STATE OF NEVADA
Jim Gibbons, Governor
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DIVISION OF ENVIRONMENTAL PROTECTION
Leo M. Drozdoff, P.E., Administrator
ndep NEVADA DIVISION OF ENVIRONMENTAL PROTECTION
protecting the future for generations

February 6, 2009

Mr. Mark Paris
Basic Remediation Company
875 West Warm Springs Road
Henderson, NV 89011

Ms. Susan Crowley
Tronox LLC
PO Box 55
Henderson, NV 89009

Mr. Curt Richards
Olin Corporation
3855 North Ocoee Street, Suite 200,
Cleveland, TN 37312

Mr. Joe Kelly
Montrose Chemical Corp of CA
600 Ericksen Ave NE, Suite 380
Bainbridge Island, WA 98110

Mr. Brian Spiller
Stauffer Management Co LLC
1800 Concord Pike
Wilmington, DE 19850-6438

Mr. Craig Wilkinson
Titanium Metals Corporation
PO Box 2128
Henderson, NV 89009

Re. **BMI Plant Sites and Common Areas Projects, Henderson, Nevada**
Guidance for Evaluating Secular Equilibrium at the BMI Complex and Common Areas

Dear Sirs and Madam:

All of the parties listed above shall be referred to as "the Companies" for the purposes of this letter. Guidance for evaluating secular equilibrium is provided in Attachment A. This guidance is a supplement to the secular equilibrium tool issued via electronic mail on January 22, 2009.

Please contact me with any questions (tel: 702-486-2850 x247; e-mail: brakvica@ndep.nv.gov).

Sincerely,

Brian A Rakvica, P.E.
Supervisor, Special Projects Branch
Bureau of Corrective Actions

BAR:s

CC: Jim Najima, NDEP, BCA, Carson City
Marysia Skorska, NDEP, BCA, Las Vegas
Shannon Harbour, NDEP, BCA, Las Vegas
Todd Croft, NDEP, BCA, Las Vegas
Greg Lovato, NDEP, BCA, Carson City
Barry Conaty, Holland & Hart LLP, 975 F Street, N.W., Suite 900,Washington, D.C. 20004
Brenda Pohlmann, City of Henderson, PO Box 95050, Henderson, NV 89009
Mitch Kaplan, U.S. Environmental Protection Agency, Region 9, mail code: WST-5, 75 Hawthorne Street, San Francisco, CA 94105-3901
Ebrahim Juma, Clark County DAQEM, PO Box 551741, Las Vegas, NV, 89155-1741
Ranajit Sahu, BRC, 311 North Story Place, Alhambra, CA 91801
Rick Kellogg, BRC, 875 West Warm Springs, Henderson, NV 89011
Kirk Stowers, Broadbent & Associates, 8 West Pacific Avenue, Henderson, Nevada 89015
George Crouse, Syngenta Crop Protection, Inc., 410 Swing Road, Greensboro, NC 27409
Nicholas Pogoncheff, PES Environmental, Inc., 1682 Novato Blvd., Suite 100, Novato, CA 94947-7021
Lee Erickson, Stauffer Management Company LLC, P.O. Box 18890 Golden, CO 80402
Keith Bailey, Environmental Answers, 3229 Persimmon Creek Drive, Edmond, OK 73013
Susan Crowley, Crowley Environmental LLC, 366 Esquina Dr., Henderson, NV 89014
Mike Skromyda, Tronox LLC, PO Box 55, Henderson, Nevada 89009
Jeff Gibson, AMPAC, 3770 Howard Hughes Parkway, Suite 300, Las Vegas, Nevada 89109
Sally Bilodeau, ENSR, 1220 Avenida Acaso, Camarillo, CA 93012-8727
Cindi Byrns, Olin Chlor Alkali, PO Box 86, Henderson, Nevada 89009
Paul Sundberg, Montrose Chemical Corporation, 10733 Wave Crest Court Stockton, CA 95209
Joe Kelly, Montrose Chemical Corporation of CA, 600 Ericksen Avenue NE, Suite 380, Bainbridge Island, WA 98110
Deni Chambers, Northgate Environmental Management, Inc., 300 Frank H. Ogawa Plaza, Suite 510, Oakland, CA 94612
Robert Infelise, Cox Castle Nicholson, 555 California Street, 10th Floor, San Francisco, CA 94104-1513
Michael Ford, Bryan Cave, One Renaissance Square, Two North Central Avenue, Suite 2200, Phoenix, AZ 85004
Dave Gratson, Neptune and Company, 1505 15th Street, Suite B, Los Alamos, NM 87544
Paul Black, Neptune and Company, Inc., 8550 West 14th Street, Suite 100, Lakewood, CO 80215
Teri Copeland, 5737 Kanan Rd., #182, Agoura Hills, CA 91301
Paul Hackenberry, Hackenberry Associates, 550 West Plumb Lane, B425, Reno, NV, 89509

ATTACHMENT A

Statistical Methods for Secular Equilibrium: For Radionuclide Data from Soil Samples Collected at the BMI Complex and Common Areas in Henderson, Nevada

Purpose

A potential problem with some of the radionuclide data from soil samples collected in the past decade from the Basic Management, Inc. (BMI) Complex and Common Areas (the Henderson site) became apparent as a result of data exploration and statistical background comparisons. Radionuclides in background within both the uranium and thorium decay chains are expected to be in approximate secular equilibrium (SE). Conceptual site models (CSMs) for some of the sub-areas at the BMI Complex and Common Areas suggest that radionuclide data should also exhibit approximate secular equilibrium. In addition, the site data in these cases should not exhibit radioactivity that is less than background, assuming background is well characterized. However, radionuclide data for some sub-areas show an unexpected pattern of failing statistical background comparisons for some radionuclides; passing for some others; and some radionuclides pass background comparisons because their activities are significantly less than the corresponding background activities. These issues raised concerns about the radiochemical analysis, which have since been investigated and the analytical problem has been corrected (see also *Guidance for Evaluating Radionuclide Data for the BMI Plant Sites and Common Areas Projects, Henderson, Nevada, Nevada Division of Environmental Protection, dated February 6, 2009*). However, the issue of passing background comparisons for some radionuclides and failing for others was still of concern. Instead of relying purely on background comparisons, which sometimes provide conflicting results, to determine if a release of radionuclide contamination has occurred, a statistical evaluation of secular equilibrium was also suggested.

Initial attempts to evaluate secular equilibrium involved using exploratory data analysis (plots and summary statistics), and analysis of variance (ANOVA) to compare the mean radioactivities of the different isotopes in the same chain. The ANOVA tests repeatedly failed, even when applied to the background data. This is a consequence of a problem with standard classical statistical methods, which are designed to find even small effects or differences as sample size increases. An alternative method was sought that could accommodate small differences. The method of statistical equivalence testing seemed to be a reasonable candidate. Statistical equivalence testing essentially involves reversing the standard null and alternative hypotheses used in ANOVA, and, in the process, allowing for non-point valued null hypothesis statements, which is the crux of the classical statistics problem.

In taking the equivalence testing approach, some flexibility is provided in terms of how approximate secular equilibrium is defined. The hypotheses allow a family or range of possible options, instead of the point null hypothesis that is common in classical statistics. The result of equivalence testing for secular equilibrium will either indicate that the radionuclides are in approximate secular equilibrium (the alternative hypothesis), or that they are not (the null hypothesis). If the radionuclide data do not exhibit secular equilibrium, then there is some indication of radionuclide-specific contamination. If the radionuclide data exhibit secular equilibrium, then either the data are similar to background, or there is more general contamination for all radionuclides in the decay chain.

Explored in this paper are methods for evaluating secular equilibrium using equivalence testing. A

description of secular equilibrium is provided first, followed by some further description of the nature of this problem at the Henderson site. This is followed by a discussion of some different models for equivalence testing, each one of which is aimed at a different problem. Although, the initial motivation for using equivalence testing for BMI data was to find a statistical approach that adequately evaluates secular equilibrium, this method might also be reasonable for background comparisons, which could make equivalence testing an even more useful for evaluating environmental data. The main focus here is secular equilibrium, but the basic approach for background comparisons is presented as part of an overall presentation of equivalence testing, starting from fairly simple models or comparisons and moving to more complex multivariate models. Finally, some examples are presented from some Henderson site soil investigations. These include results of some exploratory data analysis, standard ANOVA, and the equivalence tests performed to evaluate secular equilibrium in sub-areas at the Henderson site.

Secular Equilibrium

Secular Equilibrium (SE), as defined by the International Union of Pure and Applied Chemistry (IUPAC), is "Radioactive equilibrium where the half-life of the precursor isotope is so long that the change of its activity can be ignored during the period of interest and all activities remain constant." The implications of SE are that steady-state conditions, with respect to parent and daughter activities, can be reached when certain assumptions are met.

There are three naturally occurring radioactive decay chains: Uranium (U)-238, Thorium (Th)-232 and U-235. The main focus here is the U-238 chain (the uranium chain) and the Th-232 chain (the thorium chain). As a first approximation, SE among all daughters within a chain may be attained if the decay constant of the initial parent is much less than that of any of its daughters and the system under consideration is closed. The decay constant requirement is generally true for these three naturally occurring decay chains. The decay constant is an inverse function of half-life and the ratio of half lives of the daughters within each of these chains is at least a factor of five orders of magnitude.

However, whether steady-state activity among decay chain members is achieved in the environment also depends on:

- The open nature of the system
- The relative geochemical mobility of each radioisotope
- The system environment (rock, water, pore space – air)
- The passage of sufficient time for the buildup of daughters (ingrowth)
- The effects of field sampling laboratory radiochemical analysis.

Attainment of SE in a chain might be an indication of a closed system. In reality, environmental soil does not represent a closed system. For example, soil undergoes natural leaching via precipitation; radon escapes the system as a gas; and geochemical effects might vary by element. If there has been a release of some specific radionuclide contaminants, then sufficient time is needed to re-establish SE. Consequently, only approximate or quasi- secular equilibrium can be expected even under the best field conditions.

In addition to the natural effects of the environmental system, deviations from SE might also occur because the radiological methods for analyzing soil samples are often different between isotopes, and samples might be analyzed by different analysts, at different laboratories, and on different days. That is, some analytical effects are possible in addition to the natural effects.

Henderson Site Background

As described above, the problem has arisen within the site investigations at the BMI Complex and Common Areas in Henderson, Nevada, of testing for radioisotopic SE. That is, soil samples have been collected and analyzed for a suite of radionuclides. If the radioisotopes within a chain (uranium chain, thorium chain) are in SE, then their radioactivities should be identical. There are many reasons why it is not reasonable to expect such perfect results. Consequently, some differences in results in both mean radioactivity and variance might be expected between isotopes.

In addition to analytical, and possibly sampling, differences, it is not reasonable to expect pure SE in the natural environment. As noted above, pure SE corresponds to assumptions of closed conditions with a lack of loss of any isotope through physical or chemical means. Within the natural environment, different radionuclides might have different physical and chemical properties, causing environmental transport to occur at different rates. Nevertheless, if sampling and analytical procedures and methods are under control, and loss of radionuclides through physical and chemical transport is expected to be small (which is probably the case for radon in most natural environments), then an assumption of approximate SE might be reasonable for background conditions, and also for some contamination conditions at the Henderson site. Some radionuclide contamination conditions that might exist at the Henderson site include:

- Processing of ore containing uranium and thorium. Processing occurs and has occurred to extract other metals (titanium, magnesium, manganese, and possibly tungsten) from the ores, in which case there is no reason to believe that the radionuclides are not still in approximate SE, but disposal of the waste material on site might lead to higher activities than are seen in background.
- Disposal of radionuclide chlorides through surface disposal of liquid wastes. The wastes also contained other chloride compounds. Radionuclides are no longer likely to be in SE.
- Leaching of uranium from the soil matrix. Massive acid and solvent disposal and spills might have leached uranium and other metals/radionuclides from the soil matrix. It is not clear what effect this might have on SE. More uranium might be available for transport, but the greatest effect might be that radon is more free to exit the environmental system. Radon emanation is affected by parent radionuclides (e.g., uranium) being bound in the soil matrix. Radon might be more easily released if acid/solvent leaching has occurred. A similar effect may still be occurring because of the redox conditions that exist in groundwater. Reducing conditions exist in groundwater over a portion of the BMI Complex. Elevated metals, uranium and radon concentrations have been found in groundwater coincident with these reducing conditions. Given the relatively short timeframe since leaching first started, it is probable that SE does not exist in these areas.

For potential contamination conditions at the Henderson site, differences between activity of radioisotopes within the same chain might vary from small to large. For background radioactivity the differences should be small. Statistical methods are needed that can distinguish between statistical and practical differences between radionuclides in the same decay chains, given the natural system and analytical effects that can occur.

Background radioactivity can be used as a baseline for establishing a reasonable range for the practical differences that might represent approximate SE at the Henderson site. If an appropriate statistical method can be used to define approximate SE based on the background data, then the results

could be applied to site data. That is, the statistical differences in the background data are not statistically important, but reflect minor natural environment and analytical differences. The same is true of site data in sub-areas of no contamination. Statistical methods are needed that accommodate these small differences instead of identifying them as statistically important.

Statistical Approaches

If radioisotopes are in SE, then radioactivity from the radioisotopes in a decay chain should be the same. Measurements of radioactivity in environmental soil samples will have variation, however, from variations in the soil, measurement error, and perhaps some systematic measurement differences. If standard classical statistics *significance tests* are performed for the equality of mean radioactivity for the different radioisotopes, in a decay chain, the small differences in measurement may lead to rejection of the null hypothesis of equal mean radioactivities. This reflects a common issue with classical statistics and point null hypotheses, corresponding, in this case, to stating that all the mean radioactivities for radionuclides within a chain are the same. Collecting more data should lead to better information, but in significance testing of a point hypothesis (exact equality), more samples will in fact lead to a greater chance of rejecting the null hypothesis, since *exact* equality of the mean *measured* radioactivity will almost certainly not be observed.

As noted above, an alternative approach is to utilize the statistical method of *equivalence testing.* The basic notion behind equivalence testing is that there is a distinction between a statistically significant difference and a scientifically or practically significant difference. The techniques used in equivalence testing are quite similar to those employed in standard significance testing, except that the null hypotheses are specified in a different manner, and the set of possible conclusions can be expanded to include an "inconclusive" result, by allowing for non-point hypotheses for both the null and alternative hypotheses.

A reasonable test for SE should then allow for some differences in mean radioactivity between radioisotopes from the same decay chain, and not be strict about exact equality. Equivalence testing is a method that is widely accepted in biopharmaceutical fields that tests for near equality rather than exact equality. The reminder of this section includes a brief introduction on equivalence testing, followed by a univariate model for a simple comparison of two populations, which might be appropriate for background comparisons for a single chemical (e.g., radionuclide, metal, organic chemical), a multivariate generalization of the univariate case that compares two multivariate populations, which might be appropriate for background comparisons for many chemicals simultaneously (e.g., metals), and an approach for comparing multiple associated measurements, which is appropriate for testing for SE.

Equivalence Testing

When testing the sameness of multiple measurements, it is common to perform a significance test for the equality of the means. There are two potential problems with this approach. Significance testing assumes equality as the null hypothesis (a point hypothesis), putting the burden of proof on showing a lack of equality. This approach might not be appropriate when testing for SE, depending on external knowledge of soil conditions and analytical methods. The second issue with significance testing for equality is that when a sufficient amount of data are collected, even the smallest deviation from exact equality will lead to rejection of the equality, ostensibly in favor of inequality, a situation that is almost certain to be the case when using this approach for testing SE when small differences are expected between the measurements. As explained above, small differences can be expected between mean radioactivity in soil samples for radioisotopes from the same decay chain because of the different measurement techniques used for the different radioisotopes, and the effects of environmental geochemistry on the different radionuclides. It is preferable to deal with the issue of statistical versus

practical significance before rather than after performing the test, and this is exactly what equivalence testing accommodates.

In equivalence testing, a range of possible values is specified as the *equivalence* hypothesis, rather than a point hypothesis. The equivalence range must be chosen to represent the set of parameter values that can be considered equal, or close enough to equal, from a practical point of view. The equivalence hypothesis is set as the alternative hypothesis, leaving the burden of proof for the data on showing equivalence; this is a reverse of the standard significance test[1]. Expert knowledge is required to establish an appropriate equivalence range. This decision should be made by stakeholders in conjunction with experts in the subject matter and data collection, including measurement instrumentation, sampling schemes, etc. For background comparisons, the equivalence range should accommodate small geologic differences in the soil medium, and analytical differences because background and site data were probably collected on different days and analyzed at different laboratories or by different analysts. For secular equilibrium testing the equivalence range should also consider chemical and physical processes in the natural environment, and the laboratory analyses because different analytical methods are often used for the different radionuclides.

Specification of the equivalence range might not always be straightforward. For univariate background comparisons this might be a relatively simple matter of deciding how much difference between site and background radioactivity is considered tolerable, either in direct terms, or as a function of the background mean concentration. For example, a 10% increase over the background mean might be tolerated based on natural and laboratory effects. For the multivariate background comparisons, the range can be specified for each chemical, but the equivalence test is evaluated against a combination of these differences. In the case of SE, the equivalence range of interest is related to the difference in mean activities of each radionuclide in a decay chain. A simpler set up in this case is to consider the relative values of the radionuclides by normalizing the mean concentrations to sum to one. Each of these cases is described in more detail below.

