99.63%**	**2.357E-02**	**0.38%**	**99.62%**
5-cm removed	43.72	2.971E-02	0.27%	99.73%	2.816E-02	0.39%	99.61%	2.718E-02	0.48%	99.52%	2.355E-02	0.46%	99.54%
6-cm removed	42.72	2.969E-02	0.34%	99.66%	2.812E-02	0.53%	99.47%	2.715E-02	0.59%	99.41%	2.352E-02	0.59%	99.41%
7-cm removed	41.72	2.967E-02	0.40%	99.60%	2.809E-02	0.64%	99.36%	2.711E-02	0.73%	99.27%	2.348E-02	0.76%	99.24%
8-cm removed	40.72	2.964E-02	0.50%	99.50%	2.805E-02	0.78%	99.22%	2.707E-02	0.88%	99.12%	2.344E-02	0.93%	99.07%
9-cm removed	39.72	2.961E-02	0.60%	99.40%	2.801E-02	0.92%	99.08%	2.703E-02	1.03%	98.97%	2.340E-02	1.10%	98.90%
10-cm removed	38.72	2.957E-02	0.74%	99.26%	2.796E-02	1.10%	98.90%	2.698E-02	1.21%	98.79%	2.335E-02	1.31%	98.69%

Table 5-5. Pad W4 Source Reduction Modeling Tabular Results

MicroShield Model Summary, Pad W5	Source Thickness	Dose Point #1 3 cm Above Surface			Dose Point #2 15 cm Above Surface			Dose Point #3 30 cm Above Surface			Dose Point #4 100 cm Above Surface		
Case Description	**cm**	**Gamma Signal**	**% Signal Reduction**	**% Signal Remaining**	**Gamma Signal**	**% Signal Reduction**	**% Signal Remaining**	**Gamma Signal**	**% Signal Reduction**	**% Signal Remaining**	**Gamma Signal**	**% Signal Reduction**	**% Signal Remaining**
As Built	48.72	2.918E-02	0.00%	100.00%	2.771E-02	0.00%	100.00%	2.677E-02	0.00%	100.00%	2.320E-02	0.00%	100.00%
1-cm removed	47.72	2.916E-02	0.07%	99.93%	2.769E-02	0.07%	99.93%	2.675E-02	0.07%	99.93%	2.318E-02	0.09%	99.91%
2-cm removed	46.72	2.915E-02	0.10%	99.90%	2.767E-02	0.14%	99.86%	2.672E-02	0.19%	99.81%	2.315E-02	0.22%	99.78%
3-cm removed	45.72	2.914E-02	0.14%	99.86%	2.765E-02	0.22%	99.78%	2.670E-02	0.26%	99.74%	2.313E-02	0.30%	99.70%
4-cm removed	**44.72**	**2.912E-02**	**0.21%**	**99.79%**	**2.762E-02**	**0.32%**	**99.68%**	**2.667E-02**	**0.37%**	**99.63%**	**2.310E-02**	**0.43%**	**99.57%**
5-cm removed	43.72	2.910E-02	0.27%	99.73%	2.759E-02	0.43%	99.57%	2.663E-02	0.52%	99.48%	2.307E-02	0.56%	99.44%
6-cm removed	42.72	2.907E-02	0.38%	99.62%	2.756E-02	0.54%	99.46%	2.660E-02	0.64%	99.36%	2.304E-02	0.69%	99.31%
7-cm removed	41.72	2.905E-02	0.45%	99.55%	2.752E-02	0.69%	99.31%	2.656E-02	0.78%	99.22%	2.300E-02	0.86%	99.14%
8-cm removed	40.72	2.902E-02	0.55%	99.45%	2.748E-02	0.83%	99.17%	2.652E-02	0.93%	99.07%	2.296E-02	1.03%	98.97%
9-cm removed	39.72	2.898E-02	0.69%	99.31%	2.743E-02	1.01%	98.99%	2.648E-02	1.08%	98.92%	2.292E-02	1.21%	98.79%
10-cm removed	38.72	2.894E-02	0.82%	99.18%	2.739E-02	1.15%	98.85%	2.643E-02	1.27%	98.73%	2.287E-02	1.42%	98.58%

Table 5-6. Pad W5 Source Reduction Modeling Tabular Results

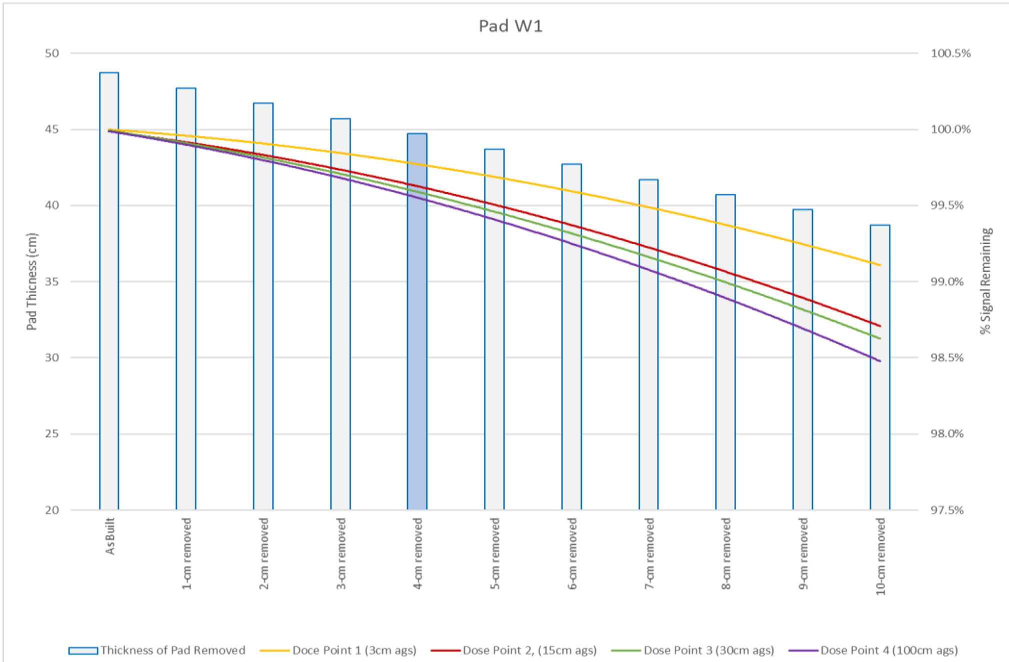

Figure 5-1. Pad W1 Source Reduction Modeling Graphical Results

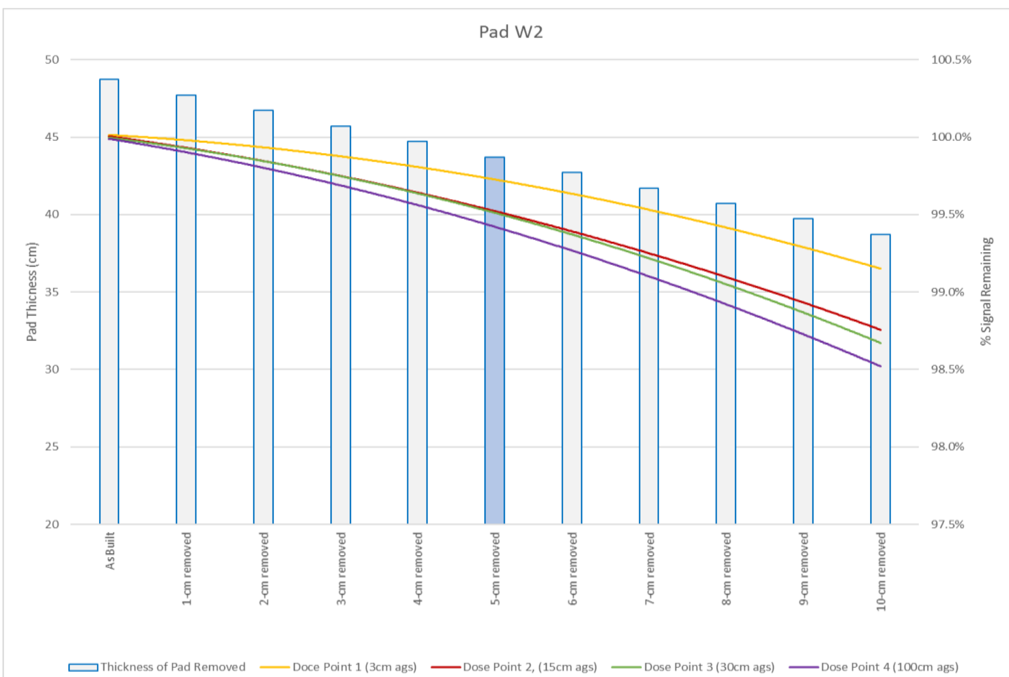

Figure 5-2. Pad W2 Source Reduction Modeling Graphical Results

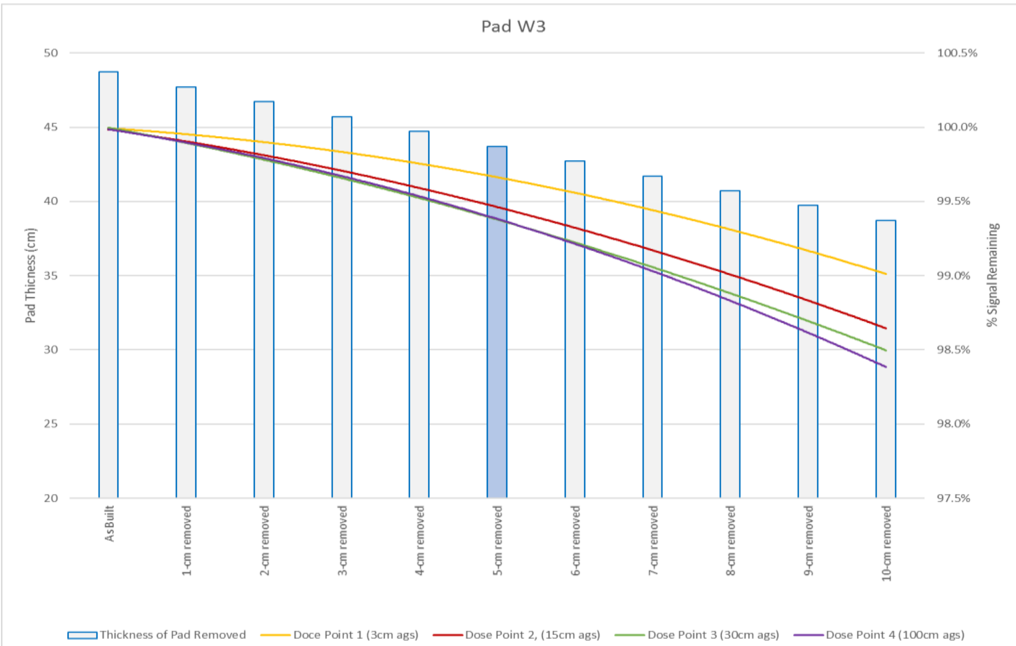

Figure 5-3. Pad W3 Source Reduction Modeling Graphical Results

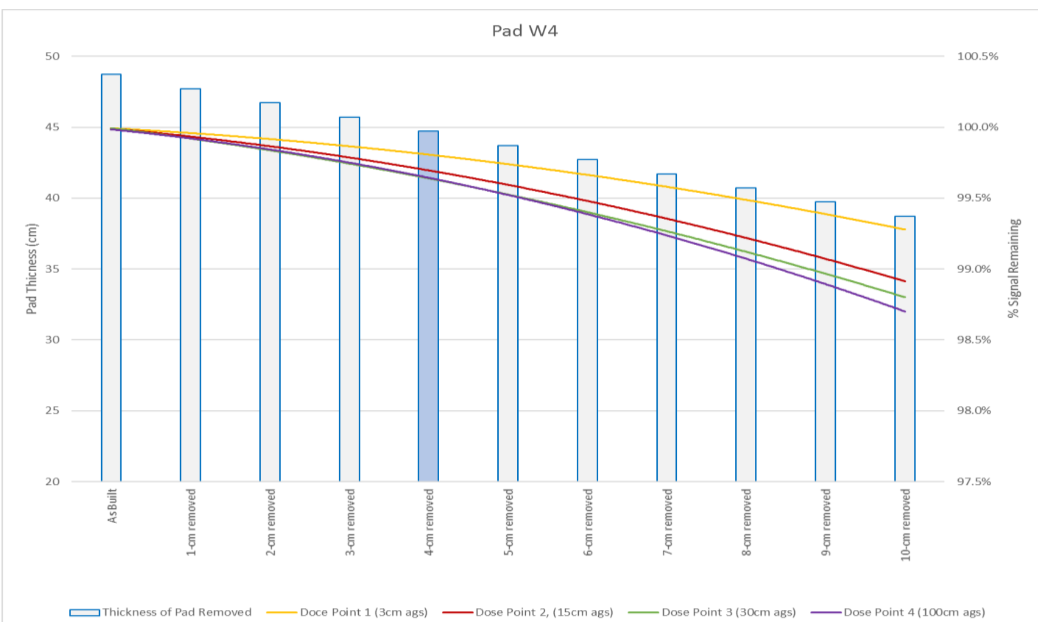

Figure 5-4. Pad W4 Source Reduction Modeling Graphical Results

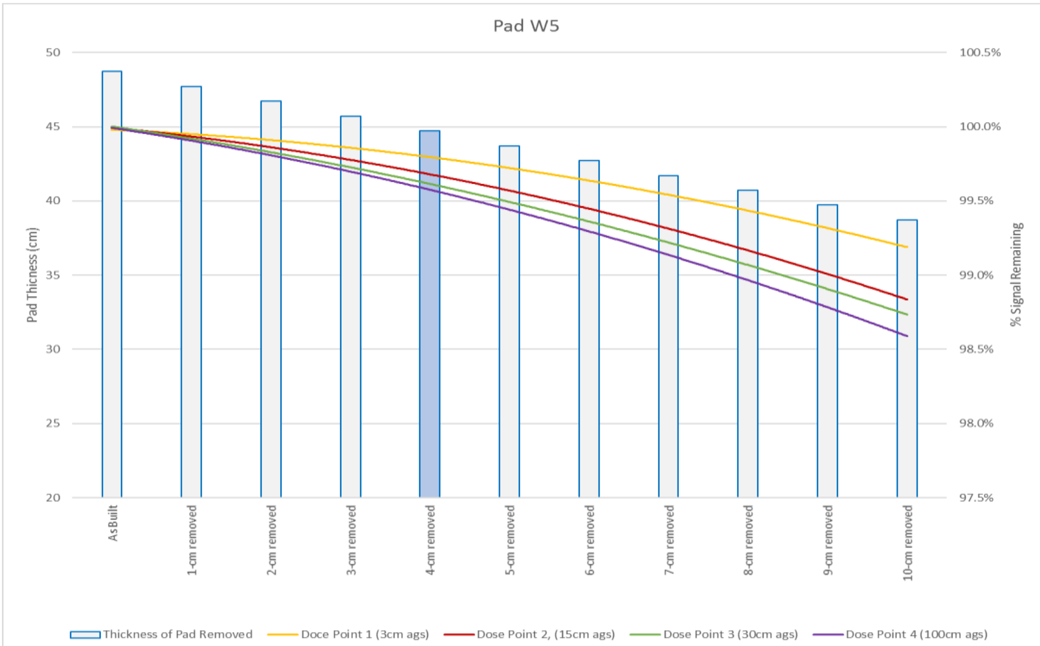

Figure 5-5. Pad W5 Source Reduction Modeling Graphical Results

As expected, the calculated reduction in the gamma fluxes due to the surface rehabilitation process on the Cal Pads is negligible given the depth of the surface veneer removed. The greatest calculated reduction in the gamma fluxes up to 1 m directly above any of the Cal Pads is less than 1% (~0.6%). Such minute variations in gamma fluxes are extremely difficult to measure confidently, even in highly controlled laboratory conditions.

The cumulative effect of increasing depth of source removal on the gamma fluxes increases but not linearly. Increasing depth of removal has a greater and greater impact on gamma fluxes directly above the Cal Pads per unit depth. For example, the removal of the first centimeter of the surface of the Cal Pad 5 (0-1 cm) reduces the gamma fluxes directly above Pad W5 by 0.09%, while the removal of the tenth centimeter of the surface of Cal Pad 5 (9-10 cm) reduces the gamma fluxes at 1 meter by 0.22%. This phenomenon, evident in the graphics presented in Figure 5-1 through Figure 5-5, is expected as the majority of the gamma fluxes emanating from the Cal Pads are generated near the surface of the pads, while the gamma fluxes generated near the bottom of the pads are largely attenuated by the pads themselves, and thus do not significantly contribute to the gamma fluxes above the pads. In other words, the removal of X cm from the surface of the pads effectively removes the bottom X cm from the source term.

It is notable to see that the removal of 10 cm from the surface of the Cal Pads (greater than twice the depth actually removed from any of the pads' surfaces) is calculated to reduce the gamma radiation fluxes directly above the Cal Pads by less than or equal to 1.0% at 3 cm above the surface of the pads and by no more than 1.4% at 1 m above the pads. This leaves at least 99.0% and 98.6% of the gamma radiation fluxes emanating from the Cal Pads at those locations intact even, after the removal of 10 cm of source depth.

6. IMPACTS OF ENVIRONMENTAL CONDITIONS

Fluctuations in environmental conditions are known to have significant influence on both the exhalation rate and the concentration of radon and thoron gases in the atmosphere near the ground surface (Pearson 1966, Israel 1965). The corresponding changing gamma fluxes induced by the variance in airborne radon and thoron concentrations is a confounding factor to the collection of radiological measurements in typical environmental concentrations at the earth's surface.

Previous research conducted at the Cal Pads indicates that there may be a seasonal variation in the gamma flux directly above the Cal Pads that was attributed to variation in the radon and thoron exhalation rates of the Cal Pads themselves (DOE 1978). Radon and thoron exhalation rates are known to be influenced, by a variety of environmental factors, including relative humidity, thermal stability, wind speed, temperature, and barometric pressure, as well as by surface moisture. The observed variances are generally most pronounced following a precipitation event, during which multiple factors that contribute to the airborne radon and thoron concentrations are altered. However, significant variances have been observed *in the absence of precipitation* (Pearson 1966). In addition to variances due to atmospheric conditions, the effects of standing water have been observed to decrease the gamma flux directly above the Cal Pads (DOE 1978). However, the significance of standing water and other environmental influences on the gamma fluxes generated directly above the Cal Pads has not yet been quantitatively assessed to a significant degree of confidence.

The local environmental conditions, including precipitation, wind speed, wind direction, relative humidity, temperature, cloud cover, and barometric pressure were recorded hourly during each day of field activities, as reported by the Grand Junction Regional Airport weather monitoring station. The environmental and background radiation conditions were monitored during field activities to identify significant fluctuations, as well as significant differences between the prevailing pre- and post-rehabilitation environmental conditions, that have a potential to impact the radiological characterization measurements.

No precipitation events occurred nor were any environmental conditions observed to be outside of expected parameters during field activities. Several environmental parameters were assessed to quantify their effects on the radiometric data. The results of these assessments are discussed in Section 10.

7. RADIOMETRIC MEASUREMENT COLLECTION

Amec Foster Wheeler collected a variety of radiometric measurements to verify and validate the calculated impacts of the rehabilitation activities on the radiological characteristics of the Cal Pads. In order to minimize potential for uncontrolled variables, both the pre- and post-rehabilitation measurements were collected following the same methodology, with the same instrumentation operated in the same configuration and with the same operational parameters.

A. OVERLAND SCAN SURVEYS

The rehabilitation activities included construction activities that extended beyond the edges of the Cal Pads, thus there is potential that the radiological characteristics of the area surrounding the Cal Pads was altered, in addition to the Cal Pads themselves. These potential changes would arise from variances in the radiological characteristics of the materials used to return the area to final grade. In order to quantify potential changes in the radiological conditions of the area surrounding the Cal Pads, overland scan surveys were performed pre- and post-rehabilitation of the area surrounding the Cal Pads.

Overland scan surveys were performed using Amec Foster Wheeler's *ScanPlot*SM push cart scan system (Figure 7-1) to enable a full-coverage spectroscopic survey of the area within 25' of the edges of the Cal Pads (Figure 7-2). The *ScanPlot*SM system was fitted with a large volume (4.2 liter) NaI gamma spectrometer positioned at a distance of 6" above the ground surface, a high-accuracy GPS receiver, and a *ScanPlot*SM software and electronics package. The *ScanPlot*SM system was moved over the surface of the area encompassing and surrounding the Cal Pads traveling at 1.0 m/s. The overland Scan Surveys were conducted on August 22 and October 30, 2017.

Figure 7-1. ScanPlot^{SM} Push Cart Scan System

Figure 7-2. Area Surveyed by ScanPlot^{SM} Overland Scan System

B. General Area Background Gamma Spectroscopic Measurements

Fluctuations in environmental conditions can affect sensitive radiometric measurements. Long-duration gamma spectroscopic measurements of the general area environmental background radiation conditions were collected. The background measurements served as a “Measurement Control” for the pre- and post-refurbishment measurements collected. The background measurements were collected with the same *ScanPlot*SM system utilized for the overland scan surveys, which was fitted with a large volume (4.2 liter) NaI detector operated as a gamma spectrometer.

