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CALIBRATION REPORT FOR THE MOBILE SODIUM IODIDE SYSTEM KNOWN AS THE GATOR

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LIST OF ACROYNMS AND ABBREVIATIONS

ASL	Analytical Support Level
cm	centimeter
DBA	Drum Baling Area
FRL	final remediation level
GPS	Global Positioning System
HPGe	high-purity germanium detector
Kev	kiloelectron volt
NaI	sodium iodide
NCPS	Net Counts Per Second
pCi/g	picoCuries per gram
ppm	parts per million
RSS	Radiation Scanning System
RTIMP	Real-Time Instrumentation Measurement Program
RTRAK	Real-Time Radiation Tracking System
WAC	waste acceptance criteria

CALIBRATION REPORT FOR THE MOBILE SODIUM IODIDE SYSTEM KNOWN AS THE GATOR

The purpose of this report is to document the calibrations used for calculating isotopic concentrations resulting from radiation measurements collected by the GATOR. The calibration process is described and the resulting calibration equations are presented. The results of a calibration verification study conducted in the radium hot spot in Area 2, Phase III are also presented.

Documentation of the calibration algorithms is required by the Real-Time Instrumentation Measurement Program (RTIMP) Quality Assurance Plan (DOE 1998a). This report is intended to fulfill those requirements as well as to inform interested stakeholders of the technical details of the calibration process. All the tasks needed to calibrate the GATOR, including hardware procurement, software development, field measurements, data analysis and issuance of operational and quality control procedures have been completed.

Background

Mobile sodium iodide gamma spectrometry systems have been in use at Fernald for several years. Two systems are currently in use, Real-Time Radiation Tracking System (RTRAK) and Radiation Scanning System I (RSS I). Studies performed to calibrate the RTRAK and RSS I systems and to document system characteristics and data quality parameters are described in the RTRAK Applicability Study (DOE 1999a). Guidelines for use of the RTRAK and RSS I systems and measurement strategies are described in User Guidelines, Measurement Strategies, and Operational Factors for Deployment of In-Situ Gamma Spectrometry at the Fernald Site (User's Manual; DOE 1998b). A third sodium iodide (NaI) based scanning system, the GATOR, consists of a 4-inch by 4-inch by 16-inch NaI detector used in conjunction with signal processing electronic modules, a computer based multi-channel pulse height analyzer, a laptop computer and Global Positioning System (GPS). The radiation detection system and signal processing electronics are the same as those on the RTRAK and RSS I systems. The GATOR is a diesel-powered utility vehicle manufactured by John Deere. It is smaller and more maneuverable than the RTRAK, and thus can be used in areas that may be inaccessible by the RTRAK. The detector is suspended from the front of the vehicle at a height of 31 centimeters (cm) and the electronics are mounted on the vehicle bed, behind the driver. The GATOR can be employed in the same manner as RTRAK or RSS I as a hot spot or waste acceptance criteria (WAC) screening tool.

Calibration Process

The GATOR was calibrated in basically the same manner as the RTRAK and RSS I systems, with some refinements, due to past experience, that will be discussed below. The same data acquisition software and the same spectral regions were used for signal and background windows for all three sodium iodide based scanning systems. The height of the NaI detector on the GATOR system was set at 31 cm to match the height of the RSS I and RTRAK. NaI Measurements were performed at ten field locations with three separate instruments: high-purity germanium (HPGe) detectors, the GATOR and the RSS I. The GATOR and HPGe measurements provided the actual calibration data, as explained below. The long axis of the GATOR NaI detector is perpendicular to the direction of travel of the GATOR. RSS I measurements were collected with the detector in two separate orientations for comparison purposes: detector axis perpendicular to the direction of motion (90 degree orientation) and detector axis parallel to the direction of motion (0 degree orientation). The RSS 90 degree detector orientation is analogous to the normal detector alignment on the GATOR and RTRAK. Although they had no direct input into the GATOR calibration, the RSS I measurements at two orientations served to indicate potential radionuclide inhomogeneity at each location and also as a test of the constancy of the response of the different sodium iodide systems.

Interpretation of calibration measurements is more straightforward if the measurements are made in areas that are reasonably homogeneous. In general, it is also desirable to have a large number of calibration data points, and to have isotopic concentrations that span the entire range of interest. However, in this instance, the calibration study was limited to the contaminant concentrations and spatial distributions that can be found in unremediated areas of the Fernald site. Consideration was given to eliminating locations from the calibration data set if the data showed evidence of inhomogeneity or some other anomaly. There is some indication of inhomogeneity in the data from locations A3-6, A3-7, A3-8 and A3-9, which are in the Drum Baling Area (DBA). It is known from previous studies like the RTRAK and RSS I calibration work that the contamination in this area is generally not uniformly distributed. On the other hand, this area is attractive from a calibration standpoint because it has contaminant levels near the upper end of the range of interest. In the interest of maximizing the number of data points and the contaminant ranges used in the calibration, none of the data points listed in Tables 1 through 3 were eliminated.

The calibration process consisted of taking HPGe and GATOR readings at a series of locations, determining the net count rates for the isotopes of interest from the GATOR spectral data, and performing multiple linear regression analyses to determine a "best fit" equation to represent each isotopic data set.

Both detectors were positioned 31 cm above the ground. During the early days of operation of the RTRAK and RSS I systems, it was learned that the net count rates for the isotopes of interest are affected by the presence of interfering gamma rays that have energies close to those of the gamma rays of interest. A radium-226 radioactive daughter contributes counts to the thorium-232 signal window, while thorium-232 daughter gamma rays contribute counts to the radium-226 background window. There are interferences in both the uranium-238 signal and background spectral regions. A more robust set of calibration equations is obtained by performing regression analyses with multiple variables to account for these spectral interferences. In previous studies performed at Fernald, it was demonstrated that in-situ measurements with HPGe detectors yielded results that were comparable to laboratory analyses of physical samples. (See the Comparability of In-situ Gamma Spectrometry and Laboratory Data, DOE 1999b.) Consequently, in this study, HPGe readings represent the "true" concentrations of the radionuclides in the soil at the measurement locations. No moisture corrections were made to the data used in the regression analyses. The calibration equations which result from the regression analyses enable the user to calculate the concentration of the isotopes of interest from the net isotopic count rates registered by the GATOR NaI detection system. Calibration equations were developed as described for four isotopes: thorium-232, radium-226, uranium-238 and potassium-40. Although potassium-40 (K-40) is not a contaminant derived from uranium production operations at the Fernald site, it is present in virtually all soils and is generally identified in most in-situ gamma ray spectra. Both the energy of its characteristic gamma ray, 1460 kiloelectron volt (Kev), and the amount of K-40 detected in the soil are frequently used as internal checks on the quality of the in-situ data. For that reason, an equation for computing K-40 activity in soil from GATOR net count rates is included in this report.

In an idealized situation where there are no interferences, the net count rate produced by a gamma ray spectrometer ought to be zero when a particular gamma emitting radionuclide is not present in the soil. (The situation is not so simple when the gamma spectrometer is unable to resolve interference peaks from the analyte peak of interest.) On theoretical grounds, one might argue that the calibration equation relating HPGe measurements and net count rates from a sodium iodide detector ought to have a zero intercept. However, the calibration curves for many analytical instruments have non-zero "offsets." When performing regression analyses, one can choose to force the regression curve through zero or allow the regression software to determine a (non-zero) intercept along with the other coefficients in the regression equation. For completeness, both types of regression analyses were performed with each of the isotopic data sets. In each case, the results of the regression analyses were generally similar. Although both zero intercept and non-zero intercept calibration equations were derived, the non-zero intercept equations were adopted because, in the vast majority of cases, the presence of the non-zero intercept will result in a higher calculated activity for a given set of net isotopic count rates. Use of the non-zero intercept equations will add a degree of conservatism to the GATOR measurement results.

Calibration Results

The calibration measurements for each instrument are summarized in Tables 1 through 3 attached to this report. The majority of the calibration data were collected between March 31, 1999 and April 8, 1999. In an attempt to enlarge the calibration data set, data from two additional locations were collected on May 17, 1999, with a recount of one of these new locations performed on June 10, 1999. The date, time and location of each measurement are shown in Tables 1 through 3, along with important measured quantities. Analogous to the RTRAK and RSS I calibrations, GATOR and HPGe measurements at a particular location were made on the same day. All GATOR calibration measurements were 300 second counts, while corresponding HPGe measurements were 900 second counts with a detector height of 31 cm. All measurements are presented on a wet weight basis. That is, no moisture corrections have been made to the data. If previously used RTRAK/RSS I calibration points were available, GATOR calibration measurements were performed at these locations. However, some of the previous calibration locations could not be used for the GATOR calibration because they have been remediated. In Tables 4 through 7, the calibration data have been rearranged to display GATOR and HPGe detector responses side by side, since the ultimate aim of the calibration process is to relate the response of the GATOR to the concentrations of various isotopes in the soil, as indicated by the HPGe isotopic readings. The arrangement of the data in Tables 4 through 7 also facilitates comparison of the GATOR and RSS I responses.

A review of Tables 4 through 7 shows that there are many instance where the GATOR net count rate is approximately the same as that of the RSS I in either orientation. But there are some locations where the count rates appear to differ by more than would be expected from normal statistical variations. For example, the zero degree RSS I count rate for thorium-232 at location A3-6 is nearly double that of the GATOR and the RSS I in the 90 degree orientation. Recall that the 90 degree RSS orientation corresponds to the normal orientation of the GATOR NaI detector. Locations A3-8, A3-7 and A3-9 in Table 5 appear to have markedly different GATOR and RSS I radium-226 net count rates. In Table 6, GATOR and RSS I net uranium-238 count rates are different at locations A3-6, A3-8 and A3-7. When there are large differences between 0 degree and 90 degree RSS data, it may be an indication of inhomogeneously distributed soil contaminants. Count rates could change when the RSS orientation

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changes because the detector sees a somewhat different area of ground even though the size of field of view remains the same. However, if there are significant differences between GATOR and 90 degree RSS count rates at multiple locations, this may also be an indication that the two instruments have different responses. The radium-226 net count rates at locations A3-8 and A3-9, and the uranium-238 net count rates at A3-6, are examples of potentially different GATOR and RSS I responses. It is difficult to explain why the response of the two instruments would be the same at some locations, but different at other locations. Interferences from other radionuclides will differ from location to location, but presumably, these interference effects will be nearly the same for the two instruments at a single location.

As stated above, to account for interferences, the calibration equation for a particular isotope involves not only the net GATOR count rate for that isotope, but also the net count rates due to interfering isotopes. Tables 8 through 11 present the data sets used in the regression analyses for the four isotopes of interest. They also show the isotopic concentrations that are predicted by the calibration equation derived from the regression analysis for each set of data. Each calibration equation is discussed in more detail below.

