Appendix F-1

Site-to-Background Comparison for Copper and Mercury
in Soil and Sediment at Site 18
New Boston Air Force Station

1.0 Introduction

This appendix provides the methodology and results of the site-to-background comparison for copper and mercury in soil and sediment at Site 18, New Boston Air Force Station (NBAFS), New Hampshire. The site data set includes the following samples:

- 8 surface soil samples (0 to 0.5 foot below ground surface [bgs]) and 14 subsurface soil samples collected in June 2008 during the Site Inspection (SI) Addendum;
- 5 surface soil samples (0 to 0.5 foot bgs) collected in November 2009 during the Remedial Investigation (RI);
- 18 surface soil samples (0 to 0.5 foot bgs) and 15 subsurface soil samples (1.5 to 2.0 feet bgs) collected in May 2010 during the RI;
- 4 sediment samples collected in June 2008 (SI Addendum);
- 8 sediment samples collected in November 2009 (RI);
- 5 sediment samples collected in May 2010 (RI).

In addition to the trace elements of concern, the June 2008 and May 2010 soil and sediment samples were analyzed for aluminum, calcium, iron, magnesium, and manganese; these are the primary reference elements used to evaluate trace elements during the geochemical evaluation step of the site-to-background comparison. The November 2009 soil and sediment samples were analyzed only for copper and/or mercury and thus could not be included in the geochemical evaluation. Table 1 lists the number of samples and percentage of nondetects for copper and mercury in each medium.

Background distributions and background screening values have been established for target analyte list metals in surface soil, subsurface soil, and sediment at NBAFS (Shaw Environmental, Inc., 2007), and they are used in the following comparison. The background surface soil samples were collected from 0 to 0.5 foot bgs, and the background subsurface soil samples were collected from 1.5 to 2 feet bgs. Background summary statistics for TAL metals in surface soil, subsurface soil, and sediment are provided in Tables 2 through 4.

2.0 Comparison Methodology

This section describes the statistical and geochemical evaluation techniques that were employed in the NBAFS site-to-background comparison.

2.1 Statistical Procedures

Contamination can be caused by a variety of processes that yield different spatial distributions of elevated contaminant concentrations. Slight but pervasive contamination can occur from non-point-source releases and can result in slight increases in contaminant concentrations in a large percentage of samples. Localized, or "hot-spot," contamination can result in elevated concentrations in a small percentage of the total number of site samples. No single, two-sample statistical comparison test is sensitive to both of these modes of contamination. For this reason, the use of multiple simultaneous tests is recommended for a valid and complete comparison of site versus background distributions (U.S. Environmental Protection Agency [EPA], 1989, 1992, and 1994; U.S. Navy, 2002).

The Wilcoxon rank sum (WRS) test is sensitive to slight but pervasive contamination but is not sensitive to localized or more extreme hot-spot situations. The background threshold comparison, or "hot measurement test," is effective in identifying localized contamination but is not sensitive to slight but pervasive contamination. The WRS test and hot measurement test are thus complementary. Both tests are nonparametric, meaning that they do not require that assumptions be made regarding the type of distribution (normal, lognormal, etc.), and they are valid for a wide variety of distributional shapes. In addition to the quantitative WRS and hot measurement tests, box-and-whisker plots are used to visually compare the site and background distributions and to properly interpret the results of the WRS test.

Analytes that fail either of the quantitative comparison tests are subject to a geochemical evaluation to determine if the elevated concentrations are most likely due to natural processes. The hot measurement test, WRS test, box plots, and geochemical evaluation are described in greater detail in the following sections.

Hot Measurement Test. The hot measurement test consists of comparing each site measurement with a concentration value that is representative of the upper limit of the background distribution (EPA, 1994). Ideally, a site sample with a concentration above the background screening value would have a low probability of being a member of the background

distribution, and may be an indicator of contamination. It is important to select such a background screening value carefully so that the probability of falsely identifying site samples as contaminated or uncontaminated is minimized.

The EPA recommends the 95th upper tolerance limit (UTL) as a background screening value (EPA, 1989, 1992, and 1994). On average, roughly five percent of uncontaminated site samples are expected to exceed the background screening value. Site samples with concentrations above this value are not necessarily contaminated, but should be considered suspect.

The 95th UTLs of the background distributions for 23 elements in NBAFS surface soil, subsurface soil, and sediment are provided in Tables 2 through 4. To perform the test, each analyte's site maximum detected concentration (MDC) is compared to the background 95th UTL. If the site MDC exceeds the background screening value, then that analyte will undergo a geochemical evaluation. If the MDC does not exceed the background screening value, then hot-spot contamination is not indicated.

Wilcoxon Rank Sum Test. The WRS test has been recommended for use in site-to-background comparisons (EPA, 2006; U.S. Navy, 2002). In this report, the WRS test is performed when the site and background data sets each contain less than 50 percent nondetects (i.e., measurements reported as not detected above the method detection limit). The WRS test is not performed on data sets containing 50 percent or more nondetects. The medians of such data sets are unknown, and hence the test lacks sufficient power to yield reliable results. Likewise, the WRS test is not performed on data sets of size $n < 5$; in such cases, the test lacks sufficient power to identify differences between the two samples.

The WRS test compares two data sets of size n and m ($n > m$), and tests the null hypothesis that the samples were drawn from populations with distributions having the same medians. To perform the test, the two sets of observations are pooled and arranged in order from smallest to largest. Each observation is assigned a rank; that is, the smallest is ranked 1, the next largest is ranked 2, and so on up to the largest observation, which is ranked ($n + m$). If ties occur between or within samples, each one is assigned the midrank. Next, the sum of the ranks of smaller data set m is calculated. Then the test statistic Z is determined,

$$Z = \frac{W - m(m+n+1)/2}{\sqrt{mn(m+n+1)/12}}$$

Where:

W = Sum of the ranks of the smaller data set
m = Number of data points in smaller group
n = Number of data points in larger group.

This test statistic Z is used to find the two-sided significance. For instance, if the test statistic yields a probability of a Type I error (p-level) less than 0.05, then there is a statistically significant difference between the medians at the 95 percent confidence level. A Type I error involves rejecting the null hypothesis when it is true. If the p-level is greater than 0.05, then there is no reasonable justification to reject the null hypothesis at the 95 percent confidence level. It can therefore be concluded that the medians of the two data sets are similar and can be assumed to be drawn from the same population.

If the p-level is less than 0.05, then the medians of the two distributions are significantly different at the 95 percent confidence level. This can occur if the site data are shifted higher or lower than the background data. If the site data are shifted higher relative to background, then contamination may be indicated, and the analyte in question will be carried on for geochemical evaluation. However, if the site data are shifted lower relative to background, then contamination is not indicated. If the p-level is greater than 0.05, then pervasive site contamination is not suspected.

Box Plots. A quick, robust graphical method recommended by the EPA to visualize and compare two or more groups of data is the box plot comparison (EPA, 1989 and 1992). These plots provide a summary view of the entire data set, including the overall location and degree of symmetry. The box encloses the central 50 percent of the data points so that the top of the box represents the 75th percentile and the bottom of the box represents the 25th percentile. The median of the data set is represented by a small box within the larger box. The upper whisker extends outward from the box to the maximum point, and the lower whisker extends to the minimum point. Nondetect results are set equal to one-half of the reporting limit for plotting purposes.

For each analyte, box plots of site and background data are placed side by side to visually compare the distributions and qualitatively determine whether the data sets are similar or distinct. Accordingly, the box plots are a useful adjunct to the WRS test. As described previously, the WRS test may indicate that the medians of the site and background data sets are significantly

different. Examination of the box plots will confirm whether that difference is caused by site data that are shifted higher or lower relative to background.

2.2 Geochemical Evaluation

Statistical site-to-background comparisons for trace elements in environmental media commonly have high false-positive error rates. A large number of background samples is required to adequately characterize the upper tails of most trace element distributions, which are typically right-skewed and span a wide range of concentrations, but such a large background data set is not always feasible. There are also concerns regarding the statistical validity of comparing site data from a small parcel with facility-wide background data that typically display higher variance than the site data. The presence of estimated concentrations and nondetects with differing reporting limits can also cause statistical comparison tests to fail.

Statistical tests consider only the absolute concentrations of individual elements, and they disregard the interdependence of element concentrations and the geochemical mechanisms controlling element behavior. However, it is well established that trace elements naturally associate with specific soil-forming minerals, and the preferential enrichment of a sample with these minerals will result in elevated trace element concentrations. It is thus important to be able to identify these naturally high concentrations and distinguish them from potential contamination.

If an analyte fails either of the statistical tests described in the previous section, then a geochemical evaluation is performed to determine if the elevated concentrations are caused by natural processes. Recent publications indicate that environmental investigations are increasingly considering these elemental associations (e.g., EPA, 1995; Barclift *et al*., 2000; U.S. Navy, 2002 and 2003; Myers and Thorbjornsen, 2004; Thorbjornsen and Myers, 2007a, 2007b, 2008). A properly executed geochemical evaluation can distinguish between naturally high element concentrations versus contamination, and it can identify the specific samples that may contain some component of site-related contamination.

Geochemical Evaluation Methodology for Soil and Sediment. Trace elements naturally associate with specific minerals in soil and sediment, and geochemical evaluations are predicated on these known associations. For example, in most uncontaminated oxic soils, arsenic exhibits an almost exclusive association with iron oxide minerals (Bowell, 1994; Schiff and Weisberg, 1997). Arsenic exists in oxic soil pore fluid as oxyanions such as $HAsO_4^{-2}$ and $H_2AsO_4^-$ (Brookins, 1988), and these negatively charged species have a strong affinity to adsorb on iron oxides, which tend to maintain a net positive surface charge (Electric Power Research

Institute, 1986). (In this report, the term "iron oxide" encompasses oxides, hydroxides, oxyhydroxides, and hydrous oxides of iron.) This association is expressed as a positive correlation between arsenic concentrations and iron concentrations for uncontaminated samples: samples with a low percentage of iron oxides will contain proportionally lower arsenic concentrations, and samples that are enriched in iron oxides will contain proportionally higher arsenic concentrations. Although there is variability in the absolute concentrations of arsenic and iron in soil at a site, the As/Fe ratios of the samples will be relatively constant if no contamination is present (Daskalakis and O'Connor, 1995). Samples that contain excess arsenic from a contaminant source (e.g., arsenical pesticides) will exhibit anomalously high As/Fe ratios compared to the uncontaminated samples.

To perform the geochemical evaluation, correlation plots are constructed to explore the elemental associations and identify potentially contaminated samples. The detected concentrations of the trace element of interest (dependent variable) are plotted against the detected concentrations of the reference element (independent variable), which represents the mineral to which the trace element may be adsorbed. In the case of arsenic, the arsenic concentrations for a given set of samples would be plotted on the y-axis, and the corresponding iron concentrations would be plotted on the x-axis. If no contamination is present, then the samples will exhibit a common trend and consistent As/Fe ratios, and the samples with the highest arsenic concentrations will lie on this trend. This indicates that the elevated arsenic is due to the preferential enrichment of iron oxides in those samples and that the arsenic has a natural source. If, however, the samples with high arsenic concentrations have low or moderate iron concentrations (anomalously high As/Fe ratios), then they will lie above the trend established by the other samples. This would indicate that the anomalous samples contain excess arsenic beyond that which can be explained by the natural iron oxide content, and such samples may contain a component of contamination.

The reference elements against which trace elements are evaluated reflect the affinity that the trace elements have for specific minerals. The concentrations of iron, aluminum, and manganese serve as qualitative indicators of the amounts of iron oxide, clay, and manganese oxide minerals in the soil (or sediment) samples. Along with arsenic, selenium and vanadium are present in oxic soil pore fluid as anions and have an affinity to adsorb on iron oxides, which tend to maintain a net positive surface charge. Concentrations of arsenic, selenium, or vanadium in a set of samples can be evaluated through comparison to the corresponding iron concentrations. Barium, cadmium, lead, and zinc are typically present in soil as divalent cations and have an affinity to adsorb on clay minerals, which tend to maintain a net negative surface charge. Concentrations of barium, cadmium, lead, or zinc can be evaluated through comparison to the corresponding

aluminum concentrations. Manganese oxides have a strong affinity to adsorb barium, cobalt, and lead (Kabata-Pendias, 2001), so concentrations of these elements can be compared to the corresponding manganese concentrations, as long as there is enough manganese present in the soil to form discrete manganese oxides.

Of particular importance at NBAFS is the presence of unweathered or partially weathered rock in the site soils, which include glacial till derived from schist, gneiss, and granite. The site soil data sets evaluated in this report are characterized by high calcium and magnesium concentrations relative to the background data set and, in general, lower aluminum and iron concentrations relative to background. The site soil boring logs note the presence of mica schist in many of the sampled intervals; such soils could contain an appreciable amount of the mica biotite (which comprises a solid solution between Fe-rich and Mg-rich end-member minerals), as well as Ca-Mg pyroxene and amphibole minerals. During soil formation, these minerals will weather to clays and oxides, which will retain trace elements that have an affinity for adsorption on clay and oxide mineral surfaces. Soils that are preferentially enriched in these types of clays and oxides will be naturally enriched in magnesium and calcium, and relatively depleted in aluminum (pyroxene and amphibole minerals generally lack aluminum). Soils derived from the weathering of mafic (magnesium- and/or iron-rich) rocks are also expected to be naturally enriched in trace elements such as chromium and nickel. It is important to note that the background soil samples were collected from several different locations that are up to three miles from the Operations Area (which encompasses Site 18 as well as Sites 3, 6, 7, 13, 15, 16, and 17). Natural differences in bedrock, glacial till composition, and soil are the likely explanation for differences in major element concentrations between the site and background soil samples. Trace element concentrations are controlled by the presence and abundance of specific minerals (via various adsorption mechanisms, element substitution, etc.), and therefore the relative abundance of trace elements in site soil samples mirrors the major element distributions, for uncontaminated samples.

It is important to note that some trace elements have very strong affinities for a particular type of mineral, whereas other elements will partition themselves between several minerals. For instance, vanadium has a particularly strong affinity for iron oxides, so correlation coefficients for vanadium versus iron in uncontaminated samples are usually very high, and this is expressed on a correlation plot as a consistent trend with little to no scatter. In contrast, chromium forms several coexisting aqueous species with different charges [$Cr(OH)_2^+$, $Cr(OH)_3^0$, and $Cr(OH)_4^-$] that will adsorb on several different types of minerals, including clays and iron oxides. This behavior will yield lower correlation coefficients for chromium versus iron or chromium versus aluminum relative to the coefficients observed for vanadium versus iron, and more scatter may

be observed on the correlation plots. Some elements are more selective than others with respect to adsorption on specific mineral surfaces, and this selectivity is dependent on site-specific conditions, including soil pH, redox conditions, and concentrations of competing elements.