This large volume NaI detector was positioned at a background location that is representative of the environmental conditions of the Cal Pads themselves, but at a distance from the Cal Pads far enough away to avoid influences from the direct gamma emissions they produce (Figure 7-3). The background detector remained at the assigned background location throughout the duration of radiological characterization field activities, and collected virtually continuous background radiation measurements, save for periodic quality control checks.

Figure 7-3. Location of Background System

C. GAMMA RADIATION EXPOSURE RATE MEASUREMENTS

Long-duration gamma radiation exposure rate measurements were collected at the center of each of the Cal Pads to quantitatively assess the impacts of the rehabilitation activities on the exposure rates produced by each of the Cal Pads. These pre- and post-rehabilitation results were evaluated as paired data sets to quantify any statistically significant differences in the gamma radiation exposure rates produced by the Cal Pads following the rehabilitation process. Exposure rates were measured using a high accuracy (+/-5% at 10μR/h) highly pressurized ionization chamber (HPIC), Reuter Stokes model RSS-112.

The HPIC was positioned at the center of the Cal Pad with the detector positioned as close to the surface of the Cal Pads as was practicable, approximately 1” above the surface. Exposure measurements were collected for a period of at least 20 hours at the center of each Cal Pad, both prior to and following the rehabilitation activities. The dates and times of collection of the gamma radiation exposure rate measurements are presented in Table 7-1.

	Pad W1		Pad W2		Pad W3		Pad W4		Pad W5	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Duration [hr]	22.0	23.9	22.6	22.6	21.0	22.9	22.0	21.7	20.5	21.9
Start	30-Aug	04-Nov	29-Aug	03-Nov	25-Aug	02-Nov	24-Aug	01-Nov	23-Aug	01-Nov
End	31-Aug	05-Nov	30-Aug	04-Nov	26-Aug	03-Nov	25-Aug	02-Nov	24-Aug	02-Nov

Table 7-1. Gamma Radiation Exposure Rate Data Collection Intervals

D. LONG DURATION GAMMA SPECTROSCOPIC MEASUREMENTS

Long-duration gamma spectroscopic measurements were collected with the *ScanPlot*SM system fitted with a large volume (4.2 liter) NaI detector to quantify the impacts of the rehabilitation activities on each of the primary radioelements in the Cal Pads (K-40, U-238 [Bi-214], and Th-232). These isotopes were measured by the intensity of the gamma emissions at specific energy levels characteristic of each element.

- Potassium 40 was measured directly using the 1.46 MeV gamma-ray energy emitted by potassium 40,
- Uranium 238 was considered to be in secular equilibrium with Ra-226 and is measured indirectly from the radiation emission of its daughter product bismuth 214 (1.76 MeV), and
- Thorium 232 was considered to be in secular equilibrium with Ra-224 and is measured indirectly from the radiation emission of its daughter product thallium 208 (2.62 MeV).

The count rates in the “full” gamma energy region (~0.2-3.0 MeV) was measured and recorded, simultaneous with the isotopic measurements.

The same NaI detector was operated in the same configuration during both the pre- and post-rehabilitation surveys. The NaI detector was positioned at the center of the Cal Pad, with the long axis of the detector parallel to the long axis of the Cal Pad. The face of the NaI detector was positioned as close as practicable, a distance of approximately 0.05 m above the surface of the Cal Pads. Gamma spectroscopic measurements were collected for a period of at least 20 hours[1] at the center of each Cal Pad, both pre- and post-rehabilitation. The dates and times of collection of the gamma spectroscopic measurements are presented in Table 7-2.

Pre-Rehabilitaion			
Pad	Duration [hr]	Start	Stop
W1	22.9	29-Aug-2017 10:28	30-Aug-2017 09:50
W2	22.9	29-Aug-2017 10:28	30-Aug-2017 09:50
W3	21.5	13-Sep-2017 10:20	14-Sep-2017 08:32
W4	16.8	28-Aug-2017 16:35	29-Aug-2017 09:26
W5	22.5	30-Aug-2017 10:45	31-Aug-2017 09:33

Post-Rehabilitation			
Pad	Duration [hr]	Start	Stop
W1	23.0	03-Nov-2017 09:50	04-Nov-2017 09:09
W2	23.0	03-Nov-2017 09:50	04-Nov-2017 09:09
W3	21.8	01-Nov-2017 10:14	02-Nov-2017 08:48
W4	22.1	31-Oct-2017 10:18	01-Nov-2017 09:14
W5	22.1	04-Nov-2017 09:38	05-Nov-2017 08:10

Table 7-2. Gamma Spectroscopic Data Collection Intervals

[1] Except on Pad 4 during the pre-rehabilitation survey which had a duration of 16.8 hours.

8. RADIOMETRIC SURVEY RESULTS

A. Overland Scan Survey Results

A statistical summary of gamma spectroscopic measurements collected during the overland scan surveys is presented in Table 8-1. The results from the areas encompassed by, and immediately adjacent to, the Cal Pads was filtered from the overland scan survey datasets such that the gamma fluxes from the Cal Pads did not confound the evaluation of the surrounding surface.

	Full		K-40		U-238		Th-232	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Average [cps]	2371.7	2436.2	105.7	105.3	21.1	23.4	18.2	18.4
Median [cps]	2401.0	2445.7	106.0	105.2	21.0	23.4	18.0	18.1
Min [cps]	2041.0	2002.1	61.0	63.5	5.0	6.4	5.0	5.2
Max [cps]	2836.0	3153.2	153.0	155.3	38.0	51.0	39.0	36.2
StDev [cps]	4.8	124.0	13.4	13.1	4.8	5.1	4.5	4.5
Count	5397	5976	5397	5976	5397	5976	5397	5976
Percent Difference	NA	1.9%	NA	-0.7%	NA	11.4%	NA	0.5%

Table 8-1. Statistical Comparison of Overland Scan Surveys, Pre- and Post- Rehabilitation

B. General Area Background Gamma Spectroscopy Results

The results of the gamma spectroscopic measurements collected at the background area are presented in Figure 8-1 through Figure 8-4, and statistically summarized in Table 8-2.

	Full		K40		U238		Th232	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Average [cps]	2553.9	2351.3	110.6	97.3	24.6	22.2	18.7	17.4
Median [cps]	2551.8	2345.8	110.8	97.3	24.5	22.1	18.7	17.4
Min [cps]	2412.9	2254.5	100.9	90.1	20.3	18.7	15.8	15.2
Max [cps]	2691.2	2514.3	118.1	103.5	29.1	27.0	21.7	19.8
StDev [cps]	60.8	54.8	2.3	1.6	1.5	1.2	0.7	0.6
Count	7516	7826	7516	7826	7516	7826	7516	7826
Percent Difference	NA	-8.1%	NA	-12.2%	NA	-9.9%	NA	-7.0%

Table 8-2. Background Gamma Spectroscopy Summary Statistics, Pre- and Post- Rehabilitation

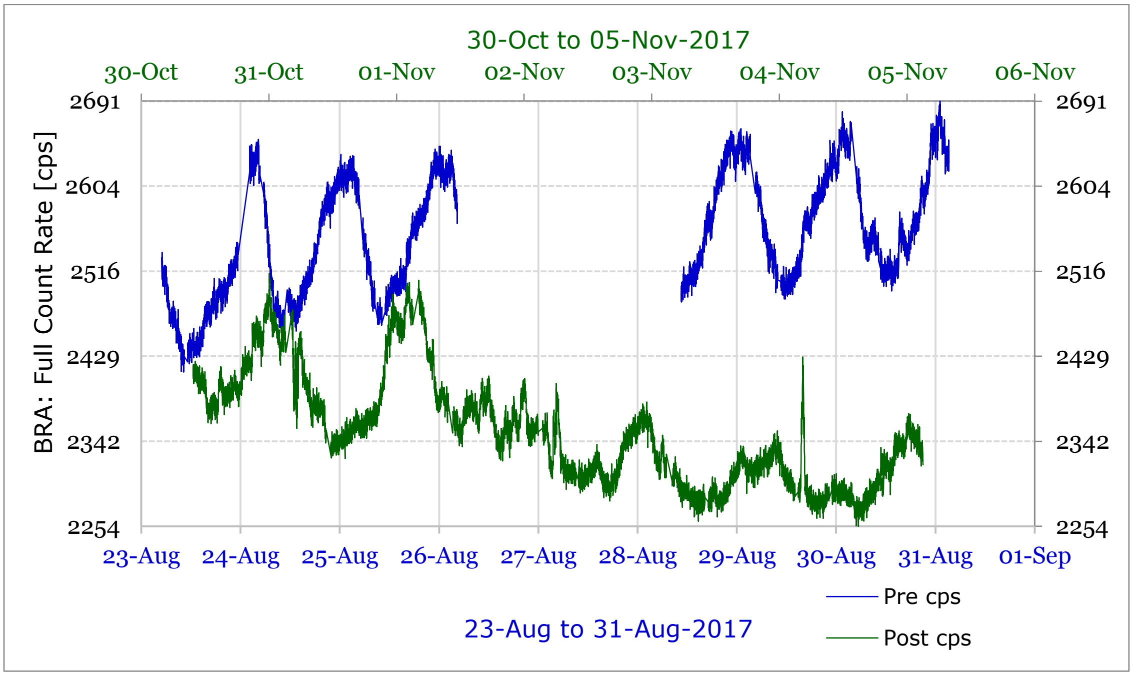

Figure 8-1. Background Count Rate in Full ROI, Pre- and Post-Rehabilitation

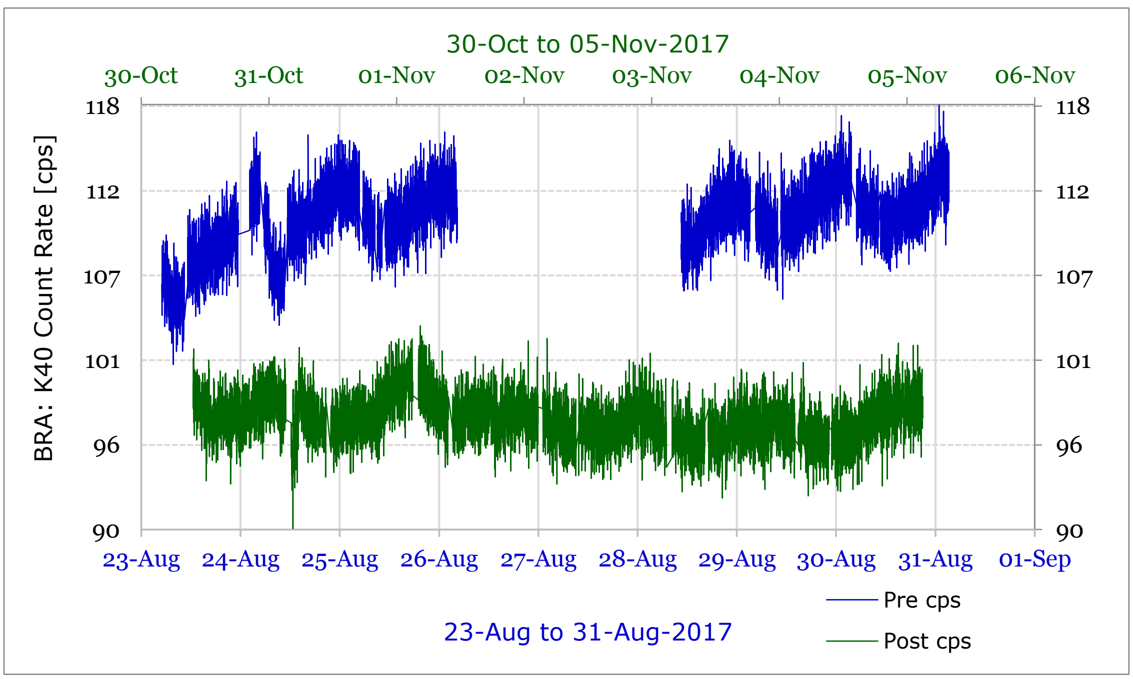

Figure 8-2. Background Count Rate in the K-40 ROI, Pre- and Post-Rehabilitation

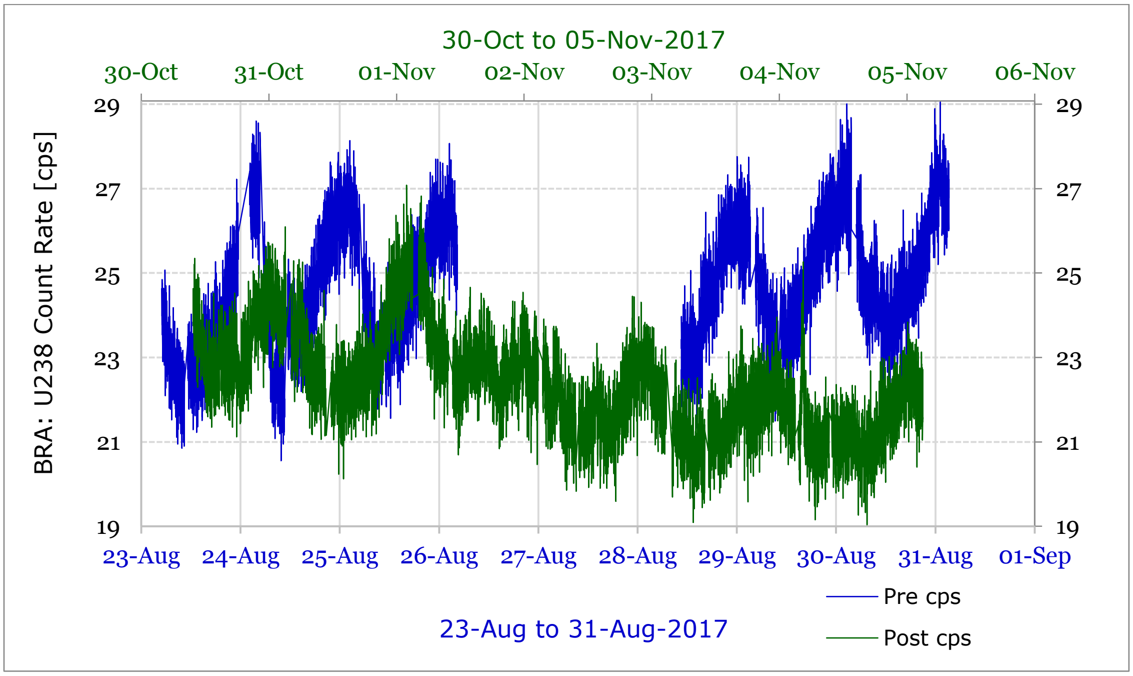

Figure 8-3. Background Count Rate in the U-238 ROI, Pre- and Post-Rehabilitation

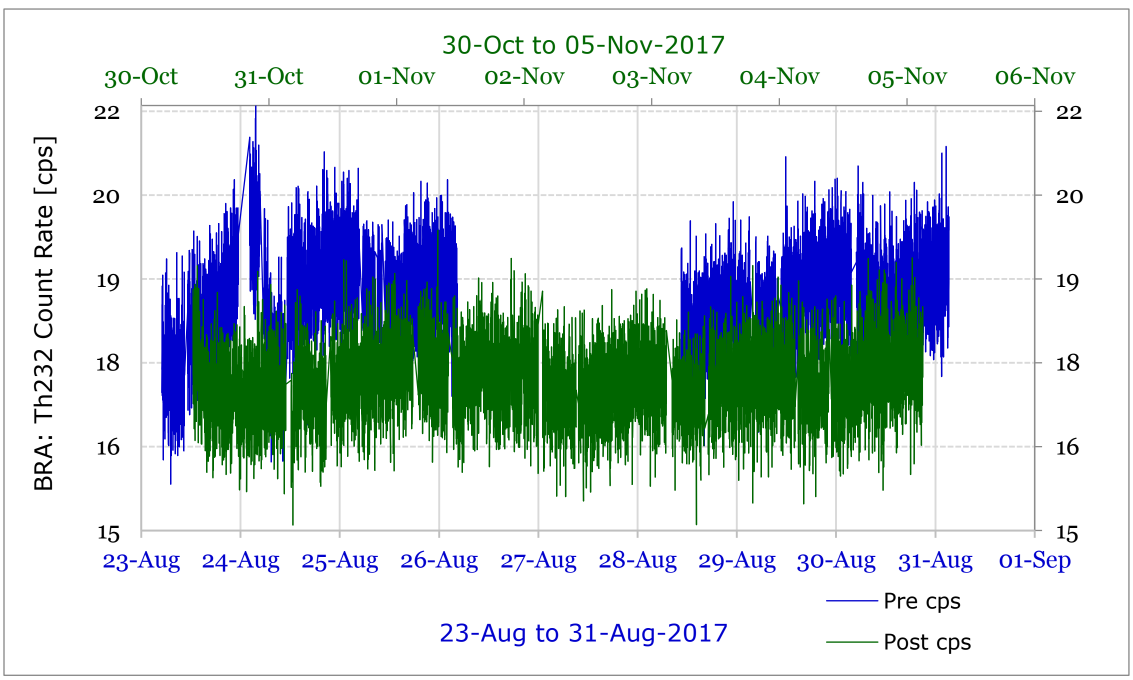

Figure 8-4. Background Count Rate in the Th-232 ROI, Pre- and Post-Rehabilitation

C. Long-Duration Gamma Exposure Results

1. PAD W1

The results of the gamma spectroscopic measurements collected on Pad W1 are presented in Figure 8-5 and statistically summarized in Table 8-3.

	Pad W1	
	Pre	Post
Average [µR/hr]	12.924	12.976
Median [µR/hr]	12.915	12.915
Min [µR/hr]	12.285	12.600
Max [µR/hr]	13.650	13.335
StDev [µR/hr]	0.238	0.167
Count	266	289

Table 8-3. Gamma Exposure Rate Summary Statistics, Pad W1, Pre- and Post- Rehabilitation

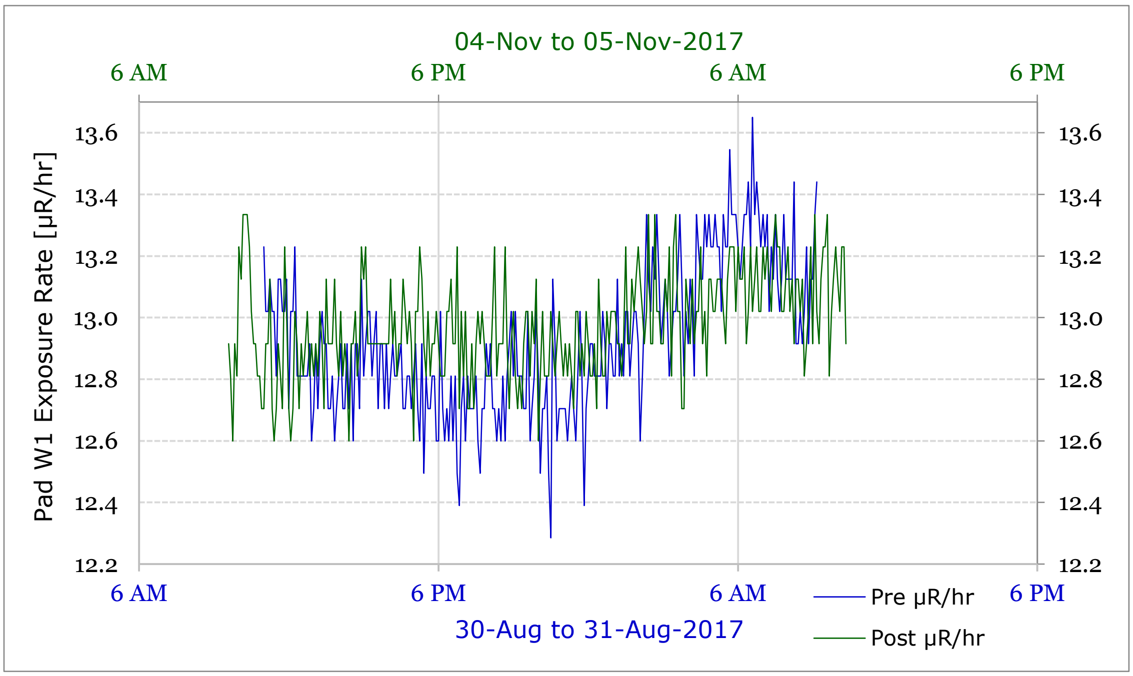

Figure 8-5. Gamma Exposure Rate, Pad W1, Pre- and Post-Rehabilitation

2. PAD W2

The results of the gamma spectroscopic measurements collected on Pad W2 are presented in Figure 8-6 and statistically summarized in Table 8-4.