Univariate Example

Suppose that a test is needed to determine if the radioactivity of a radioisotope (or concentration of any other chemical) in soil from a potentially contaminated site is the same as its activity in background soil. Background soil samples are usually collected from off-site to avoid areas of historical site activity, and any other form of activity that might impact background conditions. There are likely to be slight geologic variations between the background location and the site, even if the two locations are proximal. In addition, background and site samples will probably be collected at different dates or times, might be submitted to different laboratories, and will probably be analyzed by different laboratory analysts. Consequently, some small differences are to be expected, even if the site data represent background conditions. Significance testing will often reveal statistically significant differences even if a small, but unknown difference is expected, and the practical difference is inconsequential or expected.

For example, suppose 50 samples are collected from both the background and site locations and are analyzed for a radionuclide. Suppose the sample means are 5.00 pCi/g for the background data and 5.04 pCi/g for the site data, with a pooled sample standard deviation of 0.1 pCi/g. The common significance test for comparing the two means, a two-sample t-test, gives a p-value of 0.024 (for a one-sided test), indicating that the two means are (statistically) significantly different (at the 5% significance level). However, the practical significance of a less than 1% difference in background and site means is

1 It is certainly possible to develop a test where the equivalence hypothesis is the null hypothesis rather than the alternative, though such a test should be called a non-equivalence test instead.

questionable, and is, arguably, within the range of expected difference.

If instead it had been deemed that differences smaller than 0.1 pCi/g could be considered equivalent, an equivalence test could be performed where the null hypothesis is $H_o : \mu_{background} - \mu_{site} \geq 0.1$ and the alternative hypothesis (the equivalence hypothesis) is $H_o : \mu_{background} - \mu_{site} < 0.1$. That is, a difference of 0.1 pCi/g is considered a reasonable practical difference that should not trigger alarm. For this equivalence test, the p-value is 0.002, leading to a rejection of the null hypothesis (at the 5% significance level) and concluding that the site and background are equivalent. The test result would be stronger if a larger difference could be tolerated. For example, differences such as 1% or 10% of the background value might be considered tolerable practical differences.

The univariate model is a fairly simple case of comparing two means. The p-value of this equivalence test can be calculated analytically, because the test is still a two-sample t-test but with a non-zero difference being tested. However, another way to construct the test is to calculate the 95% upper confidence bound on the difference and then compare to the equivalence threshold of 0.1 pCi/g. In this case the 95% upper confidence limit (UCL) is 0.073 pCi/g, which is less than the equivalence threshold, in which case equivalence is concluded. The confidence bound approach proves more helpful for more complicated models.

This approach could be applied to background comparisons in general. However, it is not currently supported in United States Environmental Protection Agency (USEPA) or other environmental guidance. If such an approach were taken, then small differences that are often seen in traditional background comparisons, and which result in identification of chemicals of potential concern when only very small differences are in evidence, might no longer be regarded as significant.

Multivariate Example

A multivariate extension of the univariate equivalence test could be used to compare the concentrations of several chemicals simultaneously. Such an approach could be applied, for example, to multivariate background comparisons to determine if site concentrations are similar (equivalent) to background concentrations in general. An advantage of taking this approach to background comparisons is that the correlation structure between chemicals could be taken directly into account in the analysis. However, a multivariate version of an equivalence test is not straightforward, because the standard F-test for testing differences is not easily adapted to the non-point hypothesis. This multivariate approach is described below to demonstrate that, despite the technical challenges, this approach is feasible and, perhaps, should be evaluated as an option for background comparisons.

To keep things simple, but also to demonstrate the approach, suppose that two sites (Site 1 and Site 2, one of which might represent background) are to be compared simultaneously for two radionuclides (or chemicals), A and B. Some geologic variation from location to location is to be expected for each radionuclide, but A has more local variability than B. An equivalence region can be defined as an ellipse, as depicted in Figure 1.

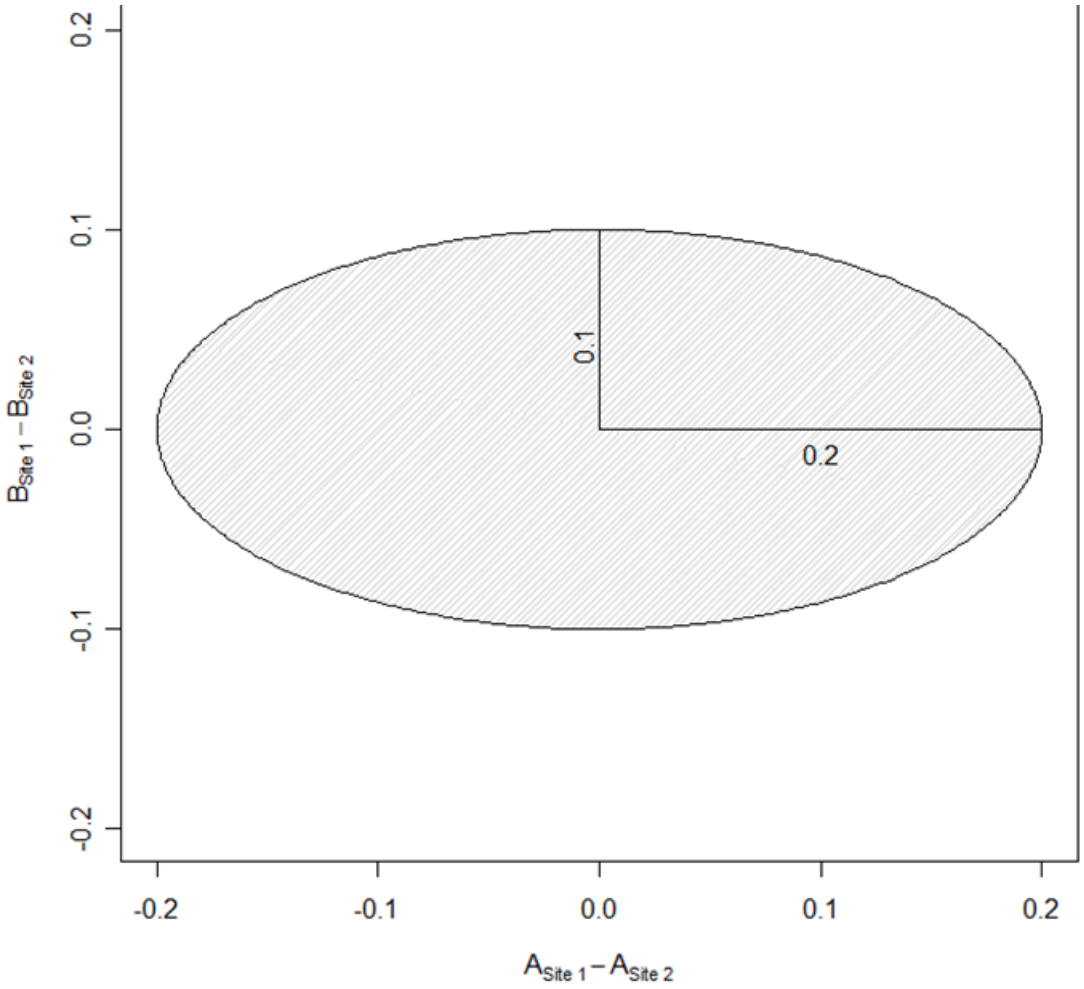

Figure 1: Equivalence region for a 2-dimensional problem.

That is, for radionuclide B, a difference of 0.1 between the mean activities at Site 1 and Site 2 would be considered tolerable or a practical difference. For radionuclide A, a difference of 0.2 is considered tolerable or practical. That is, differences this small are not considered statistical important. Mathematically, the ellipse can be defined by the inequality $(\vec{x}_1 - \vec{x}_2)^T D(\vec{x}_1 - \vec{x}_2) < 1$ where

$\vec{x}_1 = \begin{pmatrix} A_1 \\ B_1 \end{pmatrix}$ (the mean radioactivities for A and B in site 1),

$\vec{x}_2 = \begin{pmatrix} A_2 \\ B_2 \end{pmatrix}$ (the mean radioactivities for A and B in site 2), and

$D = \begin{pmatrix} \frac{1}{0.2^2} & 0 \\ 0 & \frac{1}{0.1^2} \end{pmatrix}$.

The multivariate equivalence test tests the null hypothesis: $(\vec{x}_1 - \vec{x}_2)^T D(\vec{x}_1 - \vec{x}_2) \geq 1$ against the alternative hypothesis of equivalence: $(\vec{x}_1 - \vec{x}_2)^T D(\vec{x}_1 - \vec{x}_2) < 1$. Assuming multivariate normal data, a likelihood ratio test can be constructed to perform the equivalence test. However, because the equivalence region is convex, it is simpler to perform the test by constructing the Hotelling's $100\left(1 - \frac{\alpha}{2}\right)\%$ confidence region and then checking for overlap with the null hypothesis region. If any portion of the confidence region is in the null hypothesis region, then the null hypothesis (of non-equivalence) should be accepted, at the α% significance level. Otherwise the alternative hypothesis of equivalence should be accepted. See Munk and Pflüger (1999) for details.

Suppose, for example, that 30 samples were collected from each site with the following results: mean radioactivities for Site 1 of (4.35, 3.58) in pCi/g for radioisotopes (A, B), and mean radioactivities for Site 2 of (4.28, 3.52), and pooled covariance matrix of: $S = \begin{pmatrix} 0.003 & 0.001 \\ 0.001 & 0.005 \end{pmatrix}$

The mean differences are then (0.07, 0.06), resulting in a normal theory confidence regions given in Figure 2. The large ellipse shows the equivalence region again. There are two other ellipses that are based on the data, and which correspond to a 99% confidence region, and an 80% confidence region[2]. The larger of these two ellipses extends outside of the equivalence region – i.e. overlaps with the null hypothesis region (the region outside the equivalence region); thus, the null hypothesis of non-equivalence should be accepted at the 0.5% significance level. The 80% confidence region is wholly contained inside the equivalence region; thus, equivalence would be accepted at the 10% significance level. The p-value for the test can be round with a search algorithm and corresponds to an internal ellipse that touches the equivalence region boundary. In this case the p-value is 0.041. Note: for this type of equivalence test, if the sample mean (i.e. center of the confidence region) is outside of the equivalence region, the exact p-value is not trivial to calculate, and, for purposes of this document, is simply be reported as ">0.5."

In higher dimensions, it isn't possible to view the confidence regions. However, a search algorithm can be used to determine whether one multi-dimensional ellipse (a confidence region in multiple dimensions) is wholly contained inside of another multi-dimensional-ellipse (the equivalence region in multiple dimensions).

A rectangular equivalence region can be chosen instead of an ellipse, in which case all dimensions can be tested individually and then combined using the union-intersection principle. However, an elliptical region often better describes a notion of equivalence, bounding the deviations from equality by a Euclidean distance rather than bounding the deviation in each dimension separately. The difference in volume between a multi-dimensional rectangle and ellipsoid bounded by the rectangle can get quite large as dimensionality increases, possibly producing very different test results.

This multivariate approach could be adapted to multivariate background comparisons. For now it is simply presented as one of several equivalence testing methods that are available, and might be worth consideration for environmental problems and datasets.

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2 Confidence regions of 99% and 80% were used only to clearly demonstrate the different effects. More generally, a 95% confidence region might be appropriate, since 95% confidence is often used in environmental statistics.

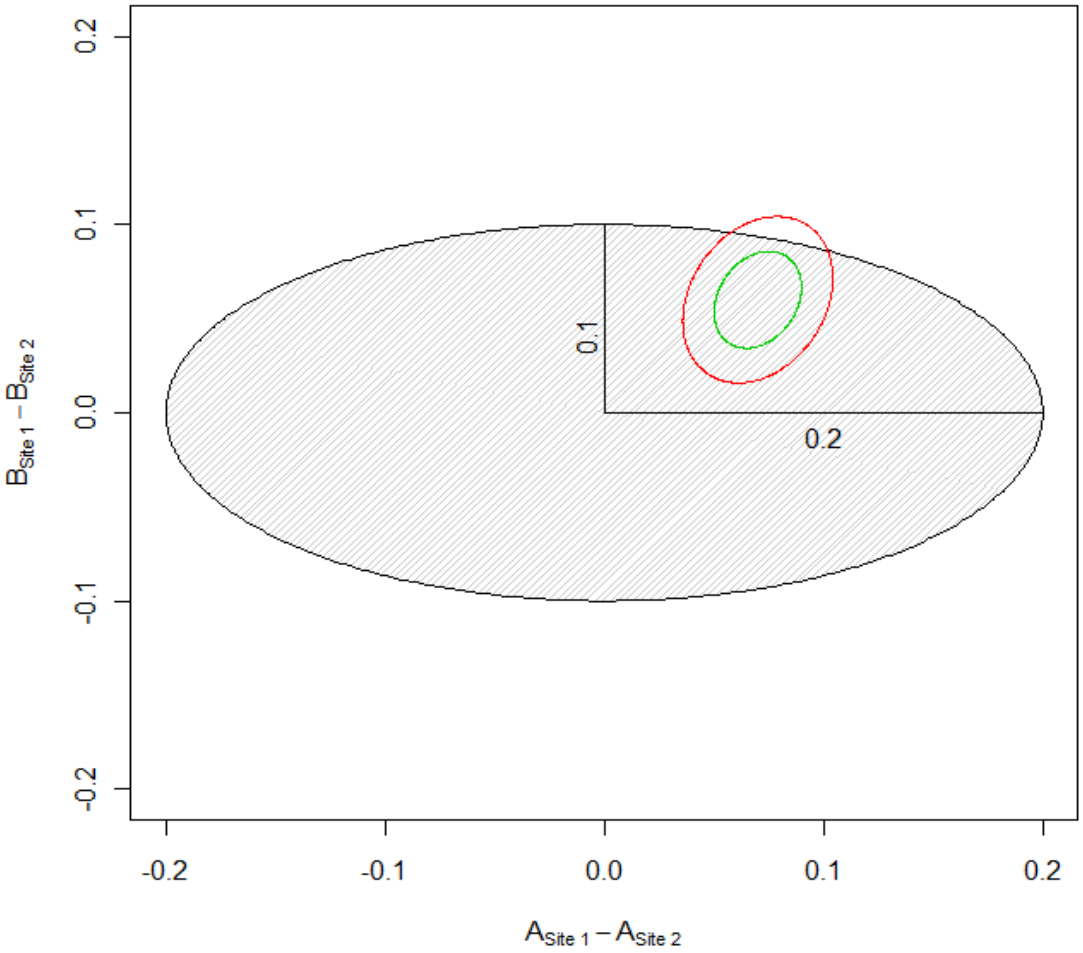

Figure 2: Confidence regions for the 2-dimensional example

Testing for Secular Equilibrium

Evaluation of SE requires comparison of mean activities for radionuclides in the same decay chain. This also assumes the data are grouped; that is, for each soil sample all the radionuclides of interest are analyzed and their radioactivities are reported. Comparison of means using standard statistical techniques corresponds to performing an analysis of variance (ANOVA) that should properly account for the correlation structure between the radionuclides[3]. Consequently, a test for SE is really a test that the mean activity of several isotopes in a decay chain are equal, $\mu_1 = \mu_2 = ... = \mu_k$, where the subscript indexes the k different isotopes under study. Due to variation in measurement devices, differences in the sensitivity to different parts of the energy spectrum, etc., it is quite probable that even when testing soil that is in secular equilibrium, this null hypothesis will not hold exactly. Further, each sample s typically tested for all radioisotopes in the same decay chain, and the natural soil variability might lead to correlations between radioisotopes from the same sample. Thus, an equivalence test that takes correlation structure into account might be preferable to a standard ANOVA.

3 Note, the standard 1-way ANOVA does not properly account for the inherent correlation between the radionuclides.

In this multivariate setting, an equivalence test might take the form, $H_o : (\vec{\mu} - \mu_o \vec{1}_k)^T D(\vec{\mu} - \mu_o \vec{1}_k) \geq 1$, where $\vec{\mu} = (\mu_1, \mu_2, ..., \mu_k)^T$, μ_o is an overall mean, $\vec{1}_k$ is the $k \times 1$ vector of ones, $\boldsymbol{D}$ is some positive-definite $k \times k$ matrix that represents the equivalence region. This null hypothesis says that the true mean must be within some multi-dimensional ellipse in *k* dimensions of the point $\mu_o, \mu_o, ..., \mu_o$. The parameter μ_o is a nuisance parameter in this set up, because the specific value of μ_0 is unimportant for inference about SE. That is, secular equilibrium indicates that all the means are the same; it does not indicate what the mean value should be. If μ_o is allowed to be arbitrary (i.e. allowing the null hypothesis to be true if it is true for any value of μ_o), then the equivalence region becomes an infinite cylinder[4]. As a practical matter, however, variation is likely to increase at higher levels of μ_o, and thus the size of the equivalence ellipsoid should probably be larger at greater values of μ_o, leading to a concave equivalence region. The concavity of the equivalence region is not a serious issue, but leads to less powerful tests when inverting a confidence region to compute the test (see Munk and Pflüger, 1999).