It should be noted that the geochemical evaluations rely in part on professional judgment. Samples that plot off the background trend on a correlation plot are certainly suspect, but because all uncertainty cannot be eliminated from the evaluation, such plots cannot be construed as definitive proof of contamination. However, anomalous samples should be flagged as suspect, and their results should be used as a basis for further investigation, risk assessment, or remediation, as appropriate.

Site samples with a trace element present as a contaminant will exhibit anomalously high trace-versus-major element ratios compared to background trace-versus-major element ratios. These elevated ratios may not always be apparent in log-log correlation plots, especially at the upper range of concentrations. Therefore, ratio plots, which depict trace element concentrations on the y-axis and trace/major element ratios on the x-axis, are employed in conjunction with correlation plots in those cases where it is not immediately apparent which site samples have anomalously high elemental ratios on the correlation plots. The ratio plots permit easy identification of samples with anomalously high elemental ratios relative to background, and they have high resolution over the entire concentration range. The presence of an anomalously high elemental ratio is not definitive proof of site-related contamination; however, such samples are discussed in the text and, unless otherwise noted, are flagged as representing potential site-related contamination. This is a conservative approach.

There is natural variability, as well as analytical uncertainty, in the elemental ratios of uncontaminated soil and sediment samples. Trace/major element ratios are calculated from two uncertain analytical results, so the resulting uncertainties in the ratios can produce some scatter in the points on a ratio plot. This is especially true when estimated ("J"-qualified) analytical results are used. This can be seen on many of the plots that show more scatter of the points at the lower end of the concentration range, where analytical uncertainties are higher and analytical results are reported with fewer significant figures.

On ratio plots, vertical trends should be expected only in those cases where the trace element adsorption is a linear process, where the trace element concentrations are controlled exclusively by adsorption on a given mineral type, and where the variances of the reference and trace element concentrations are similar (Thorbjornsen and Myers, 2007a). Nonvertical trends are more common in ratio plots, however, because adsorption processes often are not linear, trace

elements often have affinities for more than one type of sorptive surface, and the reference and trace element concentrations usually possess different variances. Nonlinear adsorption of a trace element on mineral surfaces will manifest itself as a curve rather than a straight line on a correlation plot and as a nonvertical trend on a ratio plot. In addition, the presence of competing ions in soil (or sediment) and differences in pH and redox conditions among the sample locations can add to the natural variability of elemental ratios.

Ratio plots may also be prepared for the major elements (e.g., aluminum versus Al/Fe ratios). However, adsorption is not the dominant process controlling major element concentrations. For example, aluminum and iron concentrations covary largely because they are controlled by the abundance of fine-grained minerals in the samples. The plots thus reflect physical effects rather than chemical effects such as adsorption. Constant ratios are typically not observed for major versus major elements.

3.0 Results of the Site-to-Background Comparison for Copper and Mercury in Site 18 Soil

This section presents the results of the site-to-background comparison for copper and mercury in the Site 18 surface soil and subsurface soil samples. Table 5 lists the results of the statistical tests for each element in each sampled medium. Box plots are provided in Attachment 1, and geochemical correlation plots and ratio plots are included in Attachment 2.

Surface Soil. Copper and mercury in the Site 18 surface soil data set failed statistical comparison to background (Table 5). Sixteen copper concentrations and one mercury concentration exceeded their corresponding background screening values. In addition, copper failed the WRS test; mercury passed the WRS test. Both elements were subjected to geochemical evaluation, as described below.

Subsurface Soil. Both copper and mercury in the Site 18 subsurface soil data set failed statistical comparison to background (Table 5). Fifteen copper concentrations and one mercury concentration exceeded their corresponding background screening values. In addition, copper failed the WRS test, whereas mercury could not be subjected to the test because of the high percentage of nondetects in the site data set. Both elements were subjected to geochemical evaluation, as described below.

Although they are not chemicals of potential concern, aluminum and iron are evaluated first. These are the primary reference elements used to evaluate trace elements of concern, and

therefore it is important to establish the absence of aluminum and iron contamination in the site samples. The presence of such contamination would preclude their use as reference elements in the impacted sample(s).

Aluminum and Iron in Site 18 Soil – Geochemical Evaluation

Aluminum is a primary component of common soil-forming minerals such as clays, feldspars, and micas. Aluminum also substitutes for ferric iron in iron oxide minerals, and it can adsorb on iron oxide surfaces (Cornell and Schwertmann, 2003). Iron oxides are common soil-forming minerals, and they occur as discrete mineral grains or as coatings on silicate minerals (Cornell and Schwertmann, 2003). Clays and iron oxides tend to exist as very fine particles, so both aluminum and iron are enriched in samples with finer grain sizes. A plot of aluminum versus iron concentrations can be used to qualitatively assess the relative abundance of these minerals in the Site 18 soil samples (Figure 1). In the plot, the NBAFS background surface soil samples are represented by open circles (BG SS); NBAFS background subsurface soil samples are represented by green circles (BG SB); the June 2008 SI Addendum surface and subsurface soil samples are represented by open triangles (Site SS) and blue triangles (Site SB), respectively; and the May 2010 RI surface and subsurface soil samples are represented by pink diamonds (RI SS) and yellow diamonds (RI SB), respectively. The November 2009 RI soil samples were only analyzed for copper and mercury and thus cannot be depicted in the plot.

The site and background samples form a common trend with a positive slope in Figure 1. Most of the site samples have lower aluminum and iron concentrations relative to most of the background samples; as discussed in Section 2.2, this reflects natural differences between the site and background soils. All of the site Al/Fe ratios are consistent with those of the background samples, which indicates a natural source for the site aluminum and iron concentrations. This suggests that aluminum and iron are appropriate for use as reference elements to evaluate the trace element concentrations in the site samples. The site samples with lower aluminum and iron concentrations have naturally lower clay and iron oxide content, which indicates that these samples are expected to have naturally lower trace element concentrations.

Copper in Site 18 Soil – Geochemical Evaluation

Copper is abundant in mafic and intermediate rocks; in addition, copper is contained in several minerals that are soluble and release copper ions during weathering, particularly in acid environments (Kabata-Pendias, 2001). In soils, copper is commonly present as the divalent cation Cu^{2+} and has an affinity to adsorb on clay minerals, which tend to maintain a net negative surface charge. Positive correlations between copper and aluminum concentrations are thus often observed for uncontaminated soil samples. Figure 2 depicts copper versus aluminum concentrations in the Site 18 and background soil samples. Many site samples lie on the background trend in the plot, including most of the 2008 SI Addendum soil samples. This also includes 2008 subsurface sample SIS18SB-7A, which contains relatively high copper (56.7 milligrams per kilogram [mg/kg]) but proportionally higher aluminum (36,500 J mg/kg). In contrast, one 2008 surface soil sample and the majority of 2010 RI soil samples lie above the background trend in Figure 2.

Another perspective on the data sets is provided in Figure 3, which displays the copper concentrations of the site and background samples (y-axis) versus their corresponding Cu/Al

ratios (x-axis). If a site sample contains excess copper from a contaminant source, then it will exhibit an anomalously high Cu/Al ratio relative to background and will plot to the right of the background samples in Figure 3. Subsurface sample SIS18SB-7A and many other site samples exhibit Cu/Al ratios that are within the background ratio range, which suggests that these site samples do not contain excess copper from a contaminant source and that their copper concentrations are natural. Eleven surface soil samples and 13 subsurface soil samples have Cu/Al ratios that exceed the maximum Cu/Al ratio of 1.67E-03. These samples have more copper than can be explained by their clay content and may contain copper contamination (Table 7). The copper concentrations of these 24 samples range from 22.2 to 2,810 mg/kg.

The five November 2009 surface soil samples were analyzed only for copper and mercury. Lacking analyses for the major elements (aluminum, iron, manganese, etc.), these samples could not be included in the geochemical evaluation to determine if their copper concentrations have a natural source. Copper concentrations in all five 2009 surface soil samples (230 J mg/kg to 2,170 J mg/kg) exceed the background screening value of 37.2 mg/kg, and they should be considered suspect (Table 8).

Mercury in Site 18 Soil – Geochemical Evaluation

Mercury can adsorb on the surfaces of iron oxide and clay minerals, but its concentrations are commonly controlled through organic complex formation (Kabata-Pendias, 2001). In addition, mercury detections are commonly low, estimated concentrations below the reporting limit, and such concentrations have a high degree of analytical uncertainty. As a result of these factors, poor correlations for mercury versus iron or mercury versus aluminum are often observed, even in uncontaminated soil samples. A plot of mercury versus aluminum in the Site 18 and background samples is provided in Figure 4 [the May 2010 site samples were not analyzed for mercury and thus are not depicted in the plot]. The background samples form a common trend with a positive slope, and most of the site samples lie on this trend (some scatter is observed for the site samples because 12 of the 14 depicted site mercury detections are J-qualified). The Hg/Al ratios of most site samples are similar to those of the background samples, which suggests a natural source for their mercury detections. The exception is surface sample SIS18SS-7, which has the highest mercury of the two data sets (0.63 mg/kg) but low aluminum (as well as only moderate iron). This sample has more mercury than can be explained by its clay content and may contain a component of mercury contamination (Table 7).

The five November 2009 surface soil samples were analyzed only for copper and mercury. Lacking analyses for the major elements (aluminum, iron, manganese, etc.), these samples could not be included in the geochemical evaluation to determine if their mercury concentrations have a natural source. Mercury concentrations in three 2009 samples — SIS18SS11 (1.3 J mg/kg), SIS18SS13 (0.47 J mg/kg), and SIS18SS9 (0.82 J mg/kg) — slightly exceed the background screening value of 0.39 mg/kg, and they should be considered suspect (Table 8).

4.0 Results of the Site-to-Background Comparison for Copper and Mercury in Site 18 Sediment

This section presents the results of the site-to-background comparison for copper and mercury in the Site 18 sediment samples. Table 5 lists the results of the statistical tests for each element.

Box plots are provided in Attachment 1, and geochemical correlation plots and ratio plots are included in Attachment 2.

Sediment. Both copper and mercury in the Site 18 sediment data set failed statistical comparison to background (Table 5). Seven copper concentrations and one mercury concentration exceeded their corresponding background screening values. Copper failed the WRS test, whereas mercury passed the WRS test. Accordingly, both elements were subjected to geochemical evaluation, as described below.

Although they are not chemicals of potential concern, aluminum and iron are evaluated first. These are the primary reference elements used to evaluate trace elements of concern, and therefore it is important to establish the absence of aluminum and iron contamination in the site samples. The presence of such contamination would preclude their use as reference elements in the impacted sample(s).

Aluminum and Iron in Site 18 Sediment – Geochemical Evaluation
Aluminum is a primary component of common minerals such as clays, feldspars, and micas. Aluminum also substitutes for ferric iron in iron oxide minerals, and it can adsorb on iron oxide surfaces (Cornell and Schwertmann, 2003). Iron oxides are common minerals in soil and sediment, and they occur as discrete mineral grains or as coatings on silicate minerals (Cornell and Schwertmann, 2003). Clays and iron oxides tend to exist as very fine particles, so both aluminum and iron are enriched in samples with finer grain sizes. A plot of aluminum versus iron concentrations can be used to qualitatively assess the relative abundance of these minerals in the Site 18 sediment samples (Figure 5). In the plot, the NBAFS background sediment samples are represented by green circles (BG), the June 2008 SI Addendum sediment samples are represented by blue triangles (Site), and the May 2010 RI sediment samples are represented by yellow triangles (RI). The November 2009 RI sediment samples were only analyzed for mercury and thus cannot be depicted in the plot. The site samples have Al/Fe ratios that are generally consistent with background, suggesting that the site aluminum and iron concentrations have a natural source. Sample SIS18SD-1B has the highest aluminum concentration of the two data sets (20,100 J mg/kg) and lies above the other samples in the plot, so additional evaluation was performed.

Along with aluminum, magnesium is also commonly present in clays, and aluminum and magnesium concentrations commonly covary in uncontaminated soils and sediments. Figure 6 provides a plot of aluminum versus magnesium in the Site 18 and background sediment samples. All of the site samples — including SIS18SD-1B — have Al/Mg ratios that are consistent with those of the background samples, which suggests that their aluminum concentrations have a natural source. The elevated aluminum concentration of sample SIS18SD-1B suggests that it is preferentially enriched in clay minerals relative to the other samples. This sample is therefore expected to contain naturally higher concentrations of specific trace elements that have an affinity to adsorb on clays.

Copper in Site 18 Sediment – Geochemical Evaluation

Copper is abundant in mafic and intermediate rocks; in addition, copper is contained in several minerals that are soluble and release copper ions during weathering, particularly in acid environments (Kabata-Pendias, 2001). In soils and sediment, copper is commonly present as the divalent cation Cu^{2+} and has an affinity to adsorb on clay minerals, which tend to maintain a net negative surface charge. Positive correlations between copper and aluminum concentrations are thus often observed for uncontaminated sediment samples. Figure 7 depicts copper versus aluminum concentrations in the NBAFS background sediment samples and in the nine Site 18 samples that were analyzed for copper. The four site samples with the lowest copper concentrations (2.2 to 26.3 mg/kg) lie on the background trend in the plot. They have Cu/Al ratios that are consistent with the background Cu/Al ratios (Figure 8); this suggests that the copper detected in these samples has a natural source.

In contrast to the above observations, three 2008 site samples (SIS18SD-1A, -1B, and -2A) and two 2010 site samples (SIS18SD11 and -12) have high copper concentrations (53.4 to 2,660 mg/kg) but relatively low aluminum. Their anomalously high Cu/Al ratios can also be seen in the ratio plot (Figure 8), in which they all lie to the right of the background samples (note that the Cu/Al ratio of sample SIS18SD-1B [53.4 mg/kg Cu] is 0.0027, which only slightly exceeds the maximum background Cu/Al ratio of 0.0022). These five samples have more copper than can be explained by their clay content and they may contain a component of copper contamination (Table 7).

Mercury in Site 18 Sediment – Geochemical Evaluation

Mercury can adsorb on the surfaces of iron oxide and clay minerals, but its concentrations are commonly controlled through organic complex formation (Kabata-Pendias, 2001). In addition, mercury detections are commonly low, estimated concentrations below the reporting limit, and such concentrations have a high degree of analytical uncertainty. As a result of these factors, poor correlations for mercury versus iron or mercury versus aluminum are often observed, even in uncontaminated sediment samples. A plot of detectable mercury versus iron concentrations in the Site 18 and background sediment samples is provided in Figure 9. Scatter is observed because all 11 background mercury detections and four of the depicted site mercury detections are J-qualified. The Hg/Fe ratios of most site samples are similar to those of the background samples (Figure 10), which suggests a natural source for their mercury detections. The exception is sample SIS18SD-1A, which has the highest mercury of the two data sets (2.5 mg/kg) but only moderate iron (as well as low aluminum). Given the available data, this sample contains more mercury than can be explained by natural processes and may contain a component of mercury contamination (Table 7).