	Pad W2	
	Pre	Post
Average [µR/hr]	19.053	18.935
Median [µR/hr]	19.110	18.900
Min [µR/hr]	18.480	18.480
Max [µR/hr]	19.635	19.425
StDev [µR/hr]	0.259	0.191
Count	273	273

Table 8-4. Gamma Exposure Rate Summary Statistics, Pad W2, Pre- and Post- Rehabilitation

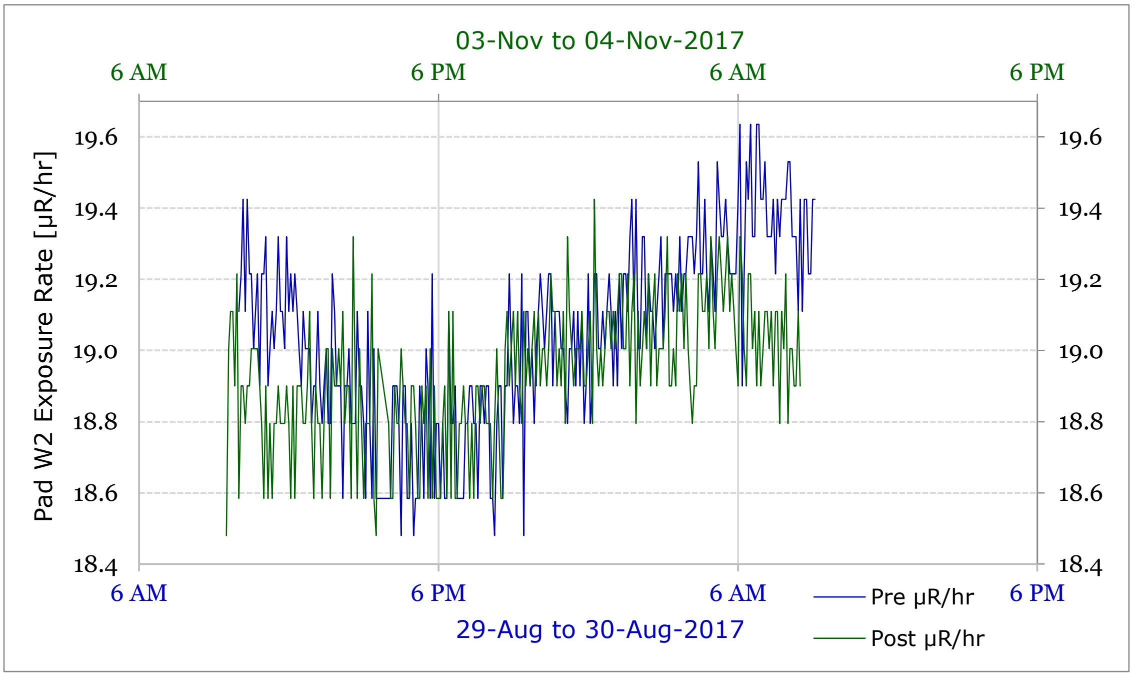

Figure 8-6. Gamma Exposure Rate, Pad W2, Pre- and Post-Rehabilitation

3. PAD W3

The results of the gamma spectroscopic measurements collected on Pad W3 are presented in Figure 8-7 and statistically summarized in Table 8-5.

	Pad W3	
	Pre	Post
Average [µR/hr]	23.980	24.164
Median [µR/hr]	23.940	24.150
Min [µR/hr]	23.310	23.625
Max [µR/hr]	24.675	24.780
StDev [µR/hr]	0.294	0.202
Count	254	277

Table 8-5. Gamma Exposure Rate Summary Statistics, Pad W3, Pre- and Post- Rehabilitation

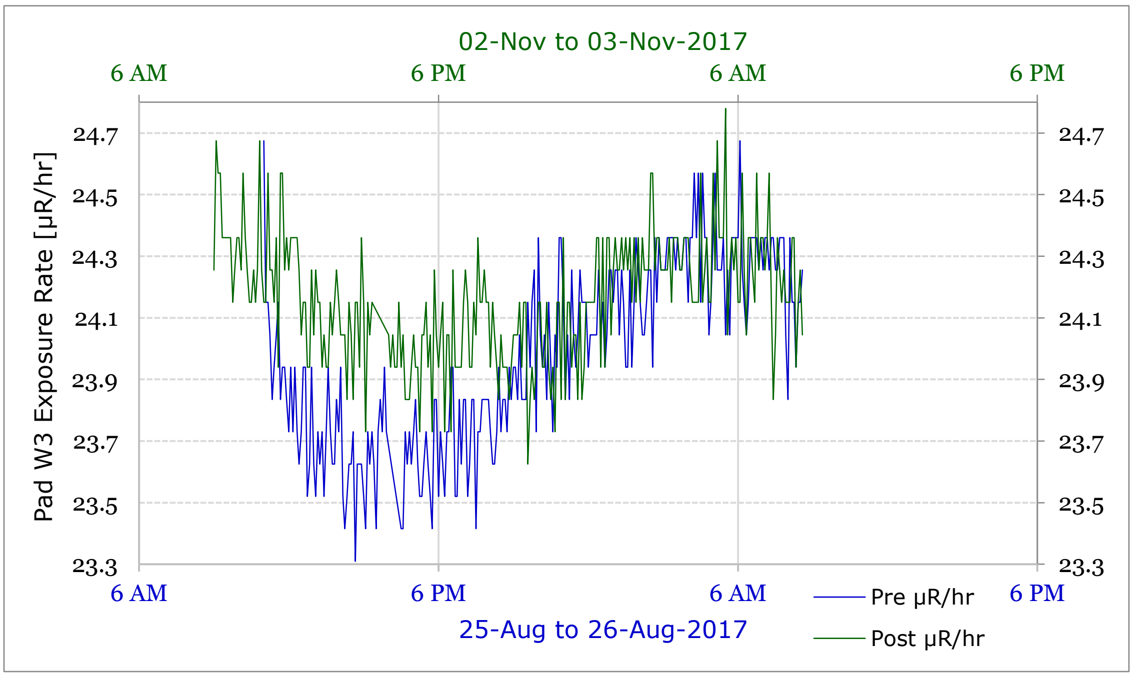

Figure 8-7. Gamma Exposure Rate, Pad W3, Pre- and Post-Rehabilitation

4. PAD W4

The results of the gamma spectroscopic measurements collected on Pad W4 are presented in Figure 8-8 and statistically summarized in Table 8-6.

	Pad W4	
	Pre	Post
Average [µR/hr]	28.754	29.710
Median [µR/hr]	28.770	29.715
Min [µR/hr]	27.930	29.190
Max [µR/hr]	29.505	30.660
StDev [µR/hr]	0.338	0.228
Count	266	263

Table 8-6. Gamma Exposure Rate Summary Statistics, Pad W4, Pre- and Post- Rehabilitation

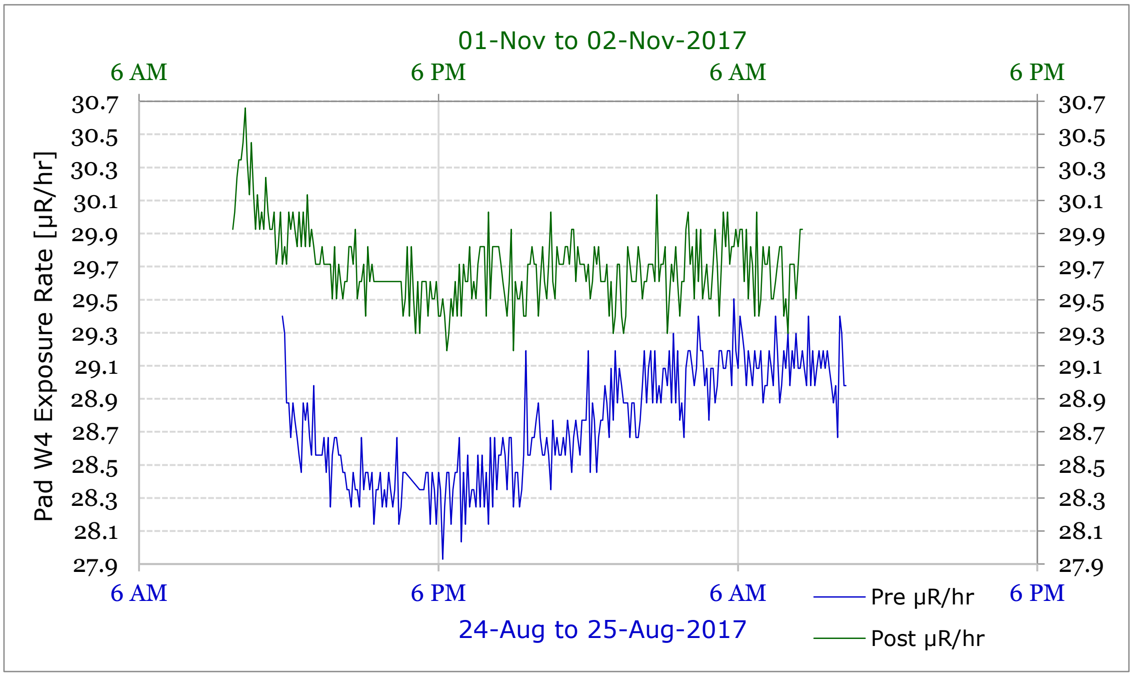

Figure 8-8. Gamma Exposure Rate, Pad W4, Pre- and Post-Rehabilitation

5. PAD W5

The results of the gamma spectroscopic measurements collected on Pad W5 are presented in Figure 8-9 and statistically summarized in Table 8-7.

	Pad W5	
	Pre	Post
Average [µR/hr]	27.797	28.011
Median [µR/hr]	27.720	28.035
Min [µR/hr]	26.985	27.300
Max [µR/hr]	28.560	28.560
StDev [µR/hr]	0.352	0.224
Count	248	265

Table 8-7. Gamma Exposure Rate Summary Statistics, Pad W5, Pre- and Post- Rehabilitation

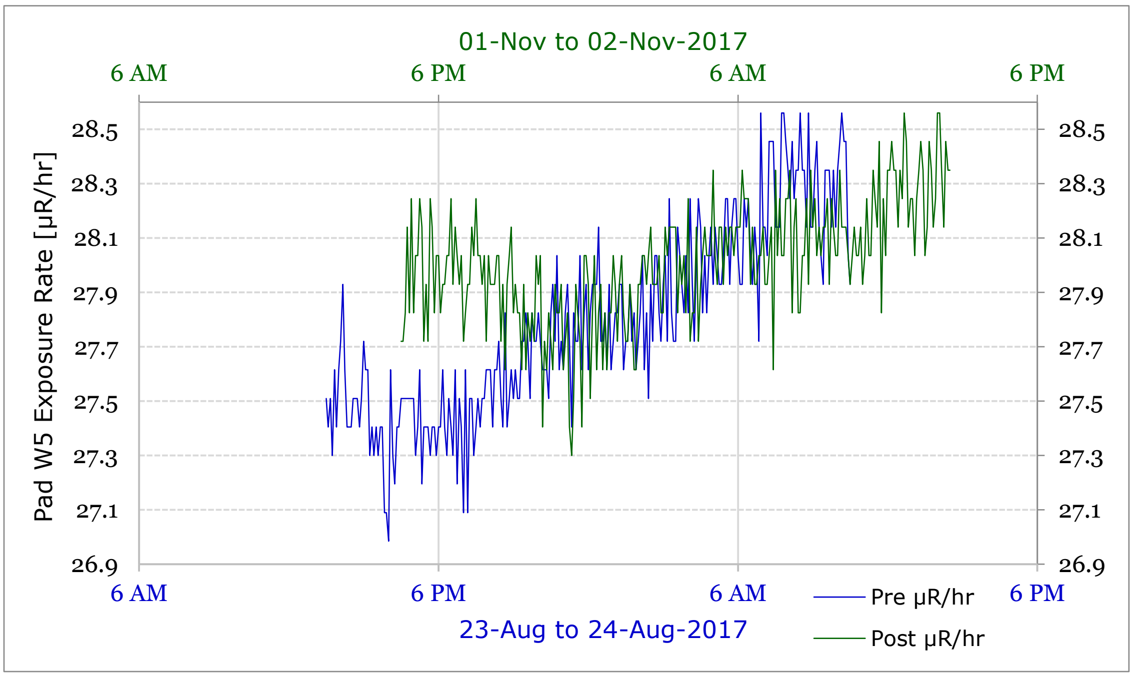

Figure 8-9. Gamma Exposure Rate, Pad W5, Pre- and Post-Rehabilitation

D. LONG-DURATION GAMMA SPECTROSCOPY RESULTS

1. PAD W1

The results of the gamma spectroscopic measurements collected on Pad W1 are presented in Figure 8-10 through Figure 8-13, and statistically summarized in Table 8-8.

	Pad W1: Full		Pad W1: K40		Pad W1: U238		Pad W1: Th232	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Average [cps]	1212.3	1169.6	57.9	48.4	12.7	11.7	11.0	10.0
Median [cps]	1212.4	1169.6	57.9	48.4	12.6	11.7	11.0	10.0
Min [cps]	1181.8	1152.6	54.5	45.2	10.9	10.4	9.6	8.6
Max [cps]	1244.0	1188.6	61.6	51.4	14.5	13.3	12.5	11.9
StDev [cps]	13.0	5.6	1.1	1.0	0.5	0.4	0.5	0.4
Count	1376	1379	1376	1379	1376	1379	1376	1379
Percent Difference	NA	-3.5%	NA	-16.5%	NA	-7.2%	NA	-8.7%

Table 8-8. Gamma Spectroscopy Summary Statistics, Pad W1, Pre- and Post- Rehabilitation

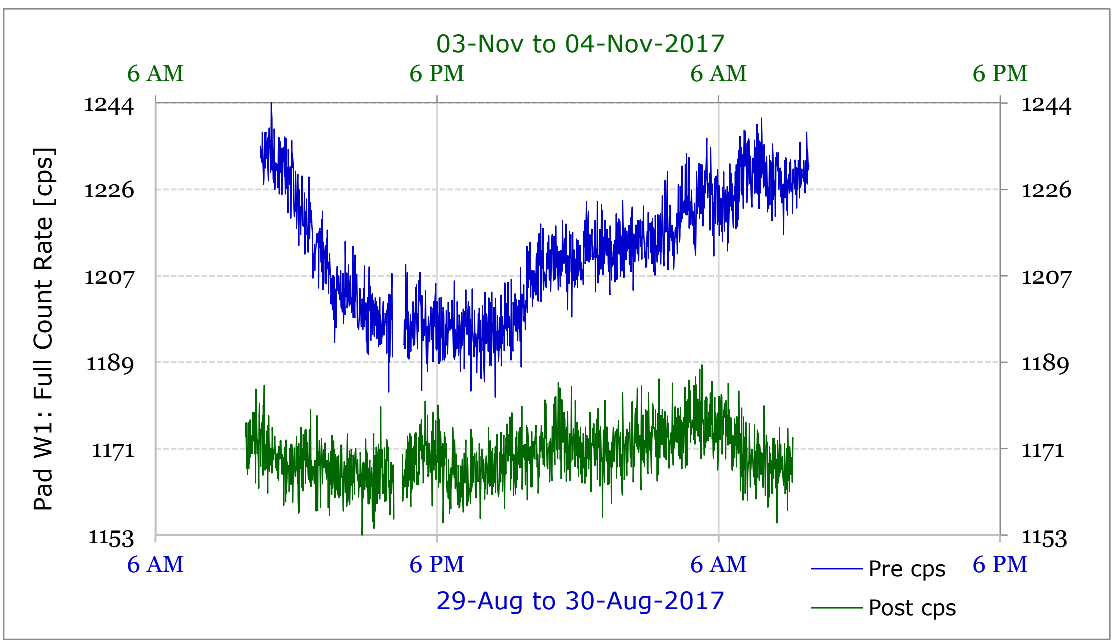

Figure 8-10. Count Rate in Full ROI, Pad W1, Pre- and Post-Rehabilitation

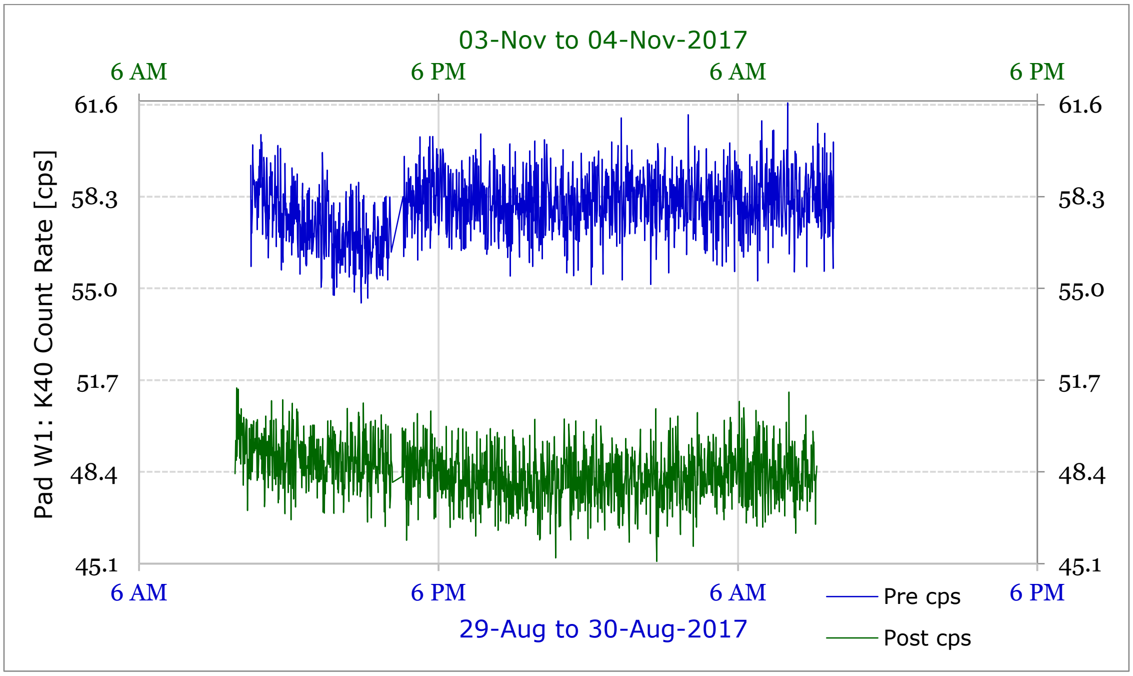

Figure 8-11. Count Rate in the K-40 ROI, Pad W1, Pre- and Post-Rehabilitation

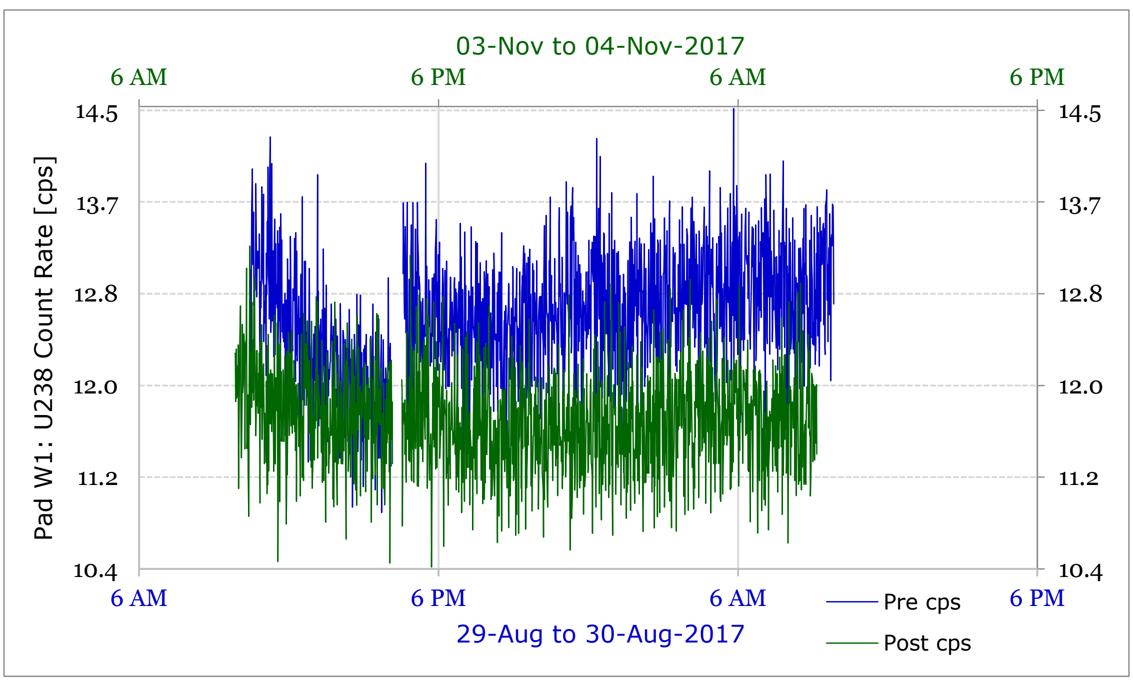

Figure 8-12. Count Rate in the U-238 ROI, Pad W1, Pre- and Post-Rehabilitation

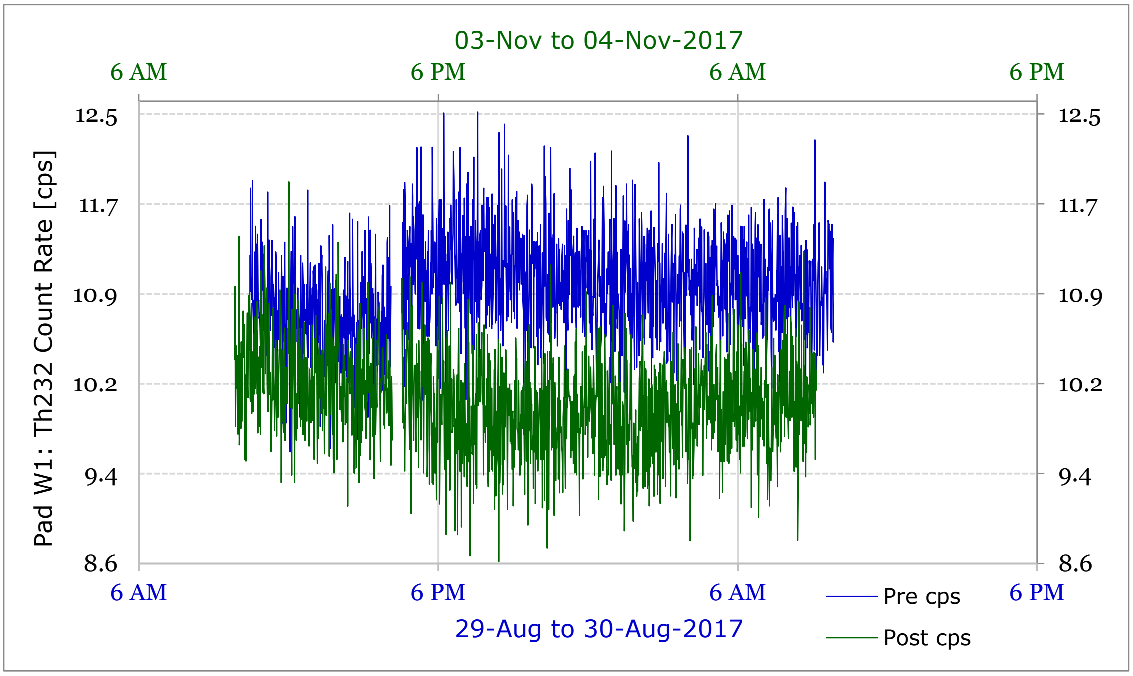

Figure 8-13. Count Rate in the Th-232 ROI, Pad W1, Pre- and Post-Rehabilitation

2. PAD W2

The results of the gamma spectroscopic measurements collected on Pad W2 are presented in Figure 8-14 through Figure 8-17, and statistically summarized in Table 8-9.