Thorium-232

Because radium-226 daughters interfere with the thorium-232 signal window, both thorium-232 and radium-226 net GATOR count rates were treated as independent variables and HPGe thorium-232 concentrations were treated as the dependent variable in the multiple linear regression analysis to derive a thorium-232 calibration equation for the GATOR. RTRAK and RSS I calibration equations were derived in the same manner. The locations used in the calibration had thorium-232 concentrations that ranged from background [less than 1 picoCuries per gram (pCi/g)] to nearly eight times the final remediation level (FRL). Using the data in Table 8, the following equation, derived from regression analyses, may be used to compute thorium-232 activity from GATOR net count rates:

$$\text{Thorium-232 pCi/g} = (0.103 * \text{ThNCPS}) - (0.002 * \text{RaNCPS}) + 0.044$$

In this calibration equation, and in the equations for the other isotopes, "NCPS" stands for Net Counts Per Second for the indicated isotope. As one would expect, the thorium net count rate is the dominant term in the equation for predicting thorium-232 activity. An assessment of the uncertainty associated with the regression coefficients shows that the RaNCPS coefficient and the intercept term are not statistically different from zero at the ninety five percent confidence level. However, it was decided not to set either of these coefficients equal to zero because the RaNCPS term has a physical interpretation related to radium interference with the thorium signal, and the intercept adds a small degree of conservatism to the equation. As a practical matter, the intercept in the equation above results in predictions that are very close to zero when the thorium-232 and radium-226 net count rates are equal to zero. Before reporting data based on this equation, moisture corrections must be applied to the calculated results.

Statistical parameters relevant to the thorium-232 regression with non-zero intercept are given in Table 12. The parameters in this table can be used to assess the goodness of the regression analyses. That is, these parameters provide a quantitative measure of how well the regression equations represent the measured data. The key indicators of the goodness of the thorium regression equation are the square of the correlation coefficient, R^2, and the standard error of the estimate. Values of R^2 close to 1.0 indicate good correlation between the data and the regression equation. The standard error of the estimate is an evaluation of that part of the variance of the dependent variable that is left unexplained by the regression analysis. Small values of the standard error of the estimate indicate that most of the variation of the dependent variable, the radionuclide concentration in the soil, is explained by the regression equation. In the case of the thorium-232 regression, R^2 had a value of 0.912, and the standard error of the regression estimate was 1.36. These parameters indicate a good fit to the thorium-232 data. Percent differences between measured thorium-232 concentrations and those predicted by the regression equation were computed. Depending on whether the predicted values are smaller or larger than the values measured by HPGe, the percent difference will be positive or negative. The mean of the absolute values of the percent differences was 22.6 percent for the thorium-232 calibration data set. The largest percent differences were associated with the lowest thorium-232 measurements, i.e., values less than 1 pCi/g. This is an indication that the thorium-232 calibration equation is less accurate below 1 pCi/g. At least under the conditions which apply to the set of calibration locations, the regression equation results in an overestimation of the thorium-232 activity in the soil when the true activity is below 1 pCi/g, which is a typical background level for the Fernald area.

Figure 1 is a graph that enables the reader to judge qualitatively how well the above equation represents the collection of calibration data points. If the solid line passes through a data point, this means that the regression prediction and the measured value are equal. If there were perfect agreement between the equation and the data set, all of the plotted points would lie on the solid line of slope one. As can be seen from Figure 1, up to approximately 4 pCi/g of thorium-232, all of the calibration data points lie quite close to the line. However, on an absolute scale, there are significant deviations from the solid line for thorium-232 concentrations above 10 pCi/g. This should not be a significant shortcoming since any NaI result greater than three times the thorium-232 FRL (4.5 pCi/g) will be confirmed with an HPGe measurement. NaI results greater than two times the FRL are also evaluated. As noted in the paragraph above, when the deviations are expressed on a percentage basis, the lower concentrations have greater deviations from the HPGe values. Once again, the solid line in Figure 1 is not a regression line, but merely a line showing equal HPGe and GATOR soil activities.

Radium-226

Because thorium-232 daughters interfere with the radium-226 background window, both thorium-232 and radium-226 net GATOR count rates were treated as independent variables and HPGe radium-226 concentrations were treated as the dependent variable in the multiple linear regression analysis to derive a radium-226 calibration equation. This was also the case for the derivation of the RTRAK and RSS I calibration equations. The locations used in the calibration had radium-226 concentrations which ranged from background (less than 1 pCi/g) to over nine times FRL. Using the data in Table 9 yields the following equation for computing the wet weight concentration of radium-226 in soil from GATOR net count rates for radium-226 and thorium-232:

$$\text{Radium-226 pCi/g} = (0.229 * \text{RaNCPS}) + (0.015 * \text{ThNCPS}) + 1.2.$$

The radium count rate coefficient is an order of magnitude larger than the thorium-232 coefficient. It shouldn't be surprising that the predicted radium-226 activity depends most heavily on the radium net count rate. Statistical analysis revealed that neither the intercept nor the coefficient of the thorium net count rate was significantly different from zero at the 95 percent confidence level. In spite of this, neither coefficient was set equal to zero because the ThNCPS term has a physical interpretation in terms of thorium interference in the radium background spectral region, and the intercept reflects a limited calibration data set. Because of the value of the intercept derived from the regression analysis, the minimum activity reported by the GATOR will be 1.2 pCi/g on a wet weight basis, unless the thorium and/or radium net count rates turn out to be negative. Using the intercept as derived from the regression analysis, despite the fact that it is not significantly different from zero, builds a degree of conservatism into the radium calibration equation. Before radium data would be used, moisture corrections and possibly radon corrections would be applied.

The statistical parameters used to quantitatively assess the overall goodness of the radium regression with non-zero intercept are displayed in Table 12. For the radium regression, R^2 had a value of 0.862 and the standard error was 2.58. Although not as good as the values for the thorium-232 data set, these parameters indicate an acceptable fit to the radium data. Computation of the mean of the absolute values of percent differences between predicted and measured radium-226 concentrations yielded 58 percent. The three lowest radium-226 measurements, which are all below 1 pCi/g, elevate the mean percent difference considerably. If the three lowest radium-226 values are excluded from the data set, the mean absolute percent difference becomes 30 percent. Like the thorium-232 calibration equation, the radium-226 equation is conservative in that it overestimates radium-226 concentrations below 1 pCi/g. This may not be universally true; but it is true for many areas of the Fernald site where the conditions are the same as those which apply to the calibration locations used for the regression analyses.

The radium-226 regression data are graphically displayed in Figure 2. This figure provides a qualitative indication of how well the radium equation represents the calibration data set. If all the data points fell on the solid line, the equation would be a perfect fit to the data set. As in Figure 1, the solid line is not a regression line, but merely a line showing equal HPGe and GATOR soil activities. Data points for radium-226 concentrations up to approximately 4 pCi/g lie close to the slope one line, while data points representing concentrations at or above 10 pCi/g show greater deviations, on an absolute scale, from the line representing equal GATOR and HPGe measurements. On a percentage basis, the larger deviations from the line occur near the low activity end of the line. The greater absolute deviations above 10 pCi/g of radium-226 are not a significant operational issue since NaI radium-226 results that exceed three times the FRL (5.1 pCi/g) will be confirmed by an HPGe measurement, and results which exceed two times the FRL will be evaluated.

Uranium-238

Radium and thorium daughters interfere with both the background and the signal windows of uranium-238. Thus the uranium-238 regression involved treating the net GATOR count rates for these three isotopes as independent variables and the HPGe uranium-238 concentrations as the dependent variable. This was also the case for the RTRAK and RSS I calibration equations. The locations used in the calibration had uranium-238 concentrations that ranged from near background [9 parts per million (ppm)] to over the WAC trigger level of 720 ppm. The data in Table 10 was used to derive the following regression equation:

$$\text{Uranium-238 pCi/g} = (1.521 * \text{UNCPS}) - (0.174 * \text{ThNCPS}) + (2.951 * \text{RaNCPS}) + 20.9$$

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Results derived from the equation above would normally be moisture corrected to obtain dry weight concentrations before being reported. The uranium and radium net count rates make large contributions to the uranium-238 activity predicted by the GATOR calibration equations, while the thorium-232 contribution is less important. This same phenomenon was seen in the uranium-238 calibration equations for the RTRAK and RSS. Statistical analysis of the GATOR regression results showed that only the radium coefficient in the uranium calibration equation is significantly different from zero. It makes little sense to adopt an equation for predicting uranium-238 activity which does not depend on the net count rate in the uranium region of the spectrum. Rather than blindly deleting coefficients that aren't statistically different from zero, we have chosen to retain all of these terms in the uranium calibration equation because each has a physical interpretation, whether it be to account for detection of gamma rays from the analyte isotope or interfering isotopes. Retaining the 20.9 pCi/g intercept in the uranium-238 equation makes it more conservative. It will most likely overestimate the uranium-238 concentration in the soil, especially when the concentration is low. If there is concern that the GATOR is erroneously flagging locations as having high uranium concentrations, these results can be verified with an HPGe detector which is capable of producing more accurate results.

Table 12 contains the relevant statistical parameters for the U-238 regression with non-zero intercept. R^2 was equal to 0.884 and the standard error of the estimate was 43.1. A review of all the parameters in Table 12 reveals that the uranium-238 equation is the least reliable of the four equations derived for the GATOR. This is not surprising since spectral interferences are the most severe for this isotope. The same was true of the RTRAK and RSS I calibrations derived from the same type of regression analyses. The average absolute percent difference between measured uranium-238 concentrations and those predicted by the regression analysis for the ten calibration points was 125 percent. But this value is very heavily influenced by the results for locations A9-1 and 15-1, which both have uranium-238 concentrations below 10 pCi/g. If the data from locations A9-1 and 15-1 are excluded from the computation, the average absolute percent difference between measured and predicted uranium-238 concentrations is 18.5 percent. Because the intercept in the uranium calibration equation is 20.9, one would not expect this equation to give accurate uranium-238 results at low concentrations. Figure 3, which contains the uranium-238 data associated with the calibration measurements, shows this behavior for uranium values below approximately 25 pCi/g. Although it has some shortcomings, the uranium-238 calibration equation should be considered acceptable in light of the fact that the data generated by the GATOR are field screening data. Such results would be classified as Analytical Support Level (ASL) A data.

Figure 3 qualitatively shows how well the predictions of the calibration equation match the measured HPGe uranium-238 results. If all the data points fell on the solid line, the equation would be a perfect fit to the data. As in Figure 1, the solid line is not a regression line, but merely a line showing equal HPGe and GATOR soil activities. In the mid-range of this graph between 25 and 150 pCi/g, the data points lie close to the line, while at both higher and lower concentrations, the data points deviate from the line.