The eight November 2009 sediment samples were analyzed only for mercury. Lacking analyses for the major elements (aluminum, iron, manganese, etc.), these samples could not be included in the geochemical evaluation to determine if their mercury concentrations have a natural source. Mercury concentrations in all eight 2009 sediment samples (0.026 J mg/kg to 0.26 J mg/kg) are below the background screening value (0.875 mg/kg), which suggests that any mercury contamination in these samples, if present, would not be significant.

5.0 Summary

The methodology used to compare the NBAFS Site 18 and background data sets consists of a hot measurement test, nonparametric two-sample Wilcoxon rank sum test, and box-and-whisker plots. Analytes that failed either of the statistical tests were subjected to geochemical evaluation to determine if the elevated concentrations could be explained by natural processes. Table 6 summarizes the results of the statistical and geochemical evaluations.

Surface Soil. Both copper and mercury in the Site 18 surface soil data set failed statistical comparison to background and were subjected to geochemical evaluation (Table 6). Geochemical evaluation indicates that the copper concentrations in 11 surface soil samples and the mercury concentration in 1 surface soil sample are anomalously high. Given the available data, these specific concentrations cannot be explained as the result of natural processes and may contain a component of site-related contamination (Table 7).

The five November 2009 surface soil samples were analyzed only for copper and mercury. Lacking analyses for the major elements (aluminum, iron, manganese, etc.), these samples could not be included in the geochemical evaluation to determine if their copper and mercury concentrations have a natural source. Copper concentrations in all five 2009 samples and mercury concentrations in three 2009 samples exceed their corresponding background screening values, and they should be considered suspect (Table 8).

Subsurface Soil. Both copper and mercury in the Site 18 subsurface soil data set failed statistical comparison to background and were subjected to geochemical evaluation (Table 6). Geochemical evaluation indicates that all detected concentrations of mercury in the site samples are most likely natural. Copper concentrations in 13 subsurface soil samples are anomalously high. Given the available data, these specific concentrations cannot be explained as the result of natural processes and may contain a component of site-related contamination (Table 7). Copper concentrations in the other subsurface soil samples are most likely natural.

Sediment. Both copper and mercury in the Site 18 sediment data set failed statistical comparison to background and were subjected to geochemical evaluation (Table 6). Geochemical evaluation indicates that the copper concentrations in five sediment samples and the mercury concentration in one sediment sample are anomalously high. Given the available data, these specific concentrations cannot be explained as the result of natural processes and may contain a component of site-related contamination (Table 7).

The eight November 2009 sediment samples were analyzed only for mercury. Lacking analyses for the major elements (aluminum, iron, manganese, etc.), these samples could not be included in the geochemical evaluation to determine if their mercury concentrations have a natural source. Mercury concentrations in all eight 2009 sediment samples are below the background screening value.

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TABLES

Table 1

**Sample Size and Percent Nondetects for Copper and Mercury
in Soil and Sediment
Site 18
New Boston Air Force Station**

Element	Number of Samples	Number of Detects	Percent Nondetects
Surface Soil			
Copper	31	31	0
Mercury	13	13	0
Subsurface Soil			
Copper	29	29	0
Mercury	14	6	57
Sediment			
Copper	9	9	0
Mercury	17	15	12

Notes: (1.) Sample counts above include the 2008 Site Inspection Addendum
samples and 2009-2010 Remedial Investigation samples.
(2.) Only copper and mercury were included in the present
site-to-background comparison. Please see the 2008 final CSE Phase II
report for the site-to-background comparison of the other elements.

Table 2

Background Summary Statistics for Surface Soil
(concentrations in mg/kg)
New Boston Air Force Station

Element	No. of Samples	Percent Nondetects	Distribution Type	Minimum	Median	Geometric Mean	Arithmetic Mean	Maximum	Standard Deviation	Coefficient of Variation	95th UTL
Aluminum	30	0	Lognormal	1,690	13,100	10,700	14,000	48,100	9,790	0.70	43,900
Antimony	29	86	Nonparametric	0.97	< 9.2	< 9.2	< 9.2	< 9.2	NA	NA	< 9.2
Arsenic	30	0	Lognormal	1.3	8.3	7.4	10.6	35.9	10.0	0.94	42.1
Barium	30	0	Normal	4.6	21.8	20.3	23.1	52.9	11.3	0.49	49.7
Beryllium	30	3	Nonparametric	0.064	0.39	0.38	0.61	6.2	1.1	1.78	5.0
Cadmium	30	100	Nonparametric	< 0.45	< 1.4	< 1.4	< 1.4	< 1.4	NA	NA	< 1.4
Calcium	30	0	Lognormal	37.3	157	165	192	815	137	0.71	694
Chromium	30	0	Normal	1.1	6.8	6.0	7.4	18.1	4.4	0.60	17.5
Cobalt	30	0	Lognormal	0.43	1.8	1.6	1.9	4.8	1.2	0.62	4.6
Copper	30	0	Lognormal	0.61	3.9	3.6	5.6	49.1	8.6	1.54	37.2
Iron	30	0	Normal	366	12,200	9,530	13,400	34,500	9,140	0.68	34,700
Lead	30	3	Nonparametric	3.8	11.7	12.2	16.7	134	23.0	1.38	95.6
Magnesium	30	0	Lognormal	44.7	586	473	673	2,210	535	0.80	2,280
Manganese	30	0	Lognormal	8.7	56.5	51.1	99.1	656	141	1.42	593
Mercury	30	0	Lognormal	0.011	0.064	0.062	0.084	0.53	0.093	1.11	0.39
Nickel	30	0	Lognormal	0.41	3.3	2.6	3.5	8.4	2.3	0.66	8.2
Potassium	30	0	Lognormal	85.9	220	242	303	1,180	250	0.83	1,200
Selenium	30	7	Lognormal	0.48	3.4	2.9	4.0	11.8	2.9	0.74	10.9
Silver	30	87	Nonparametric	0.13	< 1.6	< 1.6	< 1.6	< 1.6	NA	NA	< 1.6
Sodium	29	62	Nonparametric	407	650	663	673	1,050	120	0.18	1,030
Thallium	28	100	Nonparametric	< 4.8	< 16	< 16	< 16	< 16	NA	NA	< 16
Vanadium	30	0	Normal	3.7	18.7	17.0	19.3	36.1	8.89	0.46	37.6
Zinc	30	3	Normal	< 2.8	22.9	17.4	22.1	45	12.8	0.58	45.3

Source: Shaw Environmental, Inc., 2008, *New Boston Air Force Station Comprehensive Site Evaluation Final Phase II Report* (Appendix J).

mg/kg - Milligrams per kilogram.
NA - Not applicable.
UTL - Upper tolerance limit.

Table 3

Background Summary Statistics for Subsurface Soil
(concentrations in mg/kg)
New Boston Air Force Station

Element	No. of Samples	Percent Nondetects	Distribution Type	Minimum	Median	Geometric Mean	Arithmetic Mean	Maximum	Standard Deviation	Coefficient of Variation	95th UTL
Aluminum	30	0	Normal	3,330	15,100	14,100	15,400	23,200	5,630	0.37	23,200
Antimony	30	90	Nonparametric	1.1	< 9.9	< 9.9	< 9.9	< 9.9	NA	NA	< 9.9
Arsenic	29	0	Lognormal	1.5	9.1	8.8	11.3	33	8.4	0.74	34.4
Barium	30	0	Lognormal	8	25.3	24.2	26.3	65	11.5	0.44	63.0
Beryllium	30	0	Lognormal	0.092	0.55	0.53	0.63	1.7	0.35	0.56	1.5
Cadmium	29	100	Nonparametric	< 0.44	< 0.66	< 0.66	< 0.66	< 0.66	NA	NA	< 0.66
Calcium	30	0	Nonparametric	102	182	196	220	829	143	0.65	763
Chromium	30	0	Lognormal	2.6	8.6	8.2	9.2	19.1	4.1	0.45	18.3
Cobalt	30	0	Lognormal	0.69	2.4	2.5	2.8	6.3	1.4	0.50	6.2
Copper	30	0	Lognormal	1.5	4.4	4.6	5.5	13.8	3.4	0.62	13.4
Iron	30	0	Nonparametric	1,520	13,700	11,800	14,200	40,800	8,040	0.57	36,300
Lead	30	7	Lognormal	3.9	8.2	8.9	9.8	27	5.1	0.52	25.6
Magnesium	30	0	Lognormal	301	940	905	1,030	2,570	544	0.53	2,590
Manganese	30	0	Lognormal	16.5	56.6	66.5	93.4	430	98.3	1.05	456
Mercury	30	3	Lognormal	0.03	0.073	0.076	0.084	0.18	0.039	0.47	0.18
Nickel	30	0	Lognormal	1.4	4.3	4.4	5.1	16.2	3.0	0.59	14.5
Potassium	30	0	Nonparametric	128	318	330	380	1,450	259	0.68	1,260
Selenium	30	0	Lognormal	0.74	2.6	2.6	3.5	15	3.0	0.85	13
Silver	30	83	Nonparametric	0.15	< 1.3	< 1.8	< 1.8	< 1.8	NA	NA	< 1.8
Sodium	29	62	Nonparametric	543	650	672	681	1,080	117	0.17	1,020
Thallium	27	100	Nonparametric	< 4.4	< 18	< 18	< 18	< 18	NA	NA	< 18
Vanadium	30	0	Lognormal	4.6	17.7	17.4	19.4	51.1	9.3	0.48	46.9
Zinc	30	0	Normal	3.7	24.9	23.8	26.7	51.6	11.3	0.42	51.8

Source: Shaw Environmental, Inc., 2008, *New Boston Air Force Station Comprehensive Site Evaluation Final Phase II Report* (Appendix J).

mg/kg - Milligrams per kilogram.
NA - Not applicable.
UTL - Upper tolerance limit.

Table 4

Background Summary Statistics for Sediment
(concentrations in mg/kg)
New Boston Air Force Station

Element	No. of Samples	Percent Nondetects	Distribution Type	Minimum	Median	Geometric Mean	Arithmetic Mean	Maximum	Standard Deviation	Coefficient of Variation	95th UTL
Aluminum	15	0	Normal	2,110	6,990	6,280	7,150	13,700	3,400	0.48	13,500
Antimony	8	50	Nonparametric	0.77	< 7.4	2.8	3.4	< 12	1.8	0.55	<12
Arsenic	15	0	Nonparametric	1.7	4.1	6.4	17.2	90.7	29.9	1.73	109
Barium	15	0	Lognormal	10.7	49.6	39.5	54.4	200	48.0	0.88	194
Beryllium	15	0	Lognormal	0.23	1	0.96	1.3	3.1	0.98	0.75	3.26
Cadmium	13	62	Nonparametric	0.082	0.4	0.377	0.450	0.92	0.26	0.58	1.01
Calcium	15	0	Lognormal	132	690	703	1,240	6,430	1,620	1.31	6,690
Chromium	15	0	Lognormal	1.2	6.2	5.0	6.1	15.5	3.8	0.63	16.0
Cobalt	15	0	Lognormal	0.92	3	4.3	9.9	61.9	16.8	1.70	67.0
Copper	15	0	Normal	0.57	6.8	5.1	6.7	12.8	4.1	0.61	13.2
Iron	15	0	Lognormal	1,290	5,700	6,530	11,200	48,600	13,700	1.22	55,600
Lead	15	0	Lognormal	4	36.5	26.9	47.1	270	64.9	1.38	273
Magnesium	15	0	Lognormal	96.8	820	572	745	2,110	528	0.71	2,140
Manganese	15	0	Lognormal	6	99.2	119	754	7,190	1,850	2.45	6,980
Mercury	15	27	Nonparametric	0.043	0.099	0.095	0.147	0.87	0.207	1.41	0.875
Nickel	15	0	Lognormal	1.9	4.6	5.5	6.7	16.5	4.2	0.63	16.3
Potassium	15	0	Lognormal	121	312	286	333	769	187	0.56	798
Selenium	15	0	Lognormal	1.1	3.1	3.3	4.4	14.9	4.0	0.90	15.8
Silver	14	86	Nonparametric	0.16	< 2	0.97	1.27	< 6.1	NA	NA	< 6.1
Sodium	14	100	Nonparametric	< 1100	< 6100	< 6100	< 6100	< 6100	NA	NA	< 6,100
Thallium	14	100	Nonparametric	< 4	< 24	< 24	< 24	< 24	NA	NA	< 24
Vanadium	15	0	Lognormal	3.8	10.8	10.7	13.3	43.5	10.0	0.76	44.8
Zinc	15	0	Normal	5.6	30.3	27.3	32.6	62.7	18.1	0.55	65.6

Source: Shaw Environmental, Inc., 2008, *New Boston Air Force Station Comprehensive Site Evaluation Final Phase II Report* (Appendix J).

mg/kg - Milligrams per kilogram.
NA - Not applicable.
UTL - Upper tolerance limit.

Table 5

**Summary of the Statistical Evaluation for Copper and Mercury
in Soil and Sediment
Site 18
New Boston Air Force Station**

| Element | Hm Test | | WRS Test | | Geochemical |
	Count > BSV	Result	*p*-level [a]	Result	Eval. Required?
Surface Soil					
Copper	16	Fail	0.000 (Site > BG)	Fail	Yes
Mercury	1	Fail	0.644	Pass	Yes
Subsurface Soil					
Copper	15	Fail	< 0.001 (Site > BG)	Fail	Yes
Mercury	1	Fail	NA	NA	Yes
Sediment					
Copper	7	Fail	0.003 (Site > BG)	Fail	Yes
Mercury	1	Fail	0.417	Pass	Yes

[a] Relative positions of site and background medians are provided in parentheses
   for *p*-levels < 0.05. See box plots in Attachment 1.
BG - Background.
BSV - Background screening value (Tables 2, 3, and 4).
Hm - Hot measurement.
NA - Not applicable. The site data set contains > 50% nondetects.
WRS - Wilcoxon rank sum.

Table 6

**Summary of the Site-to-Background Comparison for Copper and Mercury
in Soil and Sediment
Site 18
New Boston Air Force Station**

Element	Hm Test	WRS Test	Geochemical Evaluation Conclusion
Surface Soil			
Copper	Fail	Fail	Anomalous concentrations (11)
Mercury	Fail	Pass	Anomalous concentration (1)
Subsurface Soil			
Copper	Fail	Fail	Anomalous concentrations (13)
Mercury	Fail	NA	Naturally occurring
Sediment			
Copper	Fail	Fail	Anomalous concentrations (5)
Mercury	Fail	Pass	Anomalous concentration (1)

Hm - Hot measurement.
NA - Not applicable. The site data set contains > 50% nondetects.
WRS - Wilcoxon rank sum.

