FERNALD ENVIRONMENTAL MANAGEMENT PROJECT
FERNALD, OHIO

RTRAK APPLICABILITY STUDY

INFORMATION ONLY

JULY 1997

U.S. DEPARTMENT OF ENERGY
FERNALD AREA OFFICE

(20701-RP-0003)
REV. 0

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EXECUTIVE SUMMARY

This report sets the stage for the routine utilization of a field-deployable analytical technique for use in soil remediation: the Radiation Tracking System (RTRAK), a mobile (tractor-mounted) sodium iodide (NaI) detector-based system for measuring gamma rays emitted by radionuclides of concern in soil. The overall objective of this report is to evaluate and document RTRAK characteristics and to evaluate RTRAK data quality parameters to determine how RTRAK can best be used for various applications in soil remediation.

A series of studies was conducted in order to evaluate the quality of data generated by the RTRAK. Three key data quality elements were examined: precision, minimum detectable concentration (MDC), and accuracy. Measurements taken using the RTRAK and a high-purity germanium (HPGe) detector in the same locations exhibit good agreement between total uranium, thorium-232 and radium-226 concentrations measured by RTRAK and concentrations of the same isotopes measured by HPGe. This is the case for both static (not moving) and dynamic (moving) measurements. Large standard deviations (low precision) for individual RTRAK measurements preclude the use of individual measurements to detect low total uranium (below about 165 ppm) and radium-226 (below about 1.6 pCi/g) concentrations, even at eight second data acquisition time. However, thorium-232 may be reliably detected close to site background levels using individual measurements. Results demonstrate that increasing the data acquisition time (counting time) improves precision. For example, increasing data acquisition time from two seconds to eight seconds decreases the standard deviation for individual measurements by a factor of two. Because MDCs are dependent upon standard deviations of the data, increasing the data acquisition time lowers the MDC. For individual measurements with an eight second data acquisition time, the MDC of radium-226 is 93% of the Final Remediation Level (FRL) of 1.7 picocuries per gram (pCi/g), and the MDC of thorium-232 is 47% of the FRL of 1.5 pCi/g. The individual measurement MDC for total uranium (46.8 pCi/g; 140 ppm) still substantially exceeds the FRL of 82 parts per million (ppm), even for an eight second data acquisition time. Effective use of the RTRAK to generate isotope-specific measurements at concentrations below FRLs may necessitate counting times well in excess of eight seconds, if project requirements dictate the use of individual measurements.

As an alternative to increasing data acquisition time to improve precision and lower the MDC, RTRAK data may be spatially averaged over an area larger than the area for the individual measurements. The

issue with spatial averages is how large an averaging area is required to reduce measurement error and MDCs to acceptable levels without sacrificing required spatial resolution. Data from precision studies show that averaging individual RTRAK measurements with a data acquisition time of two seconds over a circular area with a radius of ten feet is approximately equivalent to increasing data acquisition time to eight seconds. If RTRAK data are collected with an eight second acquisition time, increasing the averaging area from a circle with a radius of 10 feet to one of 20 feet would be equivalent to increasing the acquisition time to 32 seconds.

Generally, RTRAK applications in soil remediation fall into two broad functional applications: 1) those designed to delineate contaminant variability and heterogeneity; and 2) those designed to emphasize spatial averages of contamination. Detection of potential hot spots and Waste Acceptance Criteria (WAC) exceedances fall into the first category, while determining success in meeting FRLs is an example of the second. The table below gives guidelines for RTRAK operation and data organization parameters that will result in precision and MDCs sufficient to meet data quality objectives.

Functional Application	RTRAK Speed	Data Acquisition Time	Radius of Data Averaging Area
Delineate Contaminant Heterogeneity	1 mph	4 seconds	Circle with a 10 ft radius
Emphasize Spatial Averaging of Data	2 mph	2 seconds	Circle with a 40 ft radius

For example, calculations based upon Area 1 Phase I data demonstrate that hot spots of three times the FRL can be detected with virtually no false positives and 5% false negatives by averaging over an area having a 10 foot radius at a speed of 1.0 mph and a data acquisition time of 4 seconds.

A report on the comparability of a HPGe detector and laboratory measurements was also issued in July 1997. The HPGe is a tripod-mounted, field-deployable, in-situ gamma ray detector system. The RTRAK and HPGe systems complement each other. The RTRAK is able to provide 100% coverage of an area. Its precision and detection limits are sufficient to determine the degree of homogeneity and heterogeneity of a given area with respect to total uranium, thorium-232 and radium-226. Its data output is amenable to mapping and spatial averaging. This latter attribute makes the RTRAK a good

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tool for applications where average soil contaminant concentrations are desired. Finally, the RTRAK is ideal as a front-end survey tool to help focus and guide the use of HPGe when they are used in tandem.

The strengths of the HPGe are its ability to accurately quantify a variety of isotopes, its high degree of energy resolution (which makes interferences less likely), and its ability to average data over either large or small areas, thereby minimizing sample error and maximizing data representativeness. These characteristics justify the HPGe's use in providing high-quality data for certification/verification activities relative to remediation of soils for hot spots, WAC exceedances, and FRLs. Additionally, HPGe's strength in footprint delineation indicates that it should be used as a confirmatory tool to evaluate potential hot spot and WAC exceedance areas noted by RTRAK surveys.

Several RTRAK method development studies remain to be carried out, based upon results of this report. In particular, future method development work needs to be carried out where the RTRAK makes measurements in high contamination areas in order to extend the concentration range over which precision and accuracy are evaluated.

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LIST OF ACRONYMS AND ABBREVIATIONS

ALARA	As Low As Reasonably Achievable
COC	contaminamt of concern
cps	counts per second
CU	certification unit
DOE	United States Department of Energy
EPA	United States Environmental Protection Agency
FEMP	Fernald Environmental Management Project
FRL	final remediation level
GIS	Geographic Information System
GPS	global positioning system
HPGe	high-purity germanium
keV	kiloelectrovolts
MCA	multichannel analyzer
MDC	minimum detectable concentration
mph	miles per hour
NaI	sodium iodide
OSDF	On-Site Disposal Facility
pCi/g	picocuries per gram
PHA	pulse height analysis
PMT	photomultiplier tube
ppm	parts per million
RI/FS	Remedial Investigation/Feasibility Study
RTRAK	Radiation Tracking System
sec	seconds
Tl	thallium
U_3O_8	uranium oxide
USID	Uranium in Soils Integrated Demonstration
WAC	waste acceptance criteria

SECTION 1.0
INTRODUCTION, RTRAK DESCRIPTION, REPORT SCOPE AND OBJECTIVES

1.1 INTRODUCTION

The Fernald Environmental Management Project (FEMP) is currently conducting remediation of site soils that are radiologically and chemically contaminated. Soil contamination originated from airborne dispersion of both fugitive and stack emissions throughout the production period (1952-1989), as well as from direct releases due to spills and site disposal practices. While a number of chemicals and radionuclides contribute to site risk, contaminated soil volume, and areal extent of contamination, only five species contribute large cumulative percentages of contamination. These five species, the "primary contaminants of concern" (COCs), include total uranium, thorium-232, thorium-228, radium-226 and radium-228.

A number of potential applications makes the use of field-deployable screening instruments attractive for detecting activities of these three COCs of interest in a "real time" mode, as opposed to traditional sampling and laboratory analysis protocols. These include:

- Rapid screening of certification units (CUs) to assess the spatial patterns of contaminant distribution in soils;
- Rapid identification of elevated contamination areas and potential hot spots prior to soil restoration activities;
- Rapid identification of areas potentially exceeding Waste Acceptance Criteria (WAC);
- Rapid identification of areas potentially exceeding final remediation levels (FRLs) and hot spot criteria following soil remediation activities;
- Rapid attainment of data that allows more rigorous analytical methodologies to be focused on specific areas; and
- Support implementation of the process for achieving as low as reasonably achievable (ALARA) goals in soil remediation.

This report sets the stage for the routine utilization of a field-deployable analytical technique in soil remediation: a mobile sodium iodide (NaI) detector-based system (mounted on a John Deere tractor) for measuring gamma rays. The system, known as the Radiation Tracking System (RTRAK), is briefly described below.

1.2 BRIEF DESCRIPTION OF RTRAK SYSTEM

The RTRAK system is a gamma-ray measurement system mounted on a tractor. The measurement system consists of a 4x4x16 inch NaI detector and associated electronics that provide high-speed pulse height analysis. This system allows the collection of a gamma ray energy spectrum, which can be analyzed to identify and quantify radioactive isotopes that may be present within the detector's viewing area. The tractor is also equipped with a global positioning system (GPS), operated in a real-time differential mode to provide location coordinates. Each energy spectrum is tagged with the location coordinates provided by the GPS. All energy and location data are stored on magnetic media by an on-board computer system. This information is used to accurately locate and subsequently map radiological data within the measurement area.

The detector is positioned on the tractor at a height of approximately 31 cm above the ground. The normal operation of the RTRAK consists of driving the tractor over the measurement area at a predetermined speed. Spectra are continuously collected at regular intervals, typically a few seconds. The viewing area size is a function of the tractor speed, the acquisition time, and the detector's geometrical configuration. For example, for the 4x4x16 inch detector at the 31 cm height, the viewing area is approximately 10 m^2 when the tractor is moving at two miles per hour, with a 2-second acquisition time.

The RTRAK collects data which are used to generate a gamma photon energy spectrum. This spectrum may be processed to generate gross counts or radionuclide-specific activities. In the gross count mode, all of the counts in the spectrum are totaled and used to identify elevated activity areas; there is no radionuclide-specific information. Alternatively, the RTRAK system can be used to generate qualitative and quantitative results for uranium-238, radium-226, thorium-232, and potassium-40. These results are based on gamma rays emitted by the radionuclides or members of their respective decay chains. A more detailed description of the RTRAK, the characterization and calibration of its NaI detectors, and how gamma photons are measured and quantified is provided in Appendix A.

1.3 SCOPE OF THE REPORT

This report describes the results of a series of studies conducted at the FEMP to assess the usefulness and applicability of the RTRAK to support soil remediation. A calibration study provided data that allowed the RTRAK NaI detectors to be calibrated in order to quantify specific radionuclide concentrations. The Uranium in Soils Integrated Demonstration (USID) area study and the South Field area study were conducted to optimize data acquisition parameters and to delineate key data quality elements. The Area 1 Phase I study was conducted to acquire a large data set in order to determine the best way to display and map the data. These four studies set the basis for this report's analysis.

Three of the five primary COCs, total uranium, thorium-232, and radium-226, are the analytes of concern in this report. Because thorium-232 is in secular equilibrium with its radioactive daughters, the concentrations of thorium-228 and radium-228 are equal to that of thorium-232; hence there is no need for analysis of these two analytes. In addition, much of the report discusses uranium-238 concentrations rather than total uranium concentrations. Multiplying uranium-238 by a factor of three gives the total uranium concentration in parts per million (ppm) (assuming normally enriched uranium). **Raw RTRAK data are not included in this report because the data are so voluminous. The data are stored electronically; readers interested in accessing these data are requested to contact DOE Fernald.**

1.4 OBJECTIVES

The overall objective of this RTRAK applicability study is to delineate RTRAK system characteristics and to evaluate RTRAK system data quality parameters to determine how the RTRAK can be best used for the applications identified in Section 1.1. Specific report objectives include:

1. Describe the RTRAK system and its component subsystems;
2. Document the calibration process for RTRAK NaI detectors that enables concentrations of specific radionuclides to be calculated from raw data gathered in the field;
3. Describe and document the equations and methodologies used to quantify radionuclide concentrations from gamma photon energy spectra;
4. Identify optimal operation and data acquisition conditions;
5. Identify and define key parameters that affect the known quality of data for the RTRAK system;

6. Establish values for these key parameters such that error rates for possible applications can be established;

7. Recommend guidelines for organizing and displaying data;

8. Recommend the roles that RTRAK should have in future sitewide excavation operations; and

9. Recommend, as applicable, what additional method development research is needed to further improve system capabilities.

1.5 REPORT FORMAT

Section 1 introduces and briefly describes the RTRAK system, outlines the report scope, delineates objectives, and provides an overview of the organization of the report. Section 2 outlines the design and methodologies for the studies described in this report. Section 3 documents the detector calibration process (Objective 2). Section 4 identifies and quantifies key data quality parameters and discusses their significance with respect to decision-making (Objectives 4, 5, and 6). Section 5 recommends guidelines for organizing and displaying RTRAK data (Objective 7). Sections 6 and 7 discuss applications of the RTRAK as well as the future role of the RTRAK in soil excavation activities, and recommends additional method development activities (Objectives 8 and 9).

Supporting data and technical details are provided in Appendices A through C. Appendix A contains the detailed description of the RTRAK system and the equations and methodologies used to calculate radionuclide concentrations (Objectives 1 and 3).

SECTION 2.0
STUDY DESIGN

2.1 TYPES OF STUDIES AND LOCATIONS

As noted in Section 1.3, four studies form the basis of this report. The first, the calibration study, involved RTRAK measurements at each of the ten locations designated for collection of high-purity germanium (HPGe), in-situ gamma spectrometry data and physical sample data for the Part B Comparability Study (DOE 1997a). These ten locations are noted in Figure 2-1. The second study involved collection of a very large data set by making RTRAK measurements in conjunction with the Area 1 Phase I soil excavation project. The Area 1 Phase I RTRAK data locations are also noted in Figure 2-1.

The USID and South Field area studies (Figure 2-1) were conducted to determine optimum system operating conditions and to assign values to key data quality parameters. The USID study area involved data collection over 100% of an approximately one-acre parcel of land as well as over a single track using back and forth runs. Data collection in the South Field involved RTRAK measurements along repeated runs around a circular path. Each of these studies is described in more detail below.

2.2.1 Calibration Study

The objective (Section 1.4) of describing the calibration study is to document the calibration process for RTRAK NaI detectors that enables concentrations of specific radionuclides to be calculated. The RTRAK measures the number of gamma rays per unit time detected by the NaI sensor. Regulatory limits established by the United States Environmental Protection Agency (EPA) are expressed in terms of picocuries per gram (pCi/g) for thorium-232 and radium-226, and in ppm for total uranium. RTRAK does not measure total uranium directly, but provides uranium-238 results in pCi/g. This can be converted to ppm of total uranium by multiplying by a factor of three. The process of converting counts per unit time to pCi/g is known as calibration. The calibration method for RTRAK involved making measurements at each of ten soil locations and then correlating those measurements to the known concentration of various radionuclides in the soils as measured by HPGe.

The ten areas used to calibrate the RTRAK were the same ten areas used to collect HPGe data and physical samples for the Part B Comparability Study. Each of the ten areas was identified as a low, medium or high contamination area for uranium based on historical data and was assigned an arbitrary

identification number from one to ten. Low contamination areas (Areas 1, 8 and 9) contained less than 80 ppm total uranium; moderate contamination areas (Areas 2, 4, 5, and 6) contained between 80 and 200 ppm total uranium; high contamination areas (Areas 3, 7 and 10) contained more than 200 ppm total uranium.

HPGe measurements were taken at each of the ten areas to provide "known" concentrations. The measurements were carried out at a detector height of 31 cm (similar to the height of the RTRAK NaI detector) using 900 second counting times. The RTRAK NaI detector was centered over the exact location as the HPGe detector and measurements were obtained using 300 second count times. RTRAK calibration data were obtained in a static mode (i.e., RTRAK stationary). As will be discussed in Section 3, the RTRAK data are correlated against "known" concentrations based upon HPGe measurements in order to derive factors for converting counts per second (cps) to pCi/g.

2.2.2 Area 1 Phase I Measurements

Use of the RTRAK data obtained for Area 1 Phase I activities provides a large data set not otherwise readily obtainable under testing conditions. The NaI detector system mounted on the RTRAK was used to provide extensive coverage of Area 1 Phase I soils for both pre- and post-soil excavation activities. The NaI detector, coupled to a multichannel analyzer (MCA) and software, was calibrated to detect uranium, thorium, and radium. The system was used in a roving mode at a nominal speed of two miles per hour and minimum count times of two seconds. At this speed and count time, a gamma reading was made and recorded every 10 m^2. The mobile system was electronically coupled with a GPS rover and base unit to record the location of every reading. Counting and positioning information were recorded continuously on a field personal computer and stored on disk for future downloading to the site soil database and to the FEMP Geographic Information System (GIS).