The equation for predicting total uranium from GATOR net count rates can be derived from the U-238 equation above by using the following unit conversion:

$$\text{Total Uranium ppm} = 2.996 * \text{U-238 pCi/g}$$

Applying this conversion factor to each term in the U-238 equation gives the following equation for total uranium:

$$\text{Total Uranium ppm} = (4.557 * \text{UNCPS}) - (0.521 * \text{ThNCPS}) + (8.841 * \text{RaNCPS}) + 62.6$$

Both the uranium-238 and the total uranium equations are included in this report because both units are commonly used for uranium measurements.

Potassium-40

Although potassium-40 (K-40) is not a contaminant derived from uranium production operations at the Fernald site, it is present in virtually all soils and is generally identified in most in-situ gamma ray spectra. Both the energy of its characteristic gamma ray, 1460 Kev, and the amount of K-40 detected in the soil are frequently used as internal checks on the quality of the in-situ data. For that reason, an equation for computing K-40 activity in soil from GATOR net count rates is presented in this report. Radium-226 and thorium-232 daughters are interferences in the K-40 detection process, and thus, the radium-226 and the thorium-232 net count rates were used as independent variables in the regression analysis along with the K-40 net count rate. Regression analyses using the data in Table 12 yield the following equation for K-40:

$$\text{K-40 pCi/g} = (0.155 * \text{KNCPS}) + (0.020 * \text{ThNCPS}) - (0.052 * \text{RaNCPS}) + 4.2.$$

The equation above predicts the wet weight concentration of K-40 in soil based upon uncorrected net count rates from the GATOR. Before reporting such data, they generally would be converted to dry weight concentrations by making use of measured soil moistures. R^2 for this K-40 regression is equal to 0.945 which shows a high degree of correlation between HPGe results and isotopic net count rates. The intercept for this equation, 4.2 pCi/g, is well below typical environmental levels of K-40 in the Fernald area. Other regression statistics for the case of the non-zero intercept are shown in Table 12. Figure 4 shows the relationship between individual data points and a line of slope one, which depicts equal HPGe and GATOR measured activities. The goodness of the fit parameters for K-40 tends to validate the calibration approach. This shows what can be achieved when contaminants are homogeneously distributed and the spectral interferences are minimal.

Limitations of the GATOR Calibration Equations

It should be recognized that the GATOR calibrations, especially the equations for total uranium and uranium-238, might not be accurate at all locations at the FEMP. During the analysis of the calibration data, some unexpected correlations were noted. Correlations between uranium-238 activity as measured by HPGe detectors and radium-226 net count rates measured by the GATOR, and between GATOR uranium and thorium net count rates, were noted. Because of the correlation between UNCPS and ThNCPS, the GATOR regression can't separate uranium effects from thorium effects very well. The uranium calibration equation may not yield accurate results if applied in locations where UNCPS are not correlated with ThNCPS, as they were in the calibration data set. This situation creates the possibility that the uranium calibration equations may not be conservative when applied in locations where elevated concentrations of uranium are not accompanied by elevated concentrations of thorium and/or radium. The principal concern is that the GATOR may not identify uranium at WAC levels when the thorium-232 and radium-226 concentrations are near background levels. Fortunately, this combination of activity levels appears to be rare at the FEMP. Using only those calibration data points that have background levels of thorium-232 and radium-226, one can develop a conservative data screen to identify situations which are potentially outside the realm of applicability of the GATOR uranium equations given above. The data screen is derived from a regression of HPGe uranium-238 results on GATOR net uranium-238 count rates, using only those calibration points with background levels of radium-226 and thorium-232. Such an equation can be used to estimate the uranium-238 activity that would be measured by the GATOR when little or no radium and thorium are present. This equation, in turn, can be used to calculate net isotopic count rates which would yield uranium-238 or total uranium results at the WAC trigger level. Thus isotopic net count rates, which might be indicative of above WAC soil, can be calculated, and computer software can be used to flag any individual GATOR measurement which exceeds these values. Performing an HPGe measurement at each location where net GATOR count rates exceed administrative screening levels will insure that locations with above WAC soil will not be overlooked because the GATOR calibration equations were applied when it was not appropriate to do so. The data screens and follow-up HPGe measurements discussed above are currently being implemented for the RTRAK and RSS systems. They will also be implemented for the GATOR when it is put into service. The performance of the data screens for the GATOR will be evaluated on the basis of field experience, and adjustments will be made if necessary.

Calibration Verification

The GATOR calibration measurements were based on 5-minute stationary counts at specified locations. Normally the GATOR will acquire 4-second spectra while moving at a speed of 1 mile per hour. In order to verify that the equations derived from static GATOR measurements would provide meaningful results when the GATOR is operated in a mobile mode, calibration verification measurements were performed in an area of the Fernald South Field known as the Area 2, Phase III "Radium Hot Spot." An attempt was made to obtain, as nearly as possible, 100 percent measurement coverage of this area with the RTRAK and RSS I systems, as well as with HPGe detectors and the GATOR. All three sodium iodide tools were operated in a scanning mode (4-second counts while traveling at 1 mile per hour), but the HPGe detectors acquired 900-second static spectra from a detector height of 100 cm. The purpose of this test was to determine if the GATOR produced results in a scanning mode which were consistent with HPGe measurements and comparable to those generated by RTRAK and RSS I.

With a detector height of 100 cm, the radius of the circular field of view of an HPGe detector is 6 meters (approximately 19.7 feet). The GPS coordinates of each of the 76 HPGe measurement locations were recorded along with the measured radionuclide concentrations. RTRAK, RSS I and GATOR were driven over the same ground so that the measurements from all four systems could be compared. At a scanning speed of 1 mile per hour (0.45 meters per second), each sodium iodide vehicle might acquire multiple spectra within the field of view of each HPGe measurement. But the locations of the NaI readings did not necessarily coincide with one another or with the center point of the field of view of the HPGe readings. In certain cases, only one or two of the sodium iodide vehicles acquired spectra within the field of view of a given HPGe shot. In other cases, one or more of the sodium iodide vehicles acquired only a few spectra with position coordinates within an HPGe filed of view. This suggests that the particular sodium iodide vehicle probably drove across the outer edge of the HPGe circular field of view. Comparing NaI results to HPGe results in this circumstance could lead to erroneous conclusions because NaI results would be weighted heavily by radioactivity near the outer edge of the circle, while the HPGe results would be heavily influenced by radioactivity near the center of the circle. There were 31 HPGe readings for which all three sodium iodide tools had twenty or more readings within their fields of view. By restricting the instrument comparisons to only those cases where all the NaI tools had a reasonably large number of readings, general conclusions drawn from the comparison would be less prone to error.

Using the range of isotopic values recorded by the HPGe detectors as a gauge, there is a wide range of radium-226 activity from one location to another in the Radium Hot Spot area. Although the uranium-238 activity was always less than 20 pCi/g, it also varied by as much as a factor of four from one location to another. Thorium-232 exhibited the least variability of the contaminant isotopes. Due to the inhomogeneous distribution of two of the isotopes of concern and the differences in detector fields of view because of different detector heights and possibly detector locations, some variation in the results produced by the various detection systems can be expected. More importance should be attached to general patterns than to similarities or differences at individual HPGe locations.

Tables 13, 14, and 15 display the results from the comparative measurements performed in the Radium Hot Spot area. Each table contains HPGe results for a single isotope from the 31 locations where all of the sodium iodide tools had twenty or more readings. Along with the HPGe results, the main body of each table displays the number of NaI readings and their average values. Results are presented both in activity units and in terms of relative percent differences between the HPGe result (assumed to be the "accepted value") and the average result for a given sodium iodide tool. For each NaI tool, there were single-spectrum results which were higher than the HPGe reading and others that were lower. However, as noted above, because of field of view and positional differences, comparison of average NaI and HPGe results is more meaningful. Statistical summaries of the location-by-location comparisons are also presented at the bottom of each table. These summaries include minimum values, maximum values, grand means and standard deviations of the NaI averages corresponding to each HPGe result for each sodium iodide vehicle.

A review of the information in Tables 13 through 15, especially the data in the statistical summary at the bottom of each table, leads to the following general conclusions. There is generally good agreement among all of the instruments for thorium-232 measurements. The agreement among the various radium-226 measurements is not as good, and the uranium-238 measurements show the poorest agreement. This ranking is not surprising, given the minimum detectable concentrations (MDC) of the sodium iodide detectors and the interferences that impact the three spectral regions of interest. It should be pointed out that all of the NaI results for radium are based on sliding averages of two consecutive 4-second spectra, and that the radium-226 results from all detectors were radon corrected. Additional details are provided below for each isotope.

The thorium-232 minimum, maximum and grand mean for the HPGe, RTRAK and RSS I match up quite well. This is not surprising, in light of the uniform nature of the thorium-232 contamination in the Radium Hot Spot area. The GATOR gives slightly higher values than the other three instruments, but considering the low activities being measured, the agreement with the other instruments is reasonably good. Relative Percent Difference (RPD) is defined in the following manner.

$$RPD = \frac{\text{HPGe Result - NaI Average}}{\text{HPGe Result}} * 100\%$$

If an HPGe result is larger than the corresponding NaI average, the RPD will be positive, and if an HPGe result is less than the NaI average, the RPD will be negative. Most of the RTRAK means are lower than the corresponding HPGe results, with the RPDs generally less than 20 percent. RSS I and GATOR means were all greater than the corresponding HPGe values. The average RPD for the RSS I data was 23 percent, and the average RPD for the GATOR results was 51 percent. Considering the low thorium-232 activities encountered in this area, these differences are reasonable. Furthermore, the GATOR results are conservative relative to the other NaI tools.

The agreement among the four detection systems isn't as good for radium-226 as for thorium-232. All radium-226 results have been radon and moisture corrected. The ranges in the values reported by HPGe, RTRAK and RSS I (maximum minus minimum) are comparable, and the HPGe and RSS I means are equal. However, the RTRAK mean is 2.2 pCi/g (52 percent) lower than HPGe and RSS I, while the GATOR mean is 2.7 pCi/g (64 percent) higher. The range of the GATOR results is also noticeably smaller. As used in Tables 13 through 15, the RTRAK and RSS I data contain mostly positive RPDs, while the GATOR RPDs are mostly negative, which indicates that there is a positive bias to the GATOR results and a negative bias to RTRAK and RSS I results. The discrepancies between individual GATOR radium averages and HPGe results were significant for many of the measurement locations. The maximum RPD for a single location was 878 percent, with the RPDs at three other locations in excess of 500 percent. While discrepancies of this magnitude are not desirable, use of the GATOR would be conservative in that it overestimates the true soil activity. The hot spots identified by scanning with the GATOR could presumably be confirmed or denied by returning to those locations with an HPGe detector.