Table 7

**Samples With Anomalously High Element Concentrations
Site 18
New Boston Air Force Station**

Medium	Location Code	Sample No.	Date	Depth (ft. bgs)	Element(s)
Surface Soil	SIS18SS-7	SIS18SS-7	16-Jun-08	0 - 0.5	Copper, Mercury
Surface Soil	Site 18	SIS18SS14	20-May-10	0 to 0.5	Copper
Surface Soil	Site 18	SIS18SS15	20-May-10	0 to 0.5	Copper
Surface Soil	Site 18	SIS18SS16	20-May-10	0 to 0.5	Copper
Surface Soil	Site 18	SIS18SS19	20-May-10	0 to 0.5	Copper
Surface Soil	Site 18	SIS18SS20	20-May-10	0 to 0.5	Copper
Surface Soil	Site 18	SIS18SS21	20-May-10	0 to 0.5	Copper
Surface Soil	Site 18	SIS18SS22	20-May-10	0 to 0.5	Copper
Surface Soil	Site 18	SIS18SS25	20-May-10	0 to 0.5	Copper
Surface Soil	Site 18	SIS18SS30	21-May-10	0 to 0.5	Copper
Surface Soil	Site 18	SIS18SS31	21-May-10	0 to 0.5	Copper
Subsurface Soil	Site 18	SIS18SB14	20-May-10	1.5 to 2.0	Copper
Subsurface Soil	Site 18	SIS18SB15	20-May-10	1.5 to 2.0	Copper
Subsurface Soil	Site 18	SIS18SB16	20-May-10	1.5 to 2.0	Copper
Subsurface Soil	Site 18	SIS18SB18	20-May-10	1.5 to 2.0	Copper
Subsurface Soil	Site 18	SIS18SB19	20-May-10	1.5 to 2.0	Copper
Subsurface Soil	Site 18	SIS18SB20	20-May-10	1.5 to 2.0	Copper
Subsurface Soil	Site 18	SIS18SB21	20-May-10	1.5 to 2.0	Copper
Subsurface Soil	Site 18	SIS18SB22	20-May-10	1.5 to 2.0	Copper
Subsurface Soil	Site 18	SIS18SB23	20-May-10	1.5 to 2.0	Copper
Subsurface Soil	Site 18	SIS18SB28	21-May-10	1.5 to 2.0	Copper
Subsurface Soil	Site 18	SIS18SB30	21-May-10	1.5 to 2.0	Copper
Subsurface Soil	Site 18	SIS18SB31	21-May-10	1.5 to 2.0	Copper
Subsurface Soil	Site 18	SIS18SB32	21-May-10	1.5 to 2.0	Copper
Sediment	SIS18SD-1A	SIS18SD-1A	17-Jun-08	--	Copper, Mercury
Sediment	SIS18SD-1B	SIS18SD-1B	17-Jun-08	--	Copper
Sediment	SIS18SD-2A	SIS18SD-2A	16-Jun-08	--	Copper
Sediment	Site 18	SIS18SD11	21-May-10	--	Copper
Sediment	Site 18	SIS18SD12	21-May-10	--	Copper

Note: The samples listed above were identified via geochemical evaluation as having anomalously high concentrations
   of the specified element(s) (see Sections 3.0 and 4.0).
ft. bgs - Feet below ground surface.

Table 8

November 2009 Samples With Trace Element Concentrations
Above Background Screening Values
Site 18
New Boston Air Force Station

Medium	Location Code	Sample No.	Date	Depth (ft. bgs)	Element(s)
Surface Soil	Site 18	SIS18SS10	23-Nov-09	0 to 0.5	Copper
Surface Soil	Site 18	SIS18SS11	23-Nov-09	0 to 0.5	Copper, Mercury
Surface Soil	Site 18	SIS18SS12	23-Nov-09	0 to 0.5	Copper
Surface Soil	Site 18	SIS18SS13	23-Nov-09	0 to 0.5	Copper, Mercury
Surface Soil	Site 18	SIS18SS9	23-Nov-09	0 to 0.5	Copper, Mercury

Note: The samples listed above lack reference element analyses and thus could not be included in the
geochemical evaluation to determine if their trace element concentrations have a natural source.
They exceed the background screening value(s) for the specified element(s).
ft. bgs - Feet below ground surface.

ATTACHMENT 1:

Box Plots

Box-Plot Comparison for Copper in Surface Soil
Site 18, New Boston AFS
(concentrations in mg/kg)

Box-Plot Comparison for Mercury in Surface Soil
Site 18, New Boston AFS
(concentrations in mg/kg)

Box-Plot Comparison for Copper in Subsurface Soil
Site 18, New Boston AFS
(concentrations in mg/kg)

Box-Plot Comparison for Copper in Sediment
Site 18, New Boston AFS
(concentrations in mg/kg)

Box-Plot Comparison for Mercury in Sediment
Site 18, New Boston AFS
(concentrations in mg/kg)

ATTACHMENT 2:

Geochemical Correlation Plots and Ratio Plots

Figure 1. Aluminum vs. Iron in Soil, Site 18

Figure 2. Copper vs. Aluminum in Soil, Site 18

Figure 3. Copper vs. Cu/Al Ratios in Soil, Site 18

Figure 4. Mercury vs. Aluminum in Soil, Site 18

Figure 5. Aluminum vs. Iron in Sediment, Site 18

Figure 6. Aluminum vs. Magnesium in Sediment, Site 18

Figure 7. Copper vs. Aluminum in Sediment, Site 18

Figure 8. Copper vs. Cu/Al Ratios in Sediment, Site 18

Figure 9. Mercury vs. Iron in Sediment, Site 18

Figure 10. Mercury vs. Hg/Fe Ratios in Sediment, Site 18

Appendix F-2

**Evaluation of PAH Concentrations in Soil Samples
Sites 7 and 18
New Boston Air Force Station**

1.0 Introduction

This appendix provides an evaluation of 17 polycyclic aromatic hydrocarbon (PAH) compounds in soil samples from Sites 7 and 18 at New Boston Air Force Station (NBAFS), New Hampshire. The site data sets include samples collected during the 2007-2008 Site Inspection (SI) Addendum and the 2009-2010 Remedial Investigation (RI). The RI samples were collected to delineate potential site-related contamination identified in the earlier samples.

The Site 7 data set consists of 4 surface soil samples (0 to 0.5 foot below ground surface [bgs]; including 1 field duplicate) and 5 subsurface soil samples (1.5 to 2.0 feet bgs and 2.5 to 3.0 feet bgs; including 1 field duplicate) collected in August 2007; and 6 surface soil samples (0 to 0.5 foot bgs) and 7 subsurface soil samples (1.5 to 2.0 feet bgs; including 1 field duplicate) collected in May 2010. The Site 18 data set consists of 9 surface soil samples (0 to 0.5 foot bgs; including 1 field duplicate) and 15 subsurface soil samples (various depths ranging from 1.5 to 7.5 bgs; including 1 field duplicate) collected in June 2008; and 8 surface soil samples (0 to 0.5 foot bgs; including 1 field duplicate) and 1 subsurface soil sample (1.5 to 2.0 feet bgs) collected in May 2010. Detection frequencies of PAHs in the Sites 7 and 18 samples are discussed in Sections 4.0 and 5.0, respectively.

Thirty-three facility-wide ("background") soil samples (including three field duplicates) were collected in October 2009 and analyzed for PAHs, and they are used for comparative purposes in the evaluation. These samples were located proximal to asphalt road surfaces but away from known or suspected sources of site-related contamination, and are therefore presumed to contain anthropogenic background concentrations of PAHs. The facility-wide soil samples were collected from depths of 0 to 0.5 foot bgs and 1.5 to 2 feet bgs.

The 17 PAHs were each detected in at least one facility-wide sample, with nondetect frequencies ranging from 3 to 64 percent. The compounds with the lowest detection frequency (3 percent, or 1 of 33 samples) are 2-methylnaphthalene, acenaphthene, fluorene, and naphthalene; all of these compounds were detected in the same surface soil sample (NBPAHSS01). The compounds with

the highest detection frequency include benzo(a)anthracene (19 of 33 samples), benzo(b)fluoranthene (17 of 33 samples), chrysene (15 of 33 samples), fluoranthene (18 of 33 samples), phenanthrene (16 of 33 samples), and pyrene (21 of 33 samples). The maximum detected concentrations (MDCs) of these six compounds are 1.6 mg/kg, 3.4 mg/kg, 2.6 mg/kg, 3.7 mg/kg, 1.9 mg/kg, and 4.8 mg/kg, respectively. The facility-wide PAH detections suggest that anthropogenic background concentrations should also be expected in at least some percentage of the site soil samples, in addition to any site-related PAH impacts.

2.0 Types and Sources of PAHs

Polycyclic aromatic hydrocarbons are a family of several hundred different compounds. As their name implies, these compounds contain multiple benzene-like (aromatic) ring structures, and are comprised of hydrogen and carbon. Naphthalene ($C_{10}H_8$), consisting of two fused benzene rings, is the simplest PAH. The arrangement and number of fused rings are used to distinguish different PAHs. Sources of PAHs in soils and sediments from urban or industrial areas can be separated into three primary categories, as described below.

Petrogenic PAHs are hydrocarbons formed by the geochemical alteration of organic matter at moderate temperature (50 to150 degrees Celsius) and pressure over very long (i.e., geologic) timescales. These PAHs enter urban environments from anthropogenic sources such as petroleum (crude oil, refined oil, or fuels) spills or leaks, coal from coal-fired steam and power plants, and municipal sewage treatment plants. In some areas, the presence of naturally occurring petrogenic PAHs results from the erosion of coal beds, erosion of shales with high organic content, or naturally seeped oil.

Pyrogenic PAHs form when fuels and other organic matter are incompletely or inefficiently combusted or pyrolyzed at moderate to high temperatures (>400 degrees Celsius) over very short time intervals. These PAHs enter the environment from burning of fossil fuels, including emissions from coal- or oil-fired power plants, incinerators, and automotive engine exhaust. They also form naturally during forest and brush fires.

Biogenic PAHs include those derived from oxidation of microbial- or plant-derived compounds. Biogenic and other nonanthropogenic sources of PAHs typically occur in older, deeper sediments that were deposited prior to industrialization or urbanization, or in sediments in remote locations.

It is important to note that not all petrogenic and pyrogenic PAHs found as contaminants in soil or sediment are derived from anthropogenic sources. In some areas, the presence of petrogenic

PAHs results from eroded coal/shales or naturally seeped oil; and pyrogenic PAHs can be generated from naturally occurring forest and brush fires. The presence of PAH compounds can also be due to general non-point-source urban pollution resulting from auto, bus, truck, and freight-train traffic; burning of wood and coal for household heating; and emissions from restaurant and household cooking grills.

Polycyclic aromatic hydrocarbons are introduced into soil through a variety of anthropogenic activities from both point and non-point sources. Common point sources of PAHs in many urban and industrial areas include direct or indirect discharges from petroleum terminals, aluminum smelting, manufactured gas production facilities, wood treatment facilities, tar distillation plants, rail yards, coal distribution facilities, discharge canals, stormwater outfalls, weathering of creosote-treated wood, spilled or seeped petroleum or coal- or oil-derived tars and their associated distillation products.

Common non-point sources include atmospheric particulates (soot) and dripped/leaked petroleum (including asphalt) washed from the surrounding urban roadways, parking lots, vegetation, and structures during rainfall events. Other non-point sources of PAHs in urban and industrial areas include general surface and stormwater runoff (i.e., not entering from a specific outfall location), and direct atmospheric particulate deposition (soot from petroleum combustion, forest fires, wood stoves, coal-fired power plants, smelters, etc.). In areas remote from urban influence, background PAHs generally are limited to pyrogenic PAHs derived from particles transported over large distances (Ohkouchi *et al*., 1999). In some natural environments, oil seeps and erosion from petroleum source rocks, coal, and organic-rich shale can result in elevated concentrations from natural sources of petrogenic PAHs (Boehm et al., 2000a and 2000b). The concentrations of background PAHs in remote areas are generally much lower than background PAH concentrations in urban and industrial areas, where direct deposition of combustion-related PAHs from proximal sources and urban runoff have occurred for much of the last century.

In urban and industrial soil environments, background PAHs associated with pyrogenic sources usually are more abundant than those associated with petrogenic sources, due to the large amounts of fossil fuels combusted in urban areas. Concentrations of pyrogenic PAHs are normally highest in shallow soil layers, and decrease to a relatively constant "natural background" concentration at depths corresponding to deposition prior to urbanization. In most settings, the most highly PAH-contaminated soils were deposited between the start of heavy industrial use of fossil fuels and the present, indicating that the fraction of the total "urban background" PAHs above natural background levels is derived from the combustion of fossil fuels. Forest and brush fires can be major sources of the "natural background" pyrogenic PAHs in areas prone to these events.

Background petrogenic PAHs also are present in most urban soils, although they are usually less abundant than background pyrogenic PAHs. Their occurrence is largely attributable to uncombusted petroleum spilled or dripped onto roadways and parking lots (e.g., crankcase oil) following storm events.

Runoff from paved surfaces is an important source of soil contamination in many developed areas. Key components of urban runoff include dust containing diesel soot, street runoff containing lubricating oils and weathered asphalt, and illegal or unintentional discharging of waste oil and petroleum products. The PAHs in urban runoff are complex mixtures that tend to be dominated by higher molecular weight 4- to 6-ring PAHs (Durell *et al*., 1991; Peven *et al*., 1996). Specific PAHs observed in urban runoff include phenanthrene, anthracene, fluoranthene, pyrene, chrysene, benzo(b)fluoranthene, and indeno(1,2,3-cd)pyrene (Murphy and Morrison, 2002).

3.0 Evaluation of PAH Data

Various sources of PAHs can be classified by evaluation of selected PAH compound ratios that depend upon the thermal stability of related isomers (e.g., Mitra *et al*., 1999; Walker and Dickhut, 2001). As an example, ratios of phenanthrene to anthracene (Ph/An) and fluoranthene to pyrene (Fl/Py) are useful for differentiating between sediment PAH assemblages containing primarily pyrogenic or petrogenic PAHs (U.S. Navy, 2003). Anthracene and fluoranthene are thermodynamically less stable than their respective isomers, phenanthrene and pyrene (Baumard *et al*., 1998). Anthracene and fluoranthene are produced during rapid, high temperature pyrosynthesis, but are less favored to persist during the slow organic diagenesis leading to the generation of fossil fuels. Thus, the Ph/An ratios of pyrogenic PAH assemblages usually are less than 5, whereas petrogenic ratios usually are greater than 5. The Fl/Py ratios usually approach or exceed 1 in pyrogenic assemblages and usually are substantially less than 1 in petrogenic PAH assemblages. The use of two ratios provides independent evidence of the sources of detected PAHs.