As another practical matter, the distribution of radioactivity in soil is often slightly positively skewed, so a data transformation may be useful to take advantage of the normality assumptions of ANOVA and equivalence testing. A proportions transformation achieves the necessary effect, and has the added advantage of eliminating the nuisance parameter μ_o. The data can be transformed from radioactivity [in pCi/g] for the *k* isotopes: $\vec{x} = (x_1, x_2, ..., x_k)^T$, to proportion of the radioactivity attributable to the *k* isotopes: $\vec{p} = (p_1, p_2, ..., p_k)^T$, where:

$$p_i = \frac{x_i}{\sum_{i=1}^{k} x_i}.$$

If SE holds, then each radioisotope should be contributing equally to the radioactivity, and thus the hypothesis $\mu_{p_1} = \mu_{p_2} = ... = \mu_{p_k}$ should hold approximately, where μ_{p_i} is the mean proportion attributed radioisotope *i*. Allowing for slight variations due to sampling and measurement issues, an equivalence test for this equality would take the form $H_o : (\vec{\mu}_p - \frac{1}{k}\vec{1}_k)^T D(\vec{\mu}_p - \frac{1}{k}\vec{1}_k) \geq 1$ for some positive definite matrix $\boldsymbol{D}$ that represents the equivalence region. The matrix $\boldsymbol{D}$ would typically be diagonal, though this is not necessary. For example, if two radionuclides are analyzed by the same method, but others in the decay chain are analyzed by other methods, then some correlation in the equivalence ranges might be appropriate.

Because of the constraint that forces the vector $\vec{\mu}_p$ to sum to 1, the distribution of $\vec{\mu}_p$ cannot be multivariate normal. However, the first $k - 1$ values of the vector might be modeled well by a multivariate normal. If this assumption is reasonable, then a test can be constructed using multivariate normal confidence regions. Let the notation * indicate the vector of the first k–1 values of the k-dimensional vector: i.e. $\vec{\mu}_p = (\mu_{p_1}, \mu_{p_2}, ..., \mu_{p_{k-1}})^T$. The null hypotheses given in the previous paragraph can then be re-written as $H_o : (\vec{\mu}_p^{\,*} - \frac{1}{k}\vec{1}_{k-1})^T C^T DC(\vec{\mu}_p^{\,*} - \frac{1}{k}\vec{1}_{k-1}) \geq 1$, where $\boldsymbol{C}$ is the contrast matrix:

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4 The cylinder is *k*-dimensional. If there are 2 radionuclides in the chain ($k = 2$), then the cylinder is bounded by the ellipse, presumably with a base at 0, but with infinite height.

$$C = \begin{pmatrix} I_{k-1} \\ \hline \vec{\to} \\ 1_{k-1}^{T} \end{pmatrix},$$

where I_{k-1} is the $(k-1)\times(k-1)$ identity matrix. The multivariate equivalence test can then be applied to this $(k-1)$-dimensional space.

The matrix $\boldsymbol{D}$ needs to be specified based on expert knowledge of the sampling process. The simplest version is simply a diagonal matrix with the same value $1/\Delta^2$, where Δ represents the maximum deviation from equal proportions that is to be accepted for a single radioisotope. This specification effectively bounds the sum of squared deviations to be less than Δ^2 to statistically prove equivalence or SE. There may be reasons to specify a more general form for $\boldsymbol{D}$, if, for example, there were known biases in the sampling that might affect some radioisotopes more than others, or if some radionuclides are analyzed with the same method creating some additional correlation between their mean values. Without concrete evidence to the contrary, a specification for a single value of Δ should be sufficient for most purposes.

Example Secular Equilibrium Tests from the Henderson Site

Several datasets[5] from the Henderson site are explored and subjected to the secular equilibrium testing procedure described above. The testing procedure is straightforward to implement with the exception of the specification of $\boldsymbol{D}$ or Δ. For the analysis, and for simplicity, a single value is proposed for Δ, so that the matrix $\boldsymbol{D}$ is diagonal with the same value for each diagonal entry, $1/\Delta^2$. Several factors need to be taken into account for specification of Δ. For example, chemical and physical processes and analytical method differences could be evaluated to provide a basis for an equivalence region. However, without good information on which to base the value of Δ, the approach taken for the Henderson site is to estimate a suitable Δ based on the threshold value at which the background data are shown to be in secular equilibrium. A reasonable estimate of Δ proved to be 10%, hence $\Delta = 0.10$ was adopted as a target equivalence region for testing. Before presenting the results of the equivalence testing for the selected datasets, some exploratory data analysis including summary statistics, correlations and box plots are presented. This is followed by a comparison of the results of running an ANOVA and an equivalence tests for each dataset.

Investigations have been ongoing for more than 10 years at the Henderson site. Ten datasets were evaluated for SE, which provides a rich assortment of possibilities. Three of the datasets represent background investigations performed in the vicinity of the Henderson site. The other seven represent site investigations. Summary statistics for all ten datasets are presented below in Tables 1 and 2. The summary statistics encompass seven radionuclides; four from the uranium chain and three from the thorium chain. From a human health risk assessment perspective these are the most important radionuclides. The risk effects of much shorter-lived daughter radionuclides of radium are included in the dose conversion factors for their parents. Because these daughter radionuclides are so short-lived, SE should be attained quickly. At issue, then, is whether SE has been attained for the seven longer-lived radionuclides in the uranium and thorium decay chains.

[5] All references to the Henderson site datasets included in this analysis are provided at the end of this report in a section titled "References for the Henderson Site datasets".

Table 1: Summary statistics for the uranium decay chain radionuclides of interest

	N	Mean	Std.Dev.	Min	Q1	Median	Q3	Max
2005 BRC/TIMET Shallow Background								
Radium-226	104	1.11	0.35	0.49	0.89	1.07	1.25	2.36
Thorium-230	104	1.27	0.4	0.66	0.98	1.2	1.45	3.01
Uranium-233/234	104	1.16	0.47	0.47	0.86	1.03	1.23	2.84
Uranium-238	104	1.14	0.37	0.57	0.91	1.04	1.28	2.37
2008 Supplemental Shallow Background								
Radium-226	33	1.1	0.51	0.15	0.81	0.99	1.37	2.75
Thorium-230	33	1.49	0.57	1	1.02	1.34	1.71	3.64
Uranium-233/234	33	1.46	0.81	0.7	0.87	1.17	1.82	4.78
Uranium-238	33	1.2	0.67	0.55	0.8	0.94	1.31	4.01
2008 Deep Soil Background								
Radium-226	92	1.3	0.42	0.39	0.99	1.27	1.58	2.29
Thorium-230	92	1.37	0.43	0.53	1.06	1.37	1.64	2.6
Uranium-233/234	92	1.36	0.39	0.73	1.03	1.32	1.61	2.63
Uranium-238	92	1.29	0.37	0.57	1	1.21	1.48	2.79
TRECO								
Radium-226	57	1.73	0.39	1.12	1.48	1.67	1.97	2.62
Thorium-230	57	1.21	0.21	0.88	1.07	1.18	1.37	1.75
Uranium-233/234	57	1.13	0.25	0.75	0.96	1.05	1.22	2.03
Uranium-238	57	1.14	0.19	0.82	1	1.08	1.28	1.66
Tronox Parcels A/B								
Radium-226	64	1.04	0.13	0.84	0.95	1.02	1.08	1.48
Thorium-230	64	1.21	0.3	0.31	1.04	1.17	1.39	2.03
Uranium-233/234	64	0.59	0.4	0.23	0.32	0.47	0.72	2.31
Uranium-238	64	0.38	0.22	0.13	0.25	0.33	0.43	1.26
Tronox Parcels C/D/F/G								
Radium-226	104	1.02	0.14	0.41	0.95	1.02	1.08	1.47
Thorium-230	104	1.3	0.3	0.79	1.1	1.23	1.46	2.17
Uranium-233/234	104	1.17	0.45	0.17	0.88	1.15	1.38	2.56
Uranium-238	104	0.99	0.35	0.19	0.83	1.03	1.19	1.87
Ut lity Corridor								
Radium-226	70	1.35	0.54	0.62	1	1.17	1.51	3.1
Thorium-230	70	1.44	0.71	0.64	1.04	1.23	1.54	4.57
Uranium-233/234	70	1.54	0.78	0.56	1	1.28	1.82	4.55
Uranium-238	70	1.24	0.65	0.57	0.86	1.05	1.45	4.67
Upgradient Groundwater Wells								
Radium-226	44	0.98	0.28	0.69	0.8	0.9	1.07	1.91
Thorium-230	44	1.42	0.48	0.92	1.1	1.27	1.55	3.03
Uranium-233/234	44	0.62	0.48	0.21	0.37	0.5	0.67	2.66
Uranium-238	44	0.53	0.47	0.17	0.28	0.37	0.6	2.57
BRC Parcel 4B								
Radium-226	8	1	0.03	0.93	1	1	1.01	1.03
Thorium-230	8	0.5	0.1	0.37	0.41	0.5	0.59	0.62
Uranium-233/234	8	0.22	0.06	0.15	0.19	0.22	0.25	0.32
Uranium-238	8	0.2	0.06	0.12	0.16	0.19	0.25	0.27
Northeast Area Wells								
Radium-226	141	1.52	0.9	0.64	0.91	1.12	1.97	4.57
Thorium-230	141	1.72	0.99	0.63	0.95	1.41	2.21	5.62
Uranium-233/234	141	1.11	0.94	0.17	0.43	0.65	1.58	4.31
Uranium-238	141	1.03	0.95	0.16	0.32	0.5	1.6	3.92

Table 2: Summary statistics for the thorium decay chain radionuclides of interest

	N	Mean	Std.Dev.	Min	Q1	Median	Q3	Max
2005 BRC/TIMET Shallow Background								
Radium-228	84	1.92	0.4	0.95	1.67	1.96	2.17	2.94
Thorium-228	84	1.73	0.26	1.15	1.52	1.79	1.91	2.15
Thorium-232	84	1.66	0.26	1.22	1.46	1.69	1.86	2.12
2008 Supplemental Shallow Background								
Radium-228	33	1.54	0.55	0.57	1.22	1.38	1.98	2.86
Thorium-228	33	1.79	0.51	1.1	1.37	1.64	2.22	3.37
Thorium-232	33	1.54	0.32	1.14	1.35	1.49	1.69	2.8
2008 Deep Soil Background								
Radium-228	99	1.37	0.29	0.45	1.19	1.38	1.54	2.31
Thorium-228	99	1.58	0.28	0.94	1.38	1.54	1.77	2.18
Thorium-232	99	1.45	0.26	0.9	1.27	1.45	1.59	2.05
TRECO								
Radium-228	57	1.56	0.28	1.01	1.33	1.58	1.76	2.31
Thorium-228	57	1.83	0.18	1.42	1.71	1.8	1.92	2.3
Thorium-232	57	1.75	0.21	1.28	1.6	1.72	1.89	2.21
Tronox Parcels A/B								
Radium-228	64	1.78	0.16	1.4	1.69	1.79	1.88	2.13
Thorium-228	64	1.55	0.33	0.02	1.35	1.58	1.75	2.17
Thorium-232	64	1.46	0.3	0	1.34	1.43	1.61	2.36
Tronox Parcels C/D/F/G								
Radium-228	104	1.74	0.19	0.58	1.66	1.75	1.86	2.13
Thorium-228	104	1.63	0.26	1.07	1.48	1.62	1.77	2.33
Thorium-232	104	1.53	0.23	0.92	1.37	1.52	1.68	2.15
Ut lity Corridor								
Radium-228	70	1.9	0.79	0.29	1.43	1.77	2.35	5.59
Thorium-228	70	1.97	0.83	0.76	1.49	1.82	2.16	6.4
Thorium-232	70	1.52	0.54	0.79	1.21	1.4	1.73	4.21
Upgradient Groundwater Wells								
Radium-228	44	1.46	0.24	0.54	1.37	1.51	1.6	1.87
Thorium-228	44	1.44	0.29	0.47	1.3	1.5	1.65	2
Thorium-232	44	1.36	0.29	0.47	1.26	1.41	1.5	2.08
BRC Parcel 4B								
Radium-228	8	1.49	0.26	0.96	1.45	1.55	1.6	1.85
Thorium-228	8	0.86	0.13	0.68	0.74	0.89	0.95	1.05
Thorium-232	8	0.87	0.13	0.63	0.83	0.9	0.94	1.04
Northeast Area Wells								
Radium-228	59	1.17	0.32	0.33	1.13	1.27	1.33	1.72
Thorium-228	59	1.11	0.37	0.15	0.97	1.21	1.4	1.89
Thorium-232	59	1.05	0.37	0.1	0.89	1.12	1.26	1.99

Background Data

Background data have been collected on three separate occasions[6], covering the different geological formations around the BMI site. Box plots for these three datasets are presented in Figures 3-8. The box plots and the summary statistics generally show good agreement; the distributions look similar. However, the summary statistics and box plots do not portray the inherent correlation across the radionuclides. The correlation matrices for the three background data sets and the two decay chains are presented in Table 3. Correlations within the uranium chain are strong as expected. However, the correlations in the thorium chain are more interesting, perhaps indicating a cause for concern. In particular, the correlations with Radium (Ra)-228 are very small, suggesting a problem with either the Ra-228 results or with both the Th-228 and Th-232 results. The summary statistics, plots and correlations support the contention that the background data are in approximate SE. Table 4 shows results of the statistical tests to confirm this hypothesis. Included in Table 4 are results of an ANOVA, and results of the equivalence tests for these datasets. The ANOVA suggests that SE has not been obtained for four of the six datasets. However, the SE tests with a $\Delta = 0.1$ suggest approximate SE in all cases. If a $\Delta = 0.05$ is used instead, then SE is not demonstrated for the supplemental background dataset. Consequently, a target $\Delta = 0.1$ is used to determine SE for the site investigations.

Table 3: Correlations for the Henderson Site Background Data

2005 BRC/TIMET Shallow Background

	Ra-226	*Th-230*	*U-233/234*	*U-238*
Ra-226	1.0000	0.6632	0.6911	0.7068
Th-230	0.6632	1.0000	0.7838	0.7796
U-233/234	0.6911	0.7838	1.0000	0.8763
U-238	0.7068	0.7796	0.8763	1.0000

	Ra-228	*Th-228*	*Th-232*
Ra-228	1.0000	0.2967	0.3049
Th-228	0.2967	1.0000	0.7323
Th-232	0.3049	0.7323	1.0000

2008 Supplemental Soil Background

	Ra-226	*Th-230*	*U-233/234*	*U-238*
Ra-226	1.0000	0.7019	0.7857	0.8115
Th-230	0.7019	1.0000	0.8305	0.8393
U-233/234	0.7857	0.8305	1.0000	0.9314
U-238	0.8115	0.8393	0.9314	1.0000

	Ra-228	*Th-228*	*Th-232*
Ra-228	1.0000	0.0101	-0.1041
Th-228	0.0101	1.0000	0.5484
Th-232	-0.1041	0.5484	1.0000

2008 Deep Soil Background

	Ra-226	*Th-230*	*U-233/234*	*U-238*
Ra-226	1.0000	0.7550	0.7646	0.7508
Th-230	0.7550	1.0000	0.8300	0.8024
U-233/234	0.7646	0.8300	1.0000	0.9335
U-238	0.7508	0.8024	0.9335	1.0000

	Ra-228	*Th-228*	*Th-232*
Ra-228	1.0000	0.2016	0.2570
Th-228	0.2016	1.0000	0.6722
Th-232	0.2570	0.6722	1.0000

[6] Note that the 2005 BRC/TIMET background dataset also includes the background data collected by the City of Henderson for the Water Reclamation Facility investigation in 2002.