The uranium-238 results from the four detection systems shows even more variation than did the radium-226 results. There are significant differences between the means and the data ranges of the various detectors. The GATOR grand mean uranium-238 concentration is over five times that of the HPGe and over 2.5 times that of RTRAK and RSS I. The average of the RPDs from the individual HPGe comparisons is –503 percent, which indicates that the GATOR averages are significantly greater than the corresponding HPGe results. The RTRAK and RSS I average RPDs were smaller than this value, but they also were significantly different from the corresponding HPGe results. The heterogeneity of the uranium concentration in the study area contributes somewhat to the variability of the sodium iodide data, but it is not the sole cause. As analyte concentrations approach and fall below instrument detection limits, the uncertainty in the measured result becomes large, as does the variability of replicate measurement results. The RTRAK Applicability reports that the uranium-238 MDC for a single four-second measurement with the RTRAK traveling at 1 mile per hour is 21 pCi/g. This report also points out that the MDC can be reduced by aggregating a number of individual measurements. However, to reduce the uranium-238 detection limit of the RTRAK to 8 pCi/g, which is the average HPGe result in the Radium Hot Spot area, over 100 4-second measurements would have to be aggregated. Based on the intercept in the calibration equation, the uranium-238 MDC for the GATOR is likely to be higher than the RTRAK MDC, but it ought to be roughly comparable, given the similarity of the detectors and electronic components used on the two systems. This points to the cause of the variability in the sodium iodide data and the poor agreement with individual HPGe results. After collecting and analyzing the data, it appears that the uranium levels in this area were not high enough to provide a meaningful and unambiguous comparison of the uranium-238 measurement capabilities of the sodium iodide systems.

<u>Summary and Conclusions</u>

In this report, the method used to calibrate the GATOR has been described, and the calibration equations have been presented. The form of these equations has been justified in the sense that a physical interpretation has been given for each term in the calibration equations. Moisture corrections weren't applied to any of the data used to derive the calibration equations. It was found that performing the same type of regression analyses using moisture corrected quantities yielded virtually identical calibration equations.

The GATOR calibration equations provide a reasonably good fit to the data, as indicated by individual isotopic R^2 values between 0.86 and 0.95. The GATOR calibration equations resemble those derived for the RTRAK and RSS I. Corresponding regression coefficients for the three NaI instruments have the same algebraic signs, and most have magnitudes within a factor of two of one another, which implies some degree of consistency among the various NaI systems. The intercept terms in the GATOR uranium-238 and radium-226 equations are exceptions to the last statement. The large GATOR intercepts have implications for the accuracy of the GATOR when measuring low level uranium and radium. Both the high values of the intercepts in the radium-226 and uranium-238 equations, and the radium and thorium results from the comparison study in the Radium Hot Spot area indicate that the GATOR calibration equations are conservative, in the sense that they will over estimate the concentrations of uranium-238, thorium-232 and radium-226.

During this calibration study, it was noted that the uranium equation might not be conservative when measurements are performed in locations where the uranium and thorium net count rates from the GATOR are not correlated as they were in the calibration data set. (Indications are that such locations are not common at Fernald.) To preclude the possibility of failing to identify locations where the uranium concentration in the soil exceeds the WAC, the data generated by the GATOR will be screened to identify potential instances of uranium underestimation due to limitations in the calibration equation. HPGe measurements will be performed at all locations where the GATOR net isotopic count rates exceed predefined values. This will help to overcome the limitations in the data set that was available to calibrate the GATOR.

It is appropriate to place the GATOR into service, despite some differences between the GATOR and the other NaI systems which are not completely understood at this time. Despite the fact that the data in this report show the accuracy of GATOR measurements is not quite as good as that of the RTRAK or RSS, GATOR measurement accuracy is acceptable for a screening tool. The RTIMP already has procedures in place that will ensure that the GATOR is tested and operated in a manner consistent with quality and operational requirements. Like the RTRAK and RSS I, the GATOR is suitable for screening applications at ASL A.

REFERENCES

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U.S. Department of Energy, 1999a, "RTRAK Applicability Study," Revision 2, Fernald Environmental Management Project, DOE, Fernald Area Office, Cincinnati, Ohio.

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TABLE 1

SPRING 1999 GATOR CALIBRATION RAW DATA

GATOR System Net Count Rates - Wet Weight Basis

Acquisition Date	Acquisition Start Time	Location	Spectrum File	Count Time (sec)	Dead Time %	Spectrum Gross Counts	Th-232 NET CPS	Ra-226 NET CPS	U-238 NET CPS	K-40 NET CPS
31-Mar-99	13:24:41	GATOR-A9-1-3	2.CHN	300	4.3	736349	7.6	1.5	2.4	34.7
31-Mar-99	13:35:03	GATOR-A9-1-4D	3.CHN	300	4.4	745649	8.7	2.4	-0.3	41.1
31-Mar-99	15:34:49	GATOR-A11-3-4	4.CHN	300	6.0	1046389	12.3	2.6	7.6	45.5
8-Apr-99	10:22:02	GATOR-A3-6-1	7.CHN	300	23.6	5173052	86.5	11.3	37.2	46.8
8-Apr-99	10:29:59	GATOR-A3-8-1	8.CHN	300	25.8	5836501	123.4	2.4	91.8	35.9
8-Apr-99	10:41:58	GATOR-A3-11-1	9.CHN	300	29.3	6911629	38.5	43.5	19.2	48.5
8-Apr-99	10:54:09	GATOR-A3-10-1	10.CHN	300	41.2	11534750	44.2	74.8	66.7	50.5
8-Apr-99	11:07:33	GATOR-A3-7-1	11.CHN	300	33.6	8390989	25.6	23.8	25.0	34.6
8-Apr-99	11:17:52	GATOR-A3-9-2	12.CHN	300	39.4	10775970	39.7	35.9	38.4	40.5
8-Apr-99	11:27:47	GATOR-A3-9-3D	13.CHN	300	39.5	10800310	37.7	37.9	48.4	38.0
17-May-99	13:24:04	GATOR-15-1-1	39.CHN	300	5.9	1051448	12.4	2.4	9.8	57.2
10-Jun-99	9:50:36	GATOR-15-1-7-G	41.CHN	300	6.6	1177093	13.3	3.6	7.9	61.2
17-May-99	13:52:11	GATOR-18-1-1	40.CHN	300	4.9	849964	10.4	2.1	4.2	49.3

TABLE 2
SPRING 1999 GATOR CALIBRATION RAW DATA
31 cm HPGe Results - WET WEIGHT BASIS

Acquisition Date	Acquisition Start Time	Location	HPGe Det #	Spectrum File	Live Time (sec)	Dead Time %	Moisture Fraction	Th232 pCi/g	Th-232 % CE	Ra-226 pCi/g	Ra-226 % CE	U-238 pCi/g	U-238 % CE	K-40 pCi/g	K-40 % CE
31-Mar-99	13:40:21	GATOR-A9-1-5G	31204	481.CHN	900	2.9	0.397	0.71	2.50	0.82	2.39	3.02	13.3	9.44	1.81
31-Mar-99	14:38:16	GATOR-A11-3-1G	31204	482.CHN	900	3.8	0.397	0.99	2.09	0.89	2.43	26.5	2.16	11.0	1.69
8-Apr-99	12:21:09	GATOR-A3-6-4G	30904	1819.CHN	900	15.6	0.224	11.8	0.57	4.29	1.14	104	1.16	12.4	1.80
8-Apr-99	12:01:24	GATOR-A3-8-4G	30904	1818.CHN	900	15.6	0.215	10.9	0.58	3.33	1.35	132	0.95	12.2	1.79
8-Apr-99	11:31:00	GATOR-A3-11-2G	30904	1817.CHN	900	19.6	0.377	3.60	1.23	12.6	0.56	159	0.92	9.95	2.14
8-Apr-99	11:08:24	GATOR-A3-10-4G	30904	1816.CHN	900	26.4	0.098	3.91	1.27	15.5	0.53	293	0.62	8.94	2.46
8-Apr-99	10:16:28	GATOR-A3-7-1G	30904	1814.CHN	900	22.2	0.08	3.29	1.37	10.0	0.68	181	0.87	9.31	2.31
8-Apr-99	10:44:40	GATOR-A3-9-1G	30904	1815.CHN	900	26.1	0.116	4.34	1.19	14.7	0.55	256	0.69	9.44	2.41
17-May-99	15:38:03	GATOR-15-1-5G	30687	2594.CHN	900	2.9	0.19	0.93	2.41	0.86	2.73	37.0	1.64	13.4	1.66
17-May-99	14:01:28	GATOR-15-1-4-G	30687	2591.CHN+	900	2.8	0.19	0.90	2.47	0.86	2.73	32.4	1.85	13.0	1.70
10-Jun-99	9:10:02	GATOR-15-1-6-G	30687	2774.CHN	900	3.2	0.156	1.01	1.97	1.21	1.88	40.1	1.38	13.8	1.41
17-May-99	14:34:53	GATOR-18-1-4G	30687	2592.CHN	900	2.4	0.20	0.81	2.56	0.75	2.94	7.61	6.09	12.5	1.72

+ This HPGe measurement was obtained at a detector height of 100 cm for quality control purposes.