Polycyclic aromatic hydrocarbon data are often examined in terms of normalized ratios, which are visualized using scatter plots (Zemo, 2009). Included in this report are normalized double-ratio plots of An/(An+Ph) versus Fl/(Fl+Py), BaA/(BaA+Ch) versus Fl/(Fl+Py), and IP/(IP+Bghi) versus Fl/(Fl+Py), where An = anthracene, BaA = benzo(a)anthracene, Bghi = benzo(g,h,i)perylene, Ch = chrysene, Fl = fluoranthene, IP = indeno(1,2,3-cd)pyrene, Ph = phenanthrene, and Py = pyrene.

These double-ratio plots separate petrogenic and pyrogenic sources into clusters. The pairs used on each axis (such as fluoranthene and pyrene) are isomers with the same molecular weights, so they have similar solubilities, adsorption coefficients (K_d), and vapor pressures, and will weather at similar rates. This helps to preserve the ratios in the soil over time. A pair of isomers differ in the arrangement of the rings, with one member being more thermodynamically stable. The ratios above have the most stable form in the denominator. Pyrogenic sources have a higher proportion of the less stable member of the pair, so pyrogenic sources will have higher ratios. On double-ratio plots, the pyrogenic sources will cluster in the upper right of the plot and the petrogenic sources will cluster closer to the origin. Polycyclic aromatic hydrocarbons composed of a mixture of these two sources (including urban runoff) will cluster in the middle region between the petrogenic and pyrogenic fields.

If the site and facility-wide soil samples have similar PAH ratios and the site samples plot near or within the cluster of facility-wide samples on the double-ratio plots, then that suggests that the site PAH detections reflect an anthropogenic background signature and not site-related contamination. If, however, a site sample has a distinctly different PAH ratio and does not lie on or near the facility-wide samples on the double-ratio plots, then that suggests that some or all of the PAHs in question have a different, and possibly site-related, source.

4.0 PAH Evaluation for Soil Samples from Site 7

All 9 of the 2007 SI Addendum samples collected at Site 7 are nondetect for 2-methylnaphthalene, acenaphthylene, and naphthylene. The remaining 14 PAHs were each detected in 3 to 9 SI Addendum samples. Similarly, all 13 of the 2010 RI samples are nondetect for 2-methylnaphthalene, acenaphthylene, and naphthylene. The remaining 14 PAHs were each detected in 2 to 13 RI samples.

Figures 1 through 8 show the concentrations of eight of the PAH compounds plotted against the concentrations of pyrene. Pyrene was chosen as the reference compound because it has the largest number of detections (21 in the 33 facility-wide samples and 22 in the combined set of 22 site samples) as well as a high proportion of unqualified concentrations above the reporting limit. The facility-wide samples are represented by green circles (FW), the 2007 SI Addendum site samples are represented by blue triangles (Site), and the 2010 RI site samples are represented by yellow triangles (RI Site).

Each of the eight compounds covaries with pyrene (Figure 1 through 8), indicating that the compound-to-pyrene ratios are all fairly constant for most samples in the three data sets. The fact

that the PAHs in most samples are present in relatively fixed proportions to each other suggests that they have a common source. The SI Addendum surface soil sample SIS7SS03 has higher concentrations of three PAHs relative to the facility-wide samples: benzo(g,h,i)perylene (1.45 mg/kg, versus the facility-wide MDC of 0.76 mg/kg), dibenz(a,h)anthracene (0.303 mg/kg, versus the facility-wide MDC of 0.21 mg/kg), and indeno(1,2,3-cd)pyrene (1.61 mg/kg, versus the facility-wide MDC of 0.64 mg/kg). However, this sample lies within the cluster of other site samples and near the facility-wide samples in the normalized double-ratio plots (Figures 9 through 11). For example, sample SIS7SS03's An/(An+Ph) ratio is 0.138 and its Fl/(Fl+Py) ratio is 0.560, placing it directly adjacent to a facility-wide sample and several other site samples in Figure 9. Other PAH ratios of sample SIS7SS03 (not shown in the figures) are similar to those of the facility-wide samples. This similarity in ratios suggests a common source for the PAHs in the samples that cluster together in the normalized double ratio plots.

In contrast to the above observations, the samples from location SIS7SS/SB01 (SIS7SS01, field duplicate SIS7SS01D, SIS7SB01A, and field duplicate SIS7SB01AD) contain higher concentrations for multiple compounds relative to the facility-wide concentrations. For example, all 14 detected PAHs in surface soil sample SIS7SS01 exceed their corresponding facility-wide MDCs. In addition, the four samples from location SIS7SS/SB01 exhibit different PAH ratios relative to the facility-wide samples. As an example, samples SIS7SS01, -SS01D, and -SB01AD — which have the highest anthracene concentrations of the three data sets (2.87 J mg/kg, 0.385 J mg/kg, and 0.725 J mg/kg, respectively) — lie above the facility-wide trend in Figure 1. The SIS7SS/SB01 samples also lie apart from the facility-wide samples and other site samples in Figures 9 and 11. These four samples are relatively enriched in lower-molecular-weight PAHs, which is consistent with discharged water from an oil/water separator (such as that at Site 7).

The 2010 RI samples were collected in the vicinity of SIS7SS/SB01 to delineate the extent of the PAH contamination. Most of these additional samples (SIS7SS/SB04, -SS/SB05, -SS/SB06, -SS/SB07, -SS/SB08, and -SS/SB09) have detected PAH concentrations that are similar to those of the facility-wide samples. This can be seen in Figures 1 through 8, where for all of the depicted PAHs, the RI samples lie on the facility-wide trend and are shifted downward in concentration relative to the SI samples with higher concentrations. The exception is acenaphthene in SIS7SB07 (0.030 J mg/kg; not shown in the figures), which is an estimated concentration below the reporting limit and is only slightly higher than the maximum facility-wide acenaphthene detection of 0.024 J mg/kg. The 2010 samples' PAH ratios are consistent with the facility-wide samples' PAH ratios (see also Figures 9 and 11), suggesting a common source. The apparent exception is subsurface sample SIS7SB09, which lies above the cluster of other samples in Figure 10. Its BaA/(BaA+Ch) ratio of 0.592 and Fl/(Fl+Py) ratio of 0.537 are based on J-qualified concentrations below the

reporting limit, for all four compounds used in the ratio calculations. The analytical uncertainty associated with these estimated concentrations likely explains its different location on the plot. Another line of evidence to support a common PAH source is that all of the 2010 RI soil samples are nondetect for 2-methylnaphthalene, acenaphthylene, and naphthalene; this is consistent with the majority of facility-wide samples.

All of the above observations suggest that the PAH detections in the additional (2010 RI) soil samples represent anthropogenic background PAHs and do not contain PAH contributions from a site-related source. This also indicates that the PAH contamination has been successfully delineated in the vicinity of SIS7SS/SB01. Soil samples from location SIS7SS/SB01 contain PAHs that may reflect site-related contamination, but such contamination is highly localized.

5.0 PAH Evaluation for Soil Samples from Site 18

All 24 of the 2008 SI Addendum samples collected at Site 18 are nondetect for 2-methylnaphthalene and naphthylene. The remaining 15 PAHs were each detected in 1 to 13 SI Addendum samples. All 9 of the 2010 RI samples are nondetect for 2-methylnaphthalene, acenaphthene, acenaphthylene, anthracene, dibenz(a,h)anthracene, fluorene, and naphthalene. The remaining 10 PAHs were each detected in 1 to 6 RI samples.

Figures 12 through 18 show the concentrations of seven of the PAH compounds plotted against the concentrations of pyrene. Pyrene was chosen as the reference compound because it has a large number of detections (21 in the 33 facility-wide samples and 15 in the combined set of 33 site samples) as well as a high proportion of unqualified concentrations above the reporting limit. The facility-wide samples are represented by green circles (FW), the 2008 SI Addendum site samples are represented by blue triangles (Site), and the 2010 RI site samples are represented by yellow triangles (RI Site).

Each of the seven compounds covaries with pyrene (Figure 12 through 18), indicating that the compound-to-pyrene ratios are all fairly constant for most samples in the three data sets. The fact that the PAHs in most samples are present in relatively fixed proportions to each other suggests that they have a common source.

The detected PAH concentrations of most 2008 SI Addendum soil samples are within the concentration ranges of the facility-wide samples. This can be seen in Figures 12 through 18; the majority of SI Addendum samples have PAH concentrations that are well below their corresponding facility-wide MDCs. In addition, most of the SI Addendum samples' PAH ratios

are consistent with those of the facility-wide samples (they lie on the facility-wide trends in the Figures 12 through 18), suggesting that the site and facility-wide PAH detections have a similar source that is not related to a Site 18 release.

The exception to the above observations is surface soil sample SIS18SS-7, which contains higher concentrations for several compounds relative to the facility-wide concentrations: 8 of the 13 detected PAHs in the sample exceed the corresponding facility-wide MDCs. In addition, sample SIS18SS-7 exhibits different PAH ratios relative to the facility-wide samples. For example, this sample lies above the facility-wide trends in Figures 12, 16, and 18. It also lies apart from the facility-wide samples in Figure 19 (of note is the fact that all other site samples are nondetect for anthracene and thus cannot be depicted in the figure). PAHs were not detected in subsurface sample SIS18SB-7A, which indicates that the PAH contamination is restricted to the surface interval at that location.

The 2010 RI samples were collected in the vicinity of SIS18SS-7 to delineate the extent of the PAH contamination. All of the 2010 RI surface soil samples collected in the vicinity of SIS18SS-7 (SIS18SB28, -SS09, -SS10, -SS11, -SS12, -SS25, -SS26, -SS27, and field duplicate SIS18SS25DUPE) have detected PAH concentrations that are similar to those of the facility-wide samples. In addition, the RI samples have PAH ratios that are consistent with the facility-wide PAH ratios, as seen in Figures 12 through 18. These nine samples are nondetect for 2-methylnaphthalene, acenaphthene, acenaphthylene, anthracene, dibenz(a,h)anthracene, fluorene, and naphthalene — consistent with the low detection frequency for these compounds in the facility-wide data set.

One RI sample (field duplicate SI18SS25DUPE) lies apart from the facility-wide samples and other site samples in Figure 20; it has a BaA/(BaA+Ch) ratio of 0.690 and Fl/(Fl+Py) ratio of 0.544. When viewing normalized double-ratio plots, it is important to remember that, unlike concentration-versus-concentration scatter plots, the double-ratio plots represent proportions rather than absolute concentrations. A sample with very low concentrations can have an apparently different PAH ratio because a ratio calculated from two uncertain concentrations will also be uncertain. The benzo(a)anthracene, chrysene, fluoranthene, and pyrene concentrations of sample SIS18SS25DUPE are all low, estimated concentrations (0.040 J mg/kg, 0.018 J mg/kg, 0.049 J mg/kg, and 0.041 J mg/kg, respectively) below their reporting limits and near or at their method detection limits. These detections are also two orders of magnitude below the corresponding facility-wide MDCs. The high degree of analytical uncertainty surrounding these low detections likely explains the elevated BaA/(BaA+Ch) ratio depicted in Figure 20. Site-related contamination is not suspected for this sample.

The above observations suggest that the PAH detections in the 2010 RI samples represent anthropogenic background PAHs and do not contain PAH contributions from a site-related source. The data also suggest that the PAH contamination has been successfully delineated in the vicinity of SIS18SS-7. Surface soil sample SIS18SS-7 contains PAHs that may reflect site-related contamination, but such contamination is highly localized and limited to that location.

6.0 Summary and Conclusions

Polycyclic aromatic hydrocarbon detections in the Site 7 and Site 18 soil samples were evaluated for source attribution. The evaluations included comparison to the NBAFS facility-wide PAH soil data set in terms of detection frequency, absolute concentrations, and concentration ratios.

Site 7. For the August 2007 SI Addendum soil samples, the detected PAH concentrations in SIS7SS02, -SB02A, -SB02B, and -SB03A are within the concentration range of the facility-wide PAH samples. The PAH ratios of these four samples are also consistent with those of the facility-wide samples; this suggests that the PAHs detected in the four site samples have a similar source as the facility-wide samples and are not related to a Site 7 release. Surface soil sample SIS7SS03 has higher concentrations of three PAHs (benzo[g,h,i]perylene, dibenz[a,h]anthracene, indeno[1,2,3-cd]pyrene) relative to the facility-wide samples, but its PAH ratios are consistent with the ratios of the facility-wide samples, suggesting a common source.

In contrast, the samples from location SIS7SS/SB01 (SIS7SS01, field duplicate SIS7SS01D, SIS7SB01A, and field duplicate SIS7SB01AD) contain higher PAH concentrations and different PAH ratios relative to the facility-wide samples. These samples are relatively enriched in lower-molecular-weight PAHs, which is consistent with discharged water from an oil/water separator. Additional sampling was performed in the vicinity of SIS7SS/SB01 during the May 2010 RI field investigation to delineate the extent of the PAH contamination.

Most of the 2010 RI soil samples collected in the vicinity of SIS7SS/SB01 (SIS7SS/SB04, -SS/SB05, -SS/SB06, -SS/SB07, -SS/SB08, and -SS/SB09) have detected PAH concentrations that are similar to those of the facility-wide samples. The 2010 samples' PAH ratios are also consistent with the facility-wide samples' PAH ratios, suggesting a common source. All of the 2010 RI soil samples are nondetect for 2-methylnaphthalene, acenaphthylene, and naphthalene, which is consistent with the majority of facility-wide samples. These observations suggest that the PAH detections in the additional soil samples represent anthropogenic background PAHs and do not contain PAH contributions from a site-related source. The data also indicate that the PAH contamination has been successfully delineated in the vicinity of SIS7SS/SB01. Soil samples

from this location contain PAHs that may reflect site-related contamination, but such contamination is highly localized.

Site 18. The detected PAH concentrations of most of the 2008 SI Addendum soil samples are within the concentration range of the facility-wide samples. Most of the site PAH ratios are also consistent with those of the facility-wide samples, suggesting that the site and facility-wide PAH detections have a similar source that is not related to a Site 18 release. The single exception is surface soil sample SIS18SS-7, which contains both higher PAH concentrations and different PAH ratios relative to the facility-wide samples. Additional sampling was performed in the vicinity of SIS18SS-7 during the May 2010 RI field investigation to delineate the extent of the PAH contamination. PAHs were not detected in subsurface sample SIS18SB-7A, which indicates that the PAH contamination is restricted to the surface interval at that location.

All of the 2010 RI surface soil samples collected in the vicinity of SIS18SS-7 (SIS18SB28, -SS09, -SS10, -SS11, -SS12, -SS25, -SS26, -SS27, and field duplicate SIS18SS25DUPE) have detected PAH concentrations that are similar to those of the facility-wide samples, in addition to having PAH ratios that are consistent with the facility-wide samples' PAH ratios. Furthermore, these nine samples are nondetect for 2-methylnaphthalene, acenaphthene, acenaphthylene, anthracene, dibenz(a,h)anthracene, fluorene, and naphthalene — consistent with the low detection frequency for these compounds in the facility-wide data set. These observations suggest that the PAH detections in the 2010 RI samples represent anthropogenic background PAHs and do not contain PAH contributions from a site-related source. The data also indicate that the PAH contamination has been successfully delineated in the vicinity of SIS18SS-7. Surface soil sample SIS18SS-7 contains PAHs that may reflect site-related contamination, but such contamination is highly localized and limited to that location.