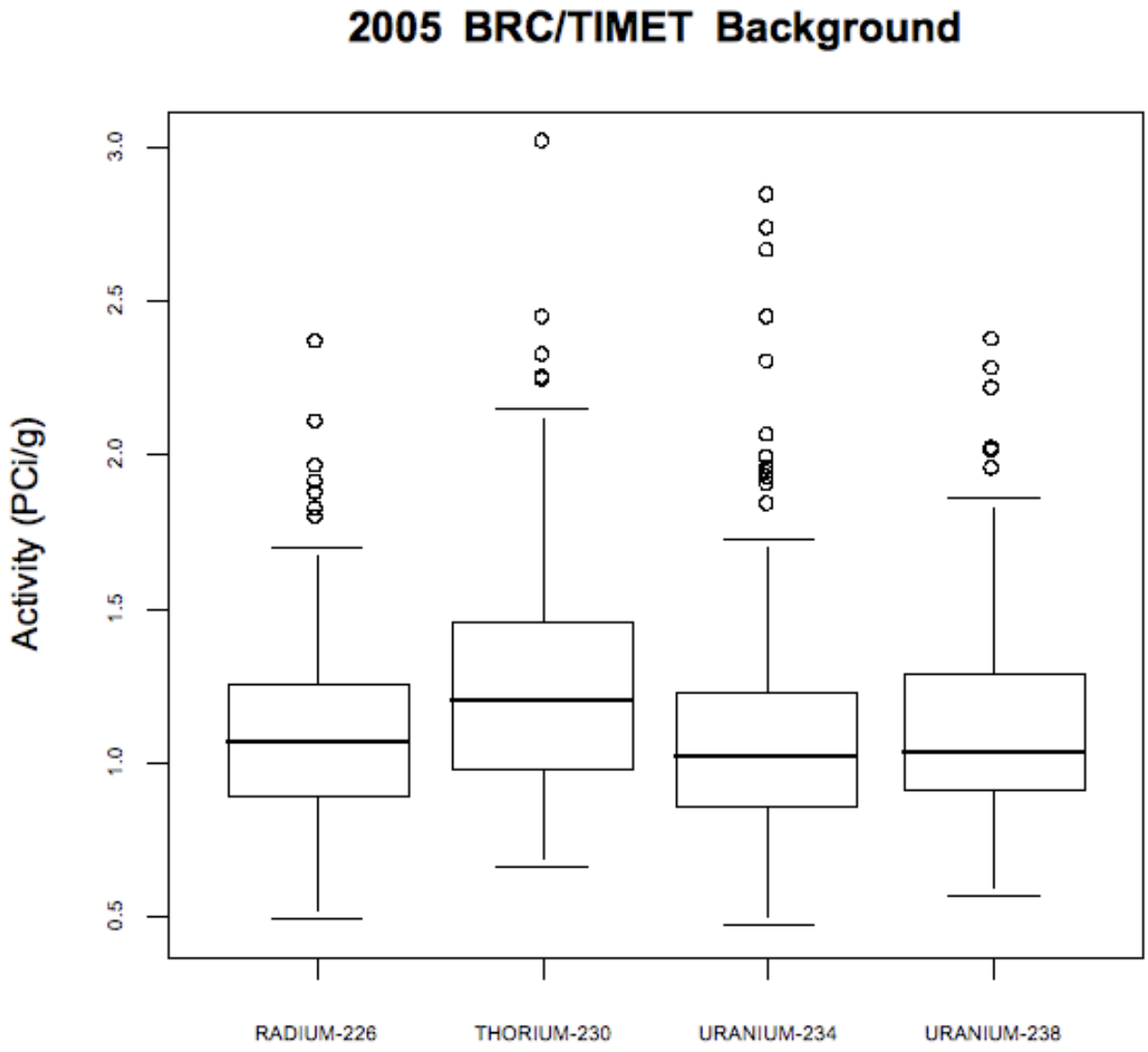

Figure 3: **Box plots for the uranium chain in the 2005 BRC/TIMET background data.**

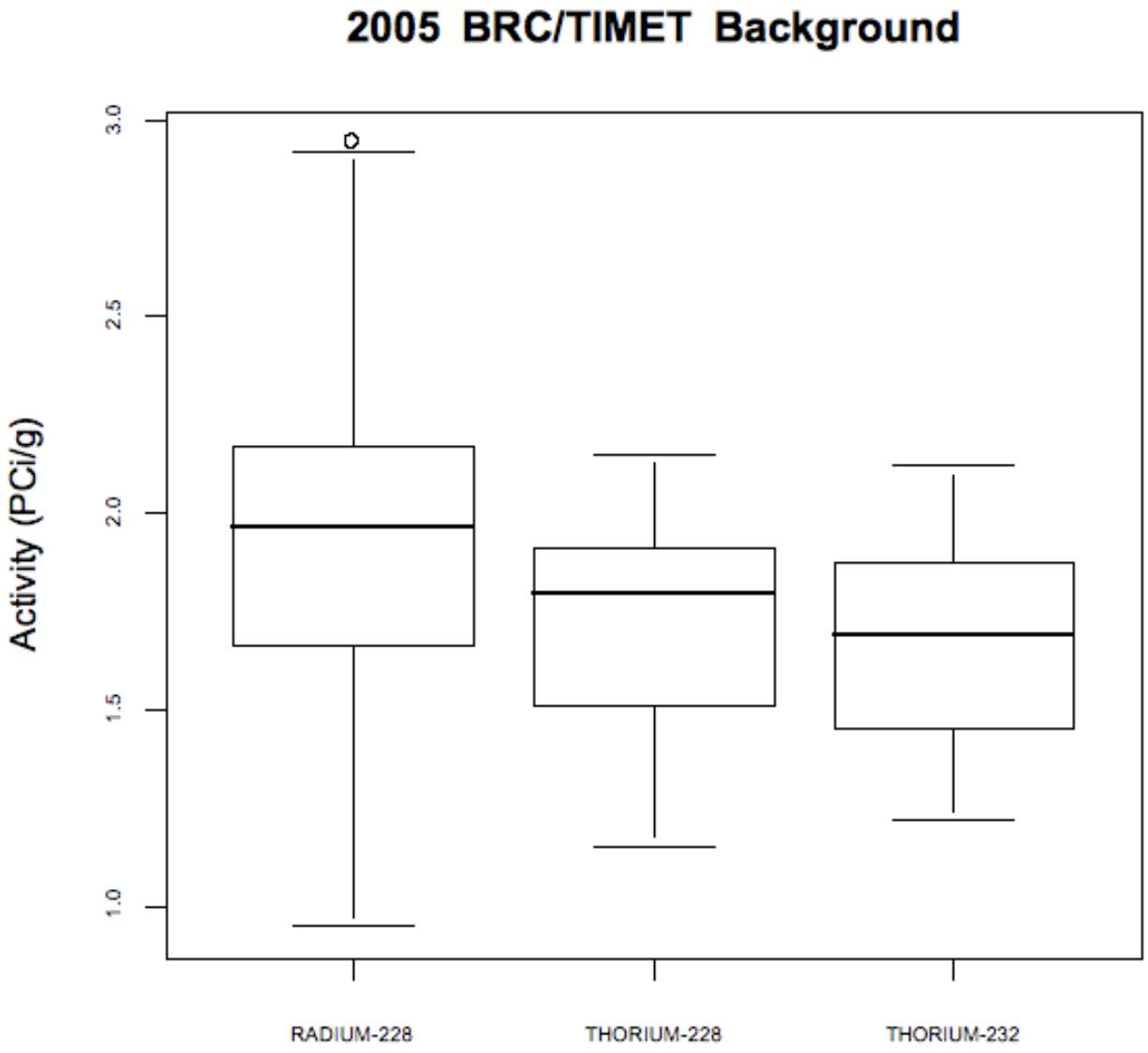

Figure 4: **Box plots for the thorium chain in the 2005 BRC/TIMET background data.**

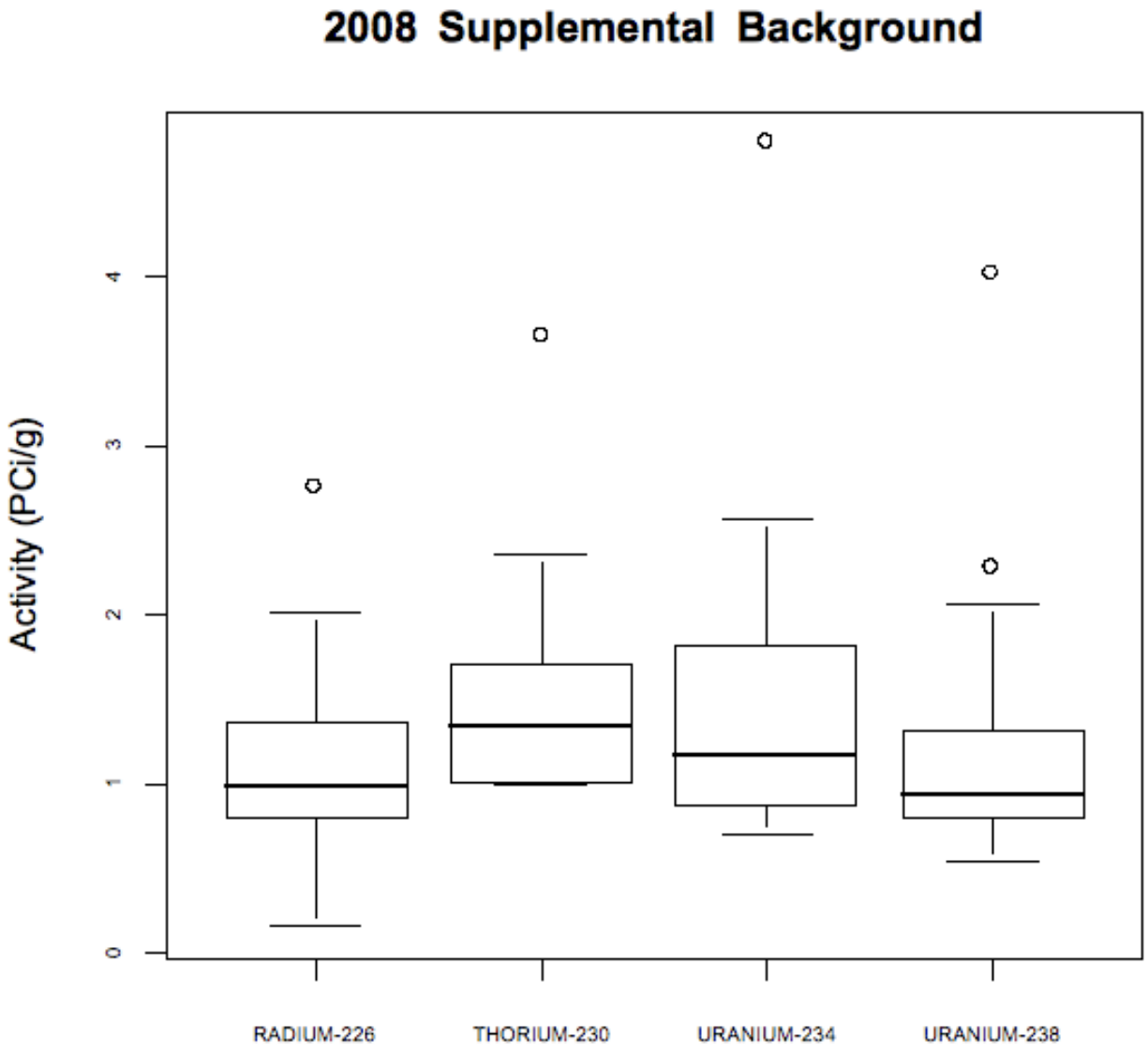

Figure 5: **Box plots for the uranium chain in the 2008 Supplemental background data.**

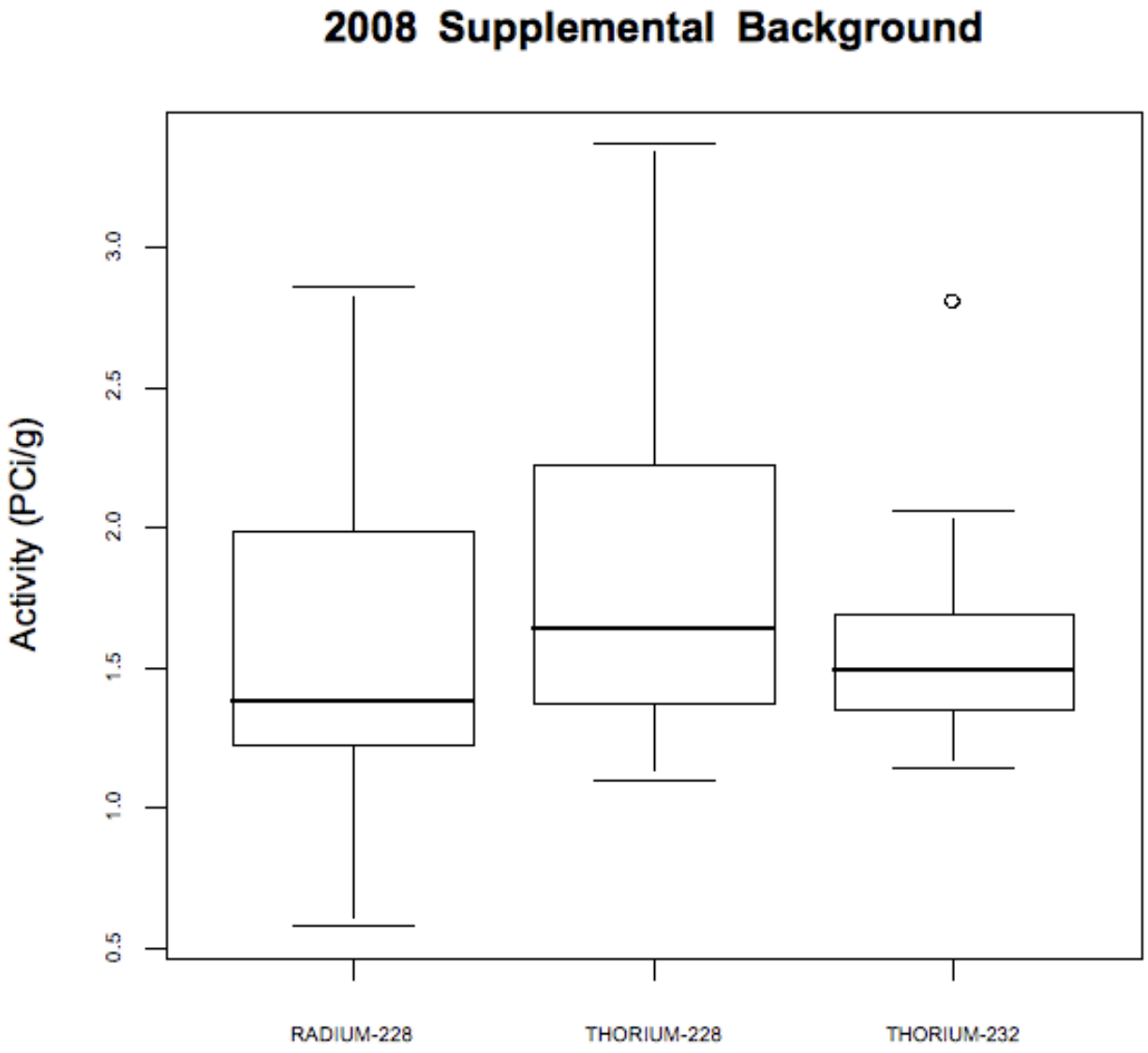

Figure 6: **Box plots for the thorium chain in the 2008 Supplemental background data.**