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TABLE 3
SPRING 1999 GATOR CALIBRATION RAW DATA
RSS System Net Count Rates - Wet Weight Basis

Acquisition Date	Acquisition Start Time	Location	RSS Orientation	Spectrum File	Count Time (sec)	Dead Time %	Spectrum Gross Counts	Th-232 NET CPS	Ra-226 NET CPS	U-238 NET CPS	K-40 NET CPS
31-Mar-99	13:06:39	GATOR-A9-1-1	0 deg.	262.CHN	300	3.7	662985	9.3	2.9	0.7	44.4
31-Mar-99	13:15:39	GATOR-A9-1-2	90 deg.	263.CHN	300	3.7	670900	10.0	3.1	1.4	44.7
31-Mar-99	13:48:21	GATOR-A11-3-2	0 deg.	264.CHN	300	5.3	957638	13.2	2.9	10.2	52.9
31-Mar-99	13:56:29	GATOR-A11-3-3	90 deg.	265.CHN	300	5.3	964456	13.3	3.1	10.2	51.6
8-Apr-99	10:44:52	GATOR-A3-6-2	0 deg.	273.CHN	300	22.3	4976583	159.3	7.4	86.9	39.4
8-Apr-99	10:51:54	GATOR-A3-6-3	90 deg.	274.CHN	300	20.6	4492582	99.8	11.7	63.2	44.5
8-Apr-99	10:31:37	GATOR-A3-8-2	0 deg.	271.CHN	300	22.6	5050454	137.4	6.3	87.4	41.4
8-Apr-99	10:35:16	GATOR-A3-8-3	90 deg.	272.CHN	300	20.3	4404038	104.2	9.2	62.3	46.1
8-Apr-99	11:19:15	GATOR-A3-11-3	0 deg.	279.CHN	300	28.8	6976494	50.3	65.4	23.5	60.5
8-Apr-99	11:21:56	GATOR-A3-11-5	90 deg.	280.CHN	300	27.2	6453914	42.6	53.5	24.4	61.9
8-Apr-99	10:11:06	GATOR-A3-10-1	0 deg.	269.CHN	300	36.5	9968205	54.1	82.1	72.3	59.7
8-Apr-99	10:25:35	GATOR-A3-10-2	90 deg.	270.CHN	300	35.4	9518543	53.0	78.1	81.1	57.0
8-Apr-99	11:04:00	GATOR-A3-7-3	0 deg.	275.CHN	300	31.8	8060365	52.8	65.8	45.5	59.9
8-Apr-99	11:08:15	GATOR-A3-7-4	90 deg.	276.CHN	300	29.9	7388560	42.6	58.2	34.6	58.1
8-Apr-99	11:10:43	GATOR-A3-9-4	0 deg.	277.CHN	300	36.3	9858137	66.5	81.2	50.3	58.1
8-Apr-99	11:14:44	GATOR-A3-9-5	90 deg.	278.CHN	300	35.6	9577113	55.0	80.6	49.1	64.0
17-May-99	13:43:46	GATOR-15-1-2	0 deg.	303.CHN	300	6	1092641	11.9	2.9	11.2	61.4
17-May-99	13:50:17	GATOR-15-1-3	90 deg.	304.CHN	300	6.1	1117981	13.0	3.5	10.2	65.4
10-Jun-99	9:54:48	GATOR-15-1-8-G	90 deg.	310.CHN	300	6.6	1214771	13.6	5.1	9.7	65.8
17-May-99	14:09:12	GATOR-18-1-2	0 deg.	305.CHN	300	5	897010	11.5	2.6	4.2	59.2
17-May-99	14:17:34	GATOR-18-1-3	90 deg.	306.CHN	300	4.9	885565	10.9	3.3	3.7	59.4

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TABLE 4

SPRING 1999 GATOR CALIBRATION RAW DATA — 2608

Thorium-232 - Wet Weight Basis

SAMPLE LOCATION	HPGe Th-232 pCi/g 0.31 m.	GATOR Th-232 ROI NET CPS	RSS Th-232 ROI NET CPS 90 Deg	RSS Th-232 ROI NET CPS 0 Deg
GATOR-A9-1	0.71	7.6	10.0	9.3
GATOR-A9-1 D		8.7		
GATOR-A11-3	0.99	12.3	13.3	13.2
GATOR-A3-6	11.8	86.5	99.8	159.3
GATOR-A3-8	10.9	123.4	104.2	137.4
GATOR-A3-11*	3.60	38.5	42.6	50.3
GATOR-A3-10	3.91	44.2	53.0	54.1
GATOR-A3-7	3.29	25.6	42.6	52.8
GATOR-A3-9	4.34	39.7	55.0	66.5
GATOR-A3-9 D		37.7		
GATOR-15-1-1	0.93	12.4	13.0	11.9
GATOR-15-1-1 Recount	1.01	13.3	13.6	
GATOR-18-1-1	0.81	10.4	10.9	11.5

* GATOR was rotated 90 degrees from normal position to avoid contamination.

TABLE 5

SPRING 1999 GATOR CALIBRATION RAW DATA

Radium-226 - Wet Weight Basis

SAMPLE LOCATION	HPGe Ra-226 pCi/g 0.31 m.	GATOR Ra-226 ROI NET CPS	RSS Ra-226 ROI NET CPS 90 Deg	RSS Ra-226 ROI NET CPS 0 Deg
GATOR-A9-1	0.82	1.5	3.1	2.9
GATOR-A9-1 D		2.4		
GATOR-A11-3	0.89	2.6	3.1	2.9
GATOR-A3-6	4.29	11.3	11.7	7.4
GATOR-A3-8	3.33	2.4	9.2	6.3
GATOR-A3-11*	12.6	43.5	53.5	65.4
GATOR-A3-10	15.5	74.8	78.1	82.1
GATOR-A3-7	10.0	23.8	58.2	65.8
GATOR-A3-9	14.7	35.9	80.6	81.2
GATOR-A3-9 D		37.9		
GATOR-15-1-1	0.86	2.4	3.5	2.9
GATOR-15-1-1 Recount	1.21	3.6	5.1	
GATOR-18-1-1	0.75	2.1	3.3	2.6

* GATOR was rotated 90 degrees from normal position to avoid contamination.

TABLE 6

SPRING 1999 GATOR CALIBRATION RAW DATA -- 2608

Uranium-238 - Wet Weight Basis

SAMPLE LOCATION	HPGe U-238 pCi/g 0.31 m.	GATOR U-238 ROI NET CPS	RSS U-238 ROI NET CPS 90 Deg	RSS U-238 ROI NET CPS 0 Deg
GATOR-A9-1	3.02	2.4	1.4	0.7
GATOR-A9-1 D		-0.3		
GATOR-A11-3	26.5	7.6	10.2	10.2
GATOR-A3-6	104	37.2	63.2	86.9
GATOR-A3-8	132	91.8	62.3	87.4
GATOR-A3-11*	159	19.2	24.4	23.5
GATOR-A3-10	293	66.7	81.1	72.3
GATOR-A3-7	181	25.0	34.6	45.5
GATOR-A3-9	256	38.4	49.1	50.3
GATOR-A3-9 D		48.4		
GATOR-15-1-1	37.0	9.8	10.2	11.2
GATOR-15-1-1 Recount	40.1	7.9	9.7	
GATOR-18-1-1	7.61	4.2	3.7	4.2

* GATOR was rotated 90 degrees from normal position to avoid contamination.

TABLE 7

SPRING 1999 GATOR CALIBRATION RAW DATA

Potassium-40 - Wet Weight Basis

SAMPLE LOCATION	HPGe K-40 pCi/g 0.31 m.	GATOR K-40 ROI NET CPS	RSS K-40 ROI NET CPS 90 Deg	RSS K-40 ROI NET CPS 0 Deg
GATOR-A9-1	9.44	34.7	44.7	44.4
GATOR-A9-1 D		41.1		
GATOR-A11-3	11.0	45.5	51.6	52.9
GATOR-A3-6	12.4	46.8	44.5	39.4
GATOR-A3-8	12.2	35.9	46.1	41.4
GATOR-A3-11*	9.95	48.5	61.9	60.5
GATOR-A3-10	8.94	50.5	57.0	59.7
GATOR-A3-7	9.31	34.6	58.1	59.9
GATOR-A3-9	9.44	40.5	64.0	58.1
GATOR-A3-9 D		38.0		
GATOR-15-1-1	13.4	57.2	65.4	61.4
GATOR-15-1-1 Recount	13.8	61.2	65.8	
GATOR-18-1-1	12.5	49.3	59.4	59.2

* GATOR was rotated 90 degrees from normal position to avoid contamination.

Table 8

Th-232 GATOR CALIBRATION DATA SET - WET WEIGHT BASIS

SAMPLE LOCATION	GATOR Th-232 ROI NET CPS	GATOR Ra-226 ROI NET CPS	HPGe Th-232 pCi/g 0.31 m.	Regression Predicted Th-232 pCi/g
GATOR-A9-1+	8.2	2.0	0.71	0.88
GATOR-A11-3	12.3	2.6	0.99	1.3
GATOR-A3-6	86.5	11.3	11.8	8.9
GATOR-A3-8	123.4	2.4	10.9	12.8
GATOR-A3-11*	38.5	43.5	3.6	3.9
GATOR-A3-10	44.2	74.8	3.9	4.5
GATOR-A3-7	25.6	23.8	3.3	2.6
GATOR A3-9+	38.7	36.9	4.3	4.0
GATOR-15-1-1+	12.9	3.0	0.97	1.4
GATOR-18-1-1	10.4	2.1	0.81	1.1

* GATOR was rotated 90 degrees from normal position to avoid contamination.

\+ GATOR NET CPS is average of two counts.

Table 9

Ra-226 GATOR CALIBRATION DATA SET - WET WEIGHT BASIS

SAMPLE LOCATION	GATOR Ra-226 ROI NET CPS	GATOR Th-232 ROI NET CPS	HPGe Ra-226 pCi/g 0.31 m.	Regression Predicted Ra-226 pCi/g
GATOR-A9-1+	2.0	8.2	0.82	1.7
GATOR-A11-3	2.6	12.3	0.89	1.9
GATOR-A3-6	11.3	86.5	4.3	5.0
GATOR-A3-8	2.4	123.4	3.3	3.5
GATOR-A3-11*	43.5	38.5	12.6	11.7
GATOR-A3-10	74.8	44.2	15.5	19.0
GATOR-A3-7	23.8	25.6	10.0	7.0
GATOR A3-9+	36.9	38.7	14.7	10.2
GATOR-15-1-1+	3.0	12.9	1.0	2.0
GATOR-18-1-1	2.1	10.4	0.75	1.8

* GATOR was rotated 90 degrees from normal position to avoid contamination.

\+ GATOR NET CPS is average of two counts.

Table 10

U-238 GATOR CALIBRATION DATA SET - WET WEIGHT BASIS

SAMPLE LOCATION	GATOR U-238 ROI NET CPS	GATOR Th-232 ROI NET CPS	GATOR Ra-226 ROI NET CPS	HPGe U-238 pCi/g 0.31 m.	Regression Predicted U-238 pCi/g
GATOR-A9-1+	1.05	8.2	2.0	3.0	26.9
GATOR-A11-3	7.6	12.3	2.6	26.5	38.0
GATOR-A3-6	37.2	86.5	11.3	104	95.8
GATOR-A3-8	91.8	123.4	2.4	132	146.2
GATOR-A3-11*	19.2	38.5	43.5	159	171.8
GATOR-A3-10	66.7	44.2	74.8	293	335.4
GATOR-A3-7	25.0	25.6	23.8	181	124.7
GATOR A3-9+	43.4	38.7	36.9	256	189.1
GATOR-15-1-1+	8.9	12.9	3.0	38.5	41.0
GATOR-18-1-1	4.2	10.4	2.1	7.61	31.7

* GATOR was rotated 90 degrees from normal position to avoid contamination.

+ GATOR NET CPS is average of two counts.