	Pad W2: Full		Pad W2: K40		Pad W2: U238		Pad W2: Th232	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Average [cps]	2456.1	2406.0	165.3	145.3	19.5	18.7	13.3	12.6
Median [cps]	2456.2	2405.7	166.8	145.0	19.5	18.6	13.3	12.6
Min [cps]	2426.4	2375.9	152.2	139.1	16.8	16.5	11.5	10.8
Max [cps]	2486.5	2433.0	176.0	152.3	22.0	20.9	15.1	14.2
StDev [cps]	11.6	8.3	5.3	2.3	0.8	0.6	0.7	0.5
Count	1257	1373	1257	1373	1257	1373	1257	1373
Percent Difference	NA	-2.1%	NA	-13.0%	NA	-4.4%	NA	-5.5%

Table 8-9. Gamma Spectroscopy Summary Statistics, Pad W2, Pre- and Post- Rehabilitation

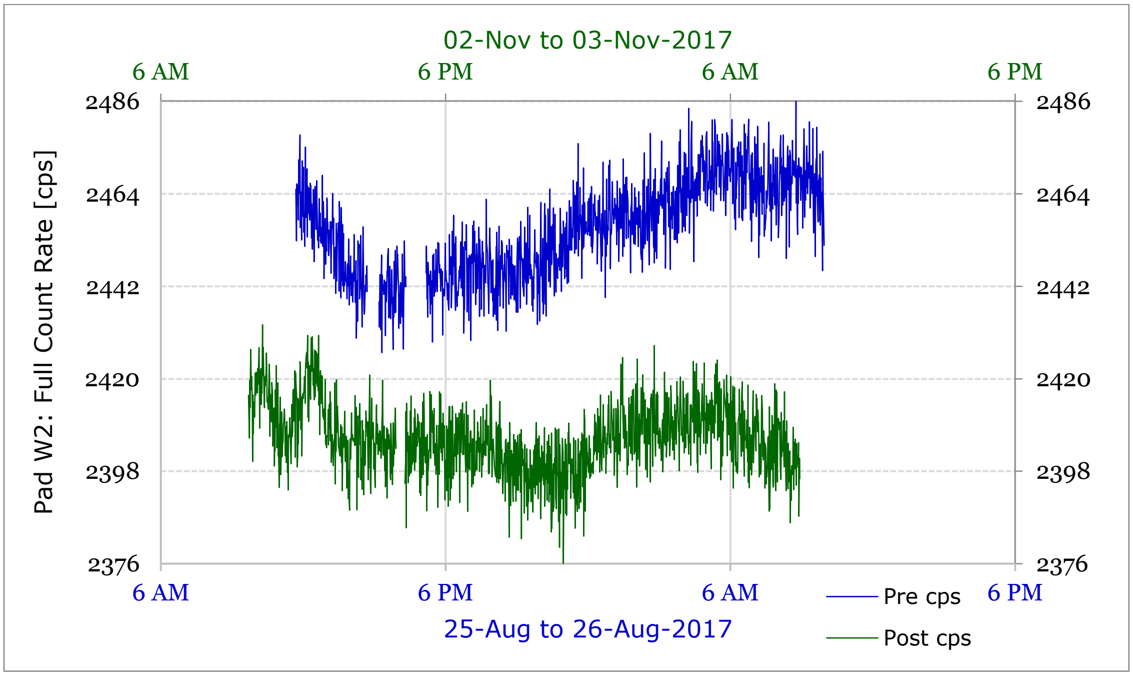

Figure 8-14. Count Rate in Full ROI, Pad W2, Pre- and Post-Rehabilitation

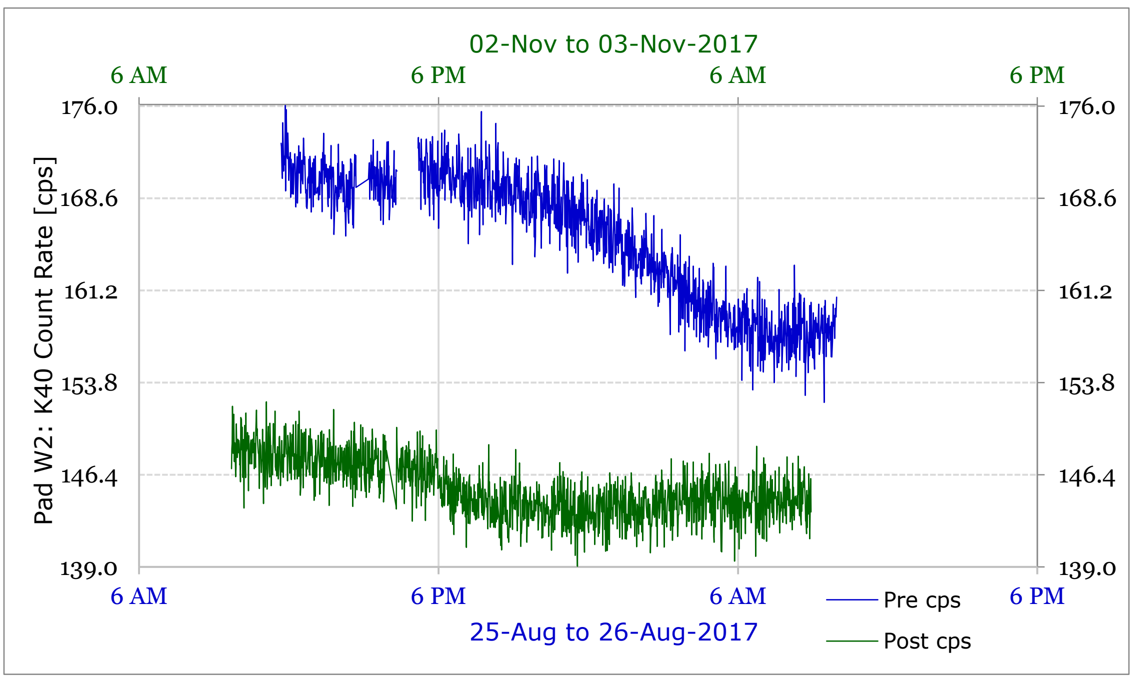

Figure 8-15. Count Rate in the K-40 ROI, Pad W2, Pre- and Post-Rehabilitation

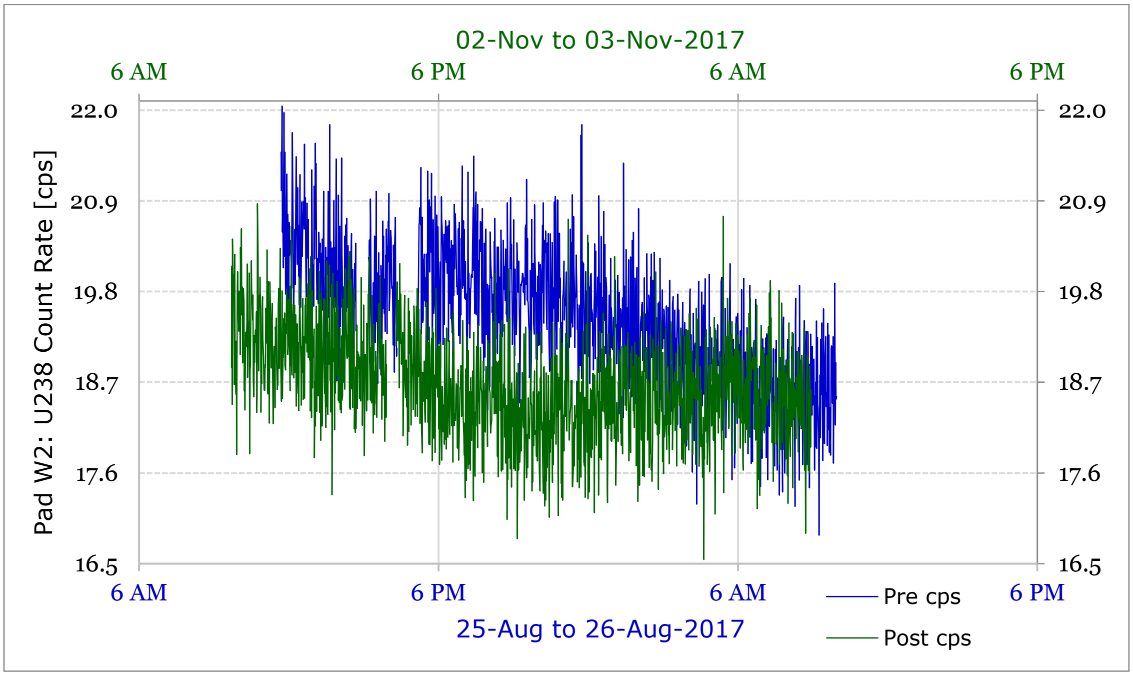

Figure 8-16. Count Rate in the U-238 ROI, Pad W2, Pre- and Post-Rehabilitation

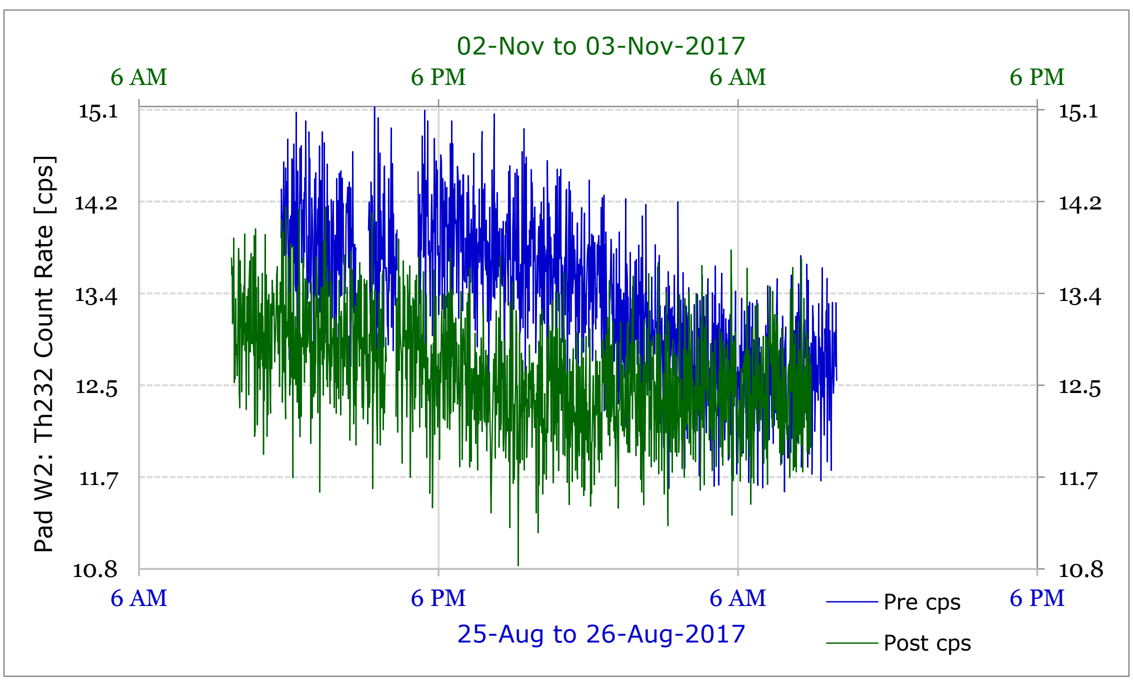

Figure 8-17. Count Rate in the Th-232 ROI, Pad W2, Pre- and Post-Rehabilitation

3. PAD W3

The results of the gamma spectroscopic measurements collected on Pad W3 are presented in Figure 8-17 through Figure 8-21, and statistically summarized in Table 8-10.

	Pad W3: Full		Pad W3: K40		Pad W3: U238		Pad W3: Th232	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Average [cps]	3736.6	3726.4	101.5	96.2	41.5	41.0	60.8	58.6
Median [cps]	3735.0	3724.9	101.8	96.2	40.3	41.0	59.9	58.5
Min [cps]	3664.7	3697.2	95.9	91.9	36.6	38.5	49.1	55.4
Max [cps]	3841.4	3779.5	106.9	100.7	47.0	44.0	68.6	62.2
StDev [cps]	14.4	13.1	2.0	1.2	2.6	0.9	3.5	1.1
Count	1291	1310	1291	1310	1291	1310	1343	1310
Percent Difference	NA	-0.3%	NA	-5.5%	NA	1.8%	NA	-2.2%

Table 8-10. Gamma Spectroscopy Summary Statistics, Pad W3, Pre- and Post- Rehabilitation