7.0 References

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FIGURES

Figure 1. Anthracene vs. Pyrene in Site 7 Soil
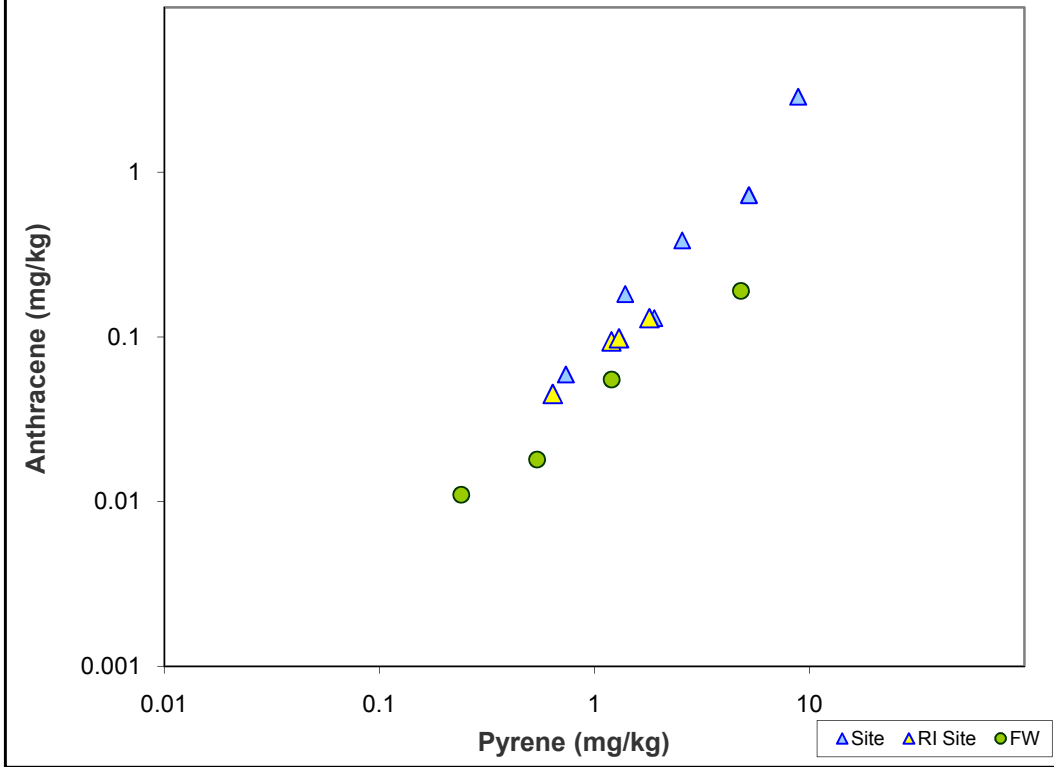
Figure 2. Benzo(a)anthracene vs. Pyrene in Site 7Soil

Figure 3. Benzo(b)fluoranthene vs. Pyrene in Site 7 Soil
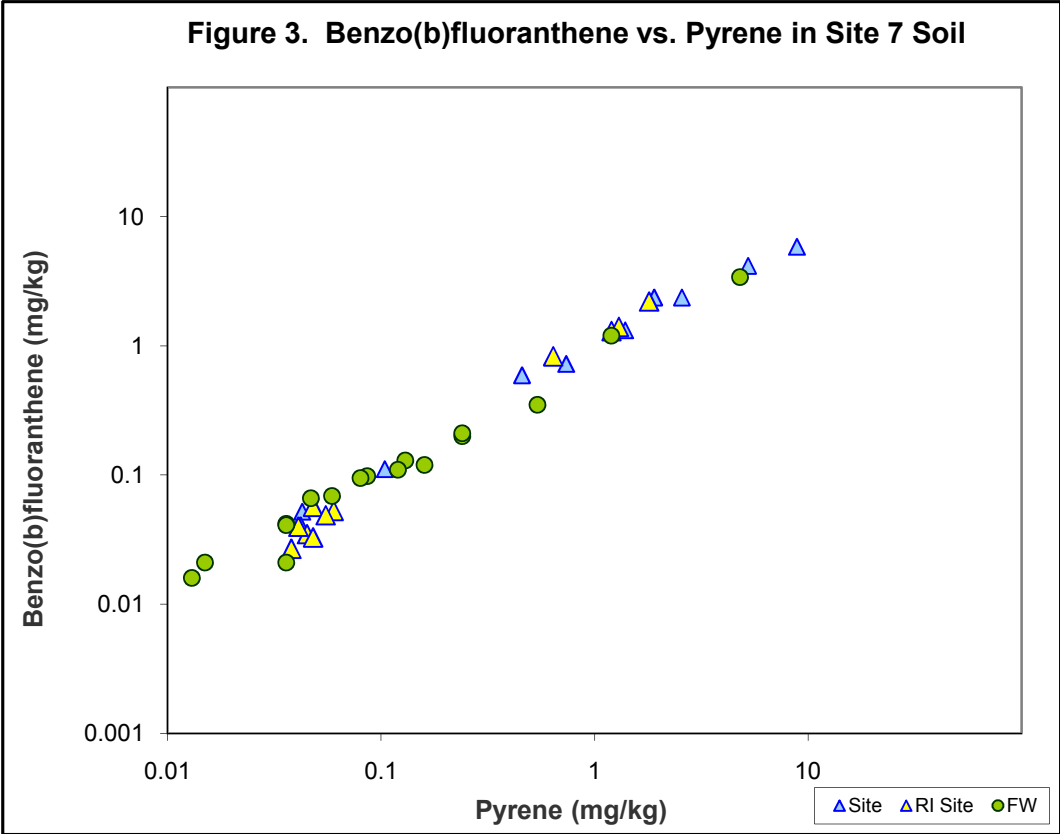

Figure 4. Chrysene vs. Pyrene in Site 7 Soil
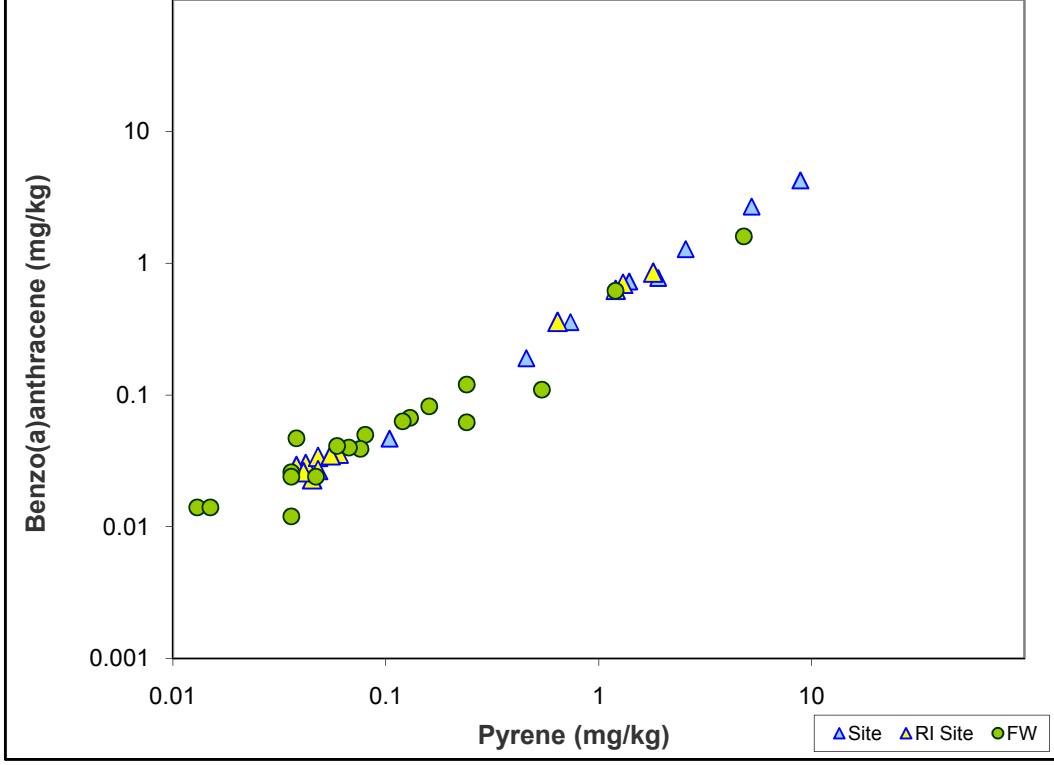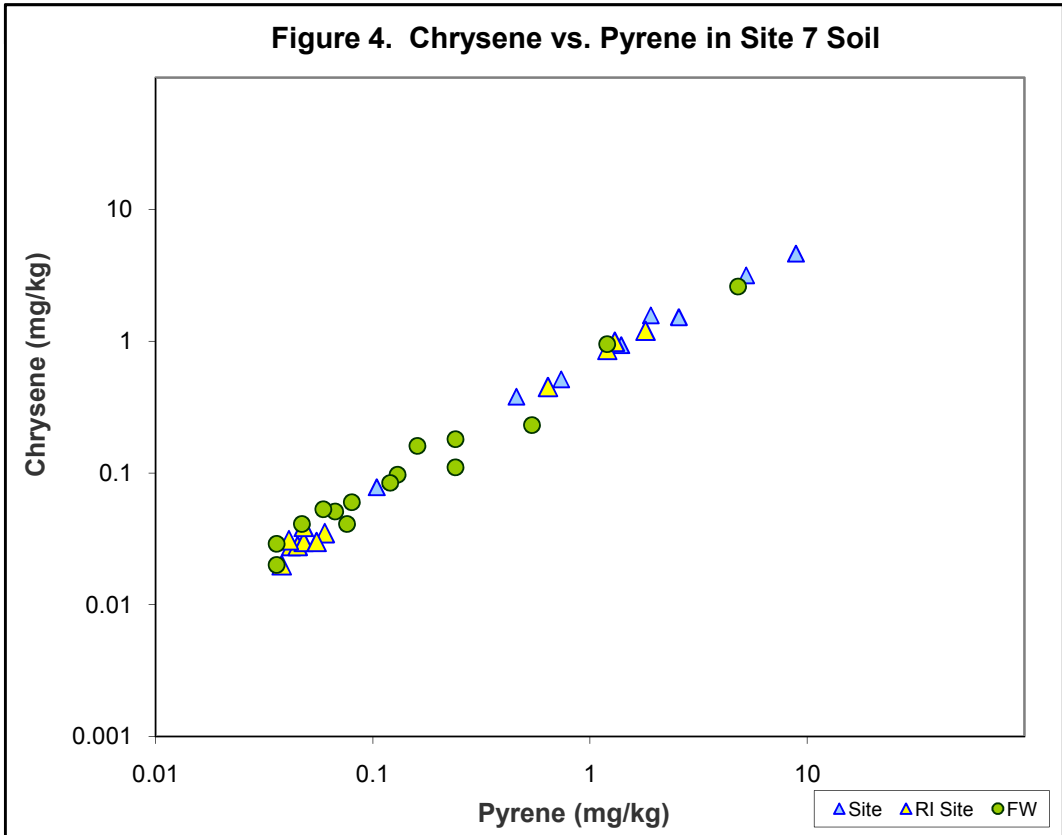
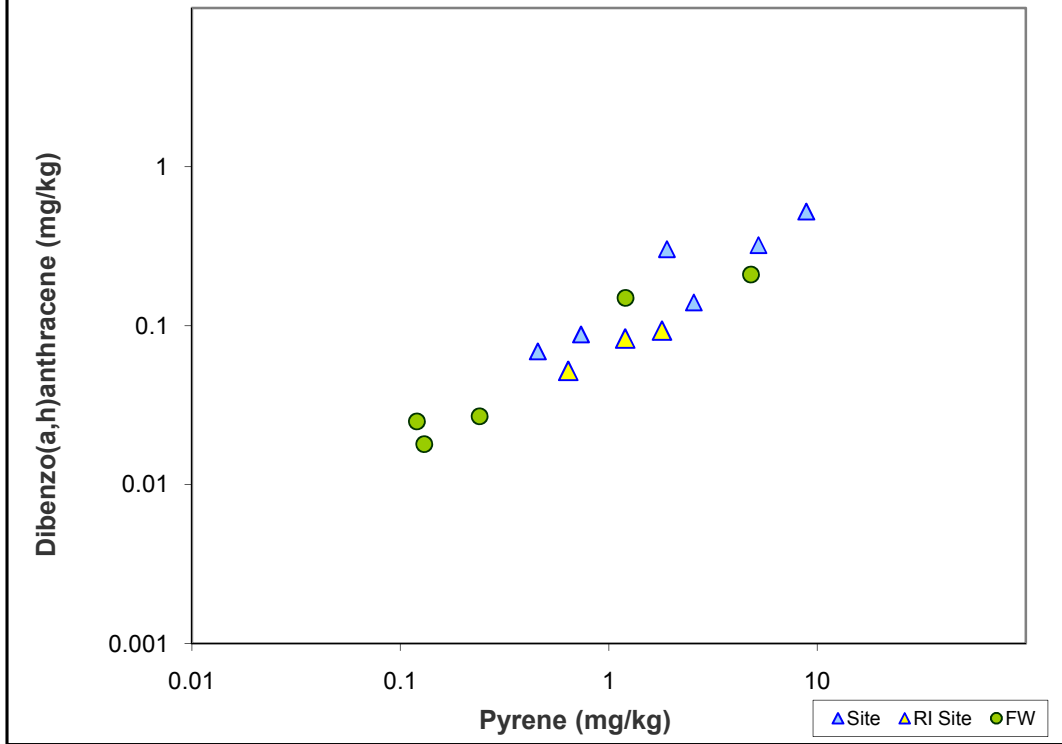Figure 5. Dibenz(a,h)anthracene vs. Pyrene in Site 7 Soil