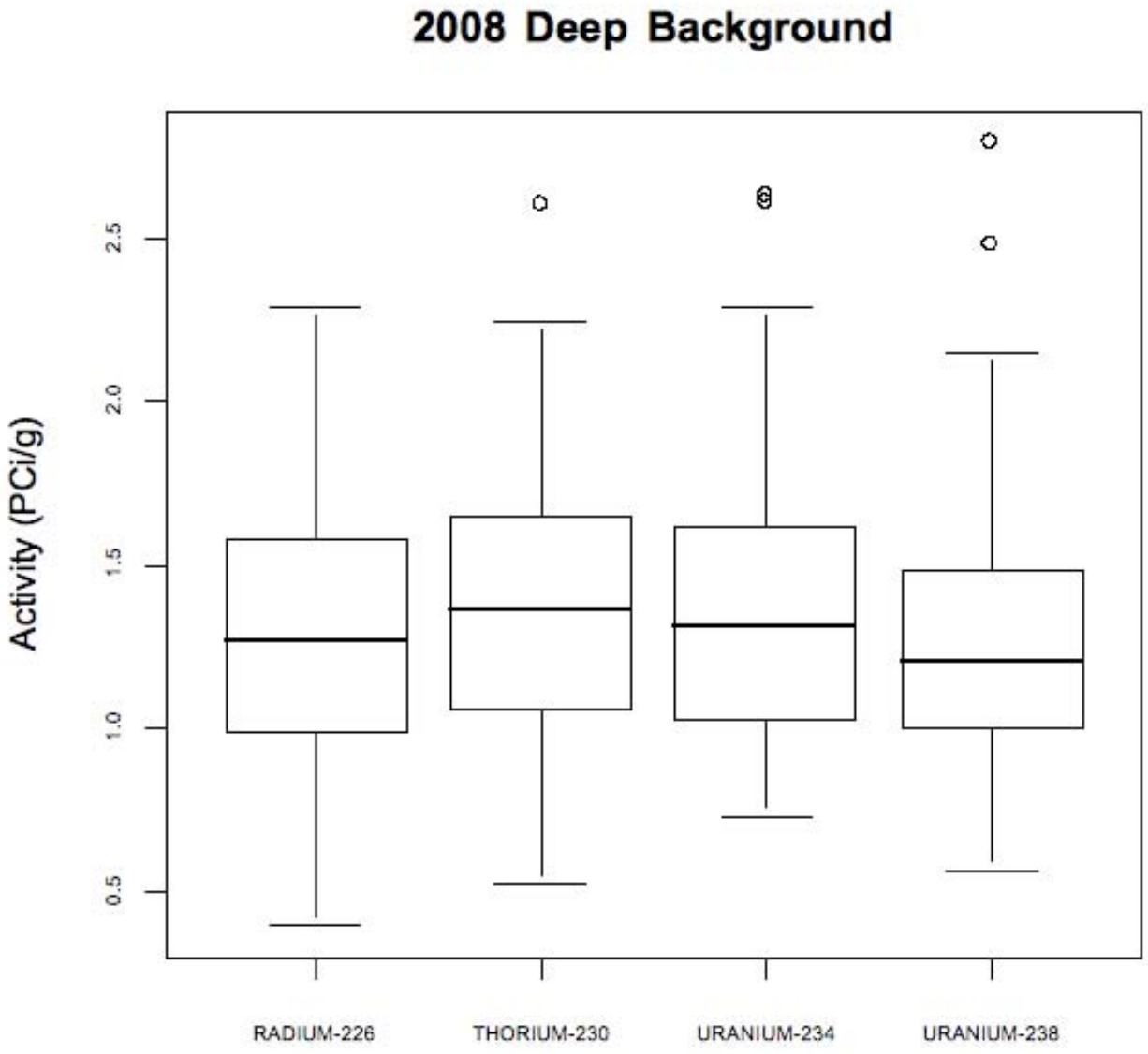

Figure 7: **Box plots for the uranium chain in the 2008 Deep background data.**

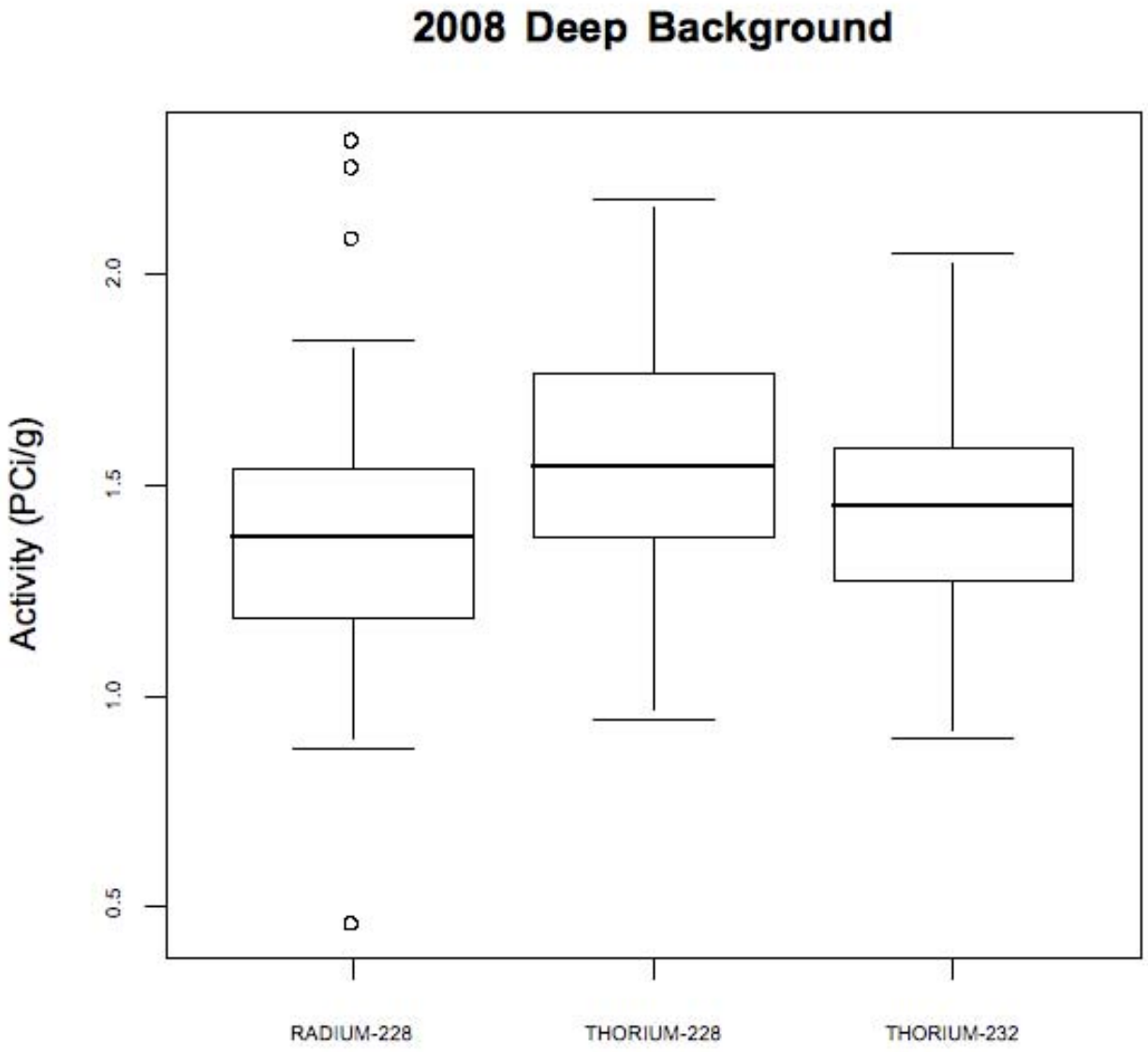

Figure 8: **Box plots for the thorium chain in the 2008 Deep background data.**

Table 4: ANOVA and Equivalence Test results for the Background Data

	ANOVA	Equivalence Test			Mean Proport on			
Site	**P-value**	**Delta**	**p-value**	**Secular Equilibrium**	**Ra-226**	**Th-230**	**U-233/234**	**U-238**
2005 BRC/TIMET Background	6.70E-03	0.05	0.00	Yes	0.2401	0.2720	0.2448	0.2431
2005 BRC/TIMET Background		0.1	0.00	Yes	0.2401	0.2720	0.2448	0.2431
2008 Supplemental Background	3.50E-02	0.05	0.50	No	0.2114	0.2934	0.2716	0.2236
2008 Supplemental Background		0.1	0.03	Yes	0.2114	0.2934	0.2716	0.2236
2008 Deep Background	6.30E-01	0.05	0.00	Yes	0.2430	0.2562	0.2569	0.2438
2008 Deep Background		0.1	0.00	Yes	0.2430	0.2562	0.2569	0.2438

	ANOVA	Equivalence Test			Mean Proport on		
Site	**P-value**	**Delta**	**p-value**	**Secular Equilibrium**	**Ra-228**	**Th-228**	**Th-232**
2005 BRC/TIMET Background	**1.70E-10**	0.05	0.00	Yes	0.3599	0.3270	0.3130
2005 BRC/TIMET Background		0.1	0.00	Yes	0.3599	0.3270	0.3130
2008 Supplemental Background	6.10E-02	0.05	0.38	No	0.3143	0.3647	0.3210
2008 Supplemental Background		0.1	0.00	Yes	0.3143	0.3647	0.3210
2008 Deep Background	**1.10E-10**	0.05	0.01	Yes	0.3117	0.3586	0.3297
2008 Deep Background		0.1	0.00	Yes	0.3117	0.3586	0.3297

Shaded cells show support for the hypothesis of SE.

Henderson Site Data

Equivalence tests for the site data are based on a $\Delta = 0.1$. Summary statistics for the seven sites were presented in Tables 1 and 2. Correlation matrices are presented in Table 5. ANOVA and equivalence test results are presented in Table 6. Box plots are presented in Figures 9-22.

For the uranium chain the correlations are high for many of the datasets. The obvious exception is for the BRC Parcel 4B data, for which the correlations of other radionuclides with Ra-226 are negative. The box plots (Figure 19) and the summary statistics show very low values for the uranium isotopes and for thorium-230. These results provide evidence of analytical problems for these radionuclides. Despite the high correlations, Table 6 shows other sites for which approximate SE does not appear to have been achieved. For soil samples collected from TRECO, Tronox Parcels A/B, Upgradient Groundwater Wells, and Northeast Area Wells, the uranium activities appear to be low. Approximate SE appears to be obtained only in the other two datasets (Tronox Parcels C/D/F/G and the Utility Corridor).

For the thorium chain, the results for most sites appear to exhibit approximate SE. The exception is BRC Parcel 4B. The box plot for this dataset (Figure 20) shows comparatively low levels of radioactivity for the thorium isotopes. Although the data for most of these sites indicate SE for the thorium chain, of concern is the lack of correlation between the thorium and radium isotopes for some of these datasets. This implies a problem between the analytical methods, which could be related to sensitivity of one or more of the methods at these activity levels, or it could be indicative of reporting problems with the data. In general, a correlation is expected between activities of radioisotopes from the same chain.

Table 5: Correlations for the Henderson site data

TRECO

	Ra-226	*Th-230*	*U-234*	*U-238*
Ra-226	1.0000	0.3294	0.1671	0.1148
Th-230	0.3294	1.0000	0.5555	0.5760
U-234	0.1671	0.5555	1.0000	0.6645
U-238	0.1148	0.5760	0.6645	1.0000

	Ra-228	*Th-228*	*Th-232*
Ra-228	1.0000	0.2316	0.2295
Th-228	0.2316	1.0000	0.5647
Th-232	0.2295	0.5647	1.0000

Tronox Parcels A/B

	Ra-226	*Th-230*	*U-233/234*	*U-238*
Ra-226	1.0000	0.6548	0.4585	0.4636
Th-230	0.6548	1.0000	0.5058	0.5069
U-233/234	0.4585	0.5058	1.0000	0.9819
U-238	0.4636	0.5069	0.9819	1.0000

	Ra-228	*Th-228*	*Th-232*
Ra-228	1.0000	0.2626	0.0036
Th-228	0.2626	1.0000	0.6560
Th-232	0.0036	0.6560	1.0000

Tronox Parcels C/D/F/G

	Ra-226	*Th-230*	*U-233/234*	*U-238*
Ra-226	1.0000	0.4141	0.3186	0.2439
Th-230	0.4141	1.0000	0.4961	0.3746
U-233/234	0.3186	0.4961	1.0000	0.9028
U-238	0.2439	0.3746	0.9028	1.0000

	Ra-228	*Th-228*	*Th-232*
Ra-228	1.0000	0.2062	0.2237
Th-228	0.2062	1.0000	0.5664
Th-232	0.2237	0.5664	1.0000

Ut lity Corridor

	Ra-226	*Th-230*	*U-233/234*	*U-238*
Ra-226	1.0000	0.6224	0.5992	0.5520
Th-230	0.6224	1.0000	0.7368	0.7290
U-233/234	0.5992	0.7368	1.0000	0.8330
U-238	0.5520	0.7290	0.8330	1.0000

	Ra-228	*Th-228*	*Th-232*
Ra-228	1.0000	0.3163	0.1109
Th-228	0.3163	1.0000	0.6544
Th-232	0.1109	0.6544	1.0000

Upgradient Wells

	Ra-226	*Th-230*	*U-233/234*	*U-238*
Ra-226	1.0000	0.8075	0.8322	0.8423
Th-230	0.8075	1.0000	0.7793	0.7995
U-233/234	0.8322	0.7793	1.0000	0.9850
U-238	0.8423	0.7995	0.9850	1.0000

	Ra-228	*Th-228*	*Th-232*
Ra-228	1.0000	0.7280	0.6814
Th-228	0.7280	1.0000	0.7009
Th-232	0.6814	0.7009	1.0000

BRC Parcel 4B

	Ra-226	*Th-230*	*U-234*	*U-238*
Ra-226	1.0000	-0.2998	-0.4563	-0.0389
Th-230	-0.2998	1.0000	0.3565	0.3748
U-234	-0.4563	0.3565	1.0000	0.0298
U-238	-0.0389	0.3748	0.0298	1.0000

	Ra-228	*Th-228*	*Th-232*
Ra-228	1.0000	0.6190	0.1974
Th-228	0.6190	1.0000	0.8198
Th-232	0.1974	0.8198	1.0000

Northeast Area Wells

	Ra-226	*Th-230*	*U-233/234*	*U-238*
Ra-226	1.0000	0.9349	0.9208	0.9206
Th-230	0.9349	1.0000	0.9038	0.9072
U-233/234	0.9208	0.9038	1.0000	0.9859
U-238	0.9206	0.9072	0.9859	1.0000

	Ra-228	*Th-228*	*Th-232*
Ra-228	1.0000	0.8674	0.8154
Th-228	0.8674	1.0000	0.9047
Th-232	0.8154	0.9047	1.0000

Table 6: ANOVA and Equivalence Test results for the Site Data

	ANOVA	Equivalence Test			Mean Proport on			
Site	**P-value**	**Delta**	**p-value**	**Secular Equilibrium**	**Ra-226**	**Th-230**	**U-233/234**	**U-238**
TRECO	5.00E-01	0.1	0.50	No	0.3168	0.1925	0.1956	0.2951
Tronox Parcels A/B	3.90E-39	0.1	0.50	No	0.3367	0.3799	0.1705	0.1128
Tronox Parcels C/D/F/G	3.20E-26	0.1	0.00	Yes	0.2530	0.2159	0.2360	0.2951
Ut lity Corridor	4.90E-02	0.1	0.00	Yes	0.2494	0.2585	0.2709	0.2211
Upgradient Groundwater Wells	8.50E-15	0.1	0.50	No	0.2906	0.4122	0.1634	0.1338
BRC Parcel 4B	1.10E-20	0.1	0.50	No	0.5249	0.2586	0.1145	0.1021
Northeast Area Wells	3.50E-09	0.1	0.50	No	0.3447	0.3058	0.1863	0.1632

	ANOVA	Equivalence Test			Mean Proport on		
Site	**P-value**	**Delta**	**p-value**	**Secular Equilibrium**	**Ra-228**	**Th-228**	**Th-232**
TRECO	3.60E-02	0.1	0.00	Yes	0.3571	0.3406	0.3023
Tronox Parcels A/B	1.90E-04	0.1	0.00	Yes	0.3786	0.3191	0.3022
Tronox Parcels C/D/F/G	6.20E-10	0.1	0.00	Yes	0.3564	0.3324	0.3113
Ut lity Corridor	8.00E-04	0.1	0.00	Yes	0.3507	0.3615	0.2878
Upgradient Groundwater Wells	4.00E-01	0.1	0.00	Yes	0.3440	0.3375	0.3185
BRC Parcel 4B	5.70E-07	0.1	0.50	No	0.4616	0.2671	0.2713
Northeast Area Wells	2.30E-02	0.1	0.00	Yes	0.3291	0.3615	0.3095

Summary

Multiple lines of evidence should be followed to understand the soil data collected at the Henderson site. Even then, the history of which analytical methods were used, including sample preparation methods, is incomplete, making conclusions different to draw. Regarding secular equilibrium, a few observations can be made:

- The standard set of summary statistics and box plots that depict each radionuclide dataset should be considered to compare means. However, these statistical analyses do not account for correlations. If the means are not similar, then this is probably an indication of contamination or analytical method problems.
- Correlations should be considered. If the radionuclides within a decay chain are in SE, then their activities should be correlated. If they are not correlated, then this is probably an indication of method problems or data reporting problems.
- Equivalence testing should be used in lieu of ANOVA so that a reasonable practical range for small differences does not trigger a statistically significant result.

If these steps are taken, then either an informed decision about secular equilibrium can be made, and can be used to support background comparisons and chemicals of potential concern (COPC) selection, or problems with the analytical methods can be uncovered. Equivalence testing for secular equilibrium should become part of the statistical arsenal used to evaluate radionuclide data from soil samples. In addition, some consideration should be given to using equivalence testing for background comparisons and other statistical analyses that are needed for environmental data.