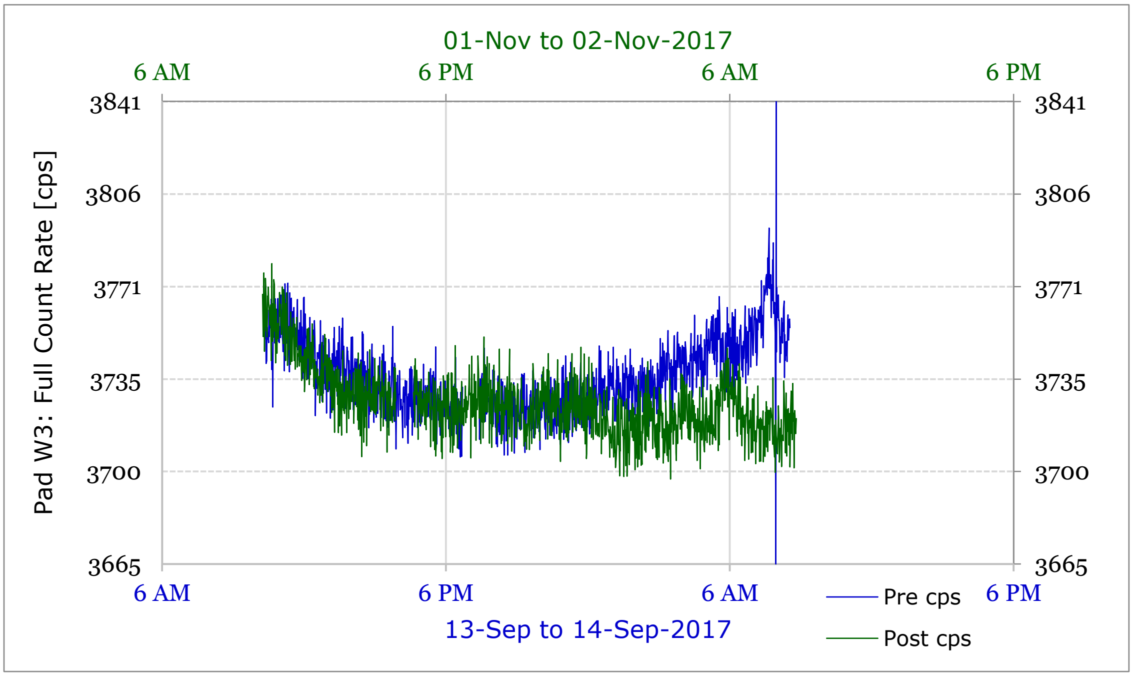

Figure 8-18. Count Rate in Full ROI, Pad W3, Pre- and Post-Rehabilitation

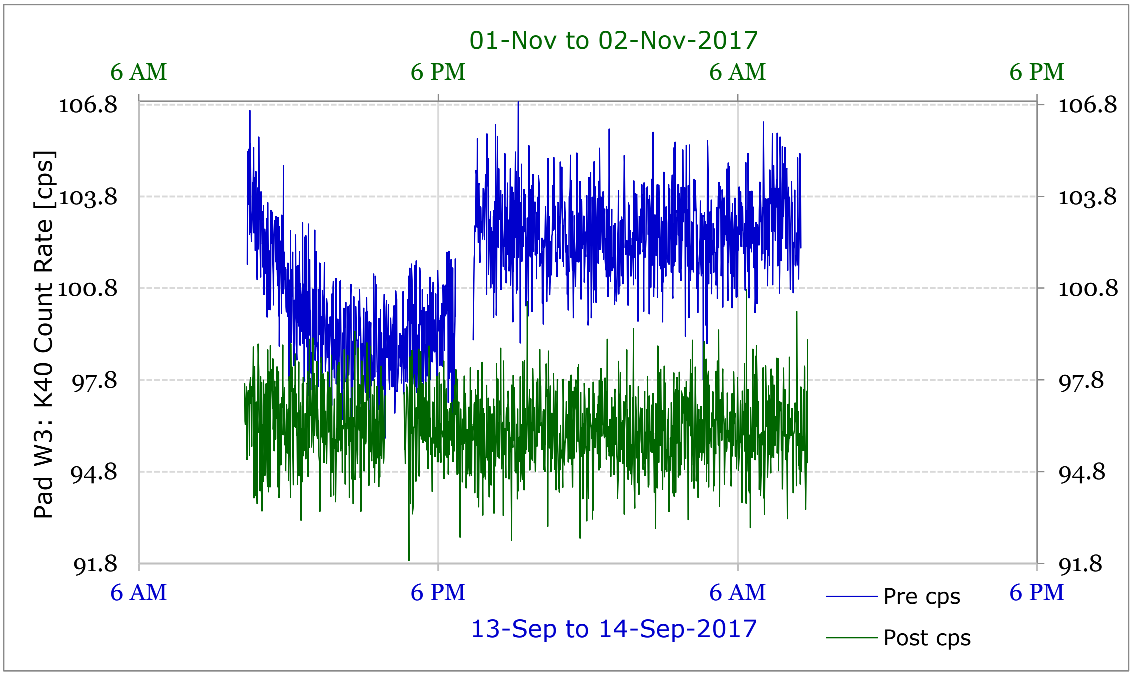

Figure 8-19. Count Rate in the K-40 ROI, Pad W3, Pre- and Post-Rehabilitation

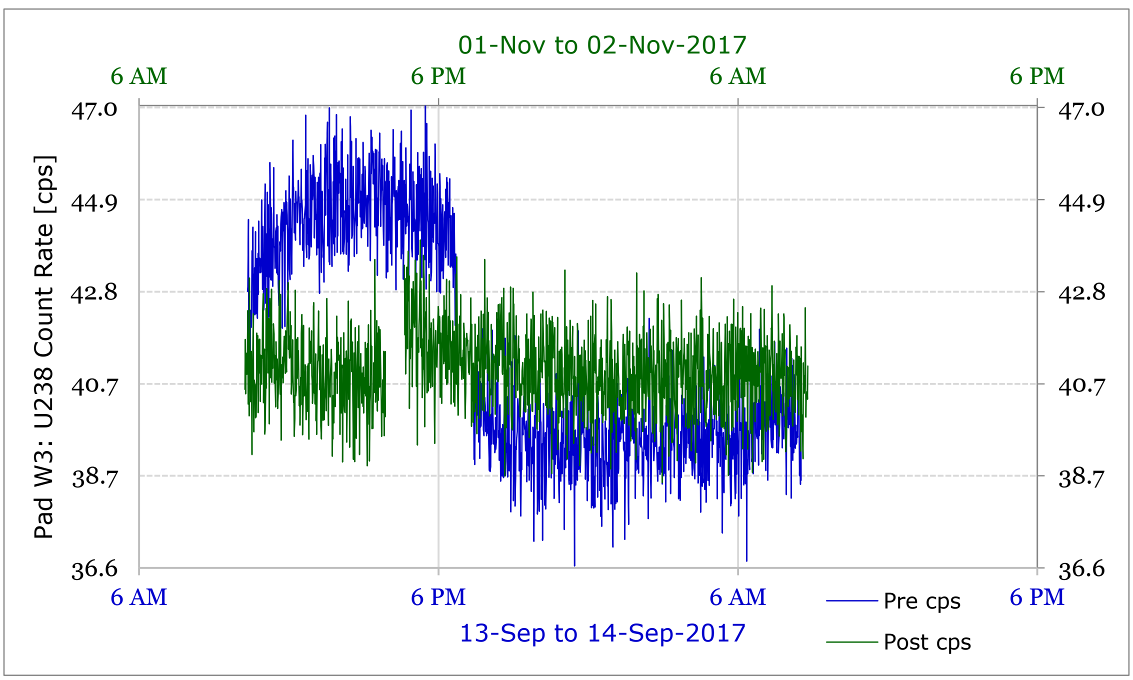

Figure 8-20. Count Rate in the U-238 ROI, Pad W3, Pre- and Post-Rehabilitation

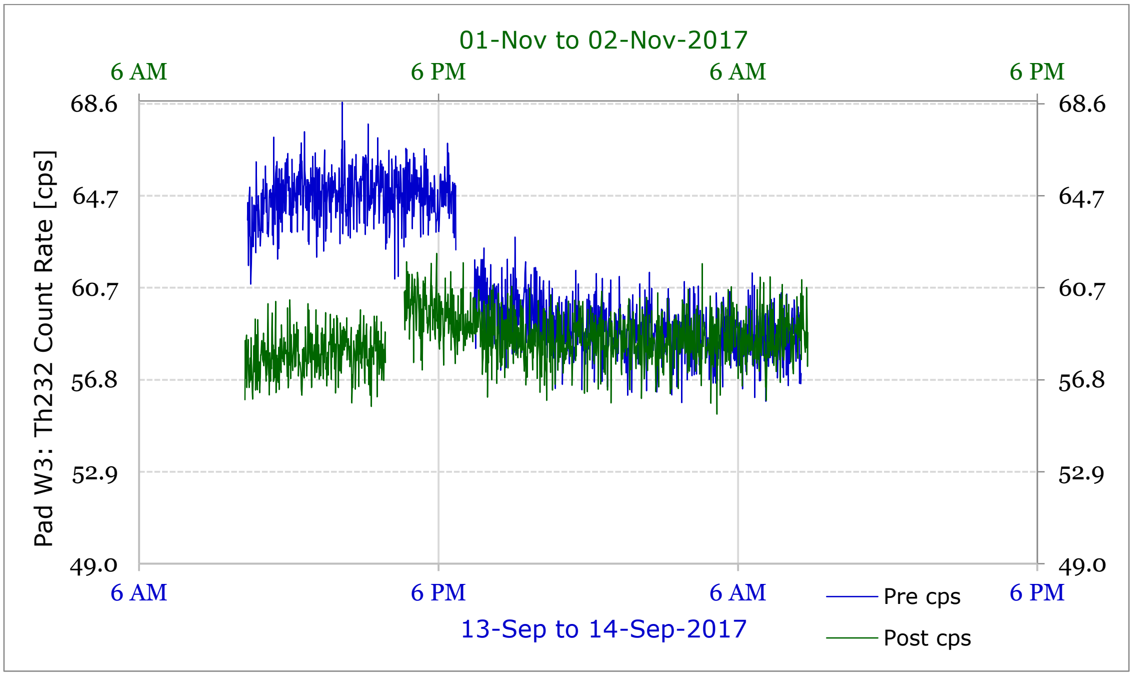

Figure 8-21. Count Rate in the Th-232 ROI, Pad W3, Pre- and Post-Rehabilitation

4. PAD W4

The results of the gamma spectroscopic measurements collected on Pad W4 are presented in Figure 8-22 through Figure 8-25, and statistically summarized in Table 8-11.

	Pad W4: Full		Pad W4: K40		Pad W4: U238		Pad W4: Th232	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Average [cps]	5289.7	5318.2	143.8	128.8	90.2	80.9	21.3	15.8
Median [cps]	5290.3	5316.1	143.9	128.0	90.4	80.5	21.3	15.4
Min [cps]	5243.0	5276.3	137.7	120.6	84.7	73.6	19.1	12.9
Max [cps]	5324.8	5365.9	149.4	138.4	95.6	88.7	23.2	20.0
StDev [cps]	14.5	16.2	2.0	4.2	1.9	3.7	0.7	1.5
Count	1009	1329	1009	1329	1009	1329	1009	1329
Percent Difference	NA	0.5%	NA	-11.0%	NA	-10.9%	NA	-27.8%

Table 8-11. Gamma Spectroscopy Summary Statistics, Pad W4, Pre- and Post- Rehabilitation

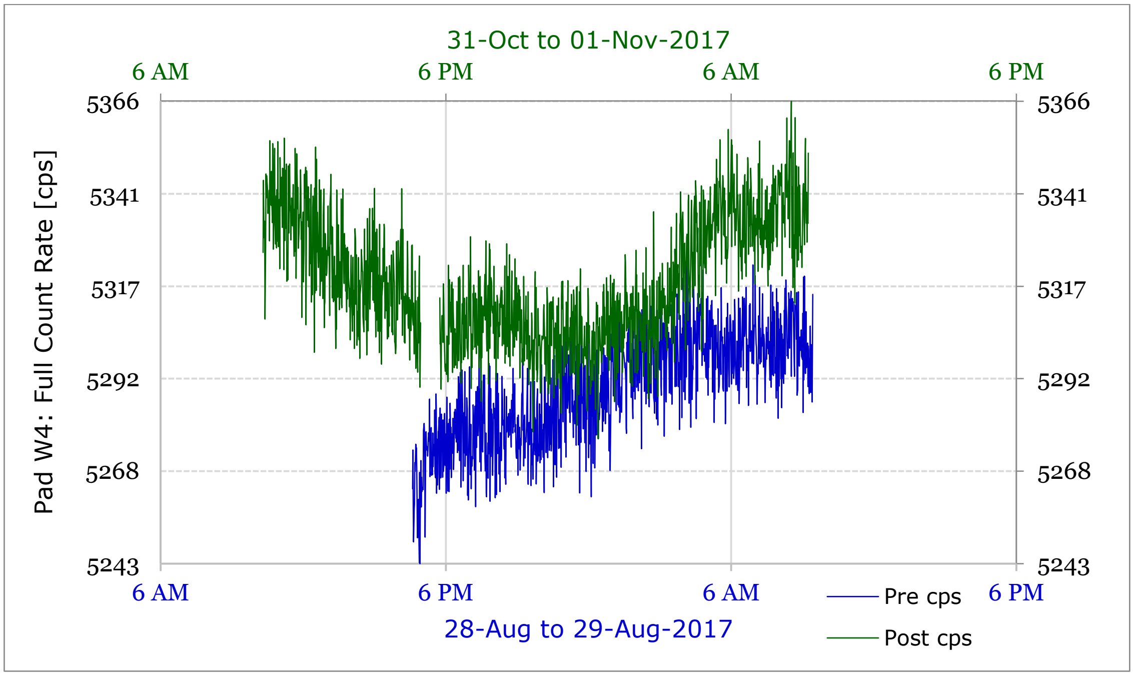

Figure 8-22. Count Rate in Full ROI, Pad W4, Pre- and Post-Rehabilitation

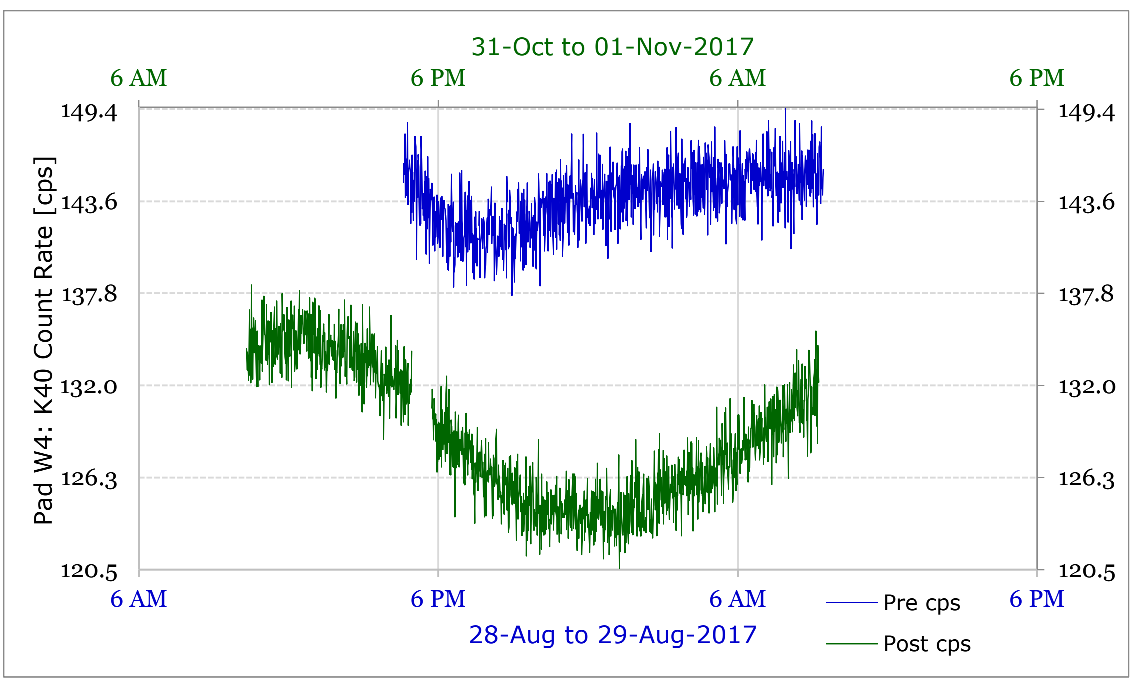

Figure 8-23. Count Rate in the K-40 ROI, Pad W4, Pre- and Post-Rehabilitation

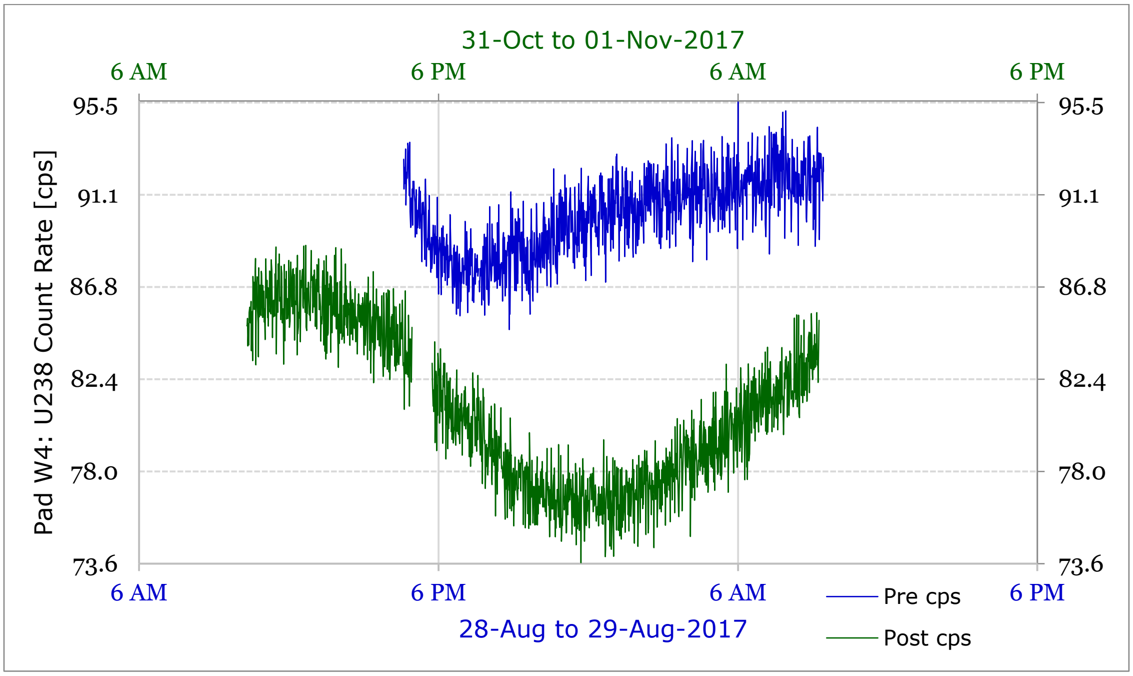

Figure 8-24. Count Rate in the U-238 ROI, Pad W4, Pre- and Post-Rehabilitation

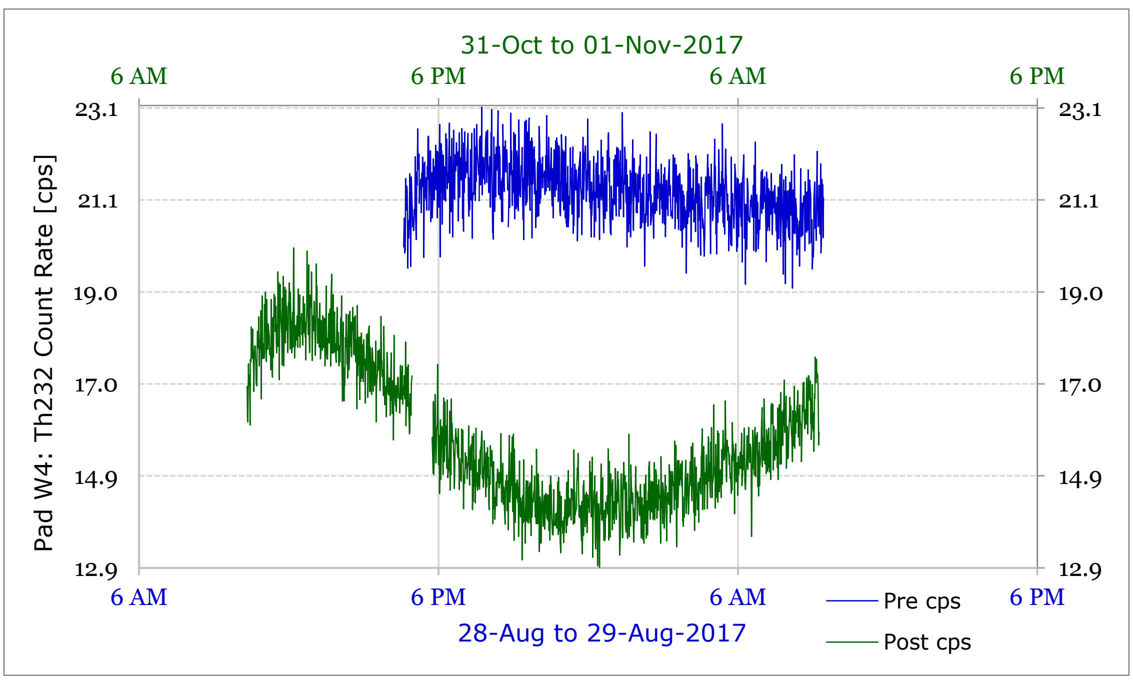

Figure 8-25. Count Rate in the Th-232 ROI, Pad W4, Pre- and Post-Rehabilitation

5. PAD W5

The results of the gamma spectroscopic measurements collected on Pad W5 are presented in Figure 8-26 through Figure 8-29, and statistically summarized in Table 8-12.

	Pad W5: Full		Pad W5: K40		Pad W5: U238		Pad W5: Th232	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Average [cps]	4697.8	4689.8	183.8	164.5	66.2	60.5	29.4	26.3
Median [cps]	4696.9	4689.5	183.7	164.3	66.2	60.4	29.4	26.2
Min [cps]	4665.2	4657.3	178.2	159.1	63.1	57.0	26.8	24.0
Max [cps]	4743.1	4740.2	190.1	170.3	69.7	65.2	32.1	29.4
StDev [cps]	13.7	10.8	1.8	2.0	1.1	1.3	0.8	1.0
Count	1349	1388	1349	1388	1349	1388	1349	1388
Percent Difference	NA	-0.2%	NA	-10.6%	NA	-8.7%	NA	-10.8%

Table 8-12. Gamma Spectroscopy Summary Statistics, Pad W5, Pre- and Post- Rehabilitation