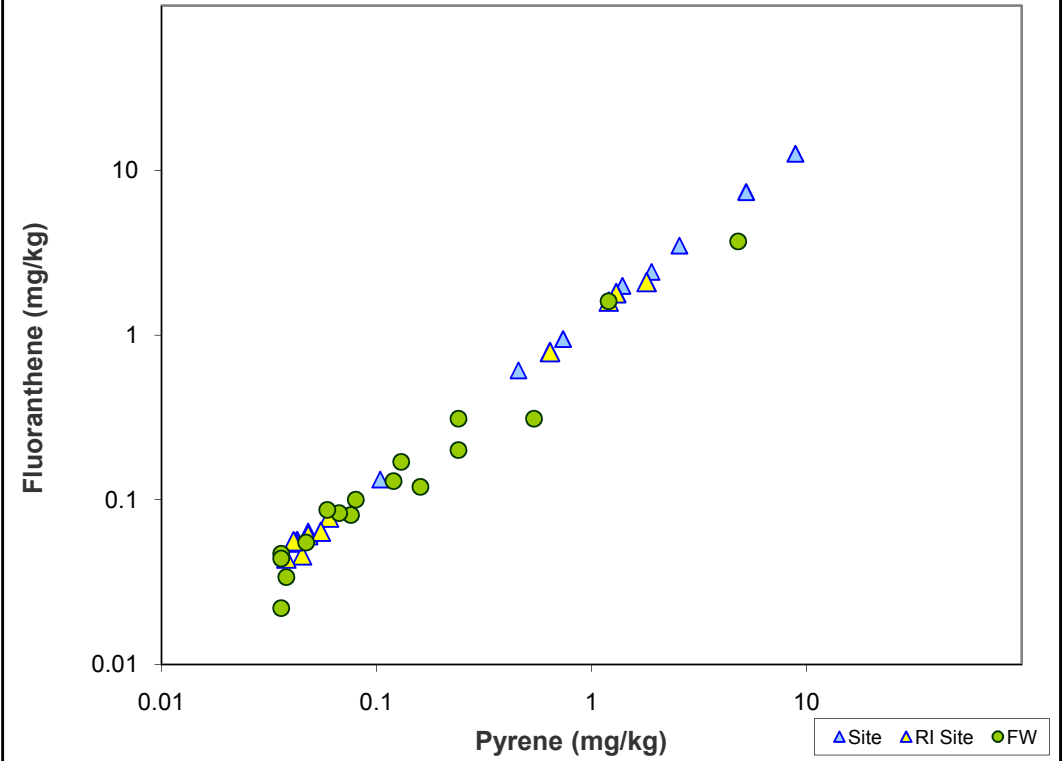Figure 6. Fluoranthene vs. Pyrene in Site 7 Soil

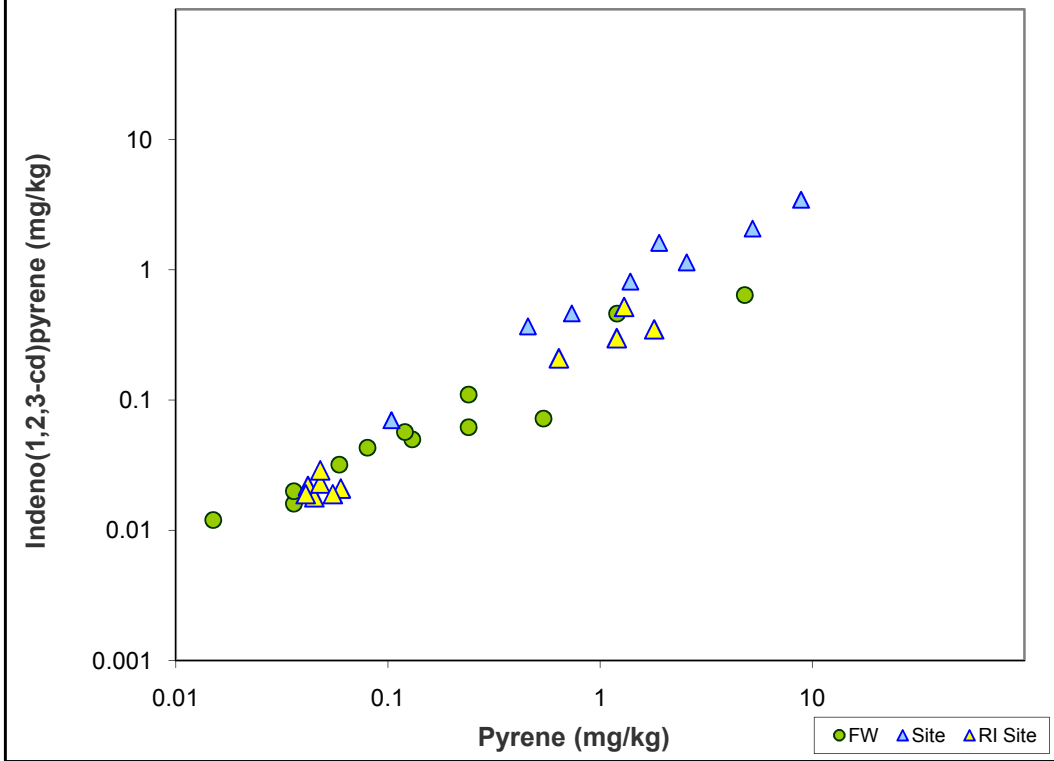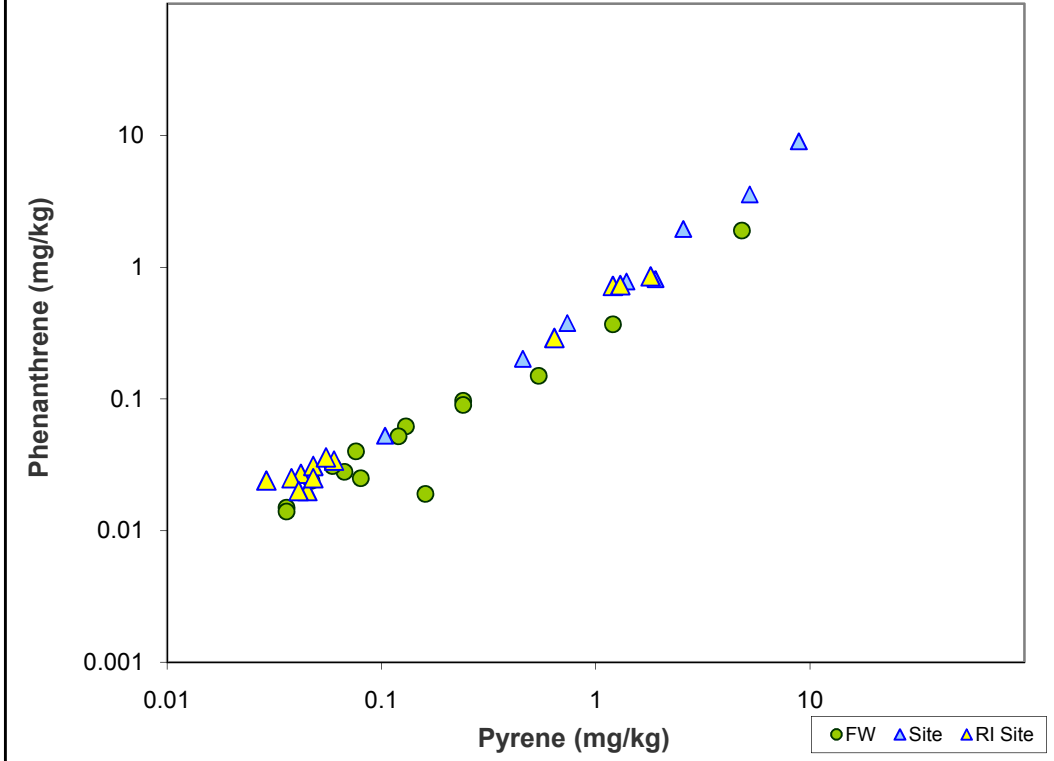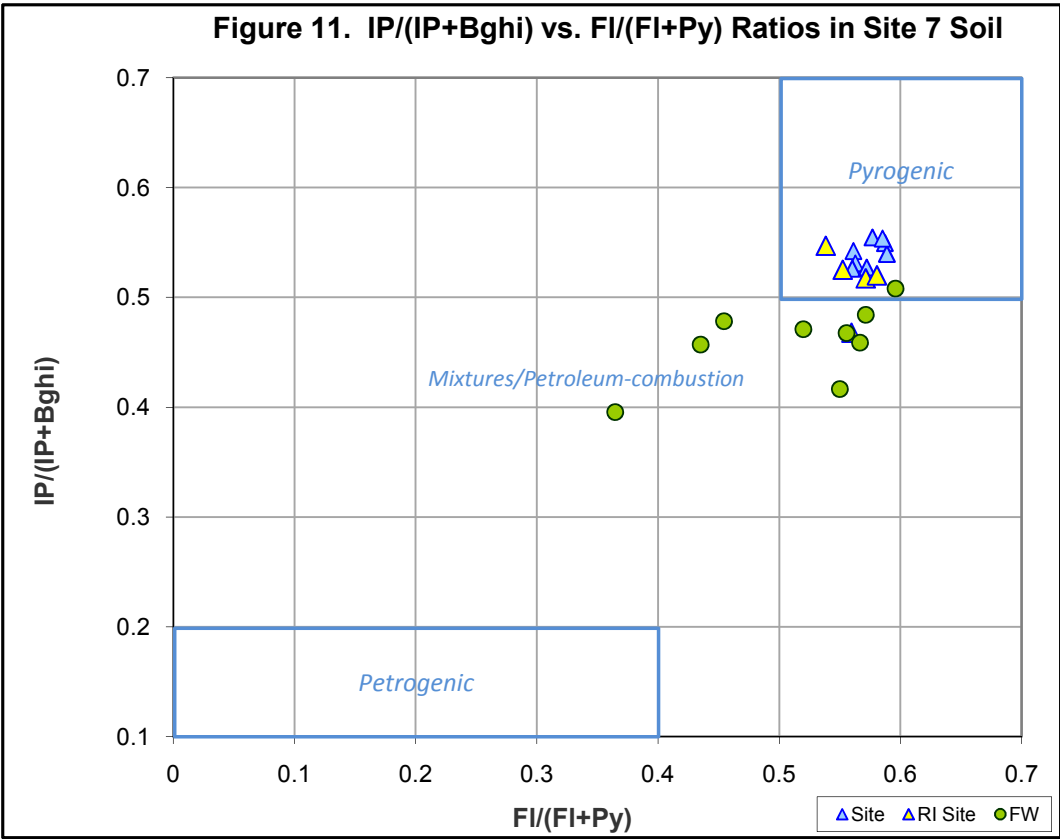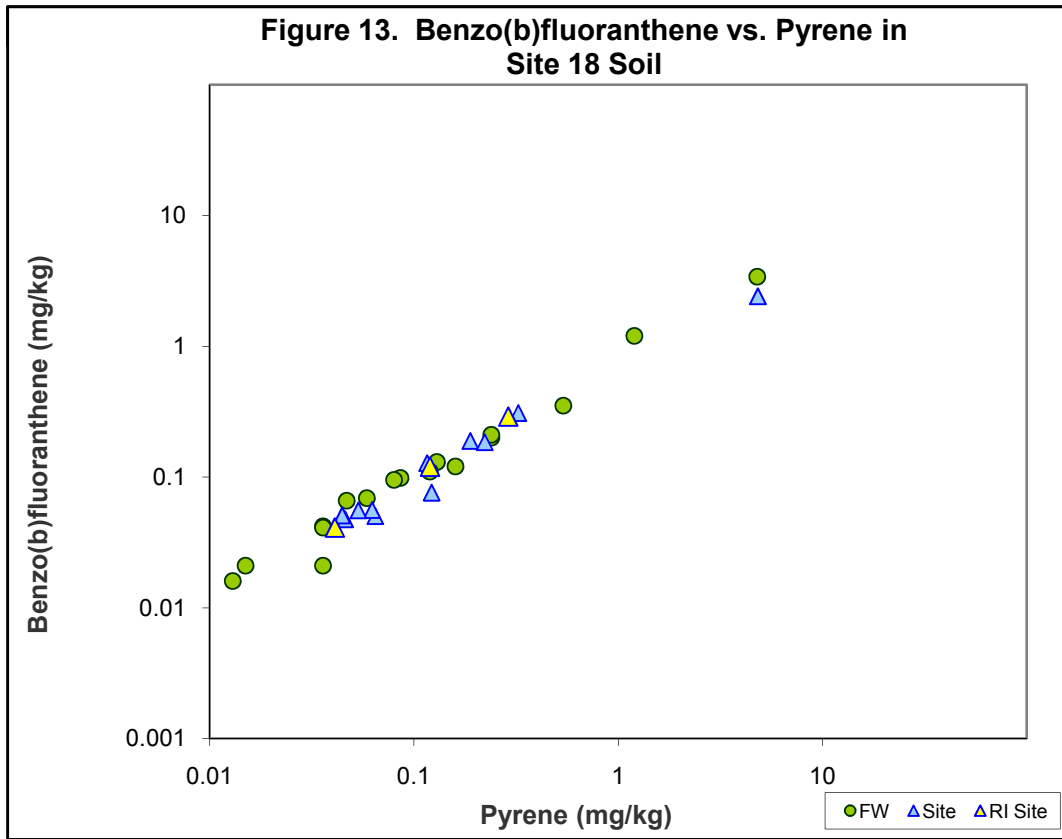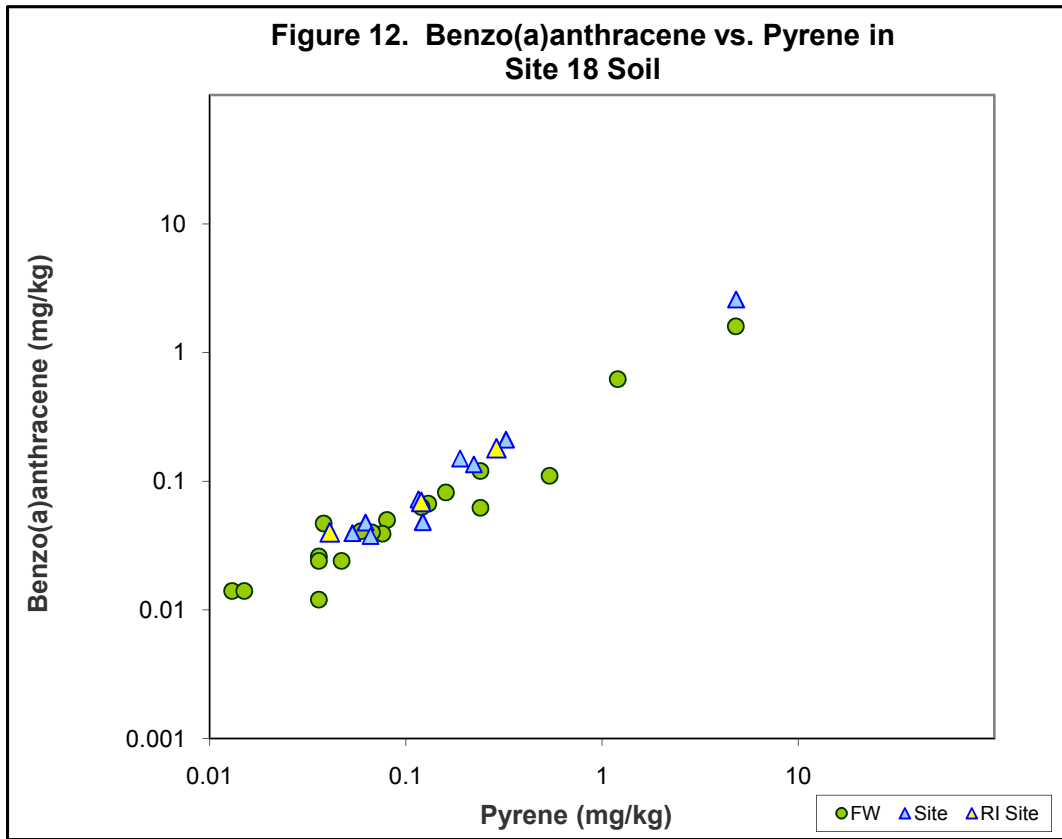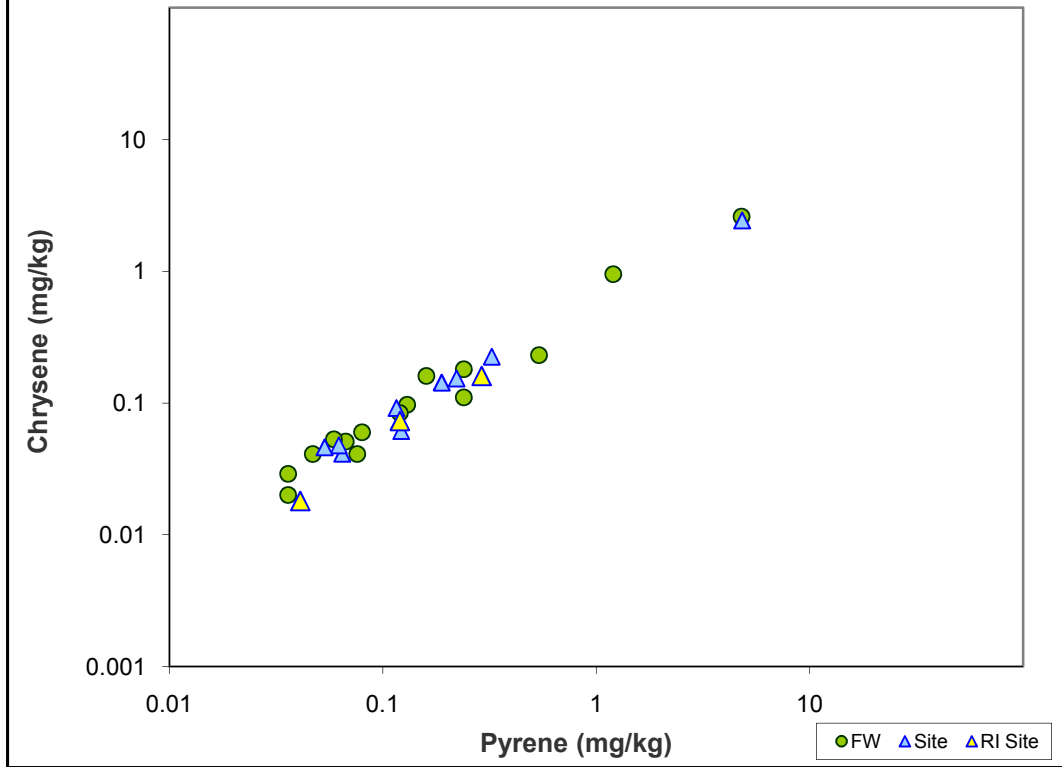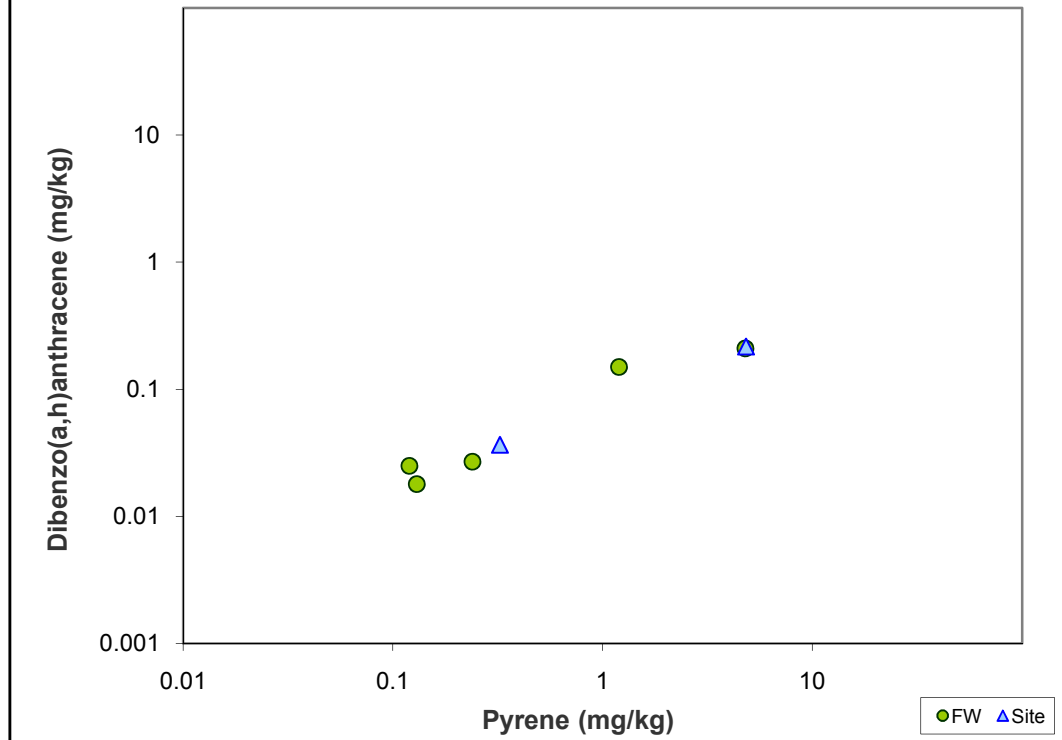Figure 7. Indeno(1,2,3-cd)pyrene vs. Pyrene in Site 7 Soil