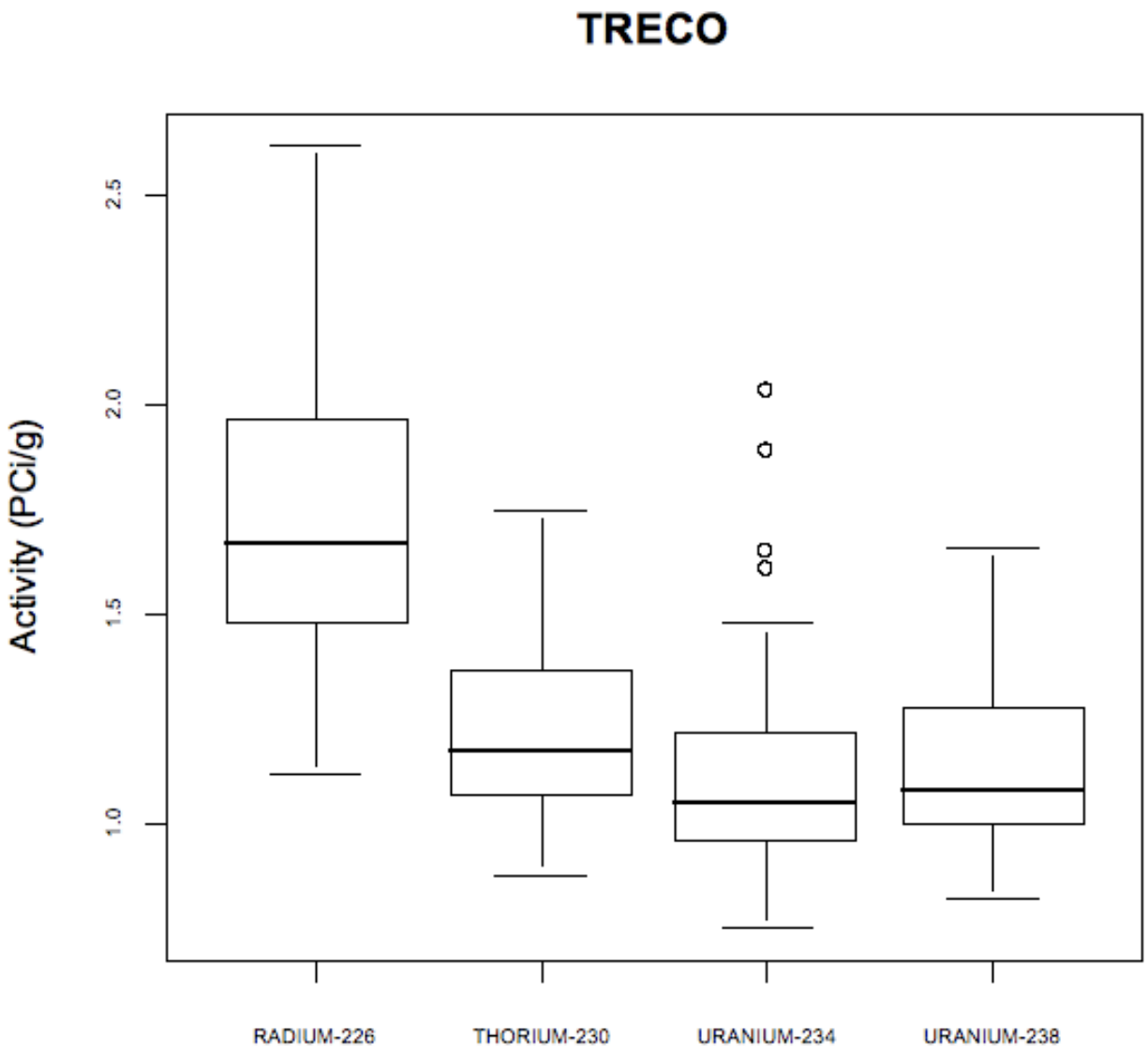

Figure 9: **Box plots for the uranium chain in the TRECO data.**

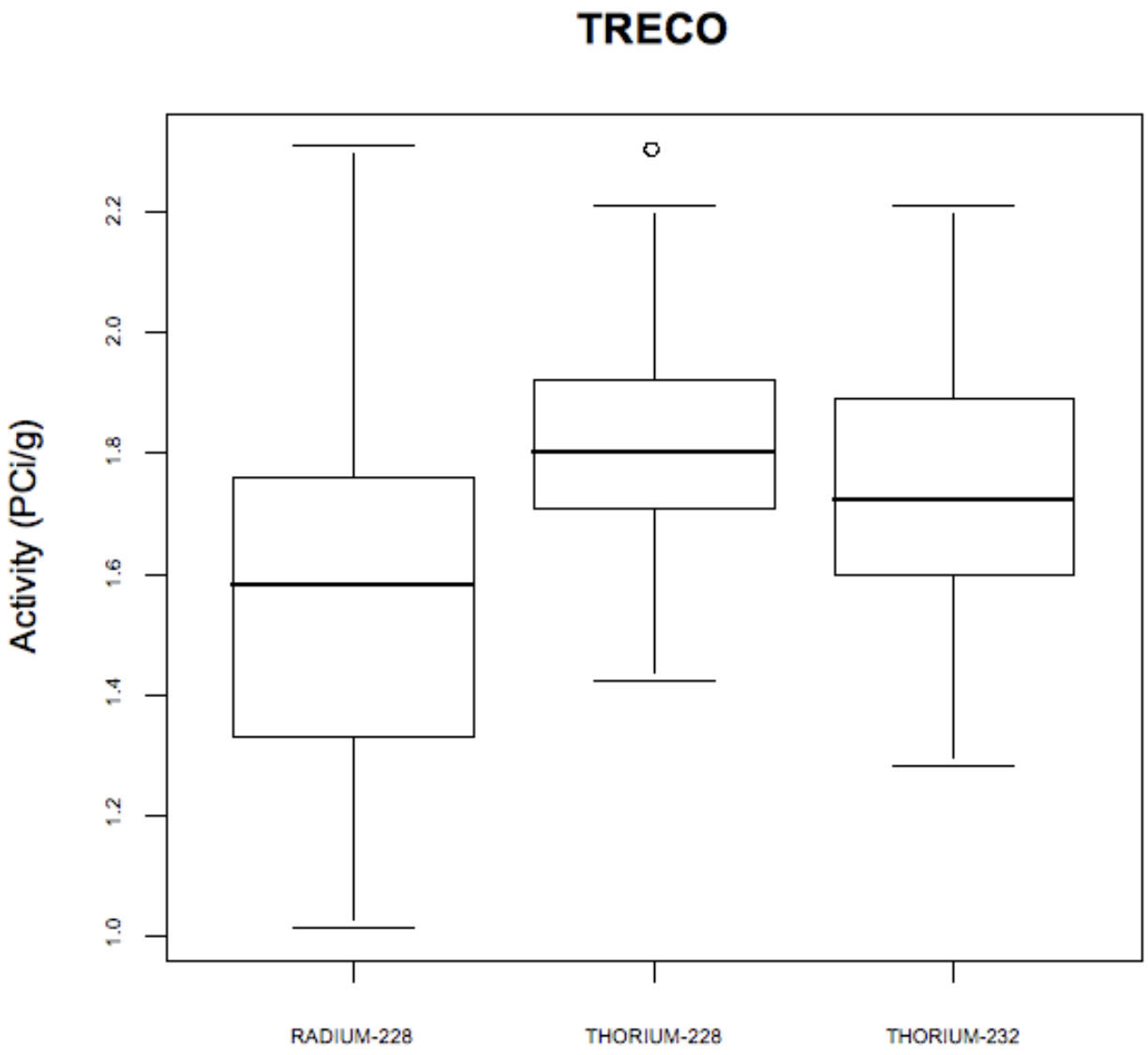

Figure 10: Box plots for the thorium chain in the TRECO data.

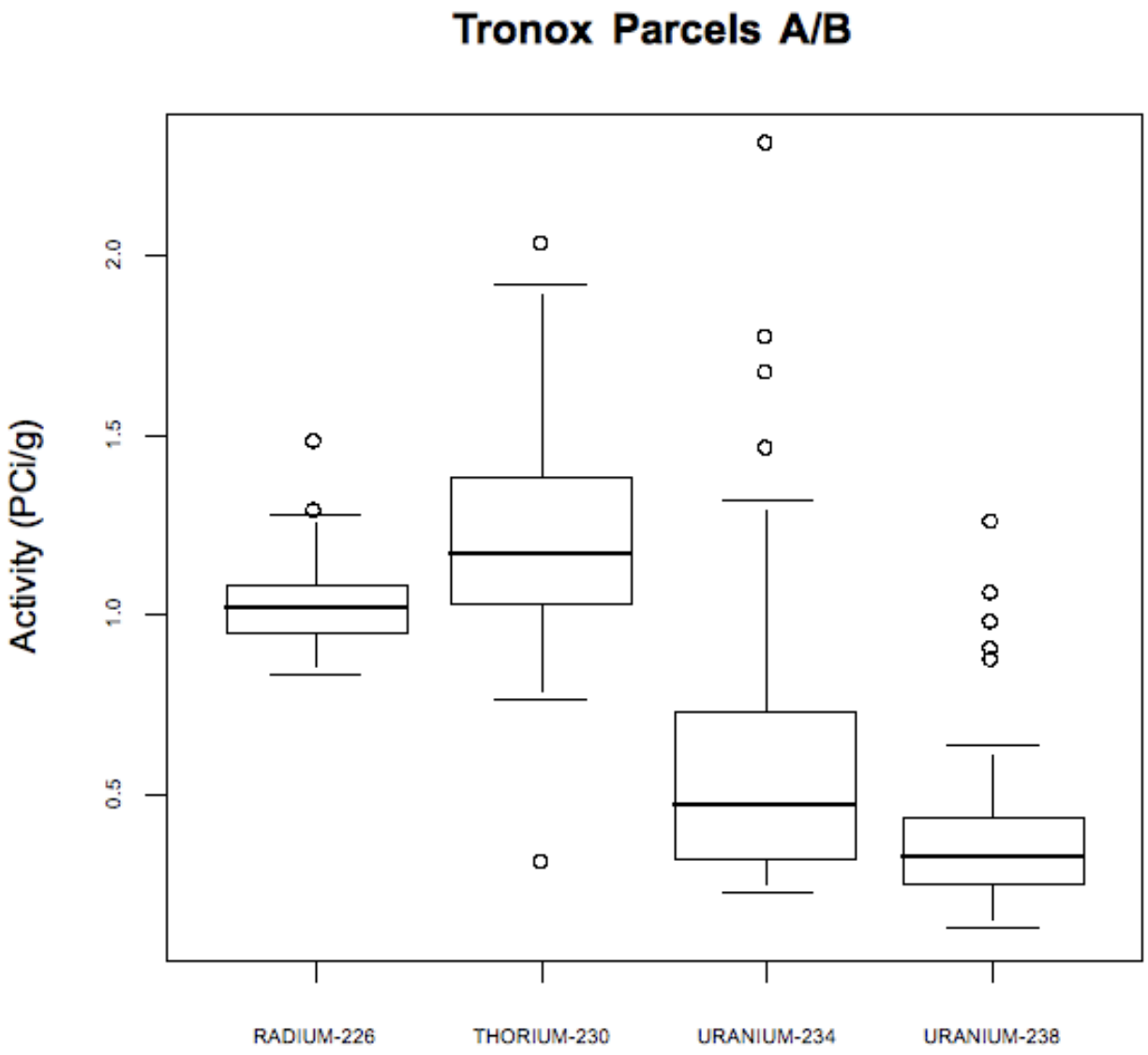

Figure 11: Box plots for the uranium chain in the Tronox Parcels A/B data.

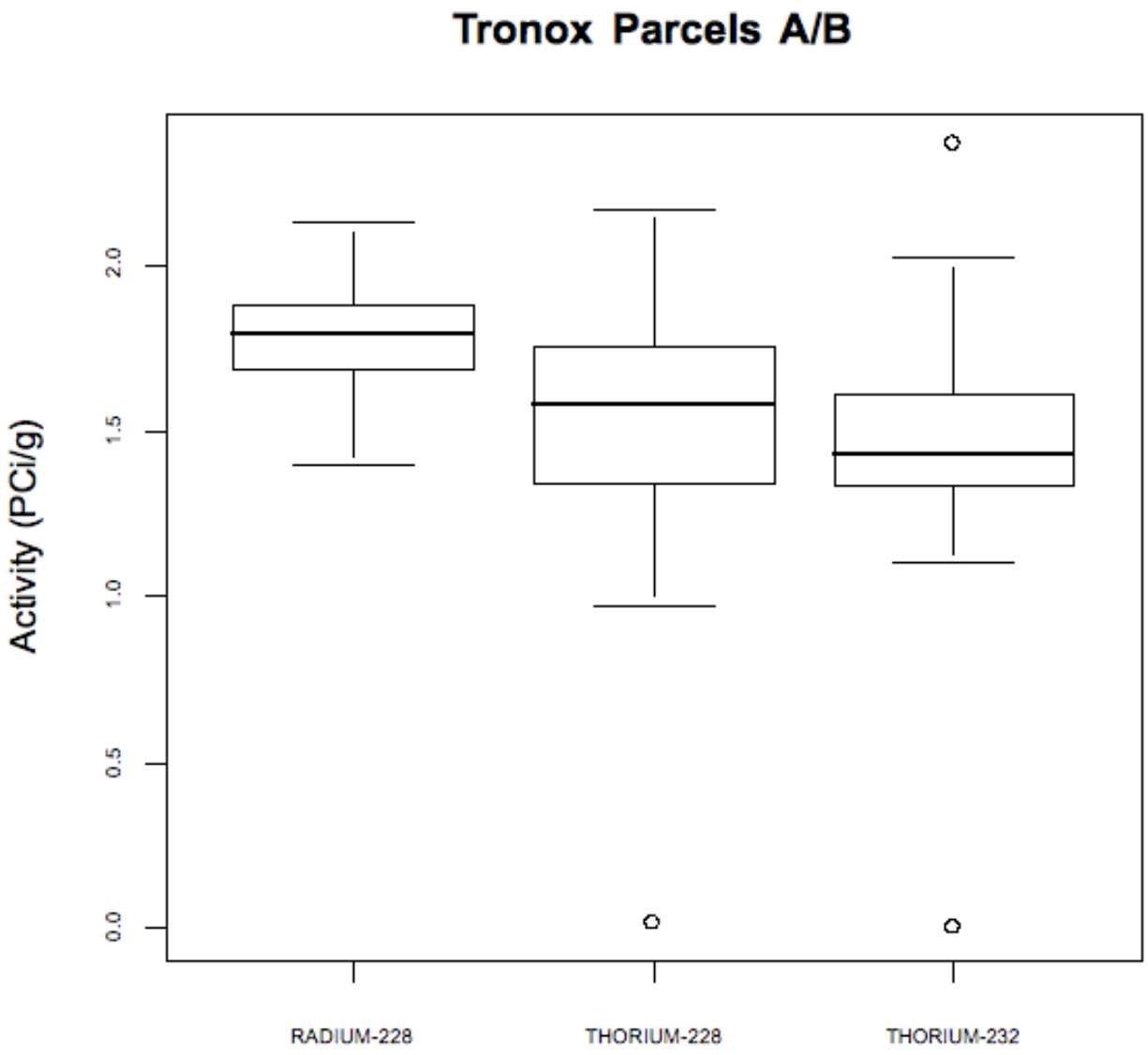

Figure 12: Box plots for the thorium chain in the Tronox Parcels A/B data.

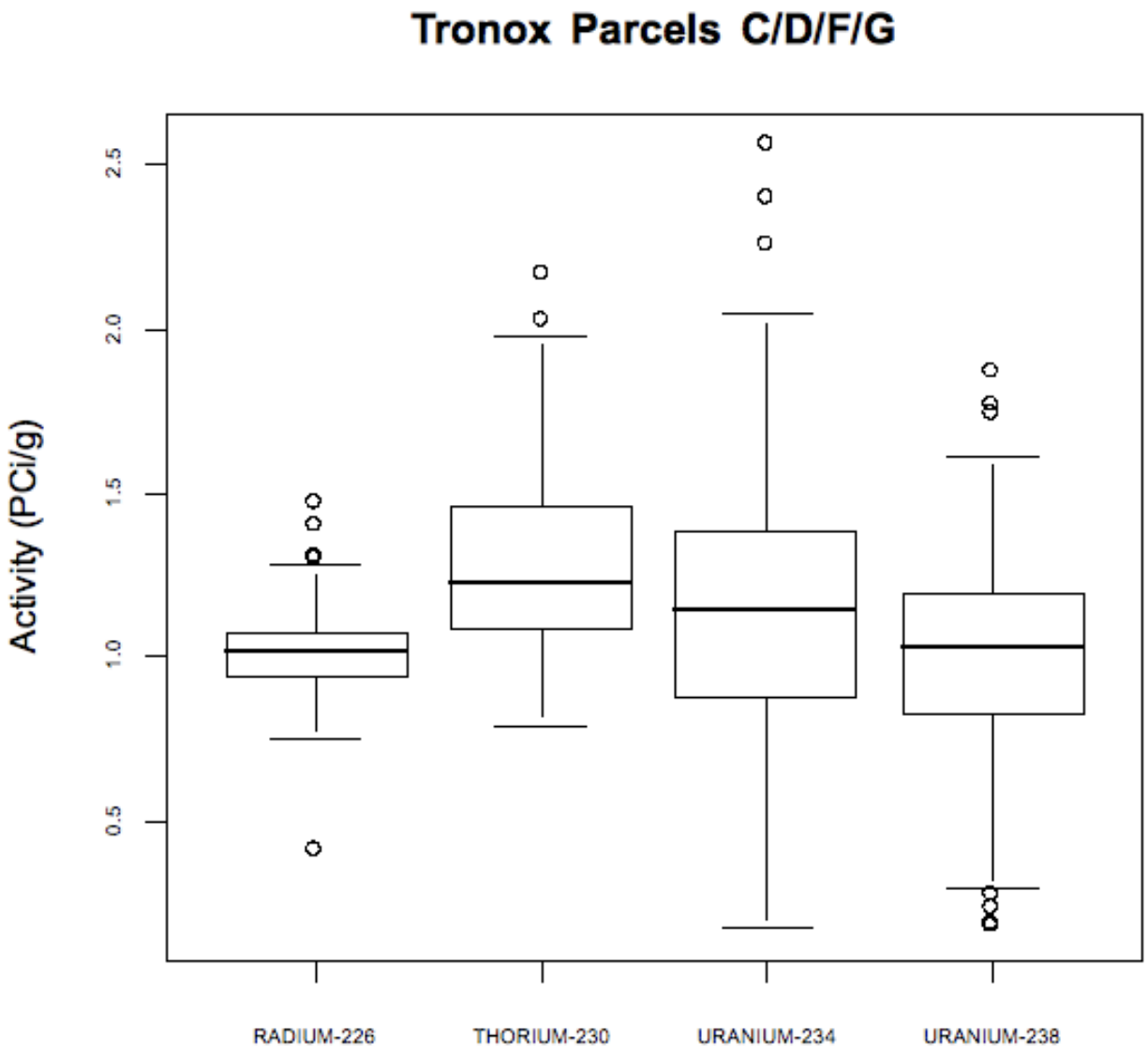

Figure 13: Box plots for the uranium chain in the Tronox Parcels C/D/F/G data.