Table 11

K-40 GATOR CALIBRATION DATA SET - WET WEIGHT BASIS

SAMPLE LOCATION	GATOR K-40 ROI NET CPS	GATOR Th-232 ROI NET CPS	GATOR Ra-226 ROI NET CPS	HPGe K-40 pCi/g 0.31 m.	Regression Predicted K-40 pCi/g
GATOR-A9-1+	37.9	8.2	2.0	9.4	10.1
GATOR-A11-3	45.5	12.3	2.6	11.0	11.3
GATOR-A3-6	46.8	86.5	11.3	12.4	12.6
GATOR-A3-8	35.9	123.4	2.4	12.2	12.1
GATOR-A3-11*	48.5	38.5	43.5	10.0	10.2
GATOR-A3-10	50.5	44.2	74.8	8.9	9.0
GATOR-A3-7	34.6	25.6	23.8	9.3	8.8
GATOR A3-9+	39.3	38.7	36.9	9.4	9.1
GATOR-15-1-1+	59.2	12.9	3.0	13.6	13.5
GATOR-18-1-1	49.3	10.4	2.1	12.5	11.9

* GATOR was rotated 90 degrees from normal position to avoid contamination.

+ GATOR NET CPS is average of two counts.

Table 12

Summary of Regression Parameters - WET WEIGHT BASIS

	Th-232 Regression	Ra-226 Regression	U-238 Regression	K-40 Regression
Coefficient of KNCPS	n/a	n/a	n/a	0.1551
Coefficient of UNCPS	n/a	n/a	1.5212	n/a
Coefficient of ThNCPS	0.103	0.0148	-0.1740	0.0202
Coefficient of RaNCPS	-0.0020	0.229	2.951	-0.0516
Intercept	0.044	1.2	20.9	4.2
R Squared	0.912	0.862	0.884	0.945
Std Error of Estimate	1.362	2.585	43.13	0.4816
Std Dev of Residuals	1.20	2.28	35.22	0.39
AVE. ABS % Difference*	22.6%	58.0%	125.4%	3.1%

* Average of the absolute values of individual residuals (I.e. measured value minus predicted value) expressed as a percentage of the measured value.

Table 13
SODIUM IODIDE MEASUREMENTS WITHIN EACH HPGe FIELD OF VIEW
Th-232 Results (Moisture Corrected) from the A2/P3 Radium Hot Spot

HPGe Spectrum File	HPGe Th-232 pCi/g	No. RTRAK Results	AVE RTRAK Th-232 pCi/g	No. RSS Results	AVE RSS Th-232 pCi/g	No. GATOR Results	AVE GATOR Th-232 pCi/g	RPD HPGe-RTRAK	RPD HPGe-RSS	RPD HPGe-GATOR
2378 & 9	0.80	42	0.68	58	0.88	33	1.1	15.4	-9.9	-38.3
1754	0.66	29	0.65	56	0.83	34	1.1	1.5	-26.4	-63.4
2377	0.83	38	0.72	75	0.88	34	1.1	13.8	-6.4	-33.2
1730	0.77	42	0.68	70	0.86	40	1.02	11.5	-11.4	-32.4
2408	0.72	34	0.66	70	0.85	50	1.1	7.9	-18.8	-50.7
2407	0.69	43	0.65	70	0.88	50	1.0	5.3	-28.4	-52.4
2406	0.70	29	0.65	67	0.86	36	1.1	6.9	-23.3	-58.9
2404	0.73	40	0.57	47	0.84	39	1.1	20.8	-16.1	-52.4
1100	0.59	45	0.58	56	0.85	66	1.1	1.6	-45.6	-82.7
1099	0.61	43	0.61	70	0.81	35	1.1	0.0	-32.7	-72.9
1767	0.65	35	0.55	48	0.86	56	0.9	14.4	-32.0	-38.8
1761	0.70	32	0.56	48	0.86	31	1.1	19.8	-21.6	-57.1
1101	0.68	21	0.66	48	0.83	41	1:1	3.6	-22.0	-57.7
1763	0.69	27	0.69	44	0.88	40	1.1	0.7	-26.9	-61.1
2403	0.69	29	0.66	77	0.84	34	0.9	3.8	-21.5	-25.0
1762	0.72	27	0.69	47	0.86	38	1.1	3.0	-20.3	-54.8
1769	0.74	25	0.61	49	0.86	41	1.1	18.2	-16.3	-43.2
1768	0.75	45	0.57	46	0.77	36	1.2	23.8	-1.8	-57.9
2416	0.62	26	0.60	51	0.78	35	1.0	2.8	-26.7	-62.7
2417	0.75	41	0.61	45	0.78	26	1.1	18.7	-3.3	-46.5
2418	0.71	24	0.69	42	0.85	42	1.0	3.5	-19.2	-46.4
1770	0.71	32	0.75	50	0.85	37	1.1	-5.4	-19.2	-59.4
2405	0.75	37	0.63	54	0.79	41	1.1	15.9	-4.5	-42.5
1103 & 4	0.64	29	0.56	50	0.84	41	1.0	12.1	-30.3	-56.1
1105	0.70	33	0.61	55	0.89	28	0.98	12.9	-27.2	-40.9

Table 13
SODIUM IODIDE MEASUREMENTS WITHIN EACH HPGe FIELD OF VIEW
Th-232 Results (Moisture Corrected) from the A2/P3 Radium Hot Spot

HPGe Spectrum File	HPGe Th-232 pCi/g	No. RTRAK Results	AVE RTRAK Th-232 pCi/g	No. RSS Results	AVE RSS Th-232 pCi/g	No. GATOR Results	AVE GATOR Th-232 pCi/g	RPD HPGe-RTRAK	RPD HPGe-RSS	RPD HPGe-GATOR
417	0.72	33	0.61	55	0.89	28	0.98	15.9	-22.8	-36.0
1764	0.65	32	0.62	44	0.85	39	0.9	3.9	-31.3	-40.8
1102	0.66	25	0.71	48	0.87	31	1.3	-8.2	-31.4	-102.3
1755	0.55	27	0.61	61	0.84	38	0.8	-9.6	-50.8	-36.2
1756	0.63	21	0.36	64	0.79	41	0.8	42.4	-26.1	-34.7
2415	0.63	31	0.64	80	0.83	33	1.0	-1.0	-30.9	-50.8

STATISTICAL SUMMARY
Th-232 Results - DRY WEIGHT BASIS

	HPGe pCi/g	RTRAK pCi/g	RSS pCi/g	GATOR pCi/g
Minimum Value	0.55	0.36	0.77	0.75
Maximum Value	0.83	0.75	0.89	1.3
Grand Mean	0.69	0.63	0.84	1.0
Std Dev of MEAN	0.011	0.013	0.0060	0.020
AVE RPD [(HPGe - NaI)/HPGe] •	na	8.9	-22.7	-51.2
# Positive RPD's	na	26	0	0
# Negative RPD's	na	5	31	31

• **Average of individual Relative Percent Difference values from table above.**

Table 14
SODIUM IODIDE MEASUREMENTS WITHIN EACH HPGe FIELD OF VIEW
Ra-226 Results (RADON and MOISTURE CORRECTED) from the A2/P3 Radium Hot Spot

HPGe Spectrum File	HPGe Ra-226 pCi/g	No. RTRAK Results	AVE RTRAK Ra-226 pCi/g	No. RSS Results	AVE RSS Ra-226 pCi/g	No. GATOR Results	AVE GATOR Ra-226 pCi/g	RPD HPGe-RTRAK	RPD HPGe-RSS	RPD HPGe-GATOR
2378 & 9	1.3	42	0.59	58	0.84	33	7.2	55.6	37.5	-440.2
1754	1.3	29	0.58	56	1.7	34	7.0	57.0	-23.3	-418.7
2377	1.3	38	0.54	75	0.60	34	6.7	59.8	55.5	-401.1
1730	1.7	42	0.52	70	0.59	40	6.91	69.5	64.9	-309.0
2408	1.0	34	0.44	70	0.47	50	6.9	56.9	54.1	-569.1
2407	1.9	43	1.7	70	7.2	50	7.2	8.6	-288.1	-291.1
2406	2.4	29	0.97	67	1.7	36	7.3	59.7	29.2	-202.1
2404	9.0	40	2.6	47	4.4	39	8.1	70.6	50.5	9.5
1100	12.4	45	3.1	56	9.5	66	7.5	74.7	23.2	39.4
1099	10.3	43	5.7	70	13.1	35	7.7	44.8	-26.8	25.9
1767	9.9	35	3.6	48	7.4	56	7.4	63.6	24.9	25.6
1761	8.7	32	2.6	48	7.1	31	8.0	70.5	18.2	8.4
1101	2.6	21	0.92	48	3.6	41	7.4	65.3	-36.2	-179.3
1763	1.1	27	0.48	44	0.66	40	6.6	56.8	40.8	-490.3
2403	3.9	29	2.4	77	12.3	34	7.2	37.5	-215.0	-85.1
1762	1.4	27	0.57	47	1.0	38	5.6	57.9	23.9	-316.0
1769	13.5	25	2.9	49	7.7	41	7.6	78.7	42.7	43.8
1768	3.9	45	1.6	46	3.6	36	8.1	59.4	6.5	-110.2
2416	2.2	26	1.4	51	2.1	35	5.8	38.2	5.0	-163.8
2417	1.2	41	0.50	45	0.68	26	6.8	57.3	42.0	-482.4
2418	1.1	24	0.47	42	0.58	42	6.4	57.2	46.4	-485.8
1770	1.2	32	0.41	50	0.75	37	5.6	65.4	37.3	-370.9
2405	13.2	37	4.5	54	13.2	41	7.6	65.4	-0.7	42.1
1103 & 4	3.7	29	3.3	50	7.5	41	7.2	10.5	-102.2	-93.8

Table 14
SODIUM IODIDE MEASUREMENTS WITHIN EACH HPGe FIELD OF VIEW
Ra-226 Results (RADON and MOISTURE CORRECTED) from the A2/P3 Radium Hot Spot

HPGe Spectrum File	HPGe Ra-226 pCi/g	No. RTRAK Results	AVE RTRAK Ra-226 pCi/g	No. RSS Results	AVE RSS Ra-226 pCi/g	No. GATOR Results	AVE GATOR Ra-226 pCi/g	RPD HPGe-RTRAK	RPD HPGe-RSS	RPD HPGe-GATOR
1105	1.0	33	0.34	55	0.68	28	6.28	67.3	34.3	-506.9
417	0.91	33	0.34	55	0.68	28	6.28	62.8	25.3	-590.3
1764	1.7	32	0.49	44	1.4	39	6.2	70.4	17.5	-272.5
1102	0.90	25	0.50	48	0.69	31	8.8	44.3	23.2	-877.5
1755	6.7	27	5.7	61	10.1	38	5.8	15.0	-51.4	12.4
1756	4.3	21	12.1	64	8.2	41	6.0	-180.4	-90.7	-38.9
2415	2.9	31	1.5	80	1.5	33	5.1	49.0	48.8	-75.5

STATISTICAL SUMMARY
Ra-226 Results - DRY WEIGHT BASIS & Radon CORRECTED

	HPGe pCi/g	RTRAK pCi/g	RSS pCi/g	GATOR pCi/g
Minimum Value	0.90	0.34	0.47	5.1
Maximum Value	13.5	12.1	13.2	8.8
Grand Mean	4.2	2.0	4.2	6.9
Std Dev of MEAN	0.73	0.44	0.76	0.15
AVE RPD [(HPGe - NaI)/HPGe]*	na	47.4	-2.7	-244.0
# Positive RPD's	na	30	22	8
# Negative RPD's	na	1	9	23

* Average of individual Relative Percent Difference values from table above.