Figure 8. Phenanthrene vs. Pyrene in Site 7 Soil

Figure 9. An/(An+Ph) vs. Fl/(Fl+Py) Ratios in Site 7 Soil

Figure 10. BaA/(BaA+Ch) vs. Fl/(Fl+Py) Ratios in Site 7 Soil

Figure 11. IP/(IP+Bghi) vs. Fl/(Fl+Py) Ratios in Site 7 Soil

Figure 12. Benzo(a)anthracene vs. Pyrene in Site 18 Soil

Figure 13. Benzo(b)fluoranthene vs. Pyrene in Site 18 Soil

Figure 14. Chrysene vs. Pyrene in Site 18 Soil

Figure 15. Dibenz(a,h)anthracene vs. Pyrene in Site 18 Soil

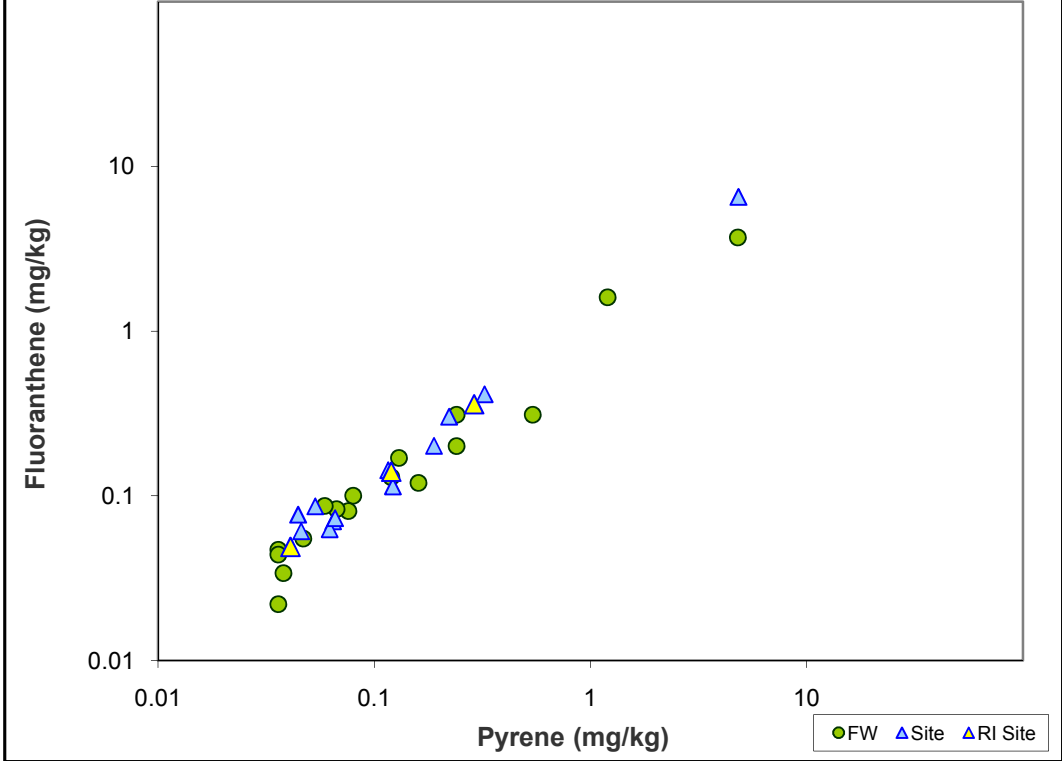Figure 16. Fluoranthene vs. Pyrene in Site 18 Soil

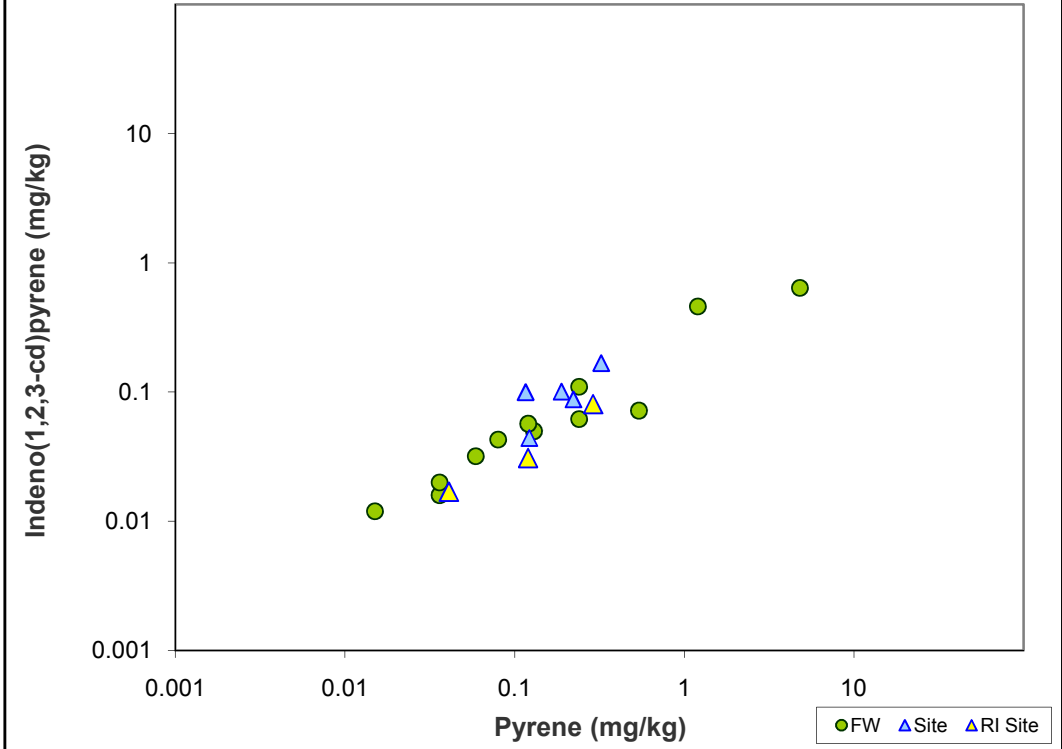Figure 17. Indeno(1,2,3-cd)pyrene vs. Pyrene in Site 18 Soil
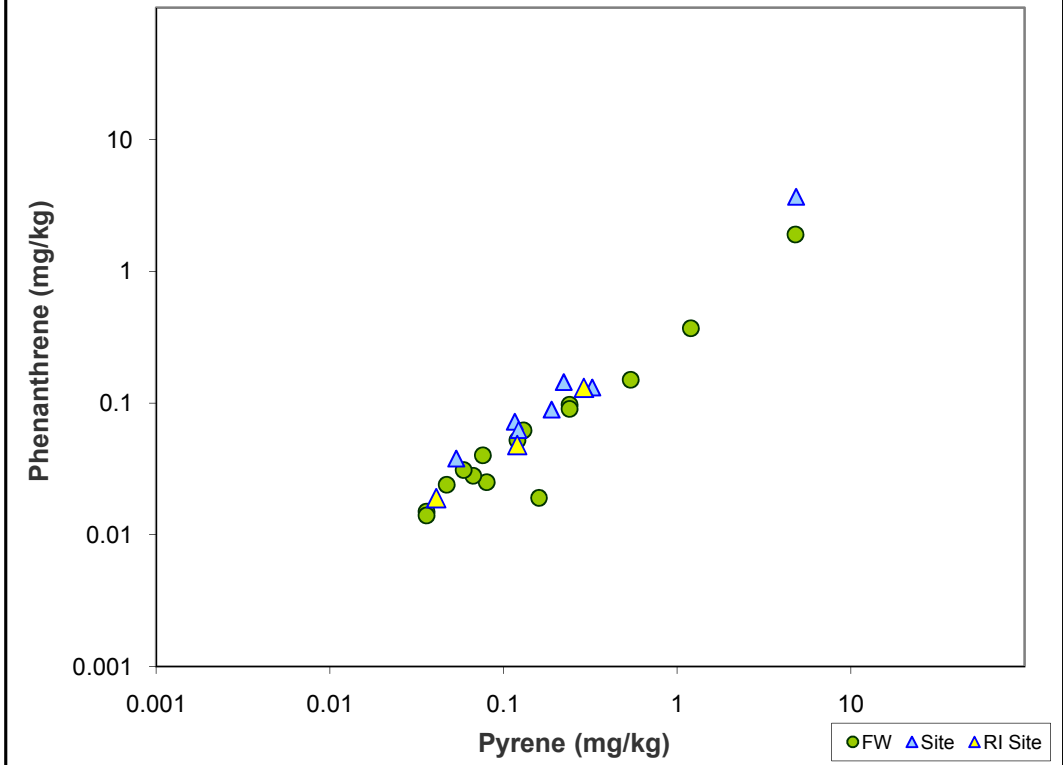
Figure 18. Phenanthrene vs. Pyrene in Site 18 Soil

Figure 19. An/(An+Ph) vs. Fl/(Fl+Py) Ratios in Site 18 Soil

Figure 20. BaA/(BaA+Ch) vs. Fl/(Fl+Py) Ratios in Site 18 Soil

Figure 21. IP/(IP+Bghi) vs. Fl/(Fl+Py) Ratios in Site 18 Soil