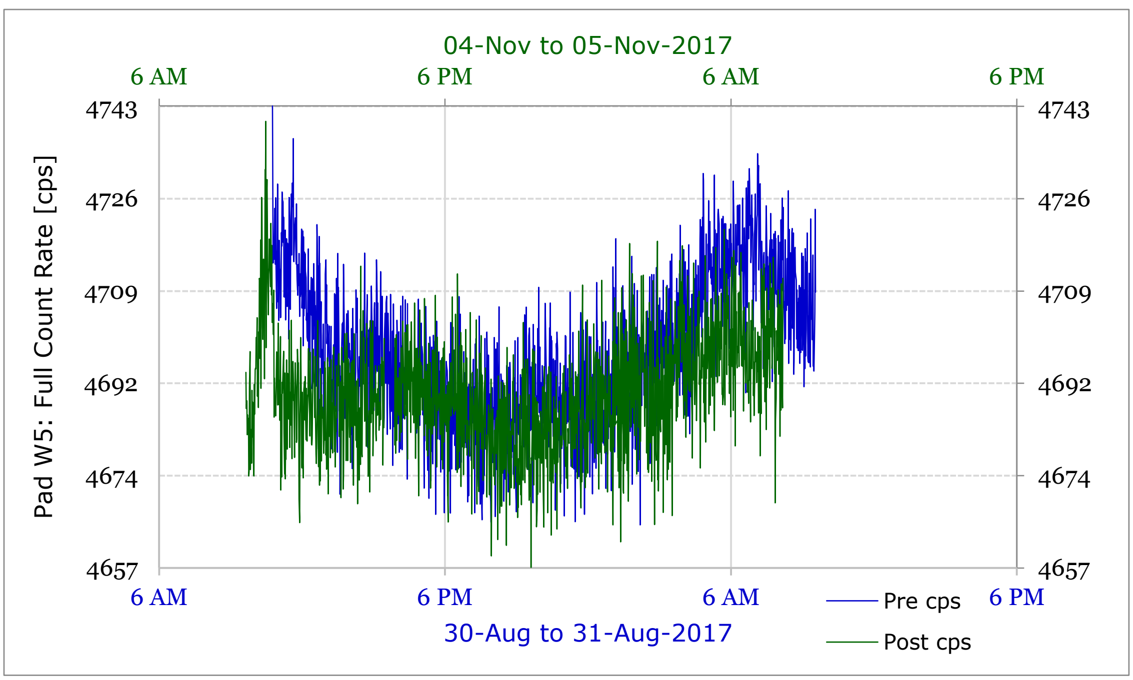

Figure 8-26. Count Rate in Full ROI, Pad W5, Pre- and Post-Rehabilitation

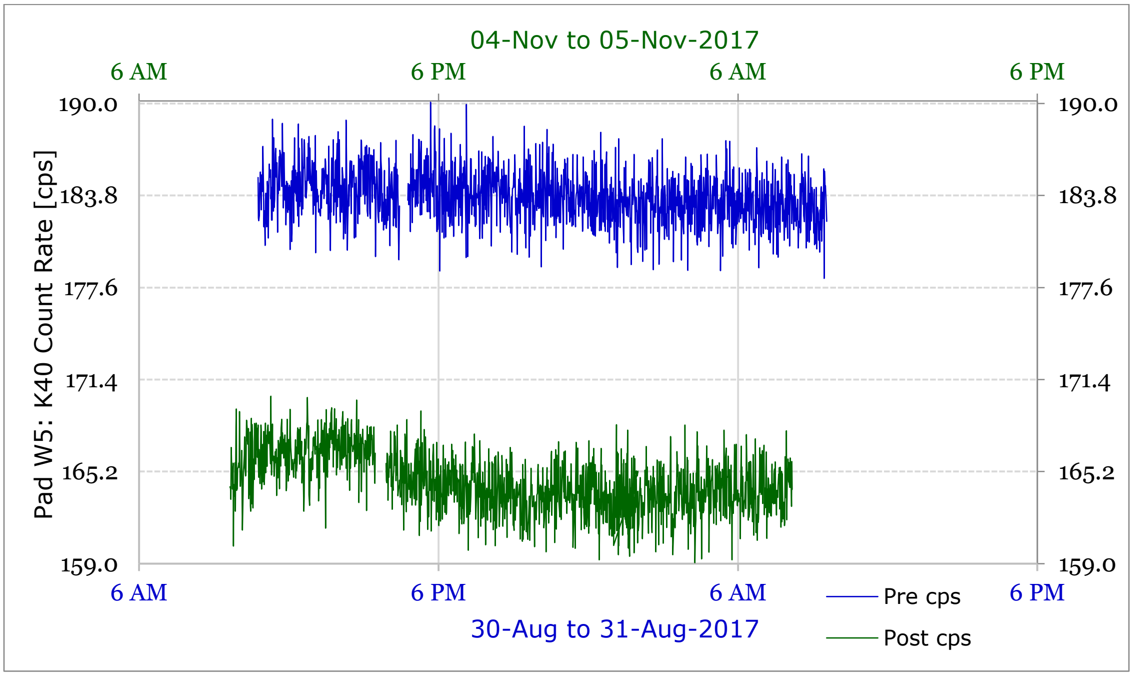

Figure 8-27. Count Rate in the K-40 ROI, Pad W5, Pre- and Post-Rehabilitation

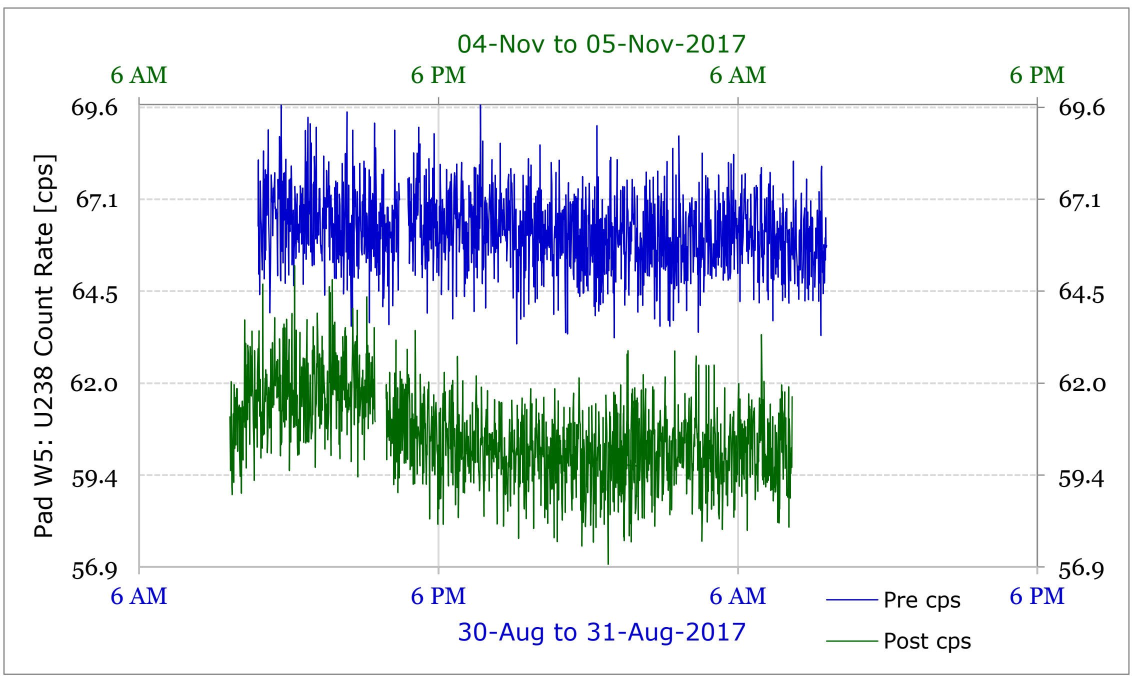

Figure 8-28. Count Rate in the U-238 ROI, Pad W5, Pre- and Post-Rehabilitation

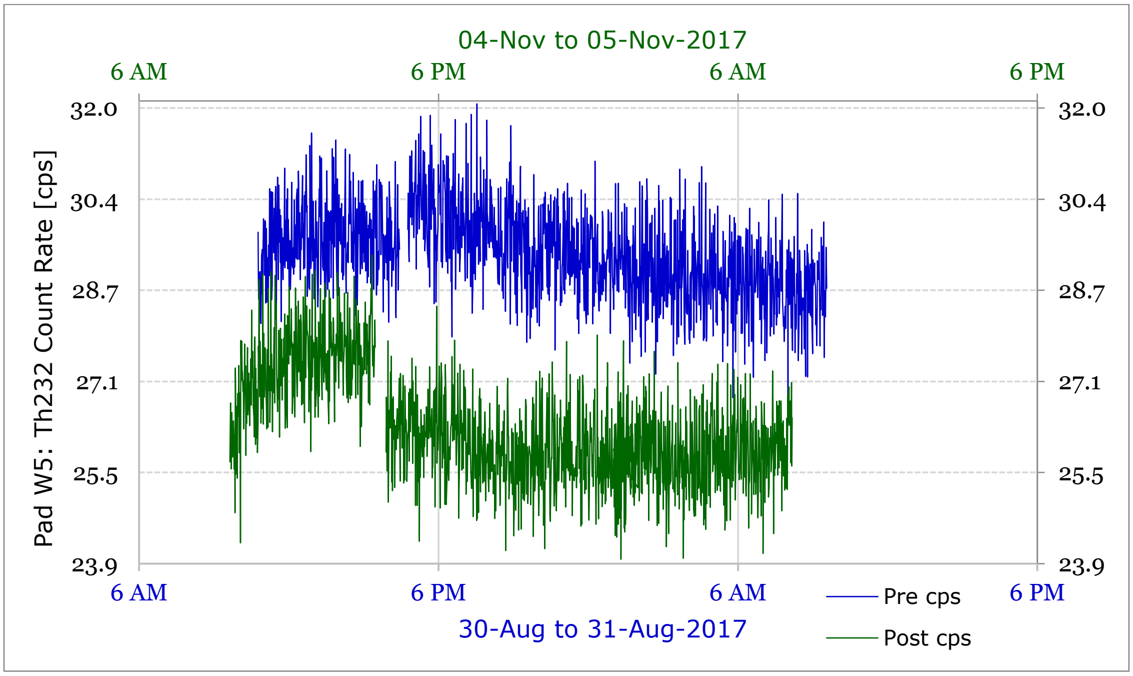

Figure 8-29. Count Rate in the Th-232 ROI, Pad W5, Pre- and Post-Rehabilitation

9. ANALYSIS OF THE CALIBRATION PADS RADIOMETRIC SURVEYS

A. OVERLAND SCAN SURVEYS

The Mann-Whitney U-test was performed on the spectroscopic data collected during the pre- and post-rehabilitation overland surveys. Each spectral region of interest was evaluated. The results of these tests are presented in Table 9-1.

	K-40	Th-232	U-238	Full
P-Statistic	1.0%	0.3%	0.0%	0.0%

Table 9-1. Overland Scan Survey Mann-Whitney U-Test Results

The P-statistic represents the probability that the pre- and post-rehabilitation datasets are statistically distinguishable. This analysis shows there is no statistically significant differences between pre- and post-rehabilitation radiometric conditions in the general area surrounding the Cal Pads, with a confidence index of 99%.

B. GENERAL AREA BACKGROUND GAMMA SPECTROSCOPY

Both diurnal and seasonal variations were observed in the general area background levels (Figure 8-1 through Figure 8-4). Stromswold hypothesized similar variations observed directly above the Cal Pads were correlated with relative humidity (DOE 1978). Barometric pressure, temperature, and wind speed are other environmental parameters known to influence the atmospheric radon concentration near the ground surface. The temporal relationship between these atmospheric parameters during the pre- and post-rehabilitation surveys and the general area Full ROI background count rates observed are presented in Figure 9-1 and Figure 9-2. Similar trends were observed in the background count rates in the K-40 (Figure 9-3 & Figure 9-4), U-238 (Figure 9-5, and Figure 9-6), and Th-232 ROIs (Figure 9-7 and Figure 9-8), with magnitude of the influence decreasing as the observed photon energy increased. This is expected as the primary gamma emissions of radon gas are less than 1 MeV, thus have little influences on higher energy ROIs.

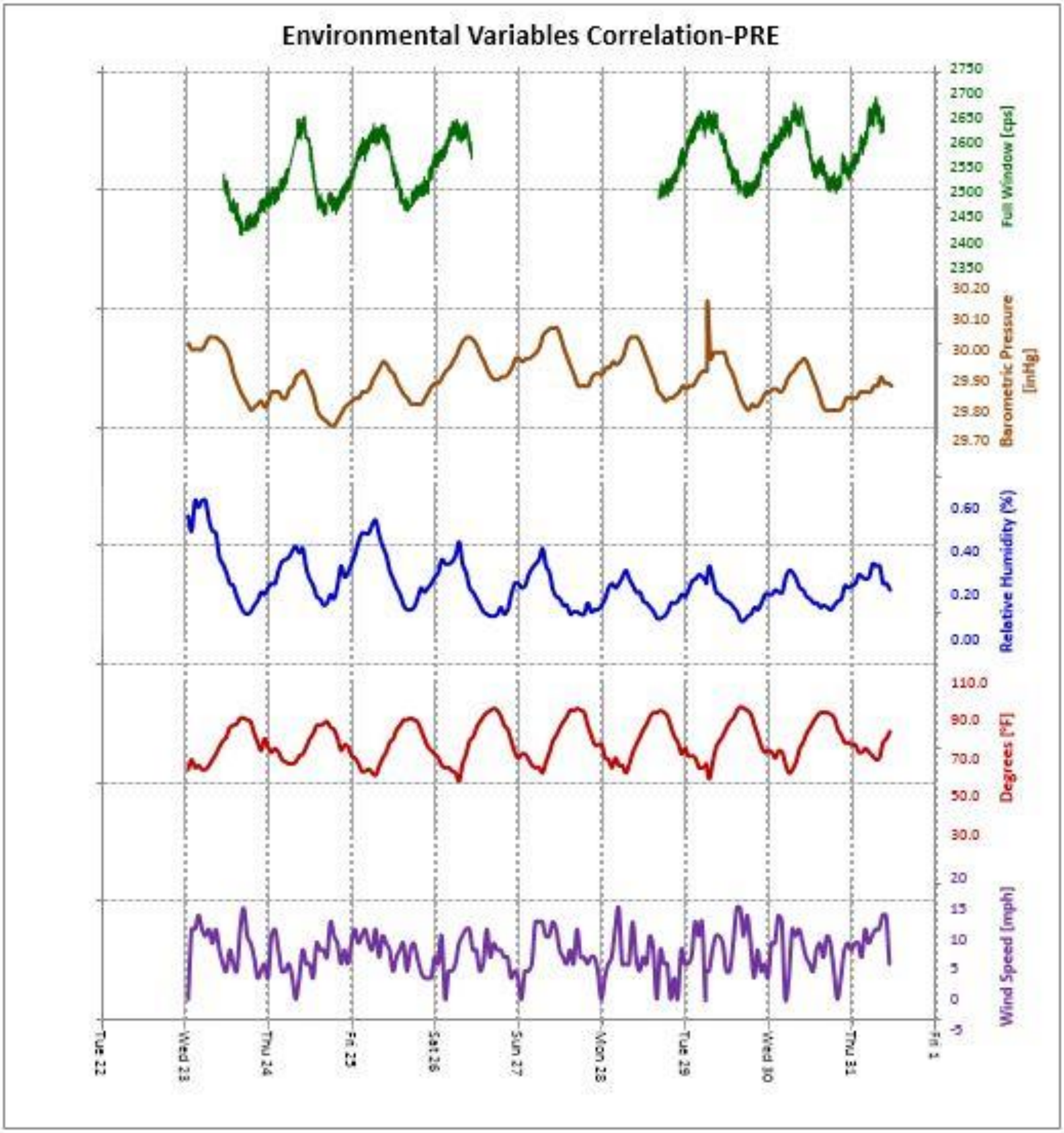

Figure 9-1. Environmental Factors and Background Full ROI Count Rate, Pre-Construction

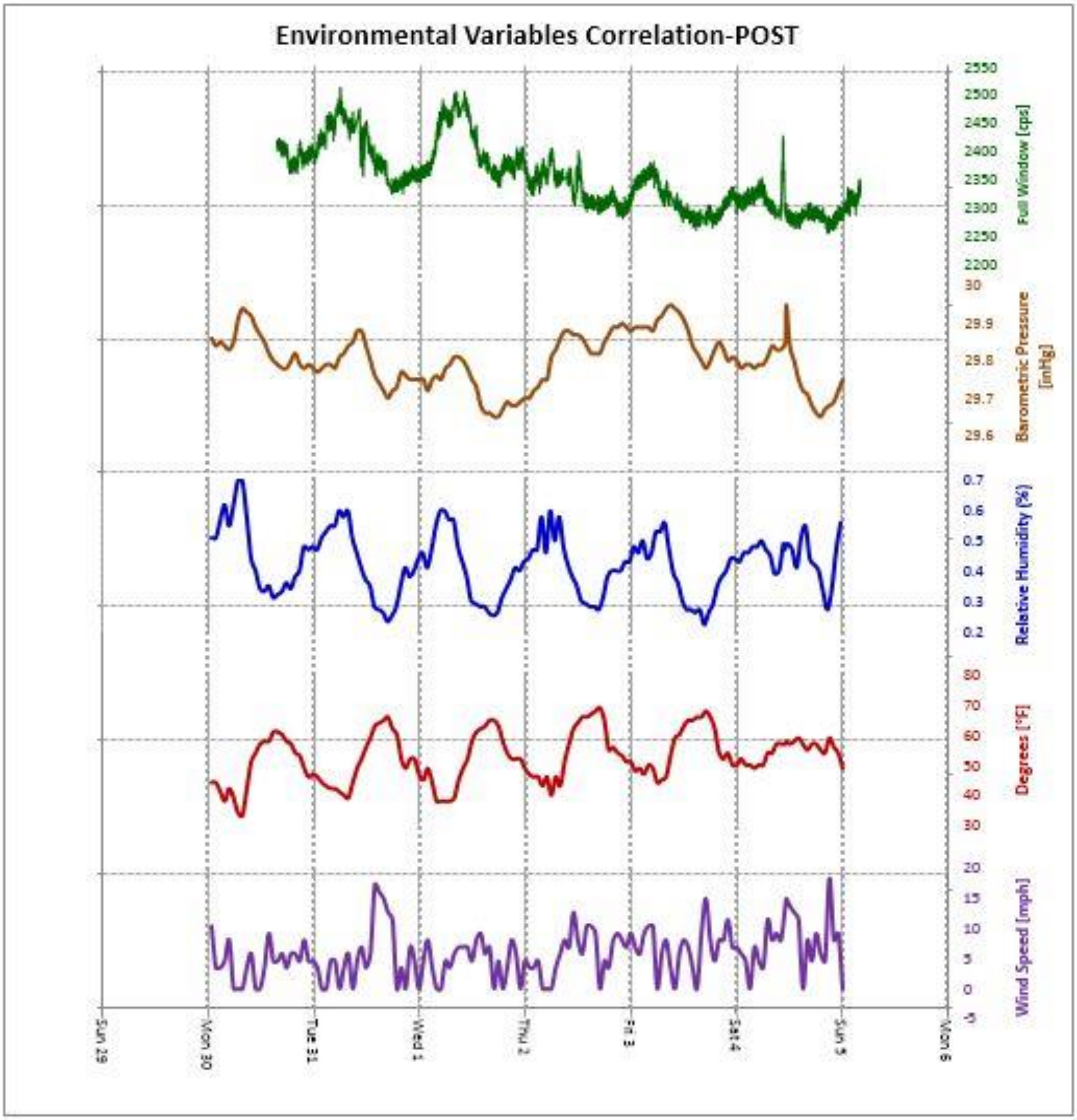

Figure 9-2. Environmental Factors and Background Full ROI Count Rate, Post-Construction

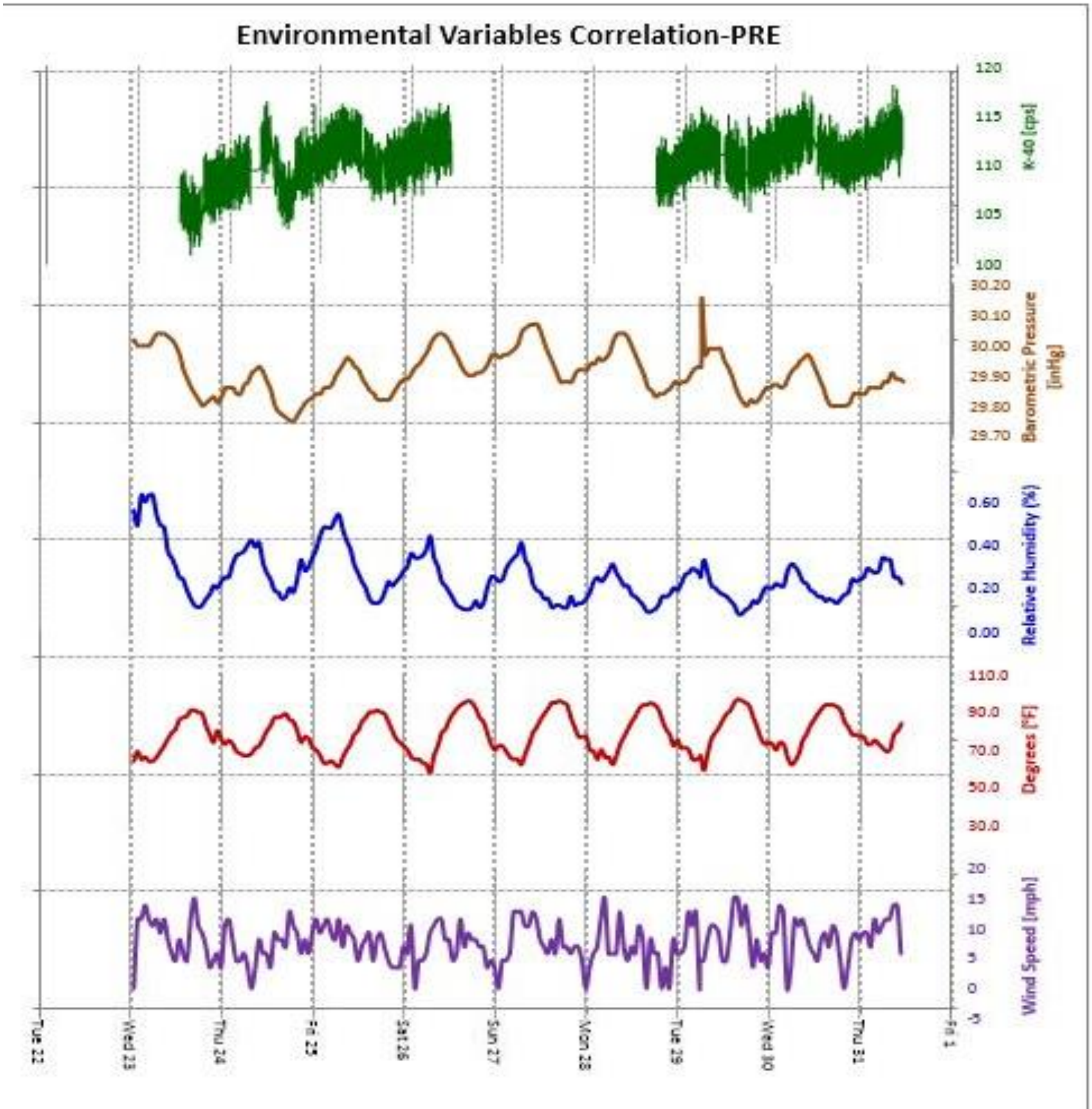

Figure 9-3. Environmental Factors and Background K-40 ROI Count Rate, Pre-Construction

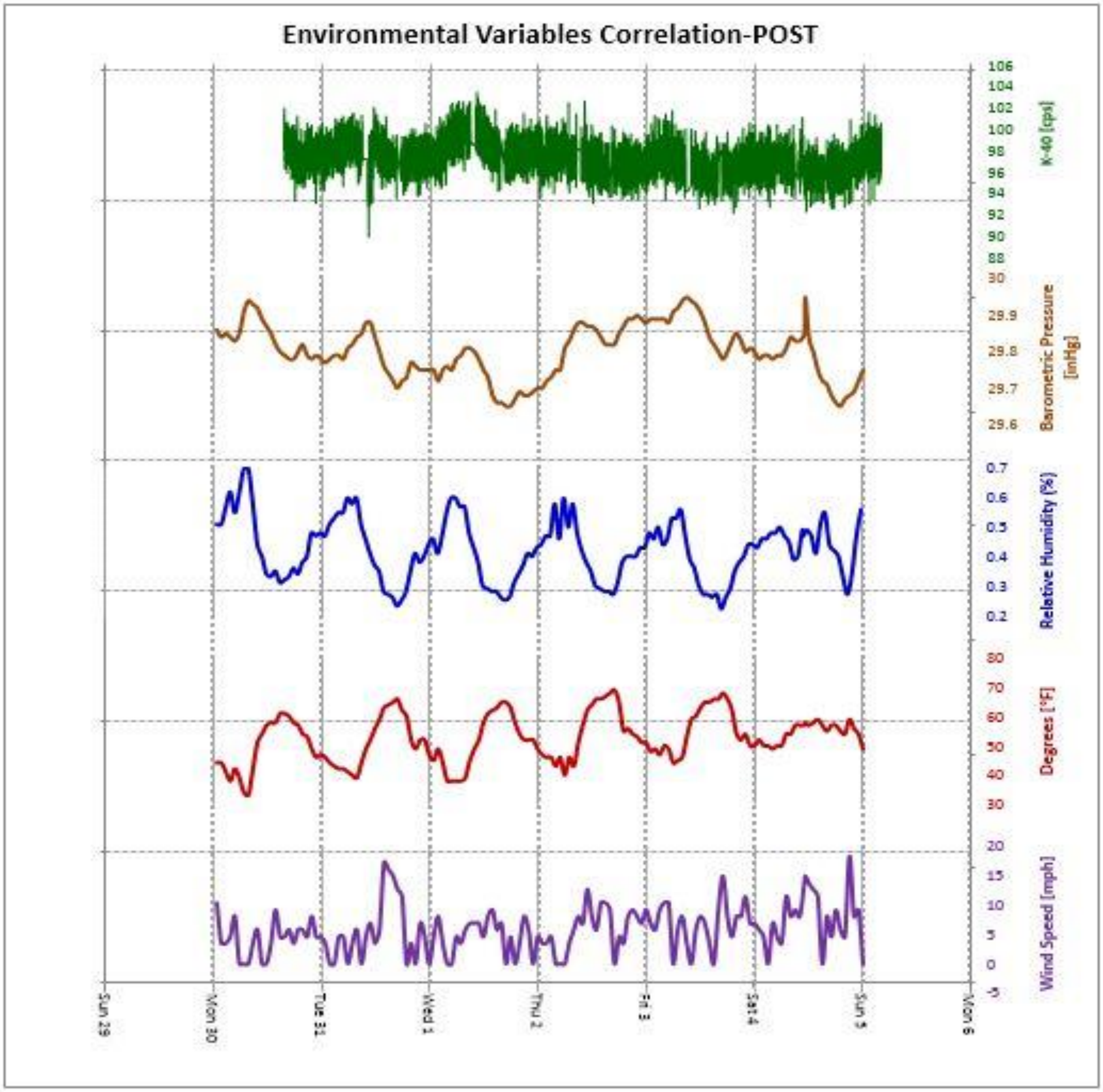

Figure 9-4. Environmental Factors and Background K-40 ROI Count Rate, Post-Construction