Table 15
SODIUM IODIDE MEASUREMENTS WITHIN EACH HPGe FIELD OF VIEW
U-238 Results (Moisture Corrected) from the A2/P3 Radium Hot Spot

HPGe Spectrum File	HPGe U-238 pCi/g	No. RTRAK Results	AVE RTRAK U-238 pCi/g	No. RSS Results	AVE RSS U-238 pCi/g	No. GATOR Results	AVE GATOR U-238 pCi/g	RPD HPGe-RTRAK	RPD HPGe-RSS	RPD HPGe-GATOR
2378 & 9	4.3	42	13.84	58	5.6	33	33.8	-223.7	-31.4	-690.9
1754	4.5	29	14.19	56	8.0	34	37.1	-212.4	-77.0	-717.4
2377	5.7	38	13.19	75	5.9	34	32.1	-130.3	-2.5	-459.4
1730	6.5	42	14.91	70	9.7	40	30.26	-128.0	-48.8	-362.7
2408	4.5	34	12.80	70	4.7	50	32.9	-183.2	-4.4	-627.9
2407	6.8	43	17.06	70	21.9	50	46.7	-152.7	-224.4	-592.1
2406	7.7	29	15.75	67	11.5	36	47.7	-104.6	-49.5	-519.3
2404	12.5	40	20.29	47	20.9	39	56.6	-62.3	-67.2	-353.2
1100	13.2	45	19.76	56	30.4	66	70.3	-49.7	-130.2	-432.9
1099	13.7	43	26.01	70	34.3	35	68.0	-89.9	-150.3	-396.6
1767	15.2	35	21.00	48	27.2	56	73.4	-38.2	-78.9	-382.7
1761	11.6	32	22.10	48	24.8	31	66.0	-90.5	-113.4	-468.9
1101	6.9	21	17.67	48	18.4	41	42.6	-158.0	-169.2	-521.5
1763	5.1	27	12.65	44	6.4	40	36.0	-149.0	-26.9	-609.6
2403	10.8	29	22.18	77	33.9	34	60.1	-105.4	-214.1	-456.2
1762	5.7	27	14.58	47	7.0	38	39.8	-155.7	-22.8	-597.8
1769	13.0	25	20.95	49	30.2	41	55.1	-61.1	-132.1	-323.6
1768	8.7	45	15.88	46	18.6	36	46.6	-81.7	-113.3	-433.0
2416	7.7	26	16.76	51	9.9	35	38.7	-117.6	-28.8	-403.1
2417	5.6	41	14.81	45	7.4	26	29.5	-162.6	-30.3	-423.7
2418	5.4	24	14.90	42	5.4	42	31.0	-177.4	-1.1	-477.0
1770	6.5	32	12.72	50	2.7	37	38.9	-95.7	58.3	-498.8
2405	16.0	37	21.17	54	39.5	41	69.0	-32.3	-146.9	-331.3
1103 & 4	8.2	29	19.58	50	27.5	41	60.0	-139.7	-236.8	-633.8
1105	5.6	33	13.54	55	4.4	28	29.89	-144.0	20.6	-438.5

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Table 15
SODIUM IODIDE MEASUREMENTS WITHIN EACH HPGe FIELD OF VIEW
U-238 Results (Moisture Corrected) from the A2/P3 Radium Hot Spot

HPGe Spectrum File	HPGe U-238 pCi/g	No. RTRAK Results	AVE RTRAK U-238 pCi/g	No. RSS Results	AVE RSS U-238 pCi/g	No. GATOR Results	AVE GATOR U-238 pCi/g	RPD HPGe-RTRAK	RPD HPGe-RSS	RPD HPGe-GATOR
417	4.6	33	13.54	55	4.4	28	29.89	-196.9	3.4	-555.5
1764	4.6	32	14.45	44	9.7	39	37.8	-216.2	-111.9	-728.0
1102	4.4	25	14.72	48	4.6	31	36.8	-237.7	-6.0	-743.4
1755	8.9	27	25.31	61	34.2	38	59.6	-184.7	-284.6	-570.0
1756	11.1	21	34.70	64	26.9	41	46.8	-212.6	-142.1	-321.4
2415	7.3	31	17.32	80	11.7	33	45.6	-137.9	-60.5	-526.3

STATISTICAL SUMMARY
U-238 Results - DRY WEIGHT BASIS

	HPGe pCi/g	RTRAK pCi/g	RSS pCi/g	GATOR pCi/g
Minimum Value	4.3	12.6	2.7	29.5
Maximum Value	16.0	34.7	39.5	73.4
Grand Mean	8.1	17.7	16.4	46.1
Std Dev of MEAN	0.63	0.88	2.1	2.5
AVE RPD [(HPGe - NaI)/HPGe] •	na	-136.5	-84.6	-503.1
# Positive RPD's	na	0	3	0
# Negative RPD's	na	31	28	31

• **Average of individual Relative Percent Difference values from table above.**

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Figure 1
COMPARISON OF GATOR AND 0.31 m. HPGe RESULTS
Th-232 Multiple Linear Regression

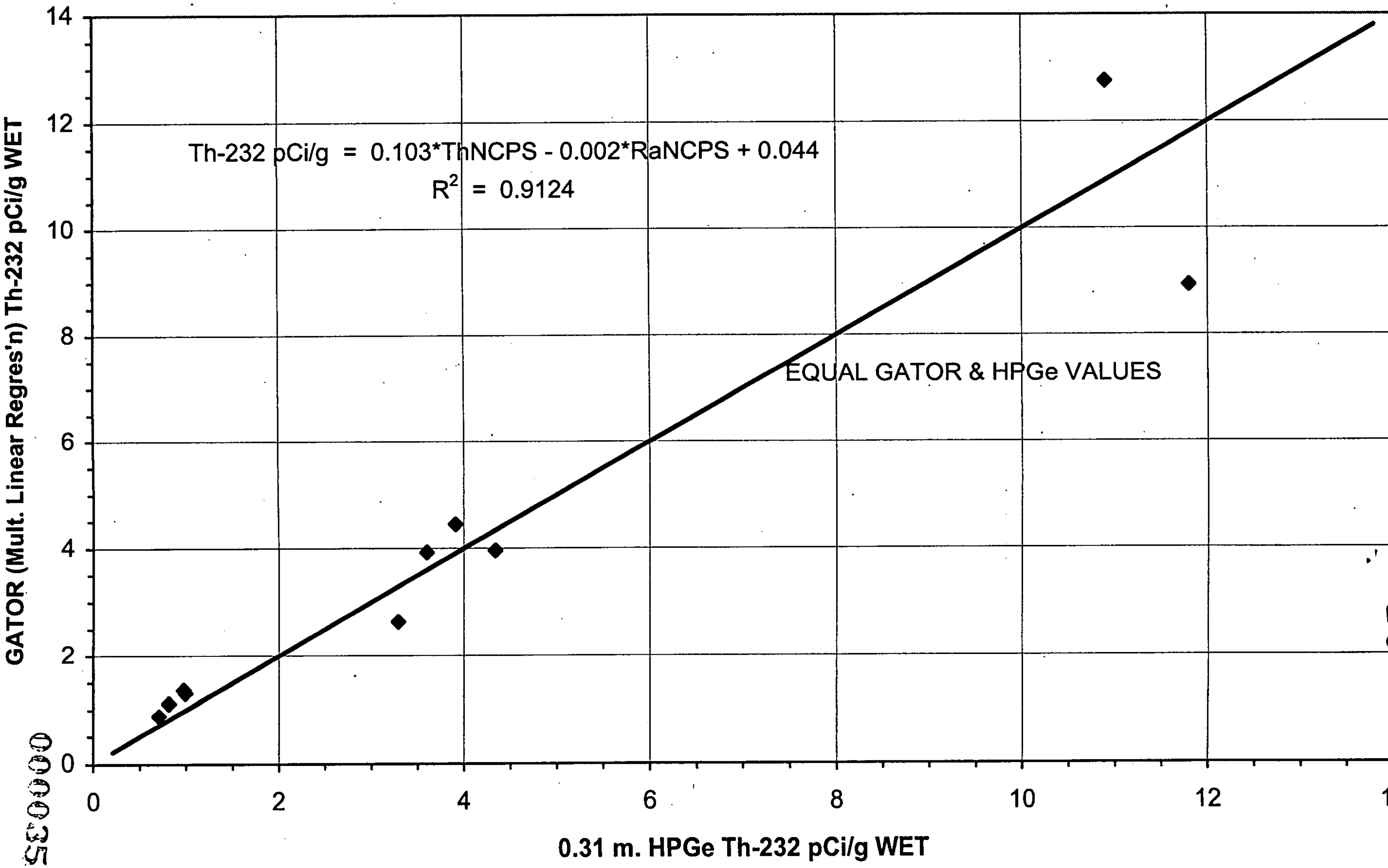

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FIG-1

Figure 2
COMPARISON OF GATOR AND 0.31 m. HPGe RESULTS
Ra-226 Multiple Linear Regression