Before excavation, the RTRAK was used to collect measurements to determine the soil concentrations of total uranium in relation to WAC for the On-Site Disposal Facility (OSDF). After soil excavation, the RTRAK covered all excavated areas with an interlocking pattern of readings to provide as close to 100% coverage as possible. Information from the NaI/GPS systems was again recorded on the computer and transferred to the Unix system through the local area network on at least a daily basis. The information was plotted on the FEMP GIS for review and evaluation.

As noted in Section 1.4 (Objective 7), the primary use of RTRAK Area 1 Phase I data in this report is to provide a large data set that can be used to establish the best ways to organize and display RTRAK data for use in environmental decision-making.

2.2.3 USID and South Field Study Areas

RTRAK data collection in the USID and South Field study areas was conducted to optimize RTRAK operating parameters as well as to assign values to key data quality parameters. These studies address objectives 4, 5, and 6 (Section 1.4).

2.2.3.1 USID Study Area

The detector speed and acquisition time studies consisted of multiple runs in the USID area north of the incinerator (see Figure 2-1). The identified testing area measured approximately one acre and was selected based on soil characterization data from previous testing and technology demonstration studies. Concentrations of uranium-238, thorium-232, radium-226, and potassium-40 were the parameters to be analyzed. To determine the optimal RTRAK operating parameters, three combinations of vehicle speed and detector acquisition time were used as follows:

- 2 mph at 2 second acquisition time;
- 0.5 mph at 2 second acquisition time; and
- 0.5 mph at 8 second acquisition time.

One hundred percent of the USID study area was characterized by the RTRAK. The objective of this coverage was to obtain a data set that could be used to ascertain the effect of aggregating measurements over areas of varying size. RTRAK measurement strategy consisted of moving in a clockwise spiral going from the perimeter of the mapped area toward the center of the mapped area. Vehicle speed and detector acquisition time were adjusted before each run.

In conjunction with the RTRAK measurements, 36 HPGe measurements at a height of one meter were taken using a triangular grid layout to characterize 100% of the 1-acre area, as shown schematically in Figure 2-2. The coordinates of each measurement point were established and located. Soil moisture and density measurements were performed in conjunction with each HPGe measurement to physically assess the soil conditions.

Static measurements using the RTRAK NaI system were performed at selected locations on the grid representing two relatively high and two relatively low contamination concentration values. These locations were determined based upon review of the RTRAK and HPGe measurement results. The static RTRAK measurements were performed at acquisition time intervals of two and eight seconds for a total of 300 seconds each. The purpose of the static measurements was to verify the validity of the calibration (Section 3.3) by comparing RTRAK and HPGe data in a different area than those in which the calibration measurements were performed.

A single track sample profile was selected based on the RTRAK and HPGe measurement results. This track was measured using the RTRAK system applying a repeated back and forth pass method for twenty iterations using each combination of acquisition time and vehicle speed (as described above). This allowed assessment of the total uncertainty associated with each combination of RTRAK speed and data acquisition time. The track location is shown on Figures 2-1 and 2-2.

A general description of the soil type and topography of the gridded measurement area was recorded, as well as a description of the soil type at each of the 36 HPGe measurement locations. Soil sample collection for laboratory analysis was not an aspect of this study; however, atmospheric temperature was recorded during all measurements using both RTRAK and HPGe detection systems.

2.2.3.2 South Field Study Area

RTRAK measurements were also taken in the South Field area because previous Remedial Investigation/Feasibility Study (RI/FS) and HPGe data indicated that higher radium and thorium concentrations were present there than in the USID area. This enabled optimization of RTRAK operating parameters and assignment of values to key data quality elements to be based, at least partially, on field locations with elevated contamination. Further, physical samples and HPGe measurements had been previously collected in several areas (Areas 13 and 16) in the South Field (Figure 2-3) in a continuation of the comparability study. RTRAK measurements were taken in the same locations to allow the measurements to be tied to HPGe and laboratory data in two areas.

RTRAK runs occurred along an oval-shaped track (Figures 2-1 and 2-3), with the western portion of the RTRAK run area intersecting the center of the circular Area 13, and the eastern portion of the

RTRAK run area intersecting the center of the circular Area 16. The centers of these areas were the sample points in the circles directly beneath the HPGe detectors.

Ten traverses of the circle were made at each of the following speeds and acquisition times:

- 2.0 mph, 2 seconds;
- 0.5 mph, 8 seconds; and
- 1.0 mph, 4 seconds.

The 1.0 mph and 4 second data acquisition time represents a compromise in operating conditions from 2.0 mph and 2 second acquisition time to 0.5 mph and 8 second acquisition time. Results from the USID area suggested that these operating conditions (1.0 mph and 4 seconds) might be the optimal ones to routinely employ.

The RTRAK study in the South Field was carried out subsequent to the South Field portion of the HPGe Comparability Study, in which certain South Field locations were measured and sampled. Because the RTRAK runs were conducted on different days and different moisture conditions than on the days that HPGe data and physical samples were calculated, Troxler moisture/density readings were re-collected at Area 13, Location 1, and at Area 16, Location 1 each day in which the RTRAK runs were conducted. Soil and air temperature and humidity readings were also recorded at the beginning of each day in which the RTRAK run is conducted. The circular RTRAK track is shown in Figures 2-1 and 2-3.

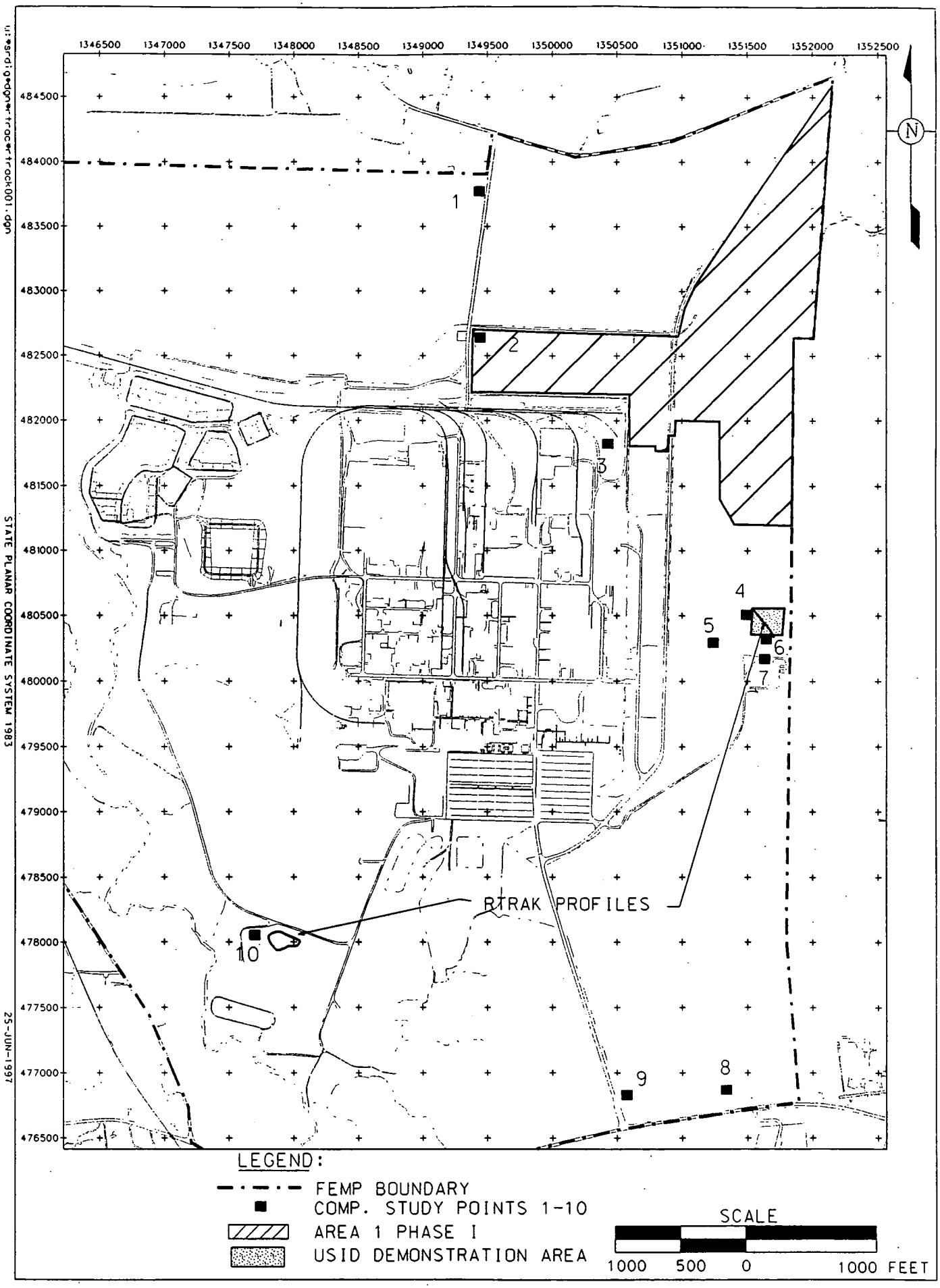
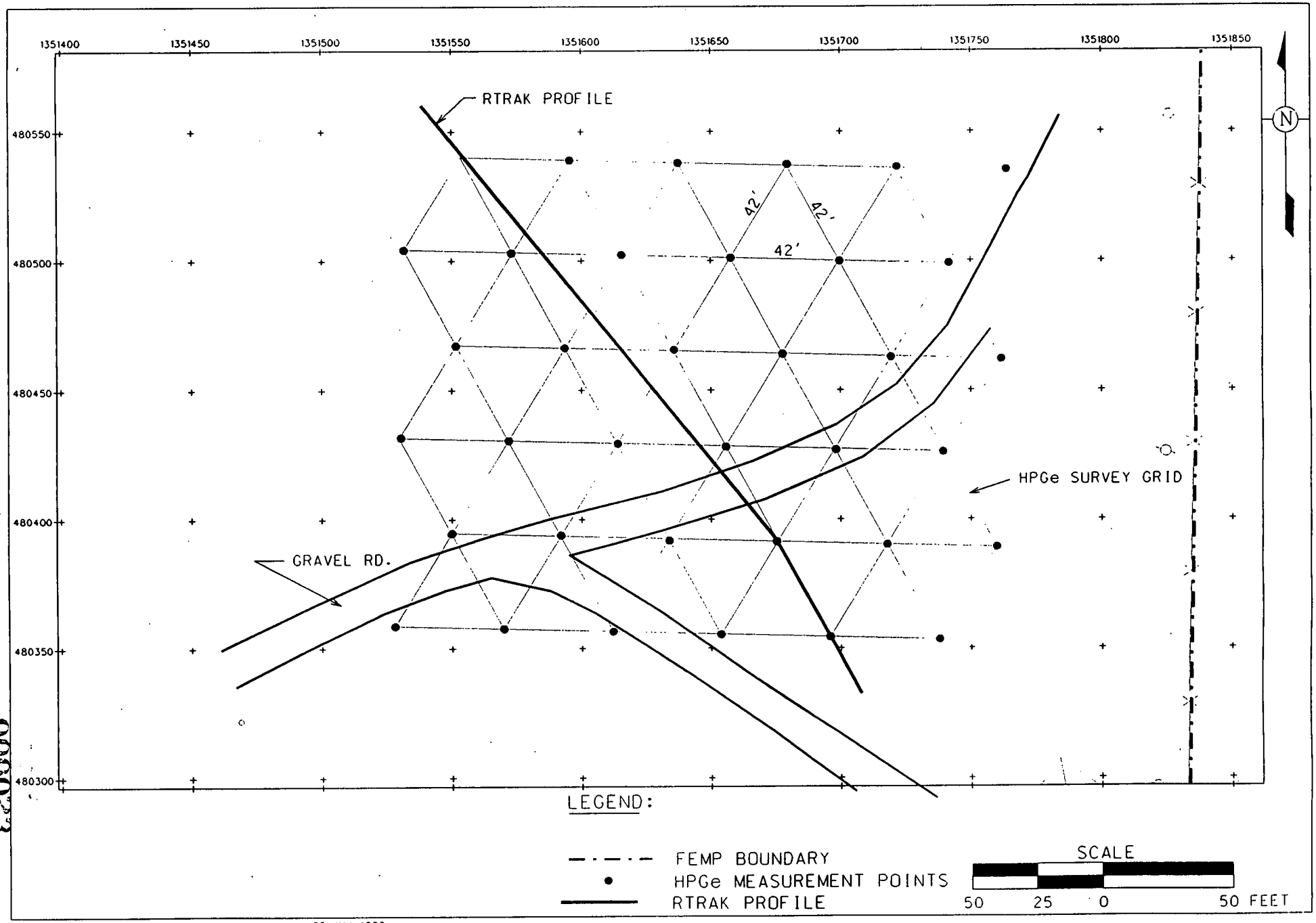


FIGURE 2-1. AREAS SCANNED BY RTRAK



c:\mge\srdig\dgn\bmp\rtrc003.dgn
STATE PLANAR COORDINATE SYSTEM 1983

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FIGURE 2-2. RTRAK AND USID TEST AREA

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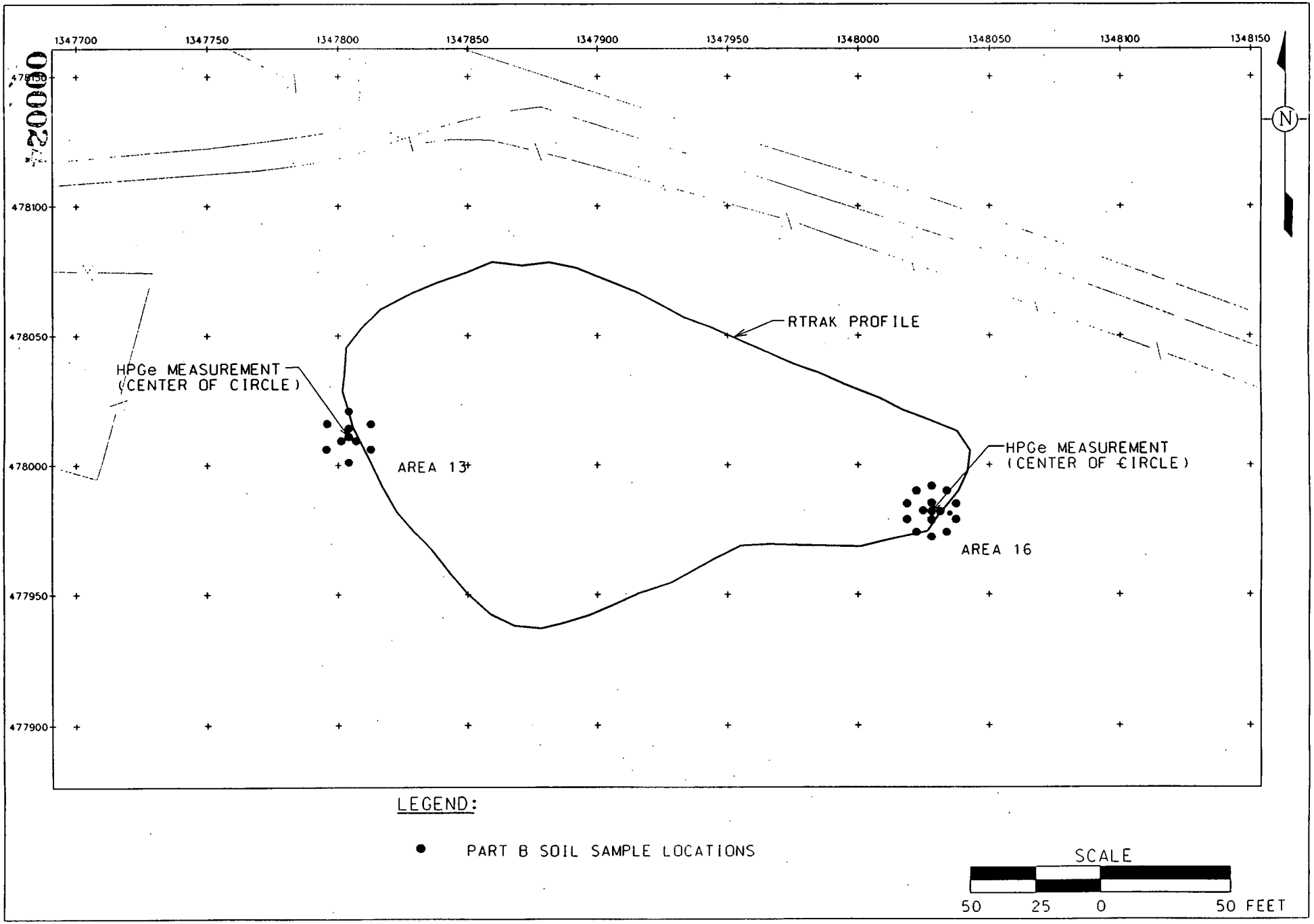

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STATE PLANAR COORDINATE SYSTEM 1983

FIGURE 2-3. RTRAK PROFILE RUN IN THE SOUTHFIELD

SECTION 3.0
CALIBRATION OF RTRAK SODIUM IODIDE DETECTORS

3.1 DETECTOR CALIBRATIONS

Normally, in the laboratory two calibrations are required on a gamma-ray counting system in order to qualitatively and quantitatively evaluate the spectrum. These two calibrations are an energy calibration, which permits identification of nuclides in the sample on the basis of the energy of gamma photon peaks in the spectrum, and an efficiency calibration, which converts the relative counts in the spectrum to activity concentrations in pCi/g by determining the system measurement efficiency at fixed and defined measurement geometries using traceable calibration sources. This section of the report briefly describes the energy calibration process and documents the efficiency calibration process for the RTRAK in considerable detail.