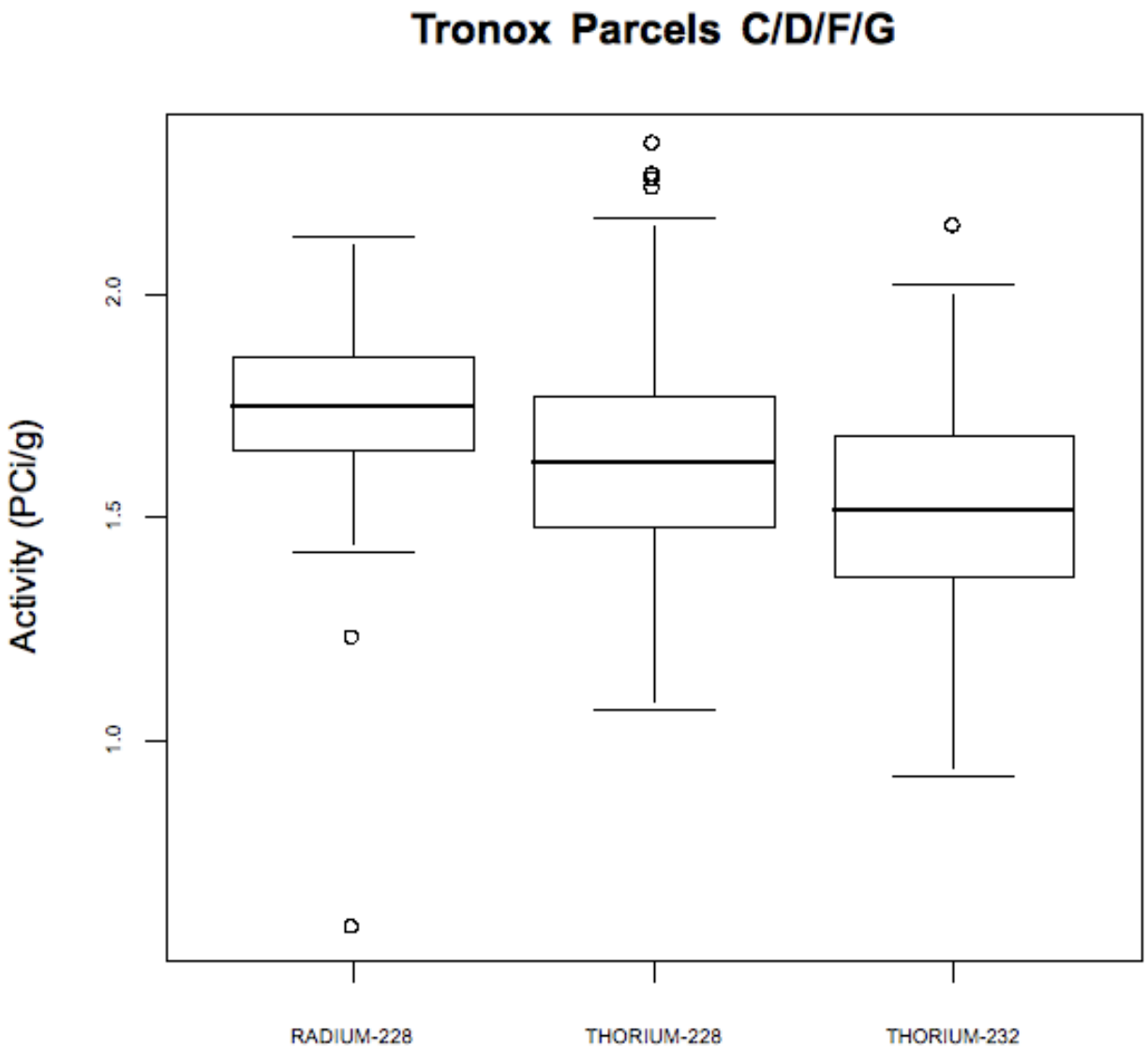

Figure 14: Box plots for the thorium chain in the Tronox Parcels C/D/F/G data.

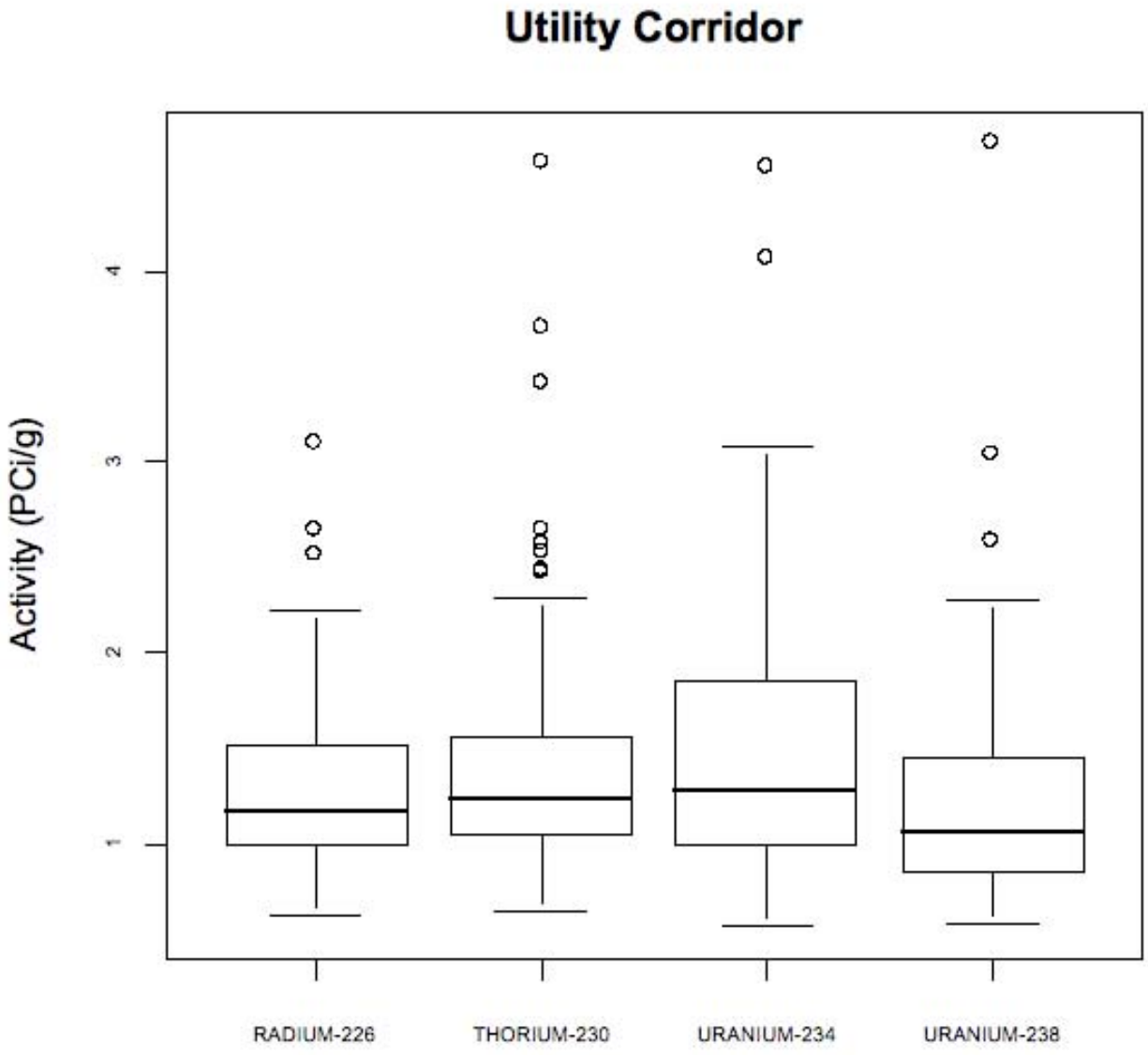

Figure 15: Box plots for the uranium chain in the Utility Corridor data.

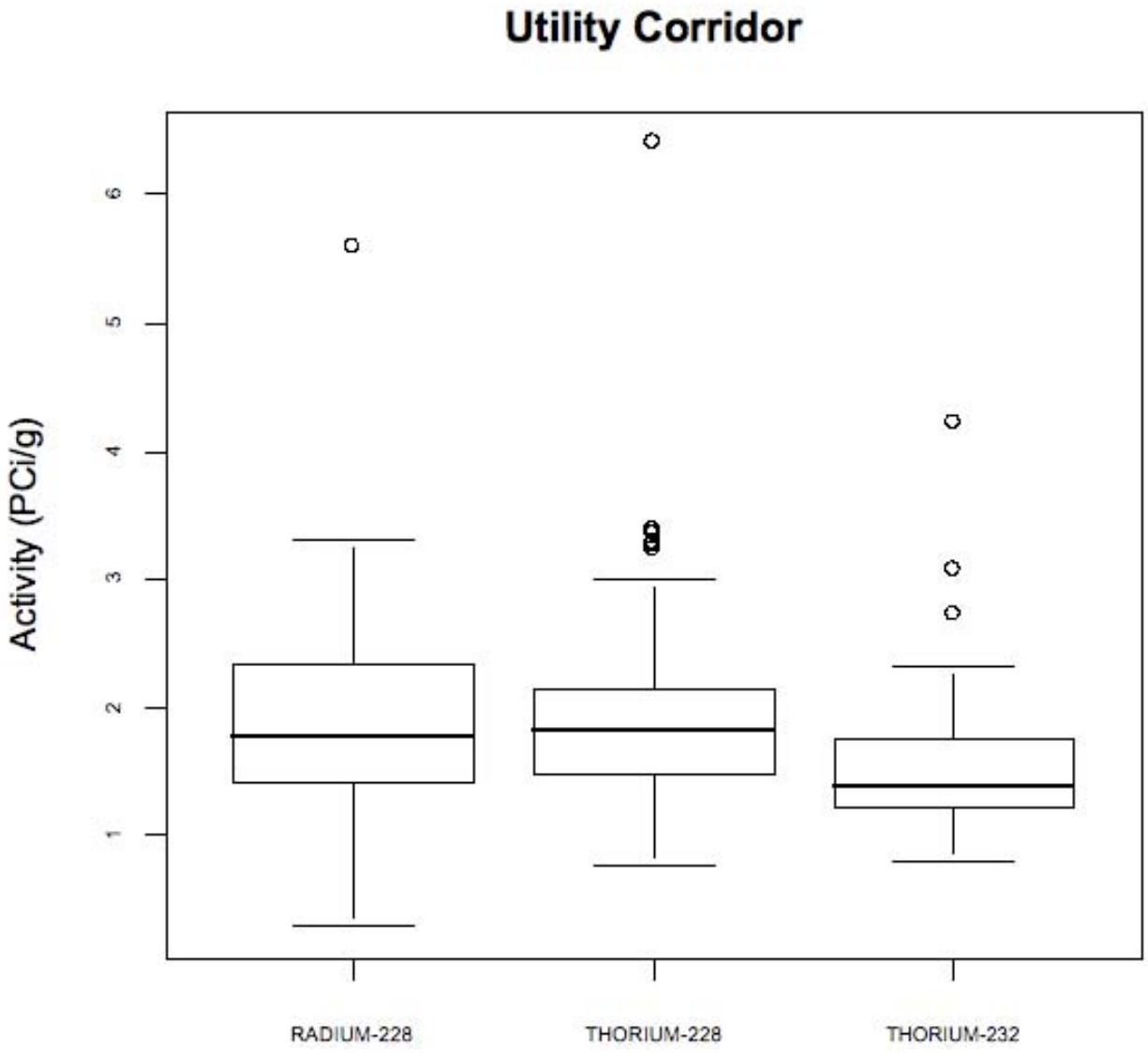

Figure 16: Box plots for the thorium chain in the Utility Corridor data.

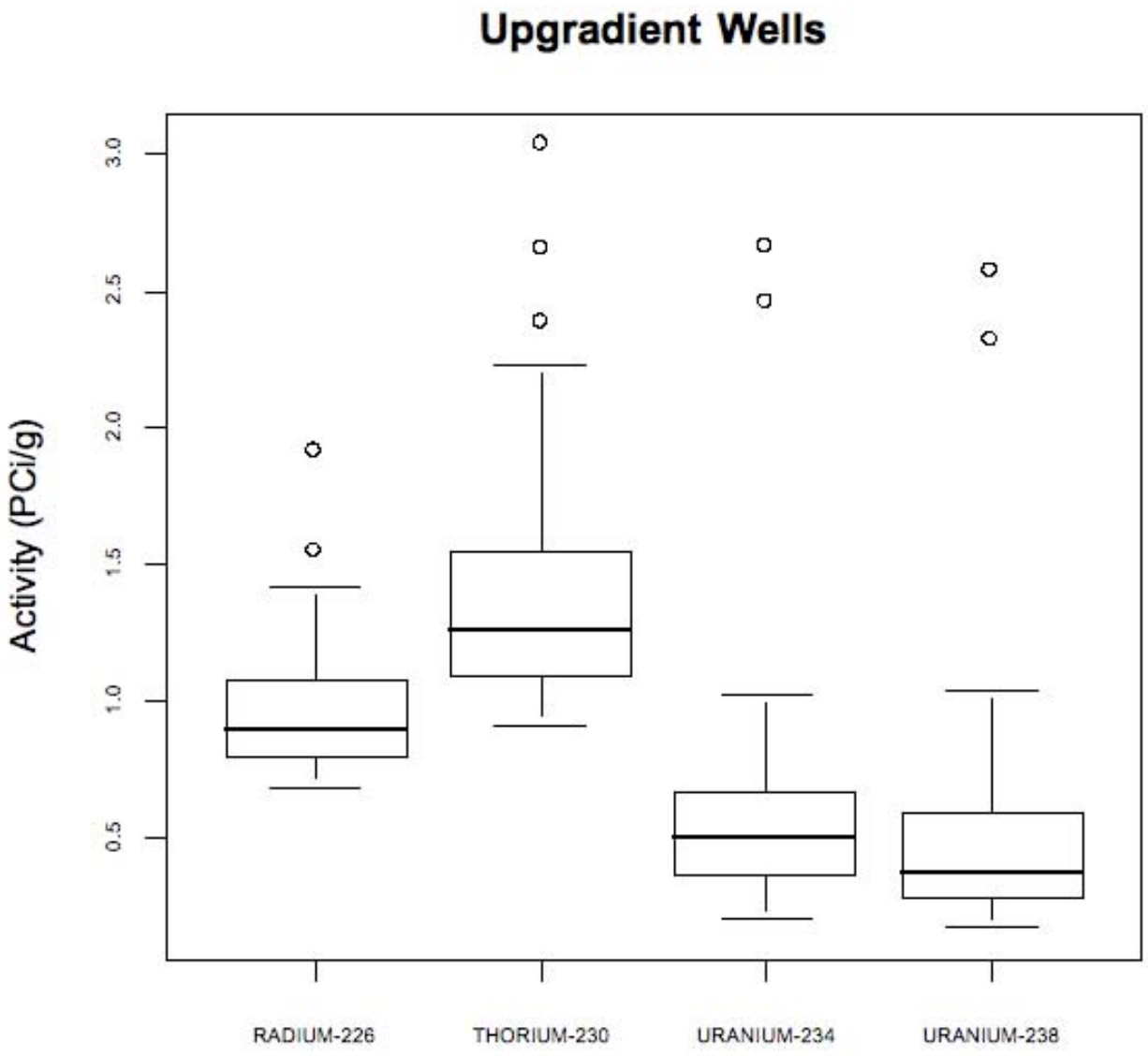

Figure 17: Box plots for the uranium chain in the Upgradient Groundwater Wells soils data.

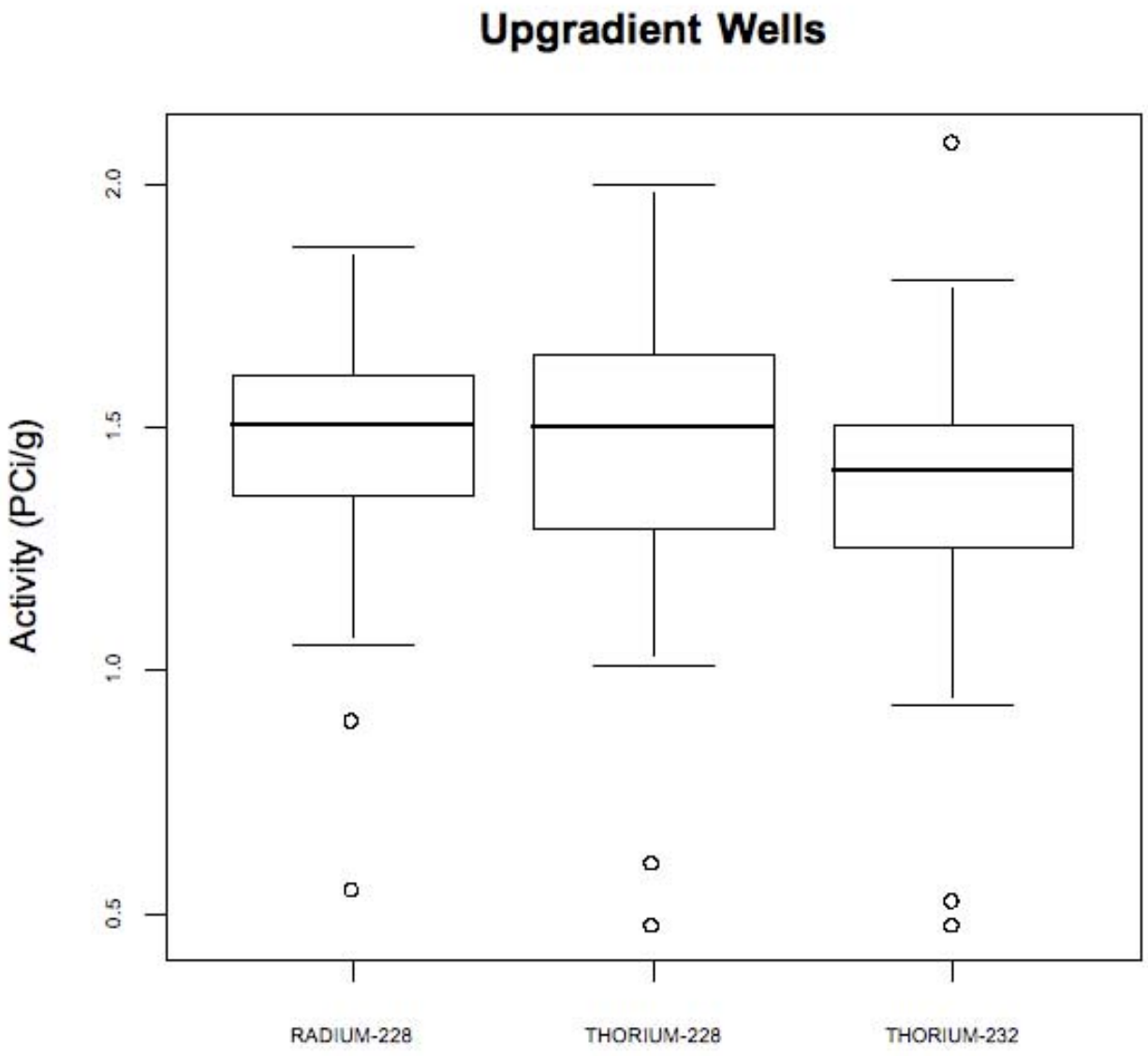

Figure 18: Box plots for the uranium chain in the Upgradient Groundwater Wells soils data.