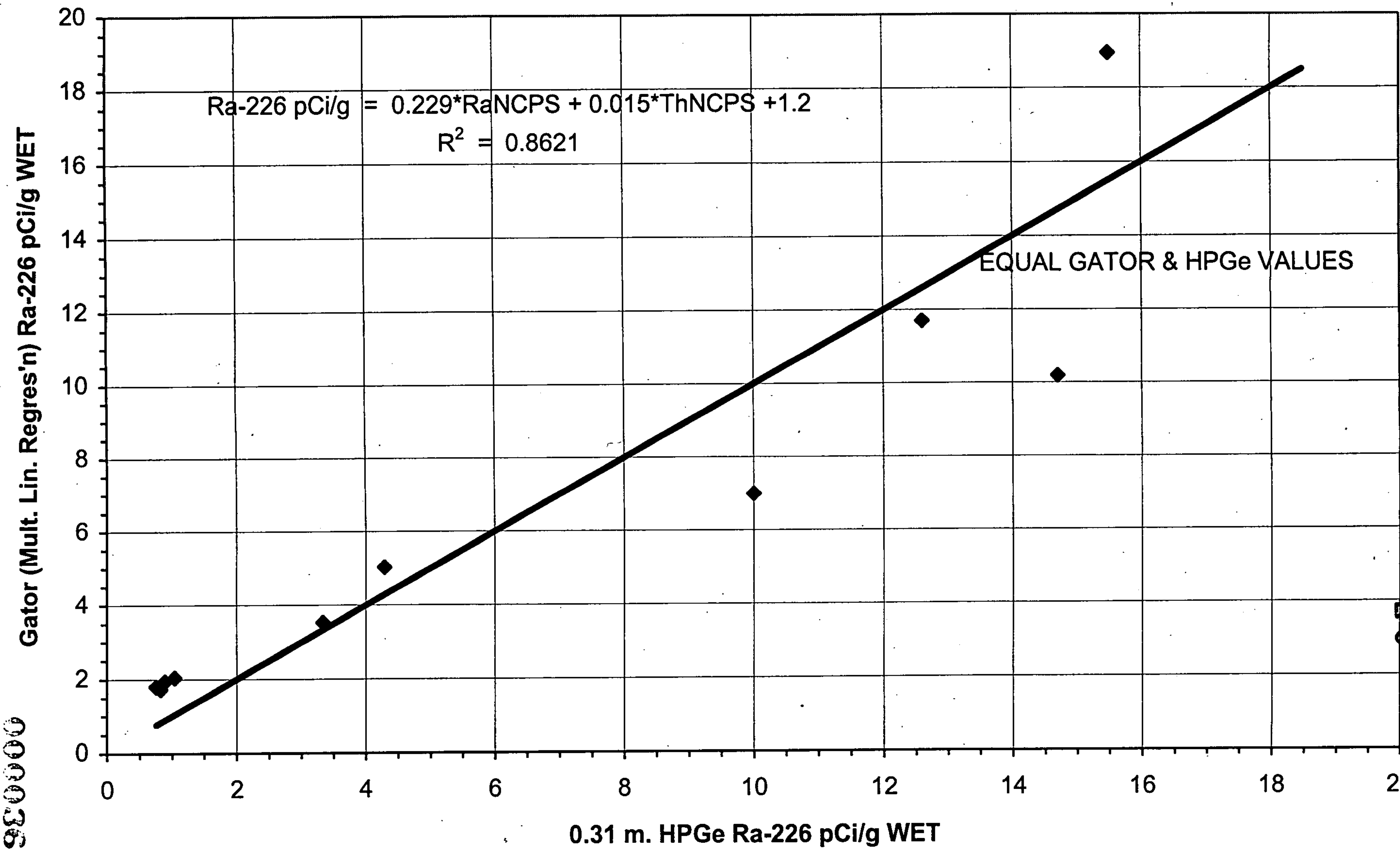

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FIG-2

Figure 3
COMPARISON OF GATOR AND 0.31 m. HPGe RESULTS
U-238 Multiple Linear Regression

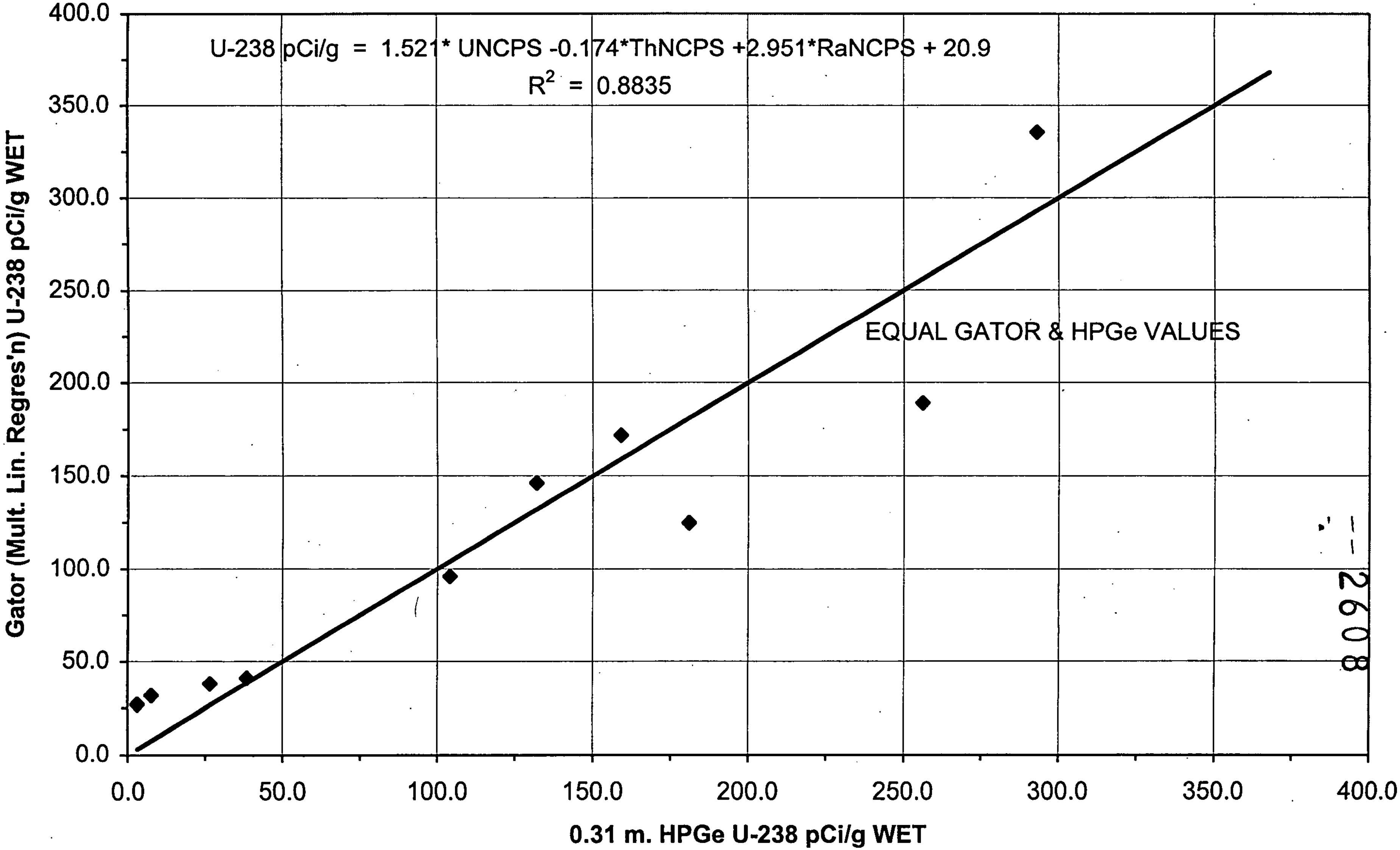

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FIG-3

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Figure 4
COMPARISON OF GATOR AND 0.31 m. HPGe RESULTS
K-40 Multiple Linear Regression

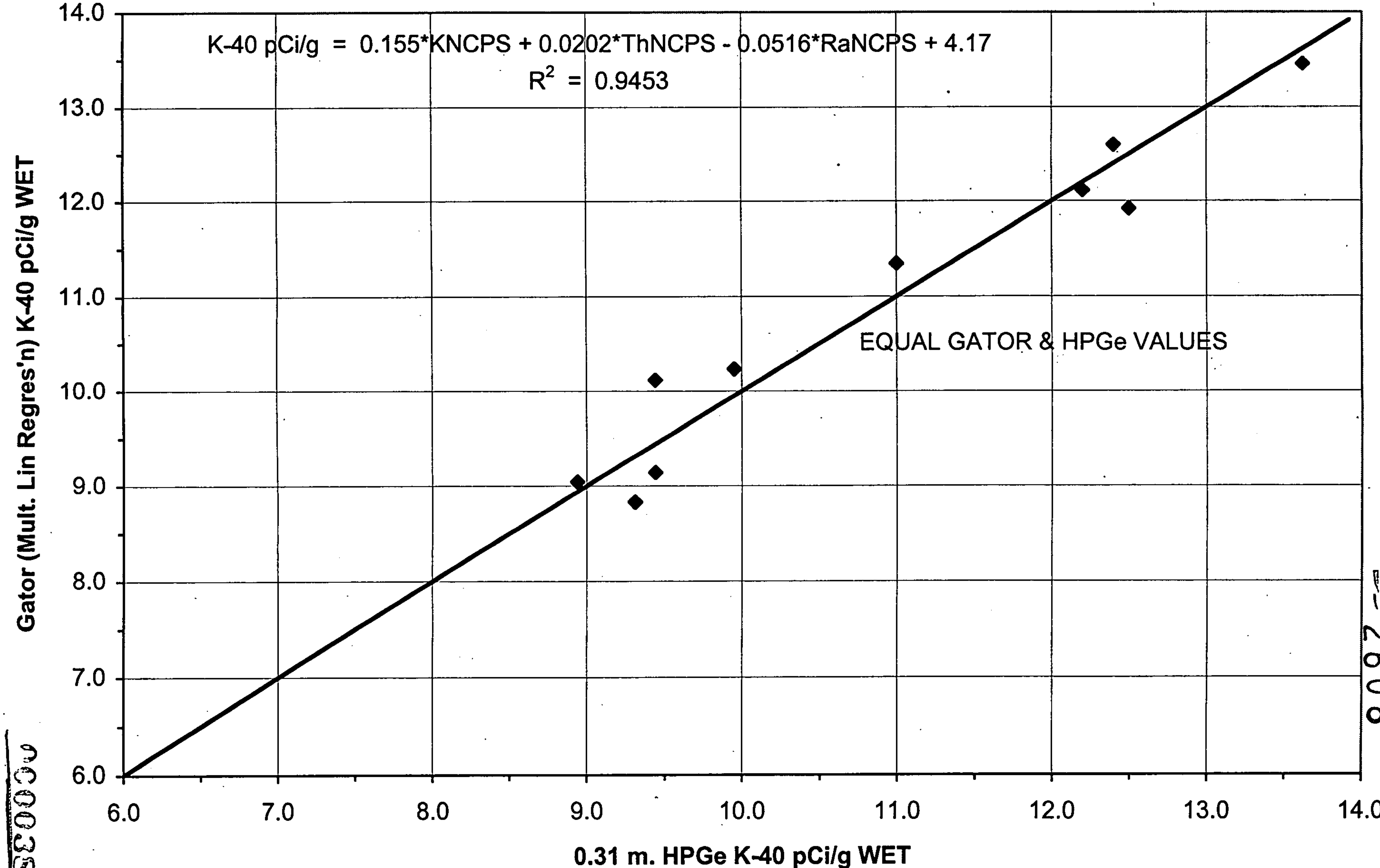

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FIG-4