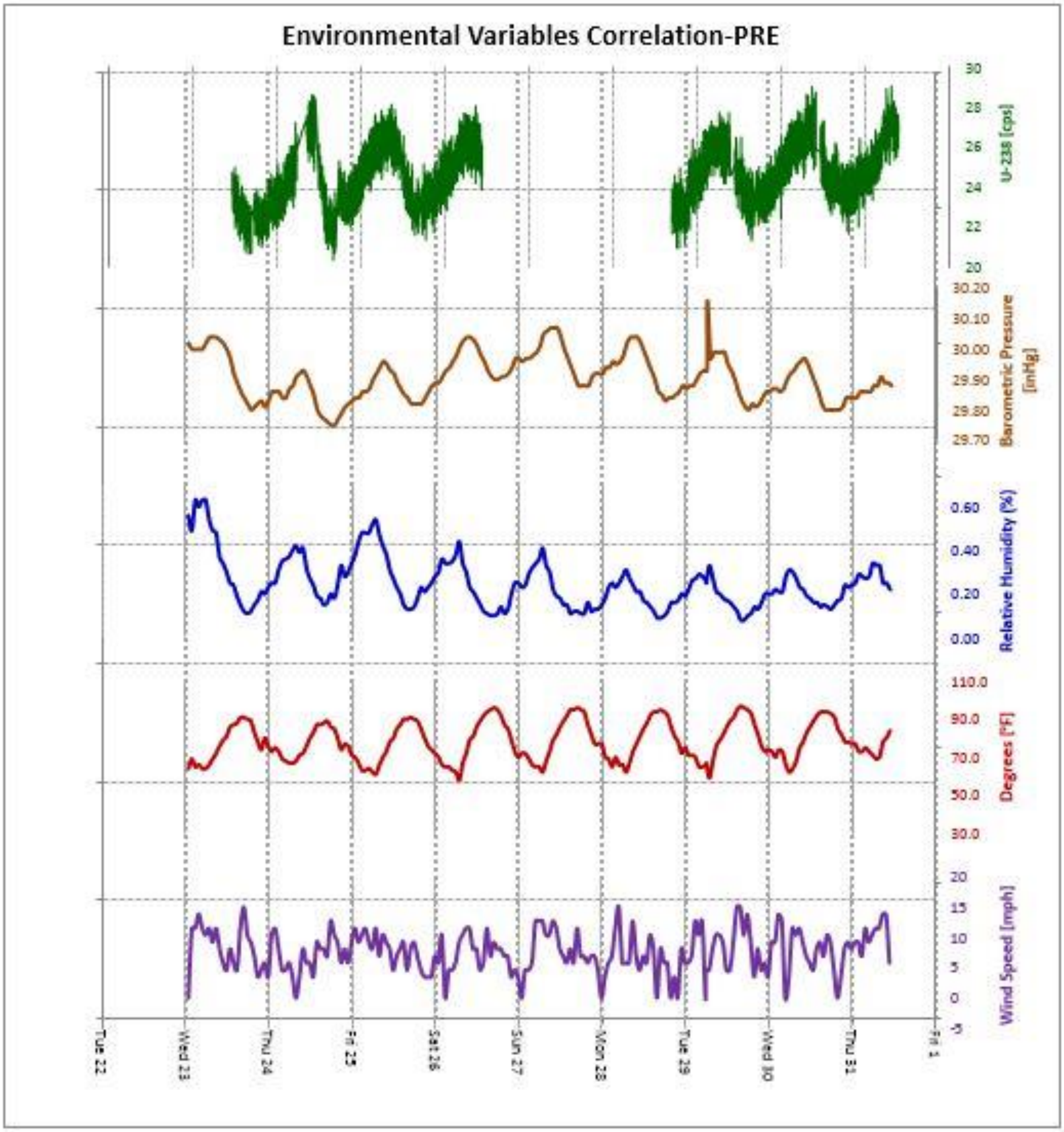

Figure 9-5. Environmental Factors and Background U-238 ROI Count Rate, Pre-Construction

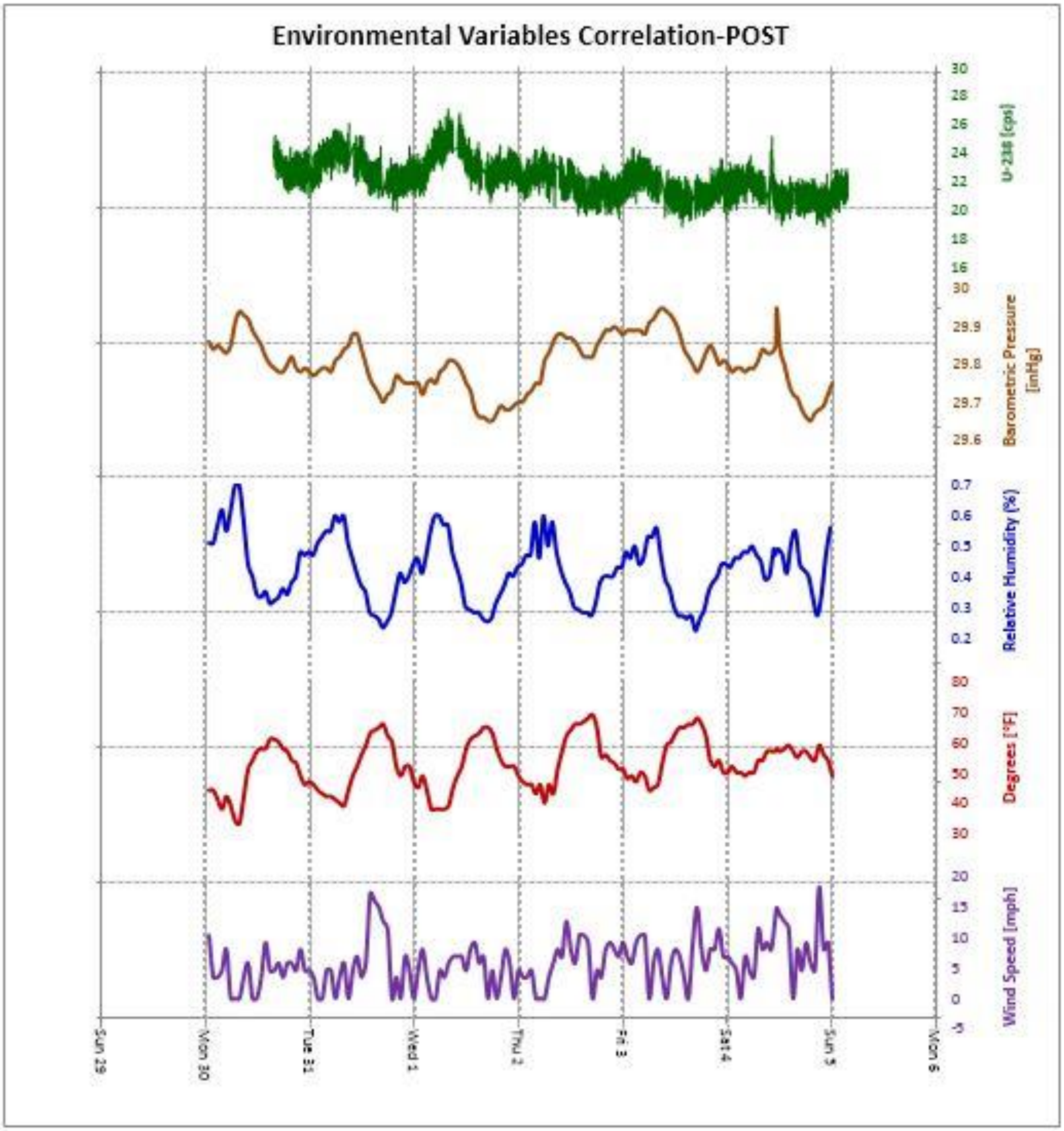

Figure 9-6. Environmental Factors and Background U-238 ROI Count Rate, Post-Construction

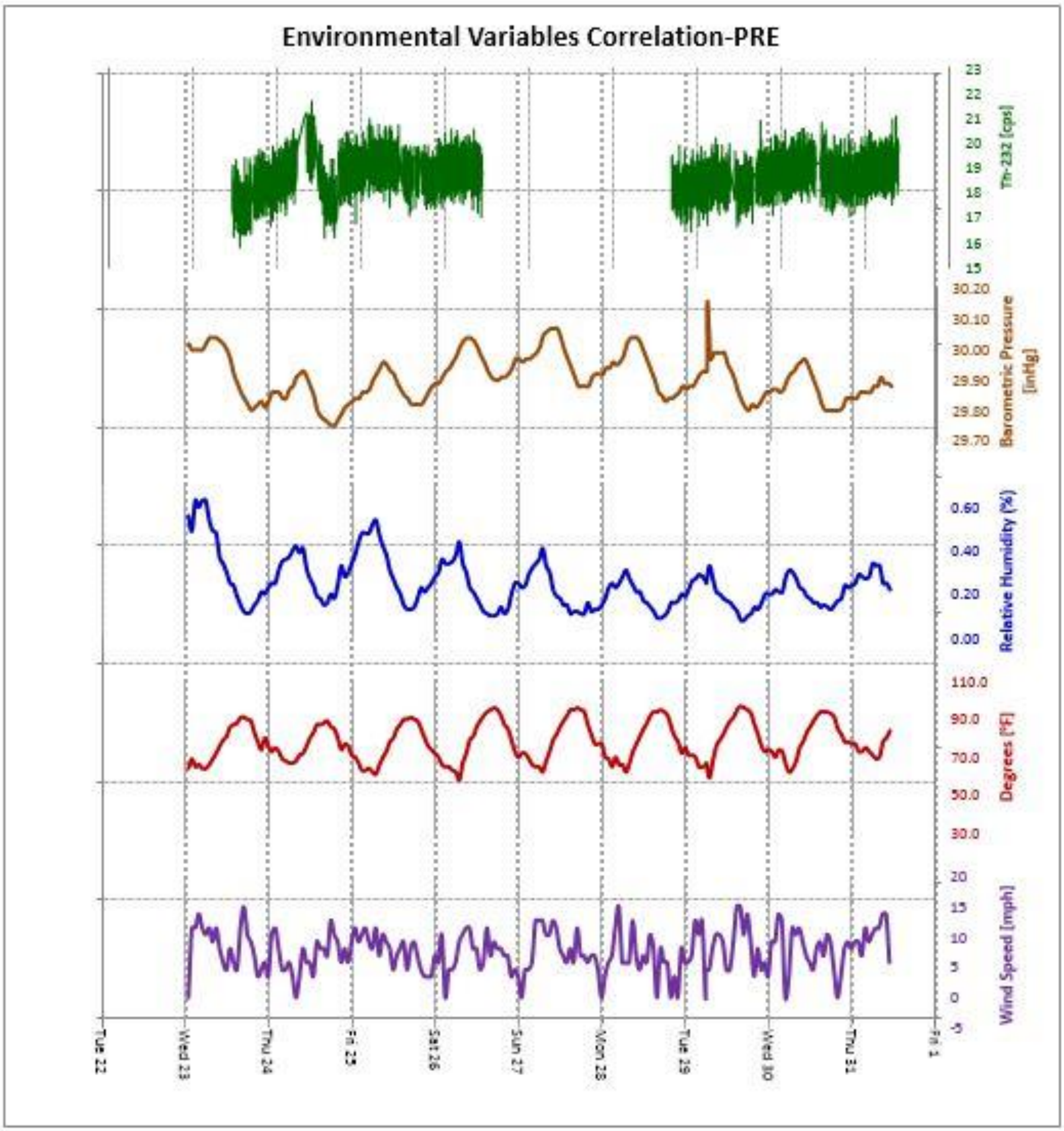

Figure 9-7. Environmental Factors and Background Th-232 ROI Count Rate, Pre-Construction

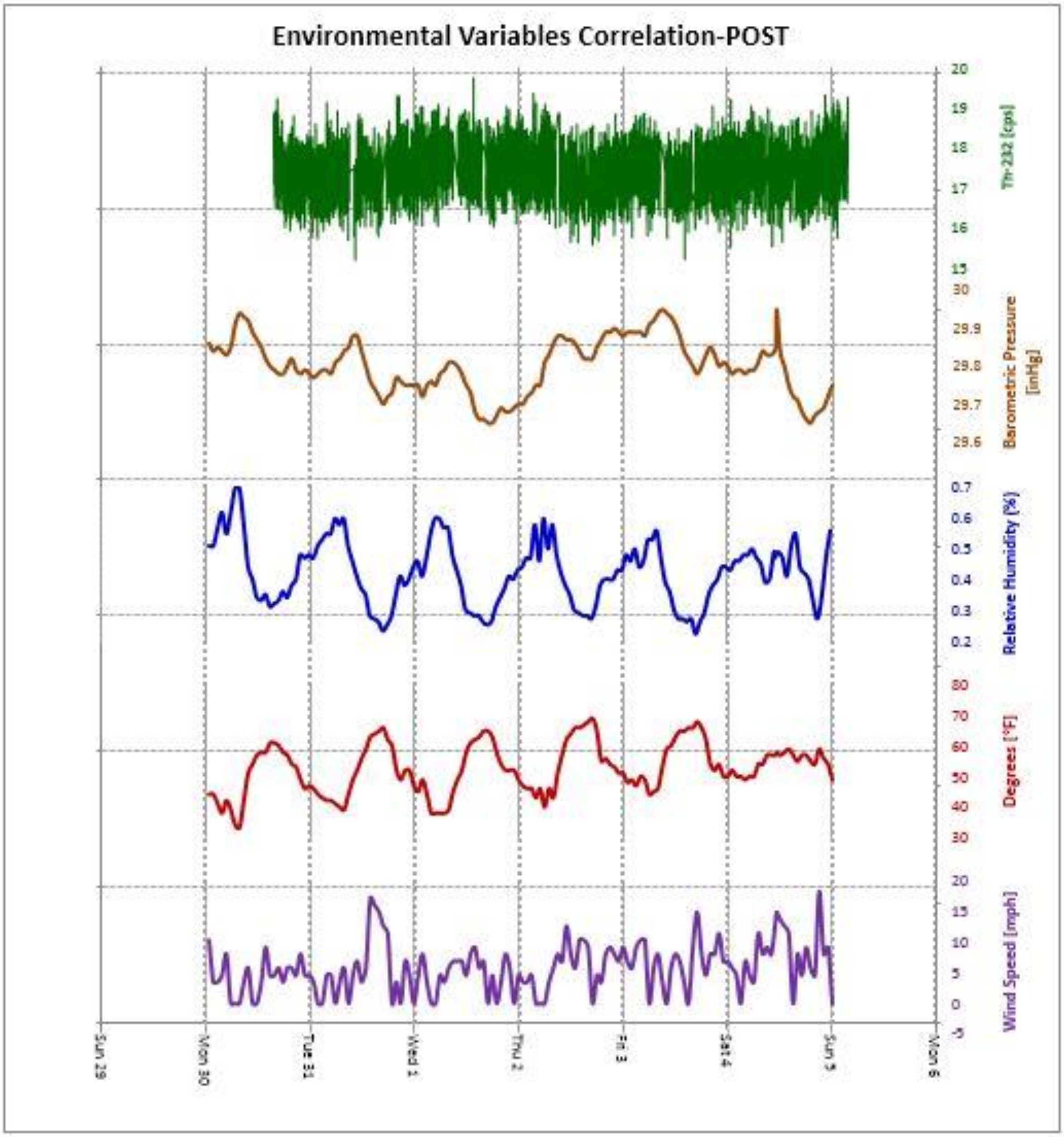

Figure 9-8. Environmental Factors and Background Th-232 ROI Count Rate, Post-Construction

C. Long-Duration Calibration Pad Measurements

A series of box plots was created to analyze the radiometric measurements collected on the Cal Pads as paired (pre- and post-rehabilitation) datasets. An example of such a figure (for the Full ROI gamma spectroscopic results from Pad W5) is presented in Figure 9-9. The pre- rehabilitation datasets are represented by the blue box plots and the post-rehabilitation datasets by the green box plots.

The calculated loss of gamma signal as determined by the MicroShield® model is represented by the horizontal light blue lines. The top light blue line represents the median value from the pre-rehabilitation (baseline) survey and the bottom blue line represents the calculated post-rehabilitation gamma signal. The thickness between the upper and lower lines represents the magnitude of the calculated loss of signal due to the rehabilitation process. In many cases both lines appear as a single line due to the negligible loss of signal caused by the rehabilitation process.

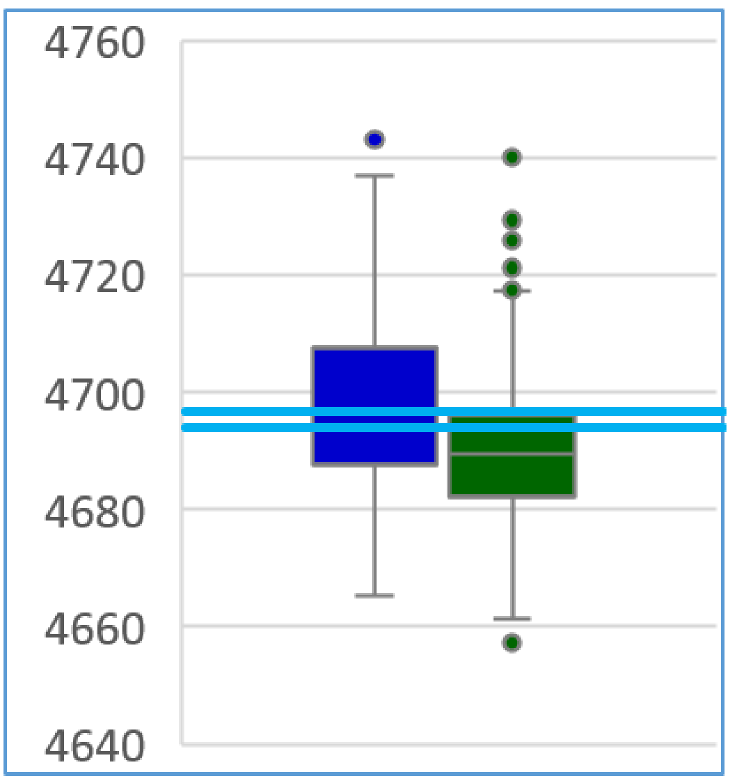

Figure 9-9. Example Paired Box-Plot Figure, Pre- and Post-Construction

The long duration gamma exposure and spectroscopy results for the measurements collected on the Cal Pads were evaluated as paired sets (pre- and post-rehabilitation), for each radiometric parameter investigated on each Cal Pad (Figure 9-10). In this context, both diurnal and seasonal variances can be discerned and compared to the calculated loss of gamma signal. The diurnal variances are those that exist within either the pre- or post-rehabilitation datasets, i.e. the structure of the box plots. Larger vertical stretches in the box-plots represent larger diurnal variations in the dataset. The seasonal variances are those that exist between the pre- and post-rehabilitation datasets, i.e. the offsets between the pairs of boxplots. Larger vertical offsets between the medians of the pre- and post-rehabilitation box-plots represent larger seasonal variations in the datasets. Notably, both diurnal and seasonal variances far outweigh the calculated variances in each case. Furthermore, the large (diurnal) variances observed in the pre-rehabilitation clearly are not due to the rehabilitation process and can only be attributed to environmental factors.

Further analysis of Figure 9-10 shows that the majority of the post-rehabilitation radiometric results decreased from the baseline, with some noteworthy exceptions. For example, on Pad W4 the K-40, U-238, and Th-232 ROI results decreased in the post-rehabilitation survey, but the Full ROI and exposure (HPIC) results increased. Also, the exposure results increased on Pads W3, W4, and W5, generally disagreeing with the spectroscopic results. These anomalies are further indication that the variances in the radiometric measurements due to the prevailing environmental conditions significantly confound the results.