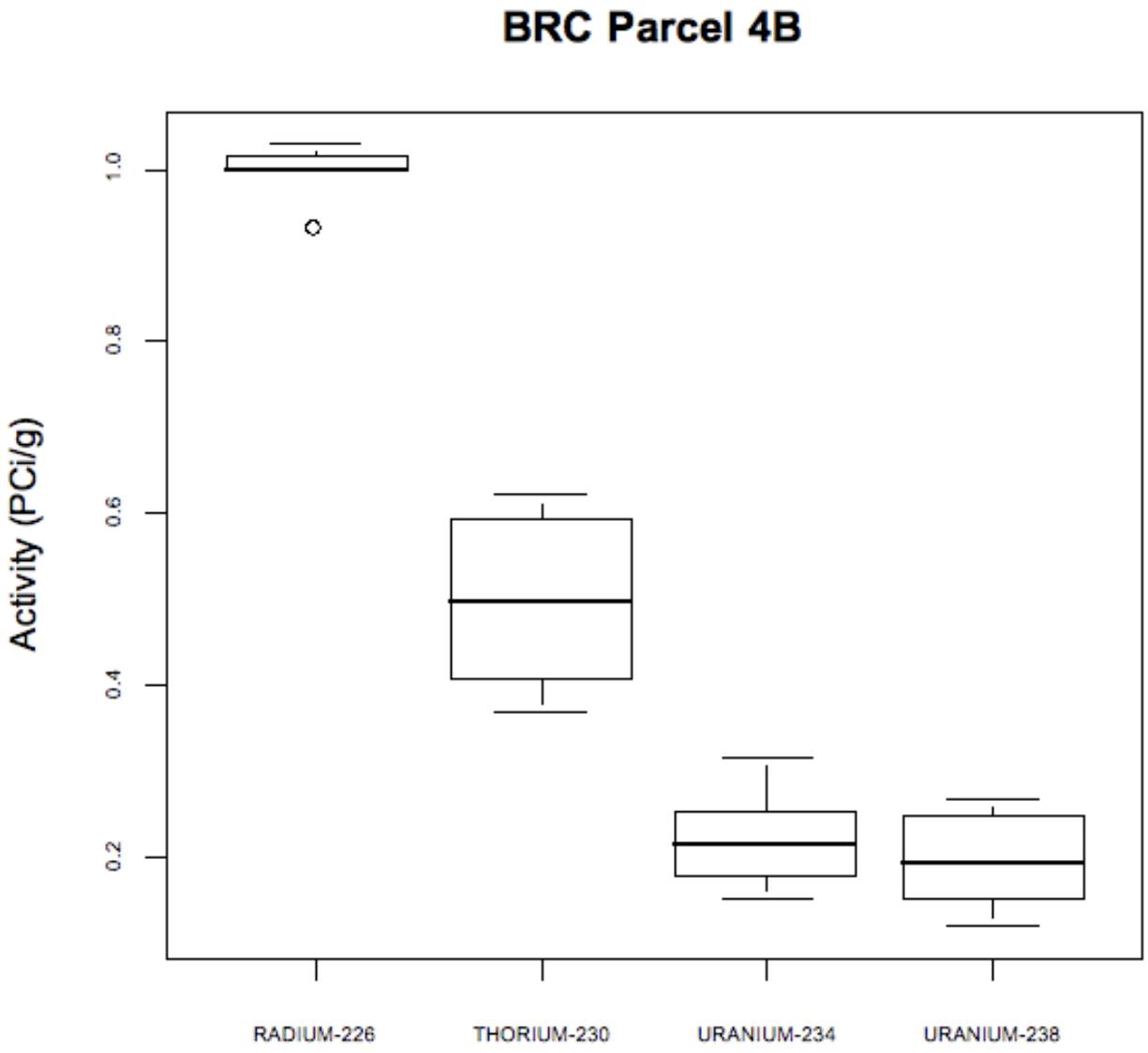

Figure 19: Box plots for the uranium chain in the BRC Parcels 4B data.

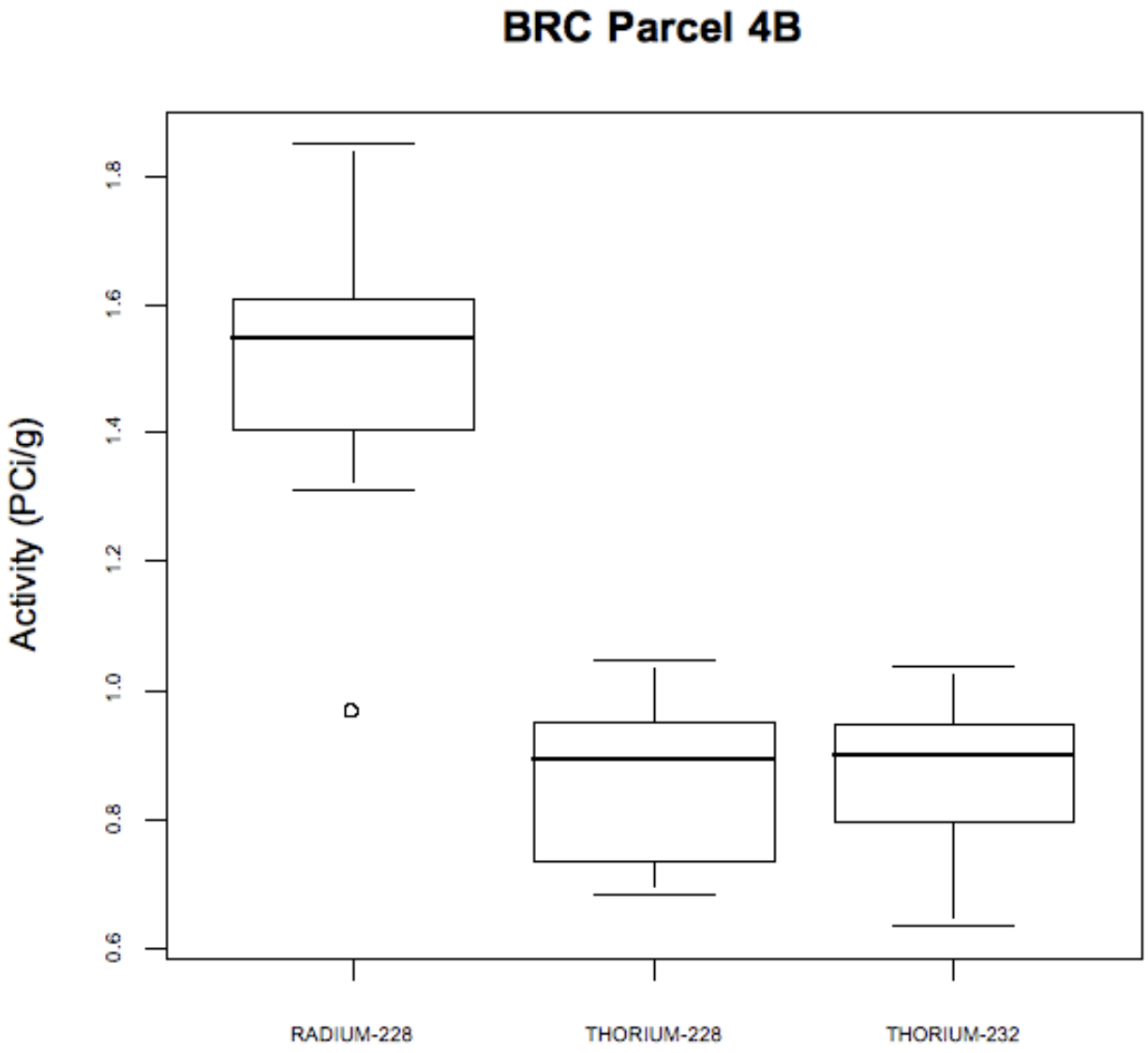

Figure 20: Box plots for the thorium chain in the BRC Parcel 4B data.

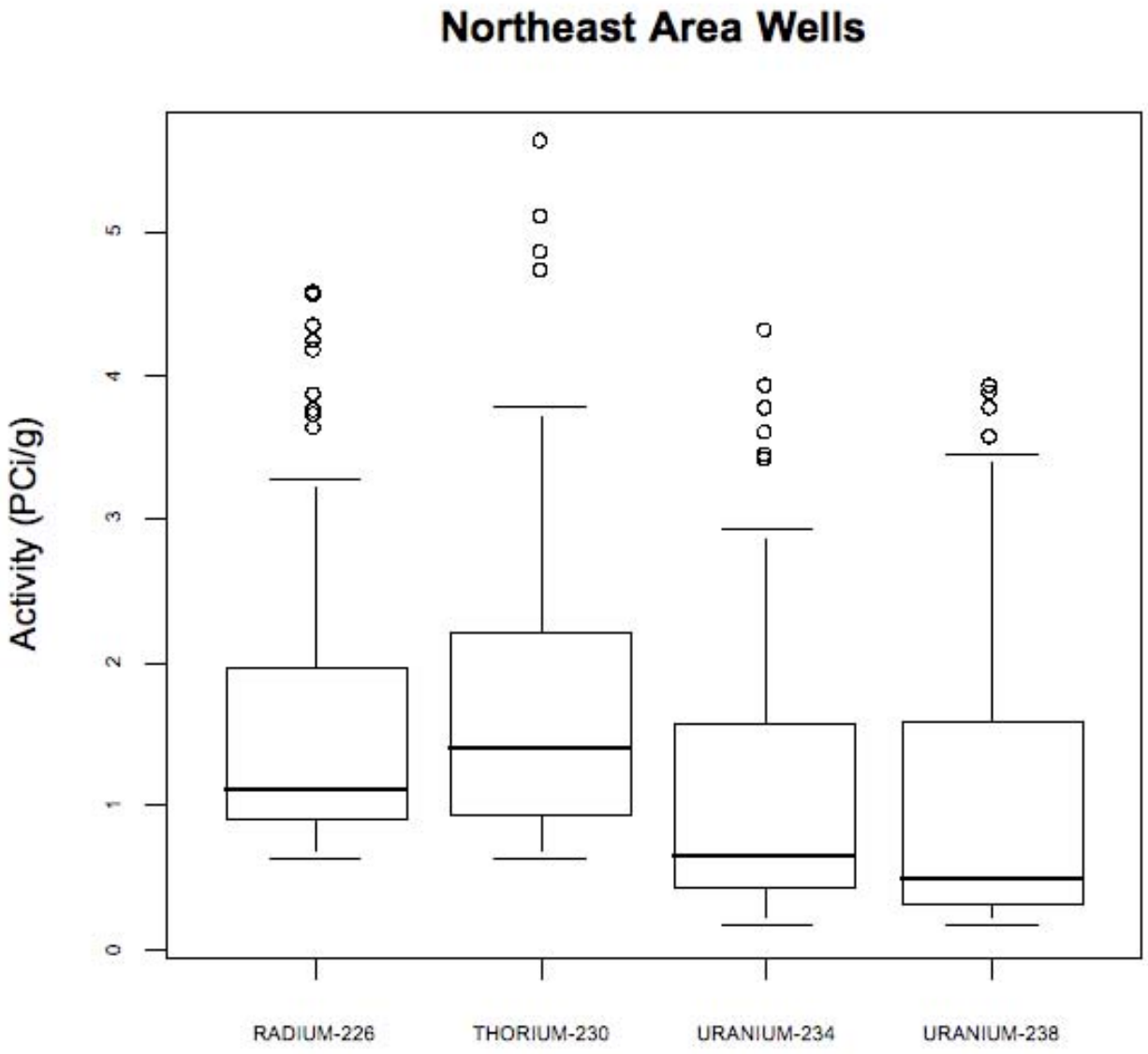

Figure 21: Box plots for the uranium chain in the Northeast Area Wells soils data.

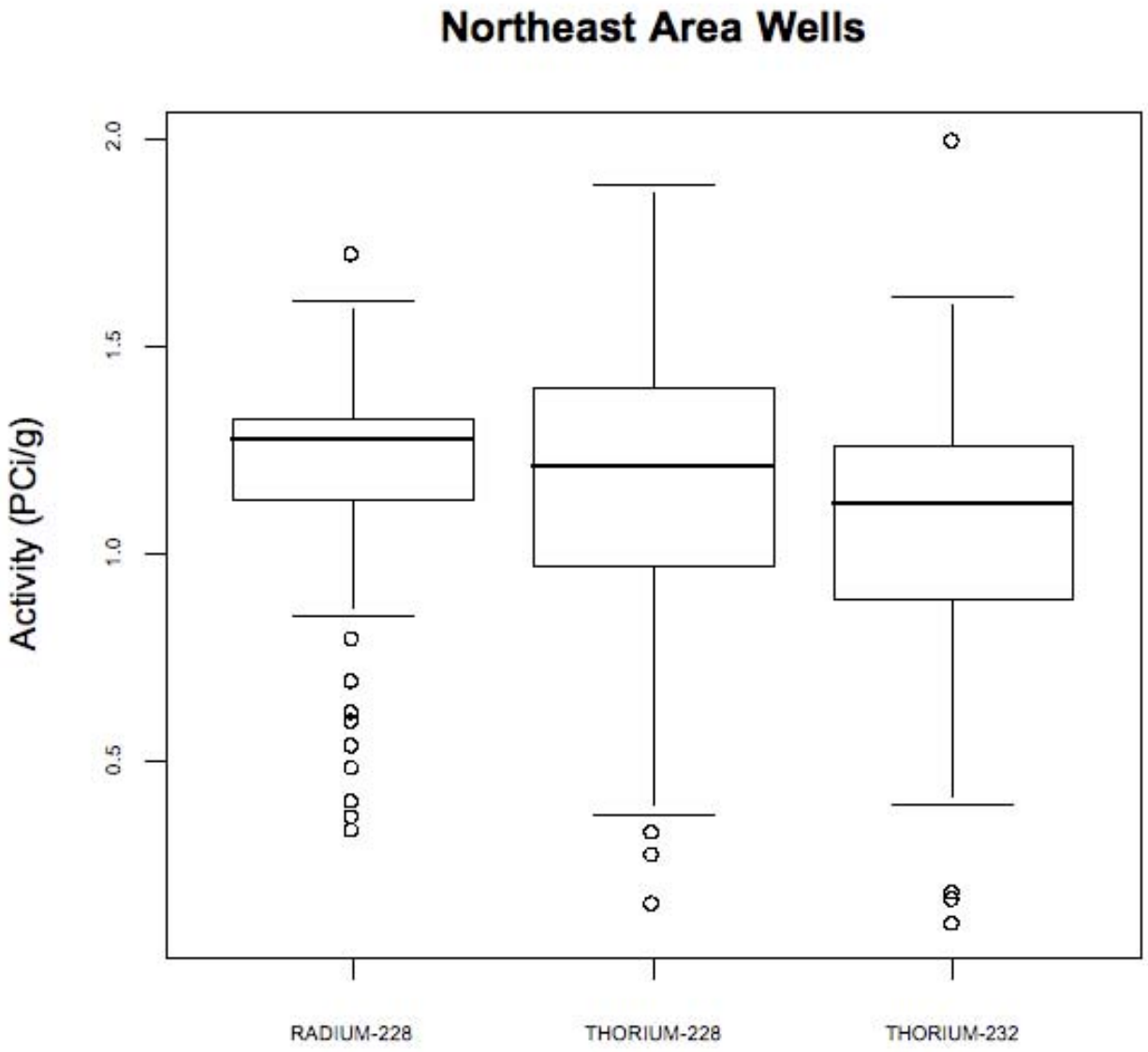

Figure 22: Box plots for the thorium chain in the Northeast Area Wells soils data.

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