3.2 ENERGY CALIBRATION

The energy calibration process is described in FEMP procedure EQT-30, "Operation of Radiation Tracking Vehicle Sodium Iodide Detection System." This procedure addresses the use of calibration sources containing radionuclides of known gamma energies to generate an energy calibration "curve." In the case of the RTRAK, a thorium-containing lantern mantle emits gamma photons for thorium-232 daughters at 238.6 keV and 2615 keV. The 238.6 keV photon is assigned to channel 40 in the multichannel analyzer, and the 2615 keV photon is assigned to channel 447. On average each channel corresponds to approximately 5.9 keV; thus, other gamma photons are linearly distributed to channels in the multichannel analyzer on the basis of their energy. Performance checks ensure that the two energies (238.6 and 2615 keV) always occur at 40 $\pm$ 2 and 447 channels, respectively.

3.3 EFFICIENCY CALIBRATION

The RTRAK efficiency calibration procedure involved making static (i.e., RTRAK is not moving) RTRAK measurements of different soil areas containing known concentrations of radionuclides and performing linear correlations of the soil concentration to the net RTRAK gamma count rate. The resultant slope and intercept are then used to convert net count rate for any area into radionuclide concentrations.

As stated in Section 2.2, HPGe measurements from the ten comparability study areas were used as the basis for "known" concentrations of uranium-238, thorium-232, radium-226, and potassium-40.

Concentrations of the various radionuclides in these ten acres are shown in Table 3-1. These concentrations are averages of measurements made at 31 cm and 1 m detector heights. The HPGe concentrations for Area 3 are based upon HPGe measurements carried out in Area 3 on different days than the HPGe measurements appearing in the Comparability Study, because conditions were too wet and muddy to take the RTRAK into Area 3 when the HPGe Comparability Study measurements were taken.

The gamma ray spectrum generated by the RTRAK system is processed by integrating the counts in the spectrum across specific energy regions of interest. These regions are associated with the energies of gamma rays emitted by the analytes of interest and with energies considered to be representative of the spectrum background. The net counts for an analyte are obtained by subtracting the spectrum background contribution from the appropriate energy region of interest. The regions of interest are addressed in Appendix A, Section A.5.1. Net counts per second are calculated by dividing the net counts by the acquisition time.

Figures 3-1 and 3-2 show linear correlations of HPGe measured concentrations of thorium-232 and radium-226 vs. RTRAK measured counts per second for the same two analytes. A high degree of correlation is indicated by the very high correlation coefficients (actually, very high squared values of the correlation coefficient, R^2). In part, the high degree of correlation reflects the fact that the regression line is anchored by low and high data points with no intermediate values. Future studies will seek to improve or reinforce this correlation by adding additional points.

The equations for the straight lines represent the conversion factors to calculate RTRAK pCi/g from net counts per second. The equations for thorium-232 and radium-226 shown on Figures 3-1 and 3-2 are given below.

Thorium-232 Conversion Factor:

$$C_{Th} = (0.06817 \times N_{Th}) - 0.042$$

Radium-226 Conversion Factor:

$$C_{Ra} = (0.19243 \times N_{Ra}) + 0.08805$$

where:

C_{Th} = activity concentration of thorium-232 in pCi/g

C_{Ra} = activity concentration of radium-226 in pCi/g
N_{Th} = net counts per second of thorium-232
N_{Ra} = net counts per second of radium-226

Figure 3-3 shows a scatter plot for potassium-40 of RTRAK net counts per second vs. HPGe pCi/g. The range of values for both parameters is too small and too variable to fit a regression with a high degree of correlation. Therefore, calibration factors for potassium-40 were calculated by averaging the ratios of HPGe concentrations to net cps measured by the RTRAK.

Table 3-2 provides ratios of HPGe potassium-40 concentrations to RTRAK potassium-40 net counts based upon data in Table 3-1. The average value for this ratio is 0.21. Using this factor, the calibration equation for potassium-40 can be written as:

$$C_{K\text{-}40} = (0.21) \times N_{K\text{-}40}$$

where:

$C_{K\text{-}40}$ = activity concentration of potassium-40 in pCi/g

$N_{K\text{-}40}$ = net counts per second of potassium-40

The conversion factor for uranium-238 cannot be determined from a simple linear correlation of RTRAK measurements vs. HPGe measurements as was the case for thorium-232 and radium-226, because corrections must be made for interferences from thorium-232 and radium-226. Accordingly, the conversion factor for uranium-238 is determined from a multiple linear regression equation of the form:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3$$

where x_1 is the measured RTRAK counts per second for uranium-238 and x_2 and x_3 are the corrections for thorium-232 and radium-226 interferences. The multiple linear regression equation for the uranium-238 conversion factor is shown below.

$$C_U = 2.994\left(N_U - \left(\frac{C_{Th}}{0.135}\right) + \left(\frac{C_{Ra}}{0.271}\right)\right) + 0.481$$

where:

C = activity concentration in pCi/g for the subscripted radionuclide
N_U = net counts per second of uranium-238 from the RTRAK

3.4 SUMMARY

Two calibrations are performed on the RTRAK system. An energy calibration allows identification of gamma photons on the basis of their energy. This makes it possible to qualitatively identify gamma emitting radionuclides in the soil that is being scanned. An efficiency calibration supplies factors to convert detector response in the form of counts per second to soil activity concentrations in pCi/g. These conversion factors have been determined from regressions of RTRAK measurements against HPGe measurements in soil areas having known concentrations of various radionuclides. These conversion factors have been used to obtain the RTRAK activity concentrations discussed in succeeding sections of this report.

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TABLE 3-1
RTRAK AND HPGe DATA USED TO GENERATE LINEAR REGRESSION LINES

Area	Acquisition Time (sec)	RTRAK U-238 (net cps)	HPGe U-238 (pCi/g)	RTRAK Th-232 (net cps)	HPGe Th-232 (pCi/g)	RTRAK Ra-226 (net cps)	HPGe Ra-226 (pCi/g)	RTRAK K-40 (net cps)	HPGe K-40 pCi/g)
PBC-01	300	3.3	2.8	8.4	0.5	3.0	0.6	52.1	11.1
PBC-02	300	4.1	9.6	14.8	0.6	2.9	0.7	35.3	7.8
PBC-03	300	15.4	81.3	24.0	2.0	28.3	5.3	52.2	11.1
PBC-03a	300	17.8	72.0	25.7	1.8	28.9	5.9	54.9	9.5
PBC-04	300	8.7	19.2	12.3	0.8	4.1	0.8	43.6	9.3
PBC-05	300	5.8	15.1	12.2	0.8	3.6	0.7	51.5	10.7
PBC-06	300	11.7	25.5	12.4	0.8	4.4	0.8	44.3	9.0
PBC-07	300	19.5	47.0	14.8	1.0	5.4	0.9	45.5	9.0
PBC-08	300	2.2	1.9	9.3	0.5	3.6	0.6	43.8	8.8
PBC-09	300	3.0	2.2	10.1	0.6	3.6	0.7	44.1	9.0
PBC-10	300	52.1	25.9	94.7	6.3	4.9	1.8	37.7	10.2

TABLE 3-2
RATIO OF HPGe POTASSIUM-40 CONCENTRATIONS TO RTRAK POTASSIUM-40 NET COUNTS

Area	HPGe Concentrations of K-40 (pCi/g)	RTRAK Net Counts of K-40 (cps)	Ratio HPGe/RTRAK (pCi/g/cps)
PBC-01	11.1	52.1	0.213
PBC-02	7.8	35.3	0.221
PBC-03	11.1	52.2	0.213
PBC-04	9.5	54.9	0.173
PBC-05	9.3	43.6	0.213
PBC-06	10.7	51.5	0.208
PBC-07	9.0	44.3	0.203
PBC-08	9.0	45.5	0.198
PBC-09	8.8	43.8	0.201
PBC-10	9.0	44.1	0.204
PBC-11	10.2	37.7	0.270

Average Ratio = 0.211
Standard Deviation = 0.023

Figure 3-1
Calibration of RTRAK for Thorium-232 by Correlation with HPGe Data

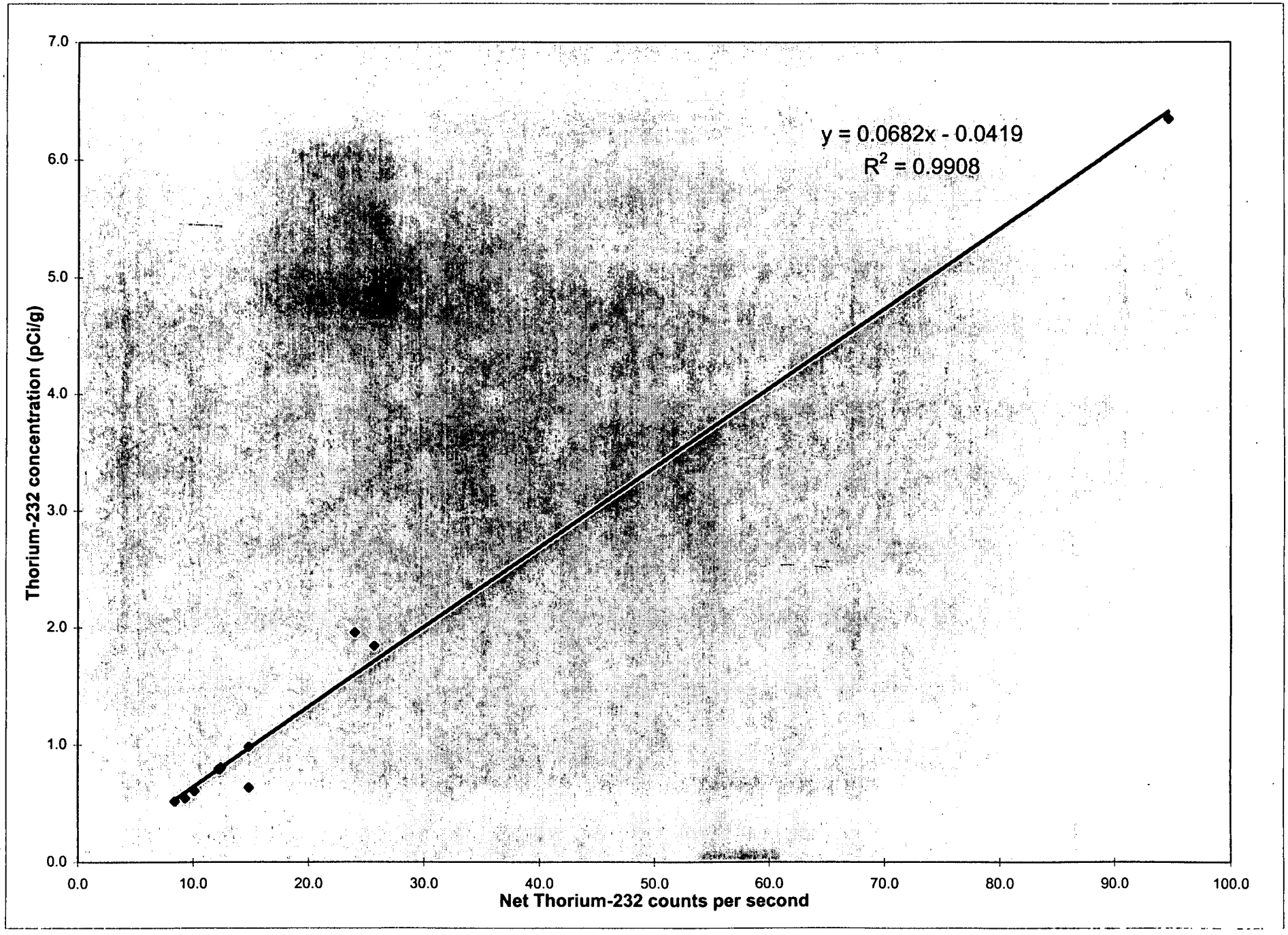


Figure 3-2
Calibration of RTRAK for Radium-226 by Correlation with HPGe Data

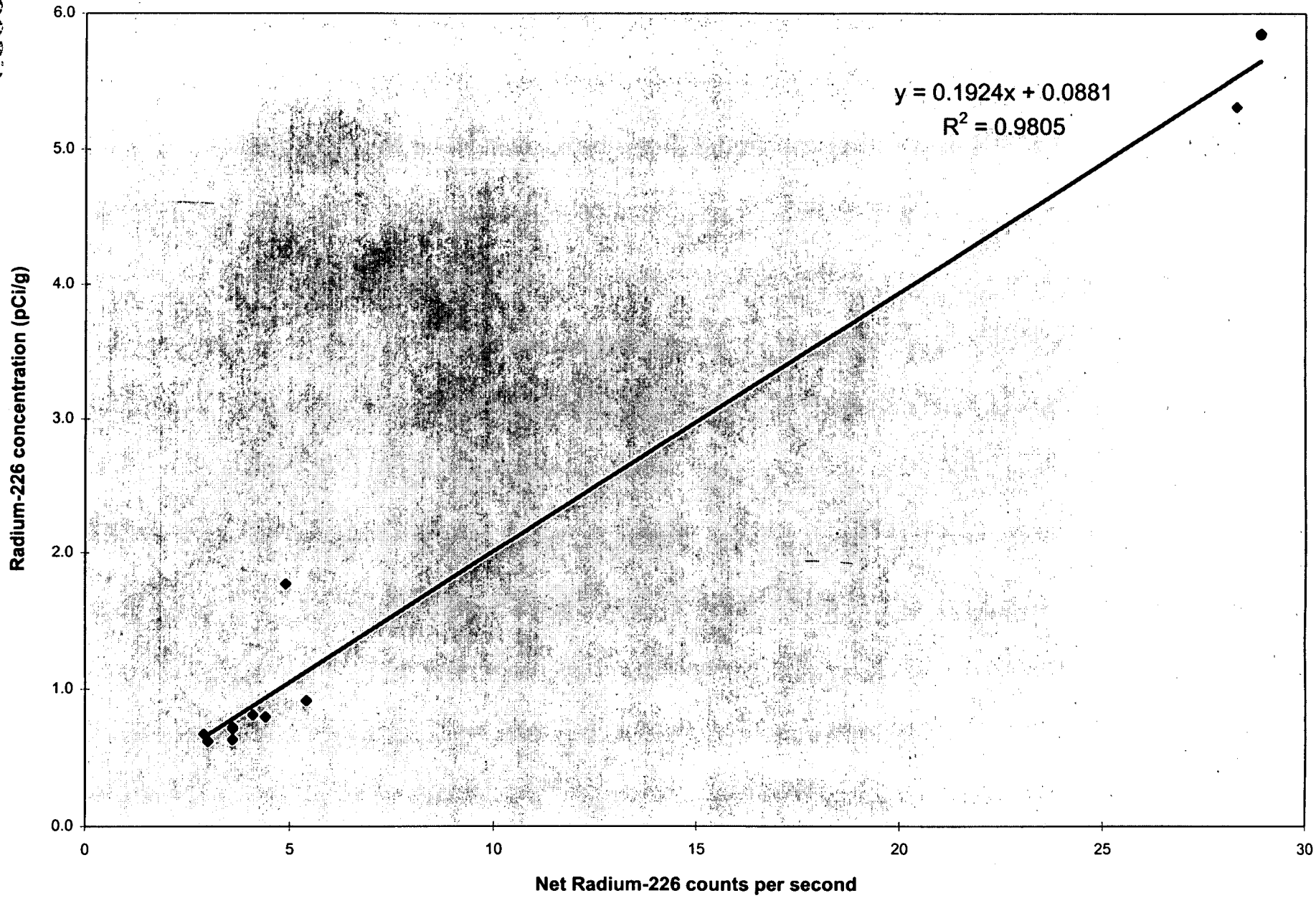
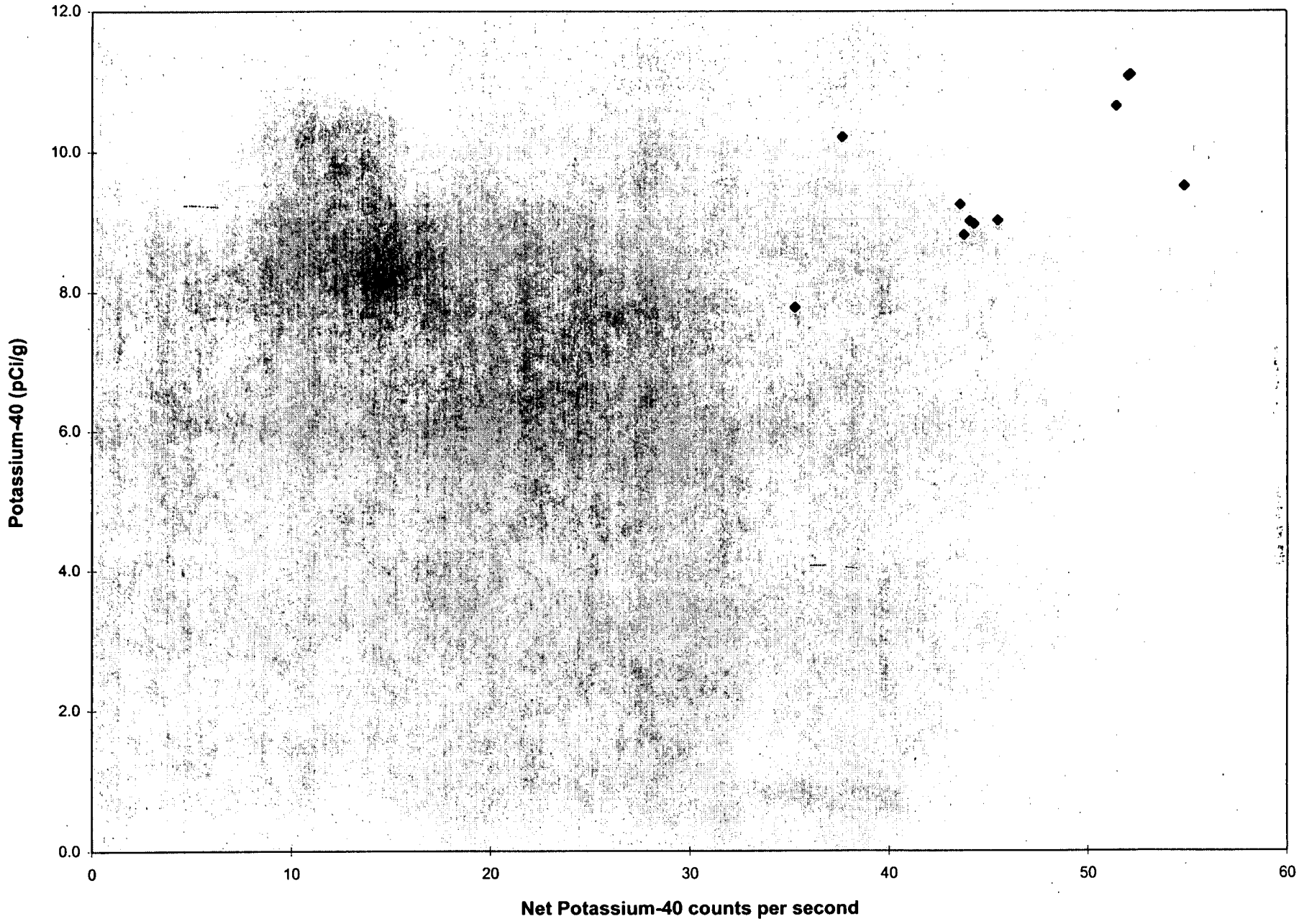


Figure 3-3

Scatter Plot of RTRAK Potassium-40 Measurements vs HPGe Potassium-40 Concentrations



SECTION 4.0
RTRAK SYSTEM QUALITY PARAMETERS

The RTRAK must generate data of known quality for it to be used in environmental decision-making. Three key data quality elements are examined in this Section: precision, minimum detectable concentration (MDC), and accuracy. Different combinations of tractor speed and data acquisition time are evaluated in order to delineate acceptable precision and MDCs. In addition, comparisons were made with HPGe measurements as a measure of the accuracy of the RTRAK system. Overall system quality parameters are based upon data taken from iterative runs along two profiles in two areas and HPGe measurements made in the same areas..

4.1 SYSTEM PRECISION

Precision is defined as the closeness in agreement of replicate measurements. Because the RTRAK is a mobile detector system, precision encompasses not only the NaI detector and associated electronics errors (including all counting and calibration errors), but also errors in the GPS system and operational errors (e.g., speed, vertical motion, etc.) inherent in the moving RTRAK system.

In most of the discussion that follows, precision is discussed in terms of uncertainty (expressed as a standard deviation). For the purposes of this report, four elements of error contribute to the overall uncertainty: spectrum background counting uncertainty, interference errors associated gamma rays other than those of interest, net peak count uncertainty, and other measurement uncertainty. The first three sources of error collectively comprise the counting error, which is expressed as:

$$\sigma = \sqrt{m}$$

where σ is the standard deviation of the total counts, m, observed within a region of interest. From the form of this equation, it can be seen that as each contribution to total counts increases (i.e., spectrum background, interference, and net peak counts), the uncertainty due to that contribution increases and the total uncertainty increases. However, the fractional uncertainty (σ as a percentage of the concentration) will decrease with an increase in total counts, because σ increases as a function of the square root of m while concentration is a linear function of m.

Spectrum background is the portion of a gamma ray spectrum beneath the peak of interest (Figure A-1, Appendix A). It is referred to as the "continuum" that occurs beneath peaks observed in a gamma spectrum. A principal component of the continuum is Compton scattering (the interaction of gamma rays with electrons resulting in imparting of energy to the electron and the deflection of the gamma ray with a decrease in its energy).

Interference errors include, for example, gamma photons used to measure thorium-232 and radium-226 having energies similar to those used to measure uranium-238 (Section 3.3). Similarly, Compton scattering of photons used to measure thorium-232 and radium-226 contribute to the background continuum for uranium-238.

Uncertainty due to net peak counts is simply that uncertainty attributable to a gamma photon peak. This element of uncertainty does not include any contribution from the spectrum background (Figure A-1, Appendix A).

Other measurement uncertainties comprise non-counting errors, such as errors in GPS positioning, errors due to a moving vehicle, calibration errors, etc.

4.1.1 Repeated Profile Measurements

The data from the repeated profile measurements (a single track in Area 1 Phase I; a circular track in the South Field) were evaluated to provide a measurement of the overall precision of the RTRAK system. The profile paths were divided into areas or segments of approximately equal size. The segment sizes were selected to minimize the contribution of spatial variations in radionuclide concentrations (i.e., to minimize heterogeneity) to the calculated standard deviations for the data within the segments. The assumption is that measurement points closest to one another should vary least in concentrations, so that the variability seen in measured and calculated data within an area of limited size should be primarily a result of the precision of the measurement system. As demonstrated in this report, the assumption is valid for the USID area, but not for portions of the South Field area. The standard deviations for the set of data within each segment represent the standard deviations or the precision associated with the individual measurements.

The profile for the USID area is a straight-line path that traverses locations of expected elevated activity (for the USID area) and a gravel-covered road. The profile was divided into 12 segments, including one encompassing the road. The segments at either end of the path were adjusted to exclude points in the segments where the RTRAK was turned at the end of each pass; 20 passes were made over this profile. The segments for the USID area are shown schematically in Figures 4-1A and 4-1B.

The other profile, located in the South Field area, was an elliptical shape, and ten repeat RTRAK runs around this elliptical profile were made. This profile was divided into 50 segments. These segments are smaller in size than those for the USID area because a high degree of variability was observed in the data within a number of larger segments that had originally been selected. A review of the individual measurements within those segments revealed that one or more measurements were significantly higher or lower than the others. These higher or lower measurements were considered an indication of actual variations in the radionuclide soil concentrations rather than indications of measurement error. To remove the impact of these variations, the segment sizes were reduced so that each segment would typically have only one or two measurements for each pass of the RTRAK (10-20 measurements in total). The segments selected for the South Field area are shown in Figures 4-2A and 4-2B.

The energy spectra for the individual measurements made in both areas were processed to provide the following data:

1. Total counts in the spectrum with no energy discrimination;
2. Activity concentrations for uranium-238, thorium-232, and radium-226;
3. Uncertainty for the individual results, based on counting uncertainty; and
4. Minimum detectable concentration (MDC) for the individual measurements, based on the counting uncertainty

The repeated profile measurements were made using varying combinations of travel speed and acquisition time. The combinations were used for the profile runs in the USID and South Field areas are listed below. For three of these time/speed combinations (i.e., 1, 3, and 4), the result is a viewing area of approximately 10 m^2. For the time/speed combination #2, the viewing area is approximately 7 m^2. The fundamental difference is the amount of time the RTRAK is allowed to measure that viewing window.

1. 2 second acquisition, 2 mph travel speed (USID area and South Field)
2. 2 second acquisition, 0.5 mph travel speed (USID area)
3. 8 second acquisition, 0.5 mph travel speed (USID area and South Field)
4. 4 second acquisition, 1 mph travel speed (South Field)

The individual results of the measurements within each segment were combined to calculate a mean concentration, the standard deviation of the distribution (i.e., the error associated with each measurement), average counting uncertainty, and the average minimum detectable concentration. The standard deviation of the distribution provides a measure of the total system precision expected for individual measurements within the area. The precision of the individual measurements is an important consideration in evaluating the usability of RTRAK data in potential applications.

4.1.2 Uranium-238

4.1.2.1 Contributions to Precision

The uranium-238 measurements display the lowest degree of precision of the three radionuclides of interest which limits the usability of the data at low concentrations. This occurs because of the high spectrum background and interferences from thorium-232 and radium-226 measurements. The uranium-238 region of interest (943.1 - 1058.9 keV) is at the lowest energy of the three radionuclides. At that energy, the spectrum background under the uranium-238 peak is relatively high because of the Compton continuum and the detector's inability to resolve naturally occurring gamma rays of comparable energies. The thorium-232 and the radium-226 contribute to the uranium uncertainty in two ways. First, the higher energy gamma rays from the radium-226 and thorium-232 undergo Compton scattering and contribute to the Compton continuum portion of the background. Second, the gamma rays associated with thorium-232 interfere with the uranium region of interest and gamma rays associated with radium-226 interfere with the uranium background region of interest. Quantifying uranium requires that counts in the regions of interest applicable to uranium be corrected for the background, the thorium concentration, and the radium concentration as discussed in Section 3.3. The uncertainties associated with these corrections combine with the high spectrum background and other sources of uncertainty, resulting in a high overall uranium-238 uncertainty. The measured number of net uranium counts within the region of interest also contribute to the uranium-238 uncertainty, but at

low uranium-238 concentrations, the uncertainty is dominated by the spectrum background with lesser but still significant contributions from the thorium-232 and radium-226 corrections (Table 4-11).

4.1.2.2 Overview of Repeated Profile Data

The uranium-238 means, standard deviations, and percent standard deviations (standard deviation as a percentage of the mean) for each of the segments in the USID and South Field profiles are presented in Appendix C, Table C-1, and in Figures C-1 through C-3 for the USID Area, and in Table C-2 and Figures C-4 through C-6 for the South Field. The data in Tables C-1 and C-2 are presented as a function of RTRAK operating speed and data acquisition time and are summarized in Table 4-1. Included in Table 4-1 are delta factors for each parameter. These are calculated by dividing the largest positive value of a parameter for any segment by the smallest positive value. The delta factors represent the range of the data. It can be seen by inspection of the tables and the figures that the means of the profile segments vary widely, but the standard deviations do not vary by much, particularly in the USID Area. For example, for the USID Area at 2 second/ 2 mph, the mean concentration is 16.7 pCi/g and the delta factor is approximately 3.4. By comparison the delta factor for the standard deviation is only about 1.4. Similarly, in the South Field area at 2 second/2 mph, the delta factor is 25.9 for the mean but only 2.3 for the standard deviation.

4.1.2.3 Uranium-238 Precision

The lack of correlation between the mean and the standard deviation is a consequence of the low uranium-238 concentrations in the study areas. At these concentrations, the standard deviation is primarily dependent on the magnitude of the Compton continuum and the thorium-232 and radium-226 uncertainties. At low concentrations, the net counts associated with the uranium-238 are small with respect to the spectrum background so they do not contribute significantly to the overall standard deviation. In the USID Area, the thorium-232 and radium-226 concentrations are low and relatively constant, so the Compton contribution is relatively constant across all of the profile segments. Consequently, the standard deviations remain relatively constant across all of the profile segments, regardless of the uranium-238 concentrations. The average standard deviations for the segments in the USID area are: 25.8 pCi/g for 2 second/2 mph, 26.7 pCi/g for 2 second/0.5 mph, and 14.1 pCi/g for 8 second/0.5 mph. The lower average standard deviation for the 8 second/0.5 mph measurements is a direct consequence of the longer data acquisition time. The standard deviation related to counting

uncertainty, for a single measurement, is proportional to the square root of the count rate for that measurement and is inversely proportional to the square root of the counting time:

$$\sigma = \sqrt{\frac{R}{T}} \qquad (1)$$

where:

σ is the standard deviation associated with the count rate
R is the count rate (cps)
T is the count time

Consequently, for an increase in the acquisition time from two to eight seconds, the counting uncertainty would decrease by a factor of two. The standard deviation for the USID data for the 8 second acquisition time is approximately one-half that of the 2 second data (14.1 vs. 25.8 and 26.7). This is an indication that the counting uncertainty dominates the overall precision of the measurement at low uranium concentrations. The average counting uncertainty for the individual measurements in the USID Area is 11 pCi/g for the 8 second/ 0.5 mph combination of operating parameters. This is approximately 78% of the measured standard deviations of the measurements within the segments, which further supports the conclusion that the counting uncertainty dominates the measurement variability at low concentrations.

In the South Field, the uranium-238 standard deviations show more variability than in the USID Area (a factor of 2.3 for low to high vs. a factor of 1.4 for low to high for the 2 second/2 mph runs). This appears to be a consequence of the wider range of thorium-232 and radium-226 concentrations; the highest uranium-238 standard deviations are seen for measurement locations where the thorium and radium results are the highest. However, the average standard deviations for the various acquisition times are still similar to those of the USID Area, and there is again no apparent relationship between the mean of the measurements within a segment and the standard deviation. The average standard deviations are: 27.3 pCi/g for 2 second/2 mph, 20.2 pCi/g for 4 second/1 mph, and 14.3 pCi/g for 8 second/0.5 mph. The standard deviation for the 8 second data acquisition time is approximately half of that for the two second acquisition time as predicted by Equation 1. The average counting uncertainty for the eight second acquisition time is approximately 11 pCi/g which is approximately 77% of the overall average standard deviation. These results are consistent with that observed for the USID Area and indicate that the background counting uncertainty dominates the standard deviation.

One important observation that can be clearly seen by inspecting Table 4-1 is that the standard deviations for the uranium-238 measurements are all larger than the segment means, with average percent standard deviations ranging from 171 to 474 %. The minimum standard deviation that can be expected for a single uranium-238 measurement is approximately 26 pCi/g for 2 second acquisition times and 14 pCi/g for 8 second acquisition times. Such large standard deviations preclude the use of individual RTRAK measurements at low concentrations. At higher uranium-238 concentrations, the background counting uncertainty will be a smaller fraction of the result, and the individual measurements can provide useable data. The actual concentration levels at which the individual RTRAK measurements could be used reliably depend on the precision requirements for using the data. For illustration purposes, it will be assumed that data for which the 95% confidence interval is less than 50% would be acceptable for use. Individual measurements would meet this criterion for uranium-238 concentrations of 102 pCi/g (306 ppm for total uranium) for 2 second acquisition times and 55 pCi/g (165 ppm for total uranium) for 8 second acquisition times.

4.1.2.4 Summary of Uranium-238 Results

The conclusions supported by the data may be summarized as follows:

1. The dominant contributor to the uranium-238 standard deviation at low concentrations is the counting uncertainty associated with the spectrum background. The counting uncertainty is approximately 77% of the overall standard deviation.

2. The standard deviations of the measurements change by a factor approximately proportional to the inverse square root of a change in the acquisition time. Precision can be improved by increasing the acquisition time. If the acquisition time is increased by a factor of four, the precision increases (standard deviation decreases) by a factor of two.

3. The presence of elevated concentrations of thorium-232 or radium-226 increases the standard deviations of uranium-238 measurements.

4. The poor precision limit the use of individual measurements at low uranium-238 concentrations. For individual measurements a 95% confidence interval of less than 50% of the reported concentration would be seen for uranium-238 concentrations greater than 55 pCi/g (165 ppm) for 8 second data acquisition times and 102 pCi/g (306 ppm) for 2 second data acquisition times.

4.1.3 Thorium-232

4.1.3.1 Contributions to Uncertainty

The thorium measurements have the lowest standard deviations of the three isotopes measured, irrespective of speed and data acquisition time. This is to be expected because there are no gamma rays of significant abundance at higher energies that contribute to the Compton continuum at the thorium region of interest. Consequently, the spectrum background is much smaller than for either uranium-238 or radium-226. In addition, there are no other gamma rays present in the FEMP soil that interfere appreciably with the region of interest (2405.4 - 2823.8 keV) used to quantify thorium-232. The thorium-232 means, standard deviations, and percent standard deviations are presented in Appendix C, Table C-3 and Figures C-3 through C-9 for the USID area, and in Table C-4 and Figures C-10 through C-12 for the South Field. These data are summarized in Table 4-2.

4.1.3.2 Overview of Repeated Profile Data

Within the USID Area, the thorium-232 concentrations are low, with the mean of the profile segments of near 0.75 pCi/g for all combinations of operating parameters and with delta factors for the means ranging from 1.58 to 2.48. This mean concentration is comparable to, or less than, expected natural background levels of thorium-232 in soils. The standard deviations are relatively constant, with delta factors ranging between 1.3 and 1.6. For most segments, the standard deviations for the measurements at the 8 second acquisition time are approximately a factor of two lower than for the 2 second acquisition time measurements, as expected. The average counting uncertainty for the 8 second/0.5 mph measurements is 0.11 pCi/g, which is about 58 percent of the average overall standard deviation (0.19 pCi/g) for 8 second/0/5 mph measurements. In the South Field area, the variability of the standard deviations is larger, with delta factors of 3.6 for 2 second/2 mph, 6.4 for 4 second/1 mph, and 5.6 for 8 second/0.5 mph.

4.1.3.3 Thorium-232 Precision

The highest standard deviations are found in segments with either high thorium-232 or high radium-226 concentrations. The average counting uncertainty for the 8 second/0.5 mph measurements in the South Field is 0.12 pCi/g, which is 54% of the overall average standard deviation of 0.22 pCi/g for the segments. These results indicate that while the counting uncertainty remains a major source of uncertainty, other sources of measurement uncertainty also contribute significantly. This is expected behavior for measurements with low spectrum backgrounds.

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As can be seen from Table 4-2, the standard deviations as a percentage of the mean are still quite high at the low concentrations observed in the study areas, ranging from a low of 26% for the 8 second acquisition time to a high of 49% for the 2 second acquisition times. The minimum standard deviation that can be expected is approximately 0.4 pCi/g for 2 second acquisition times and 0.2 pCi/g for 8 second acquisition times. This limits the useability of the data from individual measurements at concentrations near background. The actual concentration levels at which the individual RTRAK measurements could be used reliably would be dependent upon the precision requirements for use of the data. For illustration purposes, it will be assumed that data for which the 95% confidence interval is less than 50% would be acceptable for use. Individual measurements would meet that criterion for thorium-232 concentrations of 1.6 pCi/g for 2 second acquisition times and 0.8 pCi/g for 8 second acquisition times.

4.1.3.4 Summary of Thorium-232 Results

The conclusions supported by the data may be summarized as follows:

1. The counting uncertainty remains a significant contributor to the overall standard deviation, but other factors contribute approximately 46% of the total uncertainty for eight second acquisition times.

2. Precision can be improved by increasing the acquisition time. The improvement will be approximately equal to the inverse square roots of the acquisition times.

3. The precision limits the use of individual measurements at thorium-232 concentrations near background.

4. For individual measurements a 95% confidence interval of less than 50% of the reported concentration would be seen for thorium-232 concentrations as low as 1.6 pCi/g for an 8 second data acquisition time and 0.8 pCi/g for a 2 second data acquisition time.

4.1.4 Radium-226

4.1.4.1 Contributions to Uncertainty

The radium-226 means, standard deviations, and percent standard deviations are presented in Table C-5 and Figures C-13 through C-15 for the USID Area and in Table C-6 and Figures C-16 through C-18 for the South Field. These data are summarized in Table 4-3. The radium standard deviations are smaller than those for uranium, but larger than those for thorium-232. The radium-226 region of interest (1699.3 - 1850.9 keV) is at a higher energy than the uranium region of interest, and therefore, the magnitude of the Compton continuum is smaller than for uranium. For the typical FEMP

spectrum, the predominant gamma rays of significant abundance that contribute to the Compton continuum at this energy are from thorium-232. The net effect is a much lower background for radium-226 than for uranium-238. In addition, there are no interferences in the radium-226 regions of interest that are large enough to require correction, so the only counting-uncertainty contributions to the radium-226 standard deviation are the Compton continuum and the net radium-226 counts.

4.1.4.2 Overview of Repeated Profile Data

Within the USID Area, the radium-226 concentrations are low, with the means of the profile segments about 0.8 pCi/g. The average standard deviations for the 2 second acquisition-time measurements are also approximately 0.8 pCi/g, with a delta factors of about 1.4. For the 8 second acquisition-time measurements, the mean is 0.8 pCi/g and the average standard deviation 0.4 with a delta factor of 1.3. In the South Field Area, the variability of the standard deviations is larger than in the USID area, with delta factors ranging between 8.4 and 14.

4.1.4.3 Radium-226 Precision

Within the USID Area, the average standard deviation for the 8 second acquisition-time measurements is approximately a factor of two lower than for the 2 second acquisition time measurements. The average counting uncertainty for the 8 second/0.5 mph measurements is 0.3 pCi/g, which is 75% of the average overall uncertainty (0.40 pCi/g). This indicates that for radium-226 at low concentrations, the background counting uncertainty dominates the standard deviation.

The highest standard deviations in the South Field are found in segments with either high radium-226 or high thorium-232. For the high thorium-232 segments, the dominate source of uncertainty is the Compton continuum within the radium region of interest. In segments where the radium-226 is high, the Compton continuum is still a significant source, but the uncertainty associated with the net radium counts also contributes significantly. For many of the segments, the ratios of the average standard deviations are inversely comparable to the ratios of the square roots of the acquisition times. However, there are a number of cases where this is not the case. For segments where either the radium-226 or thorium-232 results are high, the standard deviation does not consistently decrease with increased acquisition time by the expected factor. The reason is not clear, but it may be a consequence of variability (heterogeneity) in the radium-226 or thorium-232 concentrations in the study area. The concentrations appear to vary rapidly over a small area, so it may be that a small change in the

positioning of the RTRAK in the repeated passes could lead to a large change in the activity within the field of view. This would lead to a larger standard deviation than would be expected simply from the counting uncertainty. This is the case for both the average standard deviations of all of the segments, and the individual segments. The average counting uncertainty for the 8 second/0.5 mph measurements is 0.4 pCi/g. This is comparable to the average overall standard deviation of the segments, but is significantly lower than the maximum value of 1.7 pCi/g. This supports the conclusion that factors other than counting uncertainty are contributing to the high standard deviations.

As can be seen from Table 4-3, the standard deviations as a percentage of the mean are very high at the low concentrations observed in the study areas, ranging from a low of 40 percent for the 8 second acquisition time to a high of 102 percent for the 2 second acquisition times. The minimum standard deviation that can be expected is approximately 0.8 pCi/g for 2 second acquisition times and 0.4 pCi/g for 8 second acquisition times. The actual concentration levels at which the individual RTRAK measurements could be used reliably would be dependent upon the precision requirements for use of the data. For illustration purposes, it will be assumed that data for which the 95% confidence is less than 50% would be acceptable for use. Individual measurements would meet that criterion for radium-226 concentrations of 3.1 pCi/g for 2 second acquisition times and 1.6 pCi/g for 8 second acquisition times.

4.1.4.4 Summary of Radium-226 Results

The conclusions supported by the data may be summarized as follows:

1. The counting uncertainty is a major contributor to the overall standard deviation, accounting for approximately 75% of the overall standard deviation.

2. Precision can be improved by increasing the acquisition time, by a factor approximately equal to the square root of the increase.

3. The precision limits the use of individual measurements at radium-226 concentrations near background. For individual measurements a 95% confidence interval of less than 50 percent would be seen for radium-226 concentrations of 1.6 pCi/g for the 8 second data acquisition times and 3.1 pCi/g for the 2 second data acquisition times.

4.1.5 Gross Counts

4.1.5.1 Contributions to Uncertainty

Gross count results are obtained from the RTRAK by simply summing all of the counts seen in the RTRAK gamma spectrum. This includes all counts from the Compton continuum as well as counts from all gammas that interact with the detector, regardless of the radionuclide. Consequently, there are no contributions to the uncertainty of the results that are comparable to spectrum background or interferences. The counting uncertainty is simply given by the square root of the total number of counts accumulated during the acquisition period. Because of the large number of counts accumulated in even a 2 second measurement in a area of low activity concentrations (frequently of the order of 10,000 counts), the fractional counting uncertainty is small, typically around 1 percent. The overall standard deviation is a combination of this small counting uncertainty plus other measurement uncertainties.

4.1.5.2 Overview of Repeated Profile Data

The means, standard deviations, and percent standard deviations for the gross count data are presented in Table C-7 and Figures C-19 through C-21 for the USID Area and in Table C-8 and Figures C-22 through C-24 for the South Field. These data are summarized in Table 4-4. The delta factors for the standard deviations range as high 45 for the 8 second acquisition time measurements in the South Field. This is in part an artifact of the very small standard deviations seen for some segments and the apparent effects of radionuclide inhomogeneity in the soils within some segments.

4.1.5.3 Gross Counts Precision

The gross-count measurements show the most consistent segment means across the three combinations of parameters and have a much smaller percent standard deviation than the isotopic data. This is to be expected because the large number of counts obtained in a single measurement results in a low counting uncertainty. For the isotopic measurements, the counting uncertainties are all high at low concentrations. The smallest average percent standard deviation for the isotopic data is for thorium which was approximately 26% for the 8 second measurement. However, for gross counts, the average percent standard deviation is about 6% for any of the acquisition times evaluated, in both the USID Area and in the South Field. The standard deviations for the individual measurements are also comparable for the three combinations of speed/time in both areas. This occurs despite the fact that the acquisition time for one of the combinations is a factor of four greater than those with the shortest

acquisition times. It would generally be expected that the measurements with the longer acquisition time would have smaller standard deviations because the counting uncertainty should be a factor of two lower as discussed earlier. The fact that this is not observed is an indication that other sources of measurement uncertainty or the variability in the actual soil activity concentration are significant contributors to the overall standard deviation of the gross count data. It is interesting to note that the highest percent standard deviations in the USID Area are observed for the road and for Areas 7 and 8. The high standard deviation for the road is in part because of the lower activity concentration at that location; the lower the activity, the fewer counts and the higher the counting uncertainty. Areas 7 and 8 are on either side of the road. Some of the measurements assigned to these areas overlap the edges of the road. This results in several measurements that have a much lower activity concentration than the other points within the areas, which increases the overall standard deviation of the data set.

Within the South Field, the highest percent standard deviations are typically in areas which have the highest radium or thorium activities. This may be an indication that the high concentrations of these nuclides are localized into very small areas and variations in the positioning of the RTRAK on the multiple passes result in significant differences in the activity concentrations within the RTRAK field of view.

For the gross counts, it is difficult to estimate the minimum expected standard deviation from the average standard deviations of the segments, because there are indications that inhomogeneity in radionuclide concentrations may be a significant contributor to the overall standard deviation. Standard deviations near 2% are common for many of the segments, and it appears that this is most likely the minimum standard deviation that can be expected. With such good precision, individual gross-counts measurements can be useable to provide general indications of elevated activity. Because gross-counts measurements provide no radionuclide-specific information it's use is limited to general radiological screening.

4.1.5.4 Summary of Gross Counts Results

The conclusions supported by the repeated profile measurements may be summarized as follows:

1. Gross counts measurements exhibit a high degree of precision.

2. The counting uncertainty does not appear to be the major contributor to the overall standard deviation.

3. Gross-counts measurements do not provide radionuclide-specific information.

4. Gross-counts measurements can be effective in defining general patterns of elevated activity.

4.2 MINIMUM DETECTABLE CONCENTRATION

The detection limit L_D refers to the statistically determined quantity of a radionuclide that can be measured at a preselected confidence level. The magnitude of L_D is a function of instrument parameters, radiological background levels, and the procedure used to make the measurement. While any confidence level could be chosen to calculate L_D, it is traditionally defined as the activity level above which there is less than 5% probability that activity will be reported as present when it is really absent (Type I error, or false detection), or reported as absent when it is really present (Type II error, or false non-detection). This confidence level has been adopted for the purposes of this study.

The concept of using the L_D for measurements of radionuclides was first proposed by L. Currie in 1968. It is intended to be an *a priori* (before the first) estimate of the activity level that a system or technique can reliably measure under a given set of conditions. The L_D is not intended to be used *a posteriori* (after the fact) to evaluate individual measurements.

L. Currie defines the detection limit L_D as:

$$L_D = 2ks,$$

where:

k = factor related to the acceptable risk for false detection and false non- detection, assuming that risk level is equal. At a 5% risk, k = 1.645

s = the standard deviation of the measurement from when the net measurement is near the background

For this study, the detection limit was calculated in units of pCi/g, and thus is referred to as the MDC.

The repeated profile runs were located so that the profile would cross a road in the USID study area. The road has been graded and covered with gravel, so that the road surface can be considered

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relatively uncontaminated. For the purpose of the RTRAK applicability study, the multiple measurements in the area encompassing the road are assumed to be representative of background. The standard deviations of the distribution are equivalent to the standard deviation of the individual measurements. These standard deviations were used to calculate a priori MDCs for the three combinations of acquisition time and travel speed. The acceptable risk for both false detection and false non-detection was set at 5%, as stated above, so k = 1.645, and the MDC = 3.29s. The lowest MDCs for all three isotopes are obtained for the 8 second acquisition time. However, even at 8 seconds, the MDC for uranium-238 significantly exceeds the FRL for total uranium (48.6 pCi/g uranium-238 equates to 140 ppm of total uranium). The MDCs at 8 seconds for thorium-232 (0.8 pCi/g) and radium-226 (1.4 pCi/g) are below their FRLs of 1.5 pCi/g and 1.7 pCi/g, respectively. For the 2 second acquisition time, only the thorium-232 MDC (1.1 pCi/g) does not exceed the FRL.

MDCs, based only on the counting uncertainty, were calculated *a posteriori* for the individual measurements for the 8 second/0.5 mph repeat profile runs in both the USID Area and South Field. Table 4-6 presents the average counting uncertainty MDCs for the two study areas. For uranium, the *a posteriori* counting uncertainty MDCs are nearly identical to the *a priori* measured at the road in the USID area, while the radium *a posteriori* counting-uncertainty MDCs are only slightly smaller than the total system *a priori* MDC. However, the thorium *a posteriori* counting-uncertainty MDCs are more than a factor of three smaller than the *a priori* MDC. This is consistent with the conclusions in Section 3.1.1, that the counting uncertainty is the dominant source of uncertainty for the uranium and radium measurements at low concentrations, but that other factors are significant for thorium measurements.

As shown in Table 4-5, increasing the acquisition time decreases the MDC. If the only contribution to the uncertainty were the counting uncertainty, the MDC would decrease by the square root of the factor by which the acquisition time has changed. That would indicate that increasing the acquisition time from 2 to 8 seconds would decrease the MDC by a factor of two. The fact that the decrease was only about a factor of 1.5 for all the nuclides indicates that other factors contribute to the uncertainty. One key factor may relate to the precision by which the RTRAK operator was able to duplicate the path for all of the repeated runs.

The standard deviation of distribution represents the precision associated with the individual measurements, or how well each measurement is likely to estimate the mean of the distribution.

However, a mean calculated from multiple measurements is a much better estimate of the true mean. The standard deviation of the mean, also called the standard error, is the measure of the precision of that calculated mean. The standard error is obtained by dividing the standard deviation of the distribution by the square root of the number of measurements used in calculating the mean, or $s/(n)^{1/2}$. Because the MDC is a function of the standard deviation, an MDC associated with a mean calculated from multiple measurements would be based on the standard error. Consequently, results calculated by aggregating multiple measurements would have a lower MDC, although that would be gained at the expense of poorer spatial resolution. The effects of aggregating or spatially averaging RTRAK measurements is discussed in detail in Section 5.5.2.

The greater the number of measurements that are aggregated to establish the mean concentration, the smaller are the standard error and the MDC. The number of measurements that should be aggregated is dependent upon the required MDC and spatial resolution. MDCs obtained by aggregating 5, 10, 50, and 100 measurements for the 8 seconds/0.5 mph run are shown in Table 4-7. The MDCs obtained for the individual measurements shown in Table 4-5 are also presented in Table 4-7 for comparison. The MDCs for uranium can be reduced to below the FRL (equivalent to 27 pCi/g of uranium-238) with the aggregation of as few as five measurements. The MDCs for radium-226 and thorium-232 are below the FRLs for individual measurements at the 8-second acquisition time, but aggregating clearly lowers their MDCs.

4.3 ACCURACY

4.3.1 Calibration Verification

As discussed in Section 3.3, the RTRAK's initial calibration was obtained by performing regression analyses of static RTRAK data and HPGe measurements made during the Comparability Study, Part B. To test whether the calibration remained valid, static RTRAK measurements and HPGe measurements were made at four locations in the USID area. The results of these measurements and their calculated standard deviations are shown in Table 4-8. The RTRAK values are the means of a series of measurements taken at each location. RTRAK measurements were taken for both 2 second (150 measurements) and 8 second (38 measurements) acquisition times for 300 seconds. The HPGe measurements are single measurements at each of the same locations at 900 seconds. The standard deviations shown on the table are the standard deviations of the mean for the RTRAK measurements and the counting standard deviation for the HPGe data.

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The data exhibit excellent agreement for the uranium-238 and thorium-232 results. The radium-226 agreement was not as good as for uranium-238 and thorium-232. Based upon these data, the uranium and thorium calibrations remain valid, but the radium calibration yields RTRAK data consistently 20% to 30% higher than HPGe data. One explanation for the radium disagreement may be that the measurements were conducted on different days, approximately one week apart. It is possible that a change in soil moisture and other environmental conditions caused a change in the rate that radon emanated from the soil; this would result in different degrees of equilibrium of the radium decay products which are the sources of gamma rays used to quantify radium. The effect of disequilibrium on in-situ gamma measurements is discussed in the HPGe Comparability Study (DOE 1997a).

4.3.2 Comparison of HPGe and RTRAK Isotopic Results

Table 4-9 compares HPGe values averaged over the entire USID Area with RTRAK values averaged over the whole area. As the table indicates, there is good agreement between the two systems for radium and thorium when their data are averaged over the whole area, with a slightly high bias present in the RTRAK. The agreement for uranium is not as good for the 2 second/2 mph run, but becomes markedly better for the 8 second/0.5 mph run.

Because of the accuracy of the HPGe and the fact that the total average for each isotope incorporates 36 HPGe shots, the standard deviation associated with the HPGe averages reflects primarily the true spatial variation present in the isotopes in this area. Note that when the RTRAK standard deviation for a particular isotope is significantly greater than that for the HPGe, it is a reflection of the effect of the counting uncertainty on the RTRAK average. For example, in the case of thorium, moving from 2 second/2 mph to 8 second/0.5 mph has little effect on the standard deviation of the estimated average because the counting uncertainty is small enough to be essentially insignificant. However, for uranium, increasing the acquisition time has a significant impact on the standard deviation for the areal average because the counting uncertainty is significant.

Table 4-10 compares in situ HPGe results with RTRAK isotopic values averaged over each of the individual HPGe viewing areas (36 in all) in the USID area for each of the three principal gamma-emitting isotopes: radium-226, thorium-232 and total uranium. Again, agreement for the individual HPGe measurement points is reasonably good for the 8 second/0.5 mph runs for all three isotopes, but

there is significant disagreement for numerous data points for the 2 second/2 mph runs. This latter disagreement may be a consequence of the low concentrations and poor precision at those levels.

4.4 SUMMARY AND CONCLUSIONS

The results of the repeated profile measurements clearly show that counting uncertainties are major contributors to the overall standard deviations of the individual measurements. For uranium-238, thorium-232, and radium-226, the precision can be improved by increasing the acquisition time. The improvement is proportional to the square root of the factor by which the acquisition time is increased. A similar effect is not observed for gross count result. This may be because the counting uncertainties are small for these measurements and other factors that are unrelated to acquisition time dominate the overall standard deviation. Table 4-11 summarizes the contributions of various sources of uncertainty to the overall standard deviation of the measurements.

Tables 4-12 through 4-14 present calculated estimated standard deviations and 95% Upper Confidence Limits for uranium-238, thorium-232, and radium-226 at various radionuclide concentrations for measurements at 2 second/2 mph, 4 second/1 mph, and 8 second/0.5 mph. These concentrations include the FRLs and 3 x FRLs for the radionuclides. The uranium-238 values are presented as total-uranium equivalents because FEMP remediation criteria are defined in terms of total uranium. These estimates are based on the minimum expected standard deviations and counting uncertainties discussed in Section 4.1. The following assumptions were made in calculating the estimates: (1) for uranium, it is assumed that thorium-232 and radium-226 are present at their respective FRLs of 1.5 and 1.7 pCi/g; (2) sources of measurement uncertainty other than counting uncertainty are unrelated to radionuclide concentration; (3) the spectrum backgrounds will remain constant with increasing radionuclide concentrations and can be represented by the average values observed for the repeated profile run measurements; and (4) the counting uncertainties and other uncertainties combine as the square of the uncertainty (i.e., variances are additive). Actual measurements are likely to have somewhat higher overall standard deviations, but these estimates are adequate for planning purposes. The high standard deviations for the individual RTRAK measurements preclude their use at low uranium-238 and radium-226 concentrations and limits their use for thorium-232 at concentrations near background. However, it can be clearly seen from Tables 4-12 through 4-13 that at higher concentrations, the fractional standard deviation (standard deviation as a percent of the concentration) becomes relatively small even for uranium.

Gross count results have high precision for the individual measurements. This would allow these data to be used even at concentrations near background. Unfortunately, because these data would provide no radionuclide-specific data, their use would be limited to cases where the primary information needed is a definition of general patterns of contamination. However, because a single measurement covers only about 10 square meters, these measurements would provide excellent spatial resolution.

The MDCs for individual measurements exceed the FRLs for all three radionuclides of interest for 2 second acquisition-time measurements. For an acquisition time of 8 seconds, the uranium-238 individual measurement MDC still significantly exceeds the equivalent FRL of 27 pCi/g, while that of radium-226 is 93% of the FRL, and that of thorium-232 is 47% of the FRL. The effective MDCs can be reduced by using an aggregation of multiple measurements rather than relying on individual measurements. This is equivalent to averaging the data over a larger area than the RTRAK field of view. While this allows the applicability of the RTRAK to be extended to low concentrations, the spatial resolution is degraded.

RTRAK and HPGe measurements taken in the same locations exhibit good agreement. This is the case for both static and dynamic measurements. For the dynamic uranium-238 measurements, there is significant disagreement for a number of data points for the 2 second/2 mph runs. This may be a reflection of the poor precision observed for the individual measurements.

While the standard deviations of the individual measurements are in some cases large, the measurements can be useful for many applications. However, if a concentration value must be estimated with a smaller standard deviation than can be obtained from the individual measurements, it may be practical to average multiple measurements. The resulting mean would represent the concentration within the area covered by the averaged measurements. In this case, the appropriate measure of uncertainty would be the smaller standard deviation of the mean rather than the standard deviation associated with the distribution of measurements. The use of aggregated measurements is addressed in Section 5.

TABLE 4-1
SUMMARY OF URANIUM-238 INFORMATION FOR USID AND SOUTH FIELD PROFILE STUDIES

Operating Conditions	Area	Isotope	Avg. Segment Means (pCi/g)	Δ Factor[a] for Segment Means	Avg. Segment SDs[b] (pCi/g)	Δ Factor[a] for Segment SDs	Avg. Segment % SDs (pCi/g)	Δ Factor[a] for Segment % SDs
2 mph/2 sec	USID	U-238	16.73	3.38	25.82	1.35	171.11	3.08
0.5 mph/2 sec	USID	U-238	14.38	3.88	26.66	1.38	217.22	3.84
0.5 mph/8 sec	USID	U-238	17.16	2.59	14.10	1.28	87.65	2.69
2 mph/2 sec	SF[c]	U-238	9.88	25.90	27.28	2.32	474.14	18.96
1 mph/4 sec	SF	U-238	10.57	11.23	20.19	2.78	277.88	26.37
0.5 mph/8 sec	SF	U-238	9.71	14.23	14.29	3.84	285.78	131.7

a Delta (Δ) factors are obtained by dividing the largest positive value in a data set by the smallest positive value. For simplicity, negative data values are ignored.
b SD = Standard Deviation
c SF = South Field

TABLE 4-2
SUMMARY OF THORIUM-232 INFORMATION FOR USID AND SOUTH FIELD PROFILE STUDIES

Operating Conditions	Area	Isotope	Avg. Segment Means (pCi/g)	Δ Factor[a] for Segment Means	Avg. Segment SDs[b] (pCi/g)	Δ Factor[a] for Segment SDs	Avg. Segment % SDs (pCi/g)	Δ Factor[a] for Segment % SDs
2 mph/2 sec	USID	Th-232	0.75	2.48	0.35	1.31	48.88	2.32
0.5 mph/2 sec	USID	Th-232	0.74	1.91	0.36	1.29	49.58	1.97
0.5 mph/8 sec	USID	Th-232	0.75	1.58	0.19	1.56	25.95	2.23
2 mph/2 sec	SF[c]	Th-232	0.82	5.62	0.39	3.62	49.54	2.40
1 mph/4 sec	SF	Th-232	0.86	8.54	0.30	6.42	37.58	4.27
0.5 mph/8 sec	SF	Th-232	0.83	5.31	0.22	5.55	26.13	3.16

a Delta (Δ) factors are obtained by dividing the largest positive value in a data set by the smallest positive value. For simplicity, negative data values are ignored.
b SD = Standard Deviation
c SF = South Field

TABLE 4-3
SUMMARY OF RADIUM-226 INFORMATION FOR USID AND SOUTH FIELD PROFILE STUDIES

Operating Conditions	Area	Isotope	Avg. Segment Means (pCi/g)	Δ Factor[a] for Segment Means	Avg. Segment SDs[b] (pCi/g)	Δ Factor[a] for Segment SDs	Avg. Segment SDs (pCi/g)	Δ Factor[a] for Segment % SDs
2 mph/2 sec	USID	Ra-226	0.77	1.57	0.77	1.40	100.43	1.24
0.5 mph/2 sec	USID	Ra-226	0.79	1.52	0.80	1.37	101.65	1.35
0.5 mph/8 sec	USID	Ra-226	0.81	1.24	0.40	1.33	50.16	1.60
2 mph/2 sec	SF[c]	Ra-226	1.36	9.43	0.91	2.75	82.08	6.63
1 mph/4 sec	SF	Ra-226	1.39	8.40	0.67	5.54	57.39	11.04
0.5 mph/8 sec	SF	Ra-226	1.38	13.79	0.47	7.17	40.84	14.20

a Delta (Δ) factors are obtained by dividing the largest positive value in a data set by the smallest positive value. For simplicity, negative data values are ignored.
b SD = Standard Deviation
c SF = South Field

TABLE 4-4
SUMMARY OF GROSS COUNTS INFORMATION FOR USID AND SOUTH FIELD PROFILE STUDIES

Operating Conditions	Area	Isotope	Avg. Segment Means (cps)	Δ Factor[a] for Segment Means	Avg. Segment SDs[b] (cps)	Δ Factor[a] for Segment SDs	Avg. Segment % SDs (cps)	Δ Factor[a] for Segment % SDs
2 mph/2 sec	USID	Gross Counts	2937	1.53	142	7.73	5.30	10.91
0.5 mph/2 sec	USID	Gross Counts	2924	1.15	152	8.16	5.78	11.98
0.5 mph/8 sec	USID	Gross Counts	2456	1.39	176	10.75	6.36	13.84
2 mph/2 sec	SF[c]	Gross Counts	2849	2.95	198	23.52	6.29	14.36
1 mph/4 sec	SF	Gross Counts	2893	3.07	194	37.57	5.90	22.60
0.5 mph/8 sec	SF	Gross Counts	2883	2.93	180	45.13	5.34	21.78

a Delta (Δ) factors are obtained by dividing the largest positive value in a data set by the smallest positive value. For simplicity, negative data values are ignored.
b SD = Standard Deviation
c SF = South Field

TABLE 4-5
COMPARISON OF CO-LOCATED STATIC RTRAK AND HPGe MEASUREMENTS

Data Point	Data Acquisition Time	Uranium-238 (pCi/g)				Thorium-232 (pCi/g)				Radium-226 (pCi/g)			
		HPGe	HPGe Std Dev	RTRAK	RTRAK SD of Mean	HPGe	HPGe Std Dev	RTRAK	RTRAK SD of Mean	HPGe	HPGe Std Dev	RTRAK	RTRAK SD of Mean
10	2 sec	22.5	0.57	20.46	2.30	0.7	0.02	0.84	0.03	0.7	0.02	0.87	0.08
10	8 sec	22.5	0.54	22.16	2.45	0.7	0.02	0.82	0.02	0.7	0.02	0.93	0.06
15	2 sec	22.4	0.58	20.77	2.20	0.8	0.02	0.89	0.03	0.7	0.02	0.91	0.07
15	8 sec	22.4	0.58	23.60	2.44	0.8	0.02	0.86	0.03	0.7	0.02	1.06	0.06
35	2 sec	13.4	0.54	10.65	2.19	0.8	0.03	0.80	0.03	0.7	0.02	0.87	0.06
35	8 sec	13.4	0.54	11.98	2.26	0.8	0.03	0.81	0.02	0.7	0.02	0.87	0.07
41	2 sec	13.3	0.54	11.74	2.18	0.7	0.02	0.80	0.03	0.7	0.02	0.95	0.07
41	8 sec	13.3	0.54	15.76	2.20	0.7	0.02	0.77	0.03	0.7	0.02	0.78	0.07

TABLE 4-6
A PRIOR MDC (pCi/g) BASED UPON MEASUREMENTS IN THE USID AREA

Nuclide	2 mph/2 sec	0.5 mph/2 sec	0.5 mph/8 sec
Uranium-238 (pCi/g)	71.8	70.2	46.8
Thorium-232 (pCi/g)	1.1	1.2	0.8
Radium-226 (pCi/g)	2.2	2.2	1.4

TABLE 4-7
A POSTERIORI AVERAGE MDC (pCi/g)
BASED ON COUNTING UNCERTAINTY ONLY (0.5 mph/8 sec)

Nuclide	USID	South Field
Uranium-238 (pCi/g)	43.0	45.0
Thorium-232 (pCi/g)	0.2	0.2
Radium-226 (pCi/g)	1.1	1.2

TABLE 4-8
MDC (pCi/g) BASED UPON TOTAL SYSTEM UNCERTAINTY FOR AGGREGATED MEASUREMENTS (0.5 mph/8 sec)

	Number of Aggregated Measurements				
Nuclide	1	5	10	50	100
Uranium (pCi/g)	46.8[a]	21.0	15.0	6.6	4.7
Thorium (pCi/g)	0.8	0.37	0.26	0.12	0.08
Radium (pCi/g)	1.4	0.63	0.45	0.20	0.14

a Numbers are MDCs

TABLE 4-9
COMPARISON OF AVERAGE RTRAK RESULTS WITH HPGe RESULTS - USID AREA

	Radium-226 (pCi/g)			Thorium-232 (pCi/g)			Total Uranium (ppm)		
	HPGe	2 mph/ 2 sec	0.5 mph/ 8 sec	HPGe	2 mph/ 2 sec	0.5 mph/ 8 sec	HPGe	2 mph/ 2 sec	0.5 mph/ 8 sec
Average	0.68	0.76	0.78	0.72	0.75	0.72	50	37	52
Std Dev	0.06	0.18	0.09	0.11	0.10	0.09	12	21	14

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TABLE 4-10
COMPARISON OF HPGe AND RTRAK RESULTS
- INDIVIDUAL HPGe MEASUREMENTS - USID AREA

		Radium-226 (pCi/g)			Thorium-232 (pCi/g)			Total Uranium (ppm)		
HPGe ID	CPS	HPGe	RTRAK 2 mph 2 sec acq	RTRAK 0.5 mph 8 sec acq	HPGe	RTRAK 2 mph 2 sec acq	RTRAK 0.5 mph 8 sec acq	HPGe	RTRAK 2 mph 2 sec acq	RTRAK 0.5 mph 8 sec acq
500349-10	3036	0.67	1.00	0.66	0.73	0.70	0.76	67.46	77.73	54.30
500349-11	2809	0.67	0.80	0.70	0.69	0.74	0.76	45.83	36.09	32.01
500349-12	2639	0.73	0.80	0.82	0.75	0.70	0.60	46.48	5.61	58.50
500349-13	2367	0.49	0.68	0.78	0.31	0.55	0.49	14.47	8.22	25.32
500349-14	2591	0.61	0.61	0.76	0.67	0.60	0.59	53.65	37.53	53.34
500349-15	2982	0.76	0.63	0.72	0.84	0.69	0.83	76.41	62.91	65.04
500349-16	2990	0.66	0.78	0.72	0.79	0.84	0.78	52.16	46.23	57.66
500349-17	2924	0.66	0.40	0.72	0.75	0.72	0.79	41.09	17.46	34.86
500349-18	3139	0.74	0.42	0.81	0.80	0.91	0.80	55.71	52.20	61.71
500349-19	3107	0.71	0.87	0.87	0.77	0.78	0.73	56.66	36.90	64.44
500349-20	2637	0.75	0.78	0.75	0.74	0.66	0.74	59.02	53.25	36.51
500349-21	2423	0.50	0.56	0.87	0.31	0.62	0.62	14.66	10.20	45.54
500349-22	2829	0.70	0.76	0.79	0.84	0.75	0.64	54.55	44.31	66.00
500349-23	3003	0.68	0.93	0.78	0.77	0.80	0.75	47.93	44.13	70.68
500349-24	3078	0.68	0.77	0.58	0.75	0.72	0.76	46.15	40.62	55.86
500349-25	3108	0.66	1.04	0.74	0.78	0.90	0.82	44.64	16.35	40.50
500349-26	3132	0.74	1.00	0.85	0.76	0.89	0.75	52.46	27.51	54.96
500349-27	3154	0.72	0.85	0.87	0.77	0.89	0.81	54.85	52.71	60.57

TABLE 4-10
(continued)

		Radium-226 (pCi/g)			Thorium-232 (pCi/g)			Total Uranium (ppm)		
HPGe ID	CPS	HPGe	RTRAK 2 mph 2 sec acq	RTRAK 0.5 mph 8 sec acq	HPGe	RTRAK 2 mph 2 sec acq	RTRAK 0.5 mph 8 sec acq	HPGe	RTRAK 2 mph 2 sec acq	RTRAK 0.5 mph 8 sec acq
500349-28	3115	0.72	0.92	0.85	0.75	0.82	0.80	57.24	72.30	53.67
500349-29	2863	0.75	0.46	0.85	0.72	0.70	0.52	50.09	10.41	48.63
500349-30	2555	0.68	0.88	0.75	0.67	0.55	0.76	47.40	39.60	32.67
500349-31	3113	0.64	0.74	0.78	0.76	0.78	0.74	49.46	50.10	40.53
500349-32	3074	0.70	0.61	0.84	0.76	0.88	0.81	52.14	18.39	47.25
500349-33	3024	0.67	0.72	0.70	0.70	0.79	0.67	52.77	11.37	47.73
500349-34	2908	0.69	0.59	0.87	0.67	0.85	0.72	47.96	6.99	63.93
500349-35	2989	0.73	0.67	0.70	0.75	0.85	0.77	40.14	6.66	38.13
500349-36	3067	0.70	0.95	0.75	0.71	0.93	0.84	44.98	21.57	61.77
500349-37	3074	0.73	0.91	0.81	0.74	0.70	0.70	49.44	75.03	35.49
500349-38	2985	0.72	0.66	0.74	0.68	0.81	0.57	47.68	28.98	49.02
500349-39	2962	0.68	1.14	0.66	0.76	0.84	0.57	51.51	53.01	49.98
500349-40	2840	0.68	0.60	0.95	0.73	0.68	0.89	50.65	47.70	68.22
500349-41	3052	0.69	0.86	0.89	0.70	0.70	0.73	39.84	61.02	50.85
500349-6	2815	0.63	0.91	0.77	0.66	0.58	0.70	41.98	27.39	36.24
500349-7	2945	0.67	0.85	0.99	0.78	0.74	0.79	69.48	61.95	75.96
500349-8	2612	0.67	0.37	0.66	0.70	0.71	0.62	59.64	18.84	48.69
500349-9	3040	0.63	0.83	0.85	0.68	0.79	0.76	64.17	60.75	87.51

TABLE 4-11
CONTRIBUTIONS OF SOURCES OF UNCERTAINTY
TO OVERALL STANDARD DEVIATIONS OF THE MEASUREMENTS

Analyte	Spectrum Background	Interfering Gammas	Net Peak Counts	Other Measurement Uncertainty	% Counting Uncertainty[a]
Uranium-238	major	major	minor	minor	79
Thorium-232	negligible	negligible	major	moderate	55
Radium-226	minor	negligible	moderate	moderate	77
Gross Counts	NA	NA	NA	major	11[b]

a The counting uncertainty was calculated for the 8 second acquisition time measurements. In this context, the counting uncertainty includes the electronic noise, spectrum background (i.e., Compton continuum), interfering gamma rays, and net peak counts.

b The counting uncertainty for the gross counts is the square root of the total number of counts acquired.

TABLE 4-12
ESTIMATED STANDARD DEVIATIONS AND UCLs
FOR 2 SECOND/2 MPH MEASUREMENTS

TOTAL URANIUM			THORIUM-232			RADIUM-226		
CONC. (ppm)	SD[a] (ppm)	UCL[b] (ppm)	CONC. (pCi/g)	SD[a] (pCi/g)	UCL[b] (pCi/g)	CONC. (pCi/g)	SD[a] (pCi/g)	UCL[b] (pCi/g)
50	80	208	0.5	0.34	1.2	0.5	0.75	2.0
82[c]	81	241	1.0	0.36	1.7	1.0	0.79	2.5
100	82	260	1.5[c]	0.38	2.3	1.7[c]	0.83	3.3
150	83	313	2.0	0.41	2.8	2.0	0.84	3.7
200	85	366	3.0	0.45	3.9	3.0	0.90	4.8
246[+]	86	414	4.5[+]	0.50	5.5	4.0	0.95	5.9
500	92	681	6.0	0.55	7.1	5.1[+]	1.0	7.1
750	98	942	7.0	0.58	8.1	7.0	1.1	9.1
1030[++]	104	1234	10	0.66	11	10	1.2	12
1500	114	1723	15	0.78	17	15	1.4	18

a SD = Standard Deviation
b UCL = 95% Upper Confidence Limit
c Value is Equivalent to the FRL
[+] Value is Equivalent to the Hot Spot Criterion of 3xFRL
[++] Value is Equivalent to the Waste Acceptance Criterion

TABLE 4-13
ESTIMATED STANDARD DEVIATIONS AND UCLs
FOR 4 SECOND/1 MPH MEASUREMENTS

TOTAL URANIUM			THORIUM-232			RADIUM-226		
CONC. (ppm)	SD[a] (ppm)	UCL[b] (ppm)	CONC. (pCi/g)	SD* (pCi/g)	UCL[b] (pCi/g)	CONC. (pCi/g)	SD[a] (pCi/g)	UCL[b] (pCi/g)
50	61	170	0.5	0.29	1.1	0.5	0.61	1.7
82[c]	62	203	1.0	0.30	1.6	1.0	0.63	2.2
100	62	222	1.5[c]	0.32	2.1	1.7[c]	0.66	3.0
150	63	274	2.0	0.33	2.6	2.0	0.67	3.3
200	64	325	3.0	0.35	3.7	3.0	0.71	4.4
246[+]	65	373	4.5[+]	0.39	5.3	4.0	0.74	5.5
500	69	635	6.0	0.42	6.8	5.1[+]	0.77	6.6
750	73	893	7.0	0.44	7.9	7.0	0.83	8.6
1030[++]	77	1181	10	0.49	11	10	0.91	12
1500	84	1664	15	0.57	16	15	1.0	17

a SD = Standard Deviation
b UCL = 95% Upper Confidence Limit
c Value is Equivalent to the FRL
[+] Value is Equivalent to the Hot Spot Criterion of 3xFRL
[++] Value is Equivalent to the Waste Acceptance Criterion

TABLE 4-14
ESTIMATED STANDARD DEVIATIONS AND UCLs
FOR 8 SECOND/0.5 MPH MEASUREMENTS

TOTAL URANIUM			THORIUM-232			RADIUM-226		
CONC. (ppm)	SD[a] (ppm)	UCL[b] (ppm)	CONC. (pCi/g)	SD[a] (pCi/g)	UCL[b] (pCi/g)	CONC. (pCi/g)	SD[a] (pCi/g)	UCL[b] (pCi/g)
50	44	136	0.5	0.22	0.9	0.5	0.41	1.3
82[c]	44	168	1.0	0.23	1.5	1.0	0.43	1.8
100	44	187	1.5[c]	0.24	2.0	1.7[c]	0.45	2.6
150	45	238	2.0	0.25	2.5	2.0	0.46	2.9
200	46	289	3.0	0.26	3.5	3.0	0.48	3.9
246[+]	46	336	4.5[+]	0.29	5.1	4.0	0.51	5.0
500	50	596	6.0	0.31	6.6	5.1[+]	0.53	6.1
750	52	851	7.0	0.32	8	7.0	0.55	7.1
1030[++]	55	1137	10	0.36	11	10	0.63	11
1500	59	1616	15	0.41	16	15	0.72	16

a SD = Standard Deviation
b UCL = 95% Upper Confidence Limit
c Value is Equivalent to the FRL
[+] Value is Equivalent to the Hot Spot Criterion of 3xFRL
[++] Value is Equivalent to the Waste Acceptance Criterion

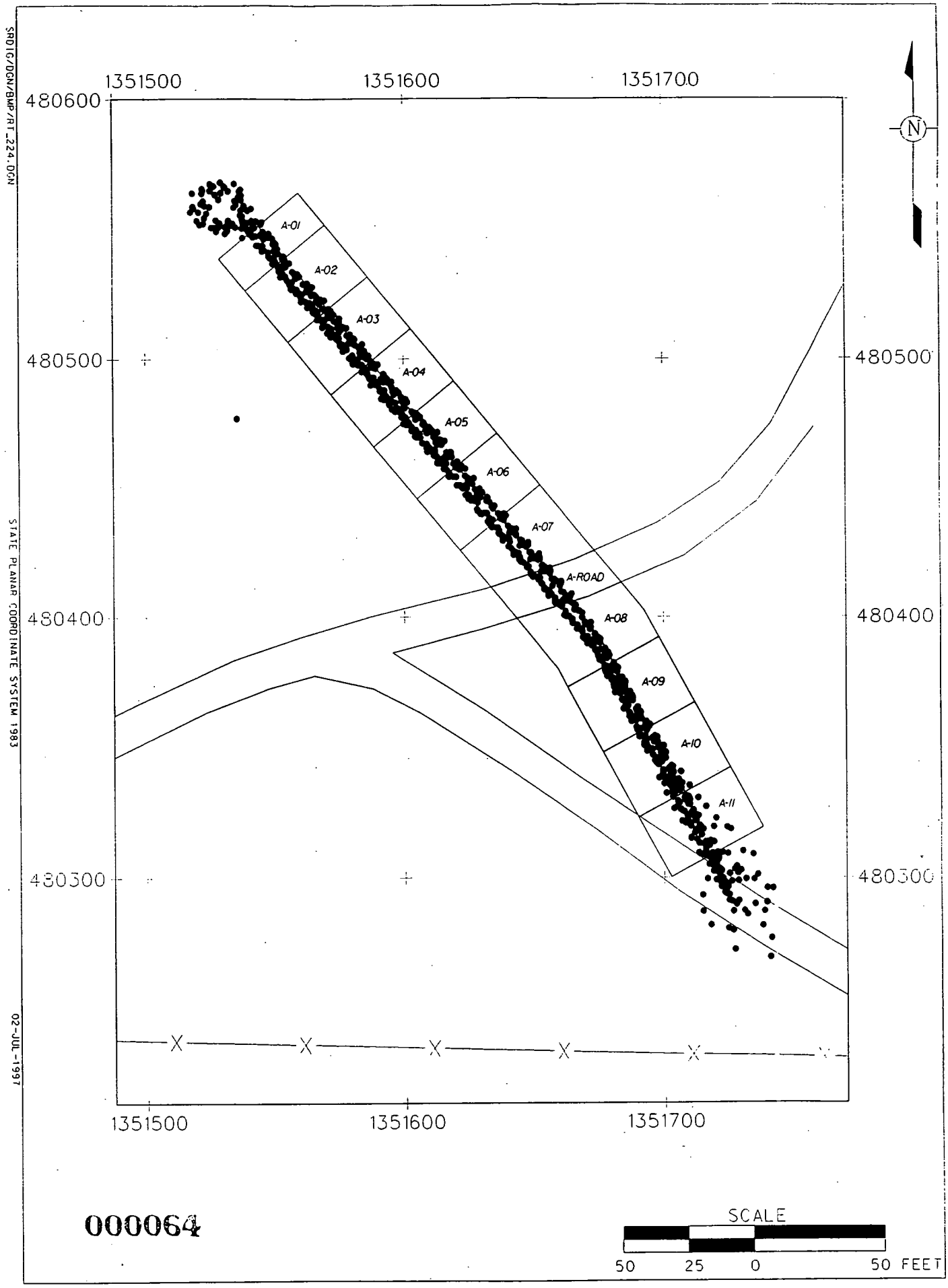

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FIGURE 4-1A. CONFIGURATION AND MEASUREMENTS IN PROFILE SEGMENTS FOR U.S.I.D. AREA - 2 M.P.H. / 2 SEC. ACQUISITION

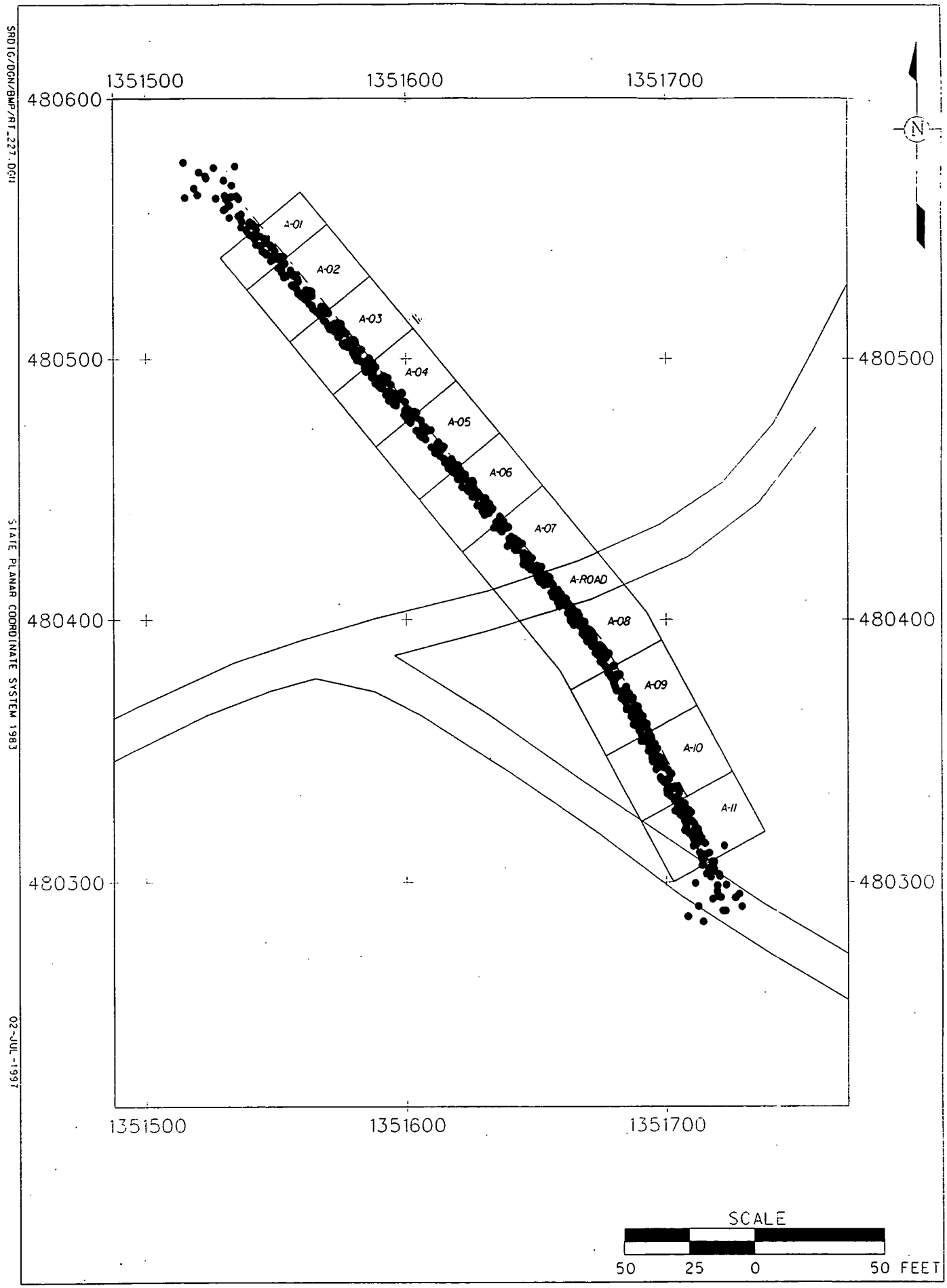

FIGURE 4-1B. CONFIGURATION AND MEASUREMENTS IN PROFILE SEGMENTS FOR U.S.I.D. AREA - 0.5 M.P.H. / 8 SEC. ACQUISITION

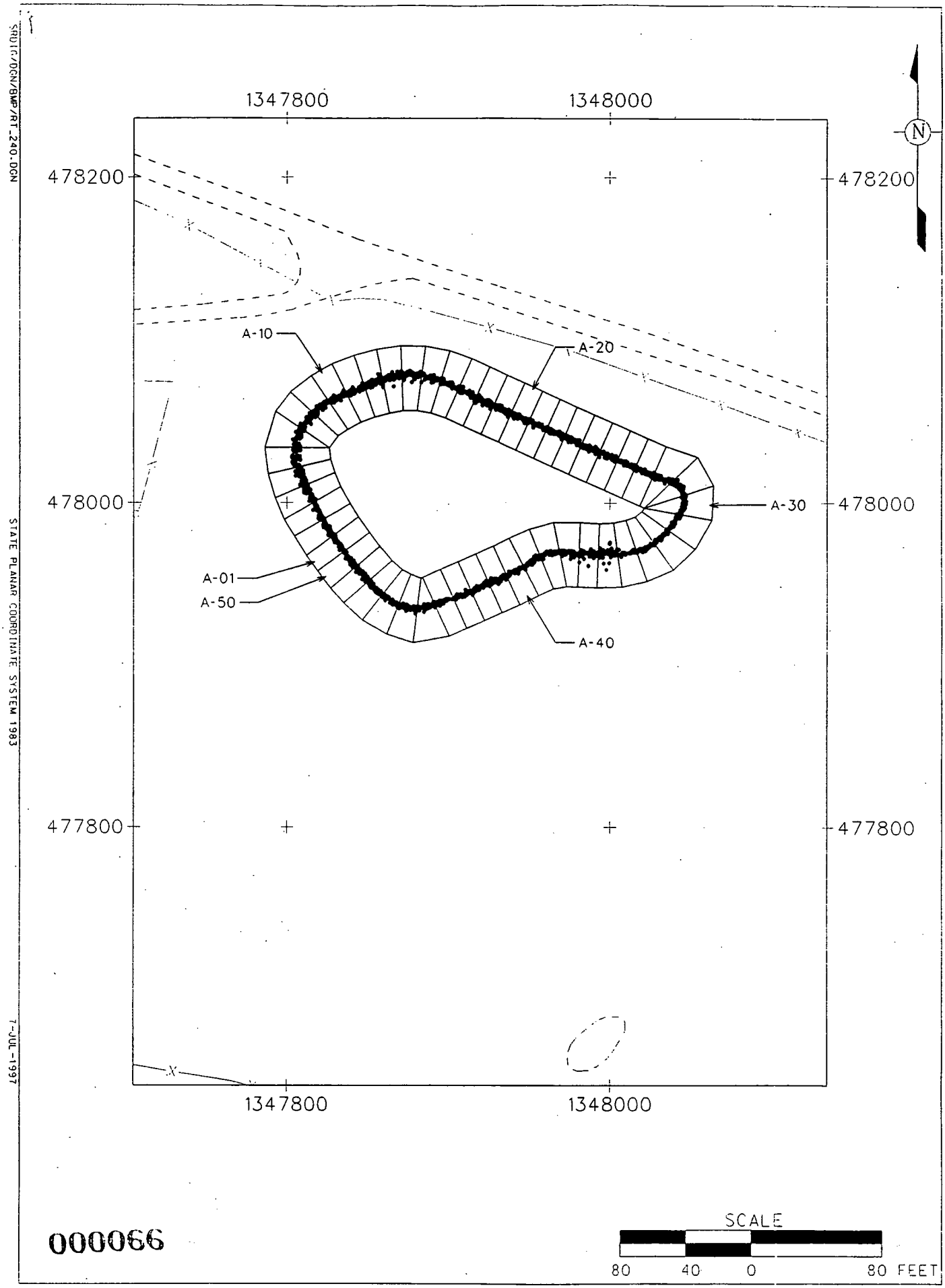

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FIGURE 4-2A. CONFIGURATION AND MEASUREMENTS IN PROFILE SEGMENTS FOR SOUTH FIELD AREA - 2 M.P.H./ 2 SEC. ACQUISITION

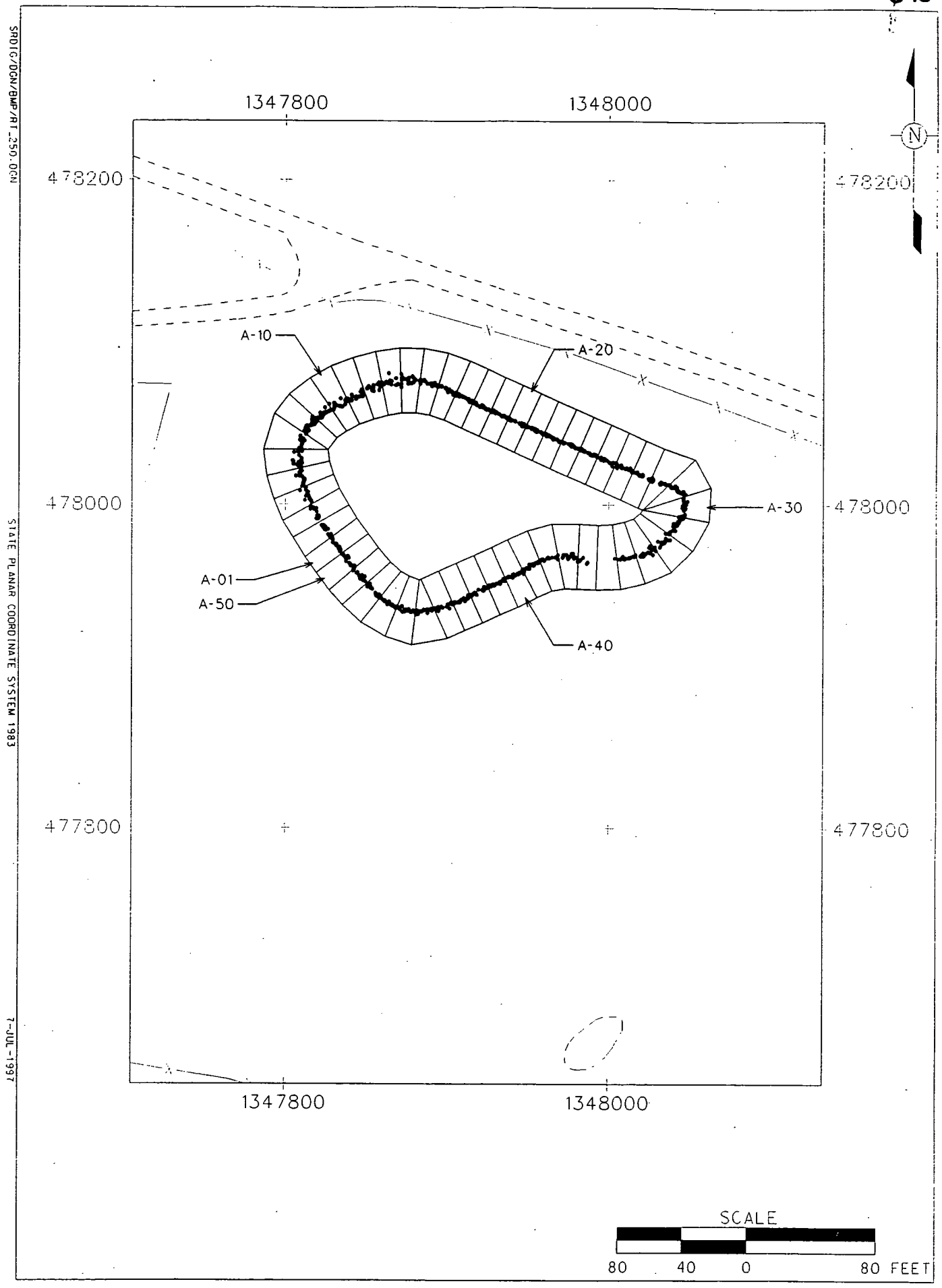


FIGURE 4-2B. CONFIGURATION AND MEASUREMENTS IN PROFILE SEGMENTS FOR SOUTH FIELD AREA - 1 M.P.H./ 4 SEC. ACQUISITION

SECTION 5.0
DATA ORGANIZATION AND DISPLAY

5.1 DATA PRESENTATION

Presenting RTRAK data in a meaningful graphical manner poses special challenges because of the volume of data, its inherent "noisiness", and many of the conclusions that are to be drawn from RTRAK data require additional data processing. This section contains examples of several different RTRAK data presentation formats. A variety of packages were used to generate the graphics contained in this section. These included data base packages for fundamental data manipulation, spread sheet packages for summary data analysis, and Geographical Information System (GIS) software such as Intergraph's MGE, ESRI's ArcINFO and ArcView products, and ConSolve's SitePlanner for data mapping and presentation.

5.1.1 RTRAK Point Measurement Data

Posting the point locations of RTRAK measurements, as in Figure 5-1 for the USID study area, provides information about the extent of RTRAK coverage for a specific area, the spacing between RTRAK measurements, and the general path the RTRAK followed. By manipulating the size of the icon representing each measurement, and by color-coding each measurement icon based on its gross activity (cps), the type of maps can be obtained that are shown in Figure 5-2, which are based on gross activity for RTRAK data from the USID study area. This type of presentation works particularly well for gross activity data because these data tend to have very little measurement error associated with them, and the result provides a clear image of the general spatial patterns associated with gross activity levels across a given area. For example, the road in the USID study area is clearly discernable in Figure 5-2. This type of presentation, however, does not work for point measurement isotopic data because the measurement error inherent in the isotopic values typically overwhelms the spatial patterns one has an interest in finding.

The presentation of hot spot and WAC attainment data can be accomplished by setting thresholds and displaying the locations of only those RTRAK data points that exceed these thresholds. Figure 5-3 provides an example of this type of graph of RTRAK data for portions of Area 1 Phase I. (Figure 5-3 is a reproduction of Attachment E in the Waste Acceptance Criteria Attainment Report, Area 1, Phase I Eastern Portion).

5.1.2 Spatially Averaged RTRAK Isotopic Data

For isotopic concentrations, spatial averaging is required to obtain concentration values for which the measurement error does not mask patterns of spatial variability. If one calculates moving window spatial averages using techniques described in Section 5.2, the original set of RTRAK measurement points is reduced to a regular grid. A variety of techniques is available for displaying gridded data, including contour lines, 3D terrain surfaces, and 2D color-coded surfaces. Figure 5-4 shows an example of a color-coded surface developed for thorium-232 