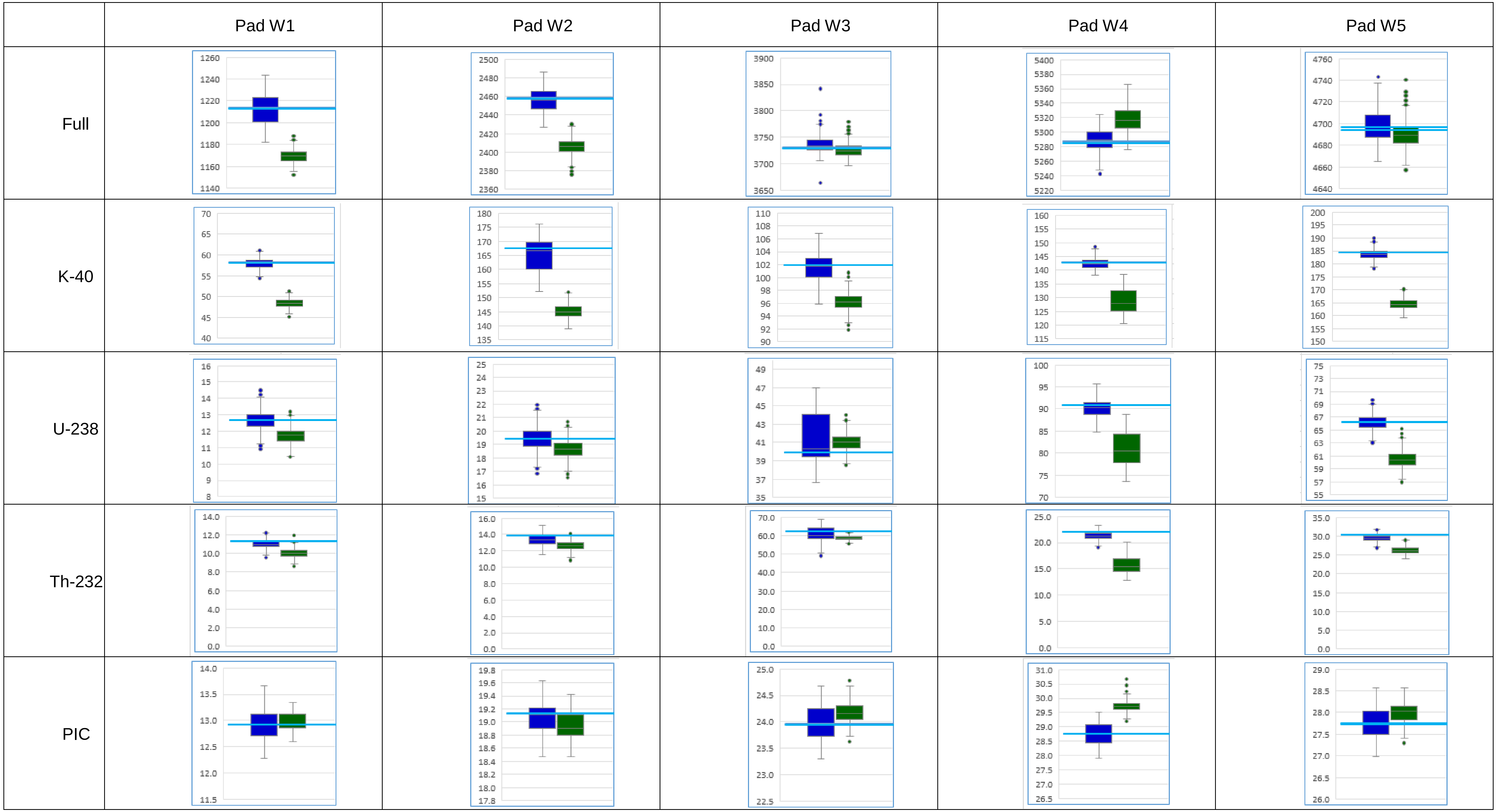

Figure 9-10. Pre- vs. Post-Rehabilitation Variance Matrix

10. ANALYSIS OF ENVIRONMENTAL PARAMETERS ON THE CALIBRATION PADS RADIOMETRIC SURVEYS

The radiometric results obtained during the Grand Junction Calibration Pad Rehabilitation Project showed significant variations due to environmental factors.

A. ASSESSMENT OF ENVIRONMENTAL FACTORS ON RADIOMETRIC MEASUREMENTS COLLECTED IN GRAND JUNCTION, CO

The general area background results indicate both diurnal and seasonal variations in radiometric measurements collected at the Grand Junction Regional Airport, up to 14% (in the K-40 ROI). These observed variances are corroborated by data obtained from the Grand Junction RadNet facility, which is a near-real time monitoring facility designed to observe the concentrations of radioactive material in the atmosphere in Grand Junction, CO. RadNet is a nationwide network of radiation detectors operated by the U.S, Environmental Protection Agency that monitors the nation's air, precipitation and drinking water for radiation.

RadNet gross gamma count rates collected at the Grand Junction facility from 2013 to 2017, presented in Figure 10-1, illustrate the annual variances observed in the gross gamma count rates in Grand Junction (RadNet 2017). The diurnal variances reported by the Grand Junction RadNet facility during the pre-rehabilitation survey are presented in Figure 10-2 (RadNet 2017). The Grand Junction RadNet facility was offline during the post-rehabilitation survey, thus no data is available for that period.

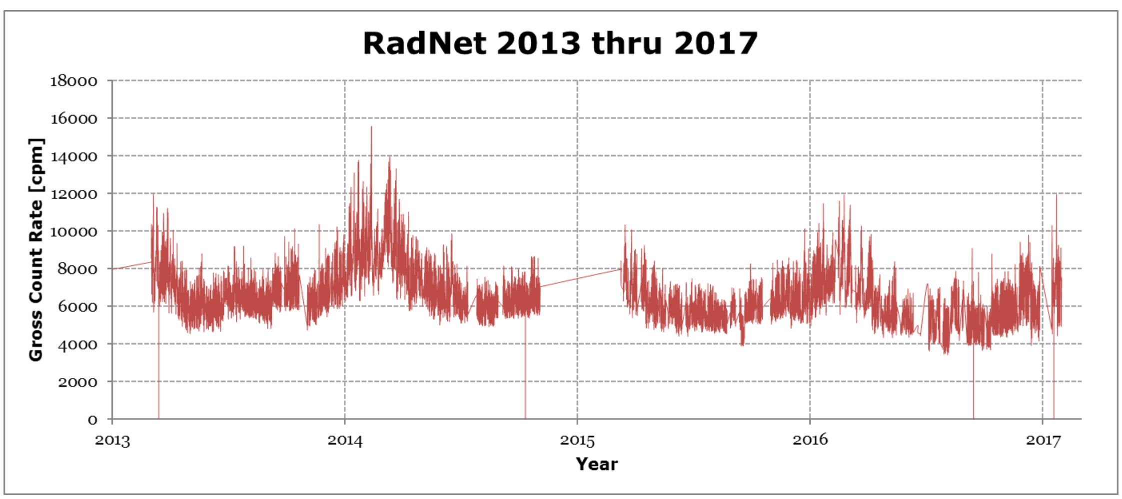

Figure 10-1. RadNet Full Gamma Count Rate, 2013 - 2017

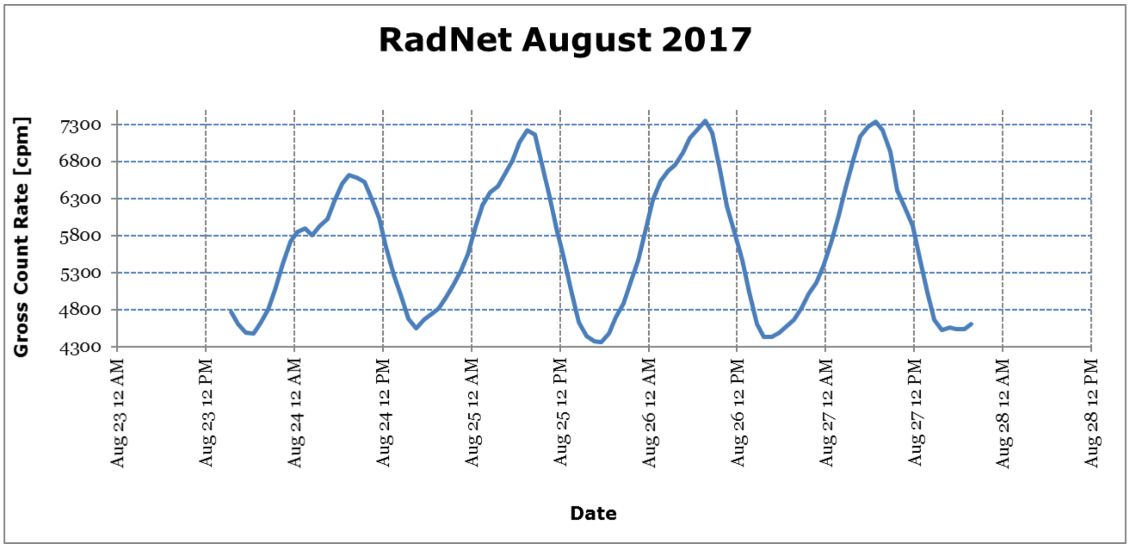

Figure 10-2. RadNet Full Gamma Count Rate, 23-28 August 2017

The radiometric diurnal cycle was quite stable in the general area background measurements during the pre-rehabilitation survey, with daily minimum and maximum results in close agreement throughout the survey (Figure 8-1 through Figure 8-4). The diurnal cycle during the post-rehabilitation survey, while still apparent, had significantly more variances among the observed daily minimums and maximums, as well as greater instability within a single diurnal cycle. The first two days of the post-rehabilitation survey are in close agreement with each other, but reduced count rates and diurnal swings were observed beginning on 2 November 2017 and continuing throughout the remainder of the survey.

B. Assessment of Environmental Factors on the Gamma Flux Directly Above the Calibration Pads

The seasonal variances in the radiometric measurements collected at the Cal Pads due to environmental factors were first observed in data collected from October 1977 - April 1978 (DOE 1978). At the time, the variances were primarily attributed to the radon exhalation rates of the Cal Pads themselves, rather than to the general area background radiometric conditions. The fact that such significant variances were now observed in the general area background measurements (up to 14% in the K-40 ROI) strongly indicates that the airborne radon and thoron concentrations in the general area (background) near-surface atmosphere affect radiometric measurements collected at the Cal Pads, in addition to the variances in the radon exhalation rates of the pads themselves. In other words, the gamma fluxes directly above the Cal Pads are influenced by two complex and independent mechanisms of radon and thoron fate and transport, one atmospheric and the other terrestrial.

The variances in the results obtained during the pre- and post-rehabilitation surveys are in general agreement with those reported in 1978, but a direct correlation is obfuscated by the fact that no measurements were collected during the summer months in the previous study.

While the seasonal observations collected in 1978 are valuable, the measurement duration is insufficient to determine an accurate assessment of the seasonal variations in radiometric conditions at the Cal Pads year over year. The additional two sets of data collected during the Grand Junction Calibration Pad Rehabilitation Project augment the existing data to some extent, but not to a degree that allows one to ascertain seasonal or annual trends. It is presumed that the radiometric conditions at the general area surrounding the Cal Pads correlate well with the radiometric conditions reported by the Grand Junction RadNet facility, but more research is required to determine if this is the case and the nature of that correlation.

The nominal 20-hour count durations on the Cal Pads were not always sufficient to discern diurnal variances for each radiometric parameter on each Cal Pad. There is clear evidence of a diurnal cycle in some of the data sets collected on the Cal Pads, particularly in the K-40 and U-238 ROIs on Pad W4 in the post-rehabilitation survey. It is presumed that longer duration measurements would reveal diurnal cycles in other data sets.

C. Assessment of Specific Environmental Parameters on the Gamma Flux Directly Above the Calibration Pads

Radon and thoron exhalation rates are known to be influenced, by a variety of environmental factors, including relative humidity, thermal stability, wind speed, temperature, and barometric pressure, thus correlations to individual environmental factors were considered. One systemic weakness in these correlations is the fact that the weather data is reported on an hourly basis, while the radiometric data was collected in 1-minute (NaI detector) or 5-minute (HPIC) intervals, preventing a true point by point analysis.

1. Barometric Pressure

Variances in radiometric measurements are generally in close temporal correlation with barometric pressure (Figure 9-1 through Figure 9-8), however the magnitude of this correlation is not consistent. For example, the Full ROI diurnal cycle in the general area background measurements collected from the mornings of 23-24 August 2017 is in close agreement with that of the 25-26 August 2017, but the barometric pressure variance is twice as large on the latter dates. Similarly, This, and other mathematical inconsistencies, preclude direct mathematical correlations between the radiometric measurements and barometric pressure.

2. Relative Humidity

Previous work at the Cal Pads concluded that relative humidity was the environmental parameter that correlated strongest with the radiometric measurements (DOE 1978). Current results also indicate a high temporal correlation to relative humidity; however, this is likely a coincidental finding. Results from the morning of 4 November 2017 show a sharp spike in the general area background Full ROI count rate simultaneous with a sharp spike in barometric pressure (Figure 9-2). Notably, there is not a corresponding spike in relative humidity, indicating that barometric pressure is the likely determinate factor, and that relative humidity simply tends to correlate with barometric pressure[2]. Additionally, the relationship between relative humidity and the radiometric measurements exhibited similar mathematical inconsistencies as barometric pressure, again precluding any consistent mathematical relationships.

3. Temperature

Temperature was poorly temporally correlated with the radiometric results. The radiometric results were generally highest at dawn and lowest at dusk, indicating a potential inverse relationship. However, the radiometric results were generally lower in the post-rehabilitation survey relative to the pre-rehabilitation survey, as was the temperature, contradicting the potential inverse correlation.

4. Wind Speed

Wind speed was poorly temporally correlated with the radiometric results. Wind speed varied from ~0-15 mph in both the pre- and post-rehabilitation surveys with no discernable impact on the radiometric measurements.

[2] A similar spike in barometric pressure was observed on 29 August 2017 without a corresponding spike in radiometric results, further emphasizing the lack of a consistent mathematical correlation between the two parameters.

11. ASSESSMENT OF THE REHABILITATION PROCESS ON THE RADIOMETRIC CHARACTERISTICS OF THE CALIBRATION PADS

The surface rehabilitation project removed approximately 4-5 cm of active source material from the surfaces of the Cal Pads. The impact, as calculated, on the gamma fluence above the Cal Pads at an array of elevations above the surface of the Cal Pads is less than 1% (and <0.5% in most cases).

Radiometric measurements collected before and after the removal of the incompetent surfaces of the calibration pads confirm that the measurable radiometric characteristics of the calibration pads remains essentially unchanged. The uncertainty in the measurements confounded by the diurnal and seasonal variability in uncontrollable environmental factors is evident in the controlled radiometric field measurements and is considerably larger than the calculated difference. The impact of the rehabilitation process on the radiometric characteristics of the calibration pads is so small that it cannot be reliably detected.

12. QUALITY CONTROL

A. Spectral Alignment

Sodium Iodide spectrometers are susceptible to a phenomenon known as "spectral drift", wherein the spectral channels (i.e. energy bins) assigned to given energies of gamma emissions can gradually migrate. This phenomenon is largely attributable to changes in temperature. To counter this phenomenon and stabilize spectral alignment over the period of measurement, the spectral detectors are deployed in thermally controlled housings with digital temperature controllers designed to maintain a constant temperature environment for the NaI crystal.

- The NaI spectrometers were spectrally aligned prior to use and at least daily.
- The as-left spectral energy assignment error was no more than +/-2% at 662 keV (Cs-137) and 1.46 MeV (K-40).

B. Source Response Checks

Source response checks (SRCs) are implemented to test the repeatability and stability of radiation instruments over time. When control charted, they also serve as an indicator of the precision of the measurements produced by the instrument and provide early indication that an instruments response is trending away from a "normal" or expected response. In order to verify that the NaI detectors and the HPIC operated as expected and within specifications of tolerable variance, SRCs were routinely performed, recorded, and control charted. Each instrument was subjected to an SRC in the following manner:

- The instrument was exposed to a known and stable radioactive artifact (a check source),
- In a standard and repeatable geometry (configuration), and
- For a fixed duration of no less than one minute.

Prior to collecting pre-rehabilitation radiological characterization measurements, a baseline SRC response value was established, consisting of a minimum of ten SRC measurements. During radiological characterization field operations, each instrument was subjected to SRCs.

- SRCs were conducted prior to use, at least daily, and at the conclusion of use.

- The SRC response specification was within +/-20% of the established baseline value.
- SRC control charts were evaluated on a daily basis to identify any trends in the instrument SRC response values that may indicate deviation from "normal" or expected instrument response.

C. Environmental Conditions

The environmental and background radiation conditions were recorded and monitored throughout the radiological characterization field activities. The potential impacts of significant fluctuations in environmental conditions on the radiological characterization measurements were evaluated for:

- Atypical deviations in the background measurements which coincided with significant deviations in environmental conditions, or
- Atypical deviations in the characterization measurements which coincided with significant deviations in environmental conditions.

As discussed, significant impacts of changing environmental conditions on both background and radiological characterization measurements were observed. These impacts, however, are the result of typical environmental conditions experienced at the Grand Junction Regional Airport (in the absence of any recent precipitation event). These diurnal and seasonal variations in environmental conditions cannot be controlled, nor expected to "stabilize" to more favorable conditions to collect measurements, therefore there was no disruption in data collection due to atypical environmental conditions.

13. CONCLUSIONS

A. Impacts of Environmental Factors on Radiometric Measurements Conducted at the Calibration Pads

Significant variances were observed in radiometric measurements collected at the Cal Pads due to diurnal and seasonal changes in environmental conditions. Strong temporal correlations between variances in measured radiometric results and variances in barometric pressure and relative humidity were observed. While environmental factors clearly have an obvious impact on the measured results, such correlations are simply not mathematically consistent and cannot, therefore, be used to "normalize" results to account for the inherent, uncontrollable diurnal and seasonal variability of environmental parameters.

B. Impacts of the Rehabilitation Process on the Radiometric Characteristics of the Calibration Pads

The impact, as calculated, on the gamma fluxes above the Cal Pads at an array of elevations above the surface of the Cal Pads is less than 1% (and <0.5% in most cases).

The uncertainty in the radiometric measurements resulting from the diurnal and seasonal variability from uncontrollable environmental factors (up to 16%) is evident in the controlled radiometric field measurements and is considerably larger than the calculated difference (<1%).

The impact of the rehabilitation process on the radiometric characteristics of the Cal Pads is so small that it cannot be reliably detected.

C. Revisions to the "*Field Calibration Facilities for Environmental Measurement of Radium, Thorium, and Potassium*"

The existing DOE document, *Field Calibration Facilities for Environmental Measurement of Radium, Thorium, and Potassium, Fourth Edition 2013* (DOE 2013), will be revised in the following manner:

"The Grand Junction Airport Calibration Pads underwent a rehabilitation process in 2017 which removed the top 4-5 cm of source material from each pad. The loss of gamma signal that resulted from this process is negligible (less than1%). This loss of signal is insignificant given the variances observed due to atmospheric conditions (up to 16%). Consideration should be given to the atmospheric conditions when utilizing the Calibration Pads."

D. Future Maintenance of the Cal Pads

The surface rehabilitation project removed approximately 4-5 cm of active source material from the surfaces of the Cal Pads, resulting in a calculated loss of gamma signal of less than 1% (and <0.5% in most cases) at 1m above the surface of the pads. The model further indicated that the removal of 10 cm from the original surface would cause a loss of gamma signal of less than 2% at 1 cm above the surface of the pads. Thus, future rehabs of a similar nature are not expected to unduly diminish the radiometric characteristics of the Cal Pads.

E. Further Studies

In order to provide more precision for users of the Cal Pads, long-term monitoring with highly temporally resolved atmospheric and radiation monitors is recommended to discern trends and mathematical relationships that users could implement to normalize the apparent gamma fluxes directly above the Cal Pads based on the relevant environmental parameters.

14. REFERENCES

DOE 2013 U.S. Department of Energy, Legacy Management, 2013, *Field Calibration Facilities for Environmental Measurement of Radium, Thorium, and Potassium, Fourth Edition,* U.S. Department of Energy Document #LMS/S07707.

DOE 1978 U.S. Department of Energy, *Monitoring of the Airport Calibration Pads at Walker Field, Grand Junction, Colorado for Long-Term Radiation Variation, August 1978, David Stromswold.*, U.S. Department of Energy Document # GJBX-99(78).

Grove 2014 MicroShield® 10.00, Grove Engineering, Inc., 2014, Rockville, MD. www.radiationsoftware.com.

Israel 1965 Israel, Gerhard W., 1965, *Thoron (Rn-220) measurements in the atmosphere and their application in meteorology,* Tellus, 17:3, 383-388, DOI: 10.3402/tellusa.v17i3.9062.

Pearson 1966 Pearson, John E. and Moses, Harry, 1966, *Atmospheric Radon-222 Concentration Variation with Height and Time,* Argonne National Laboratory, Argonne, Ill.

RadNet 2017 U.S. Environmental Protection Agency/RadNet, 2017, *RadNet Air Data From Grand Junction, CO*.

https://www.epa.gov/radnet/radnet-air-data-grand-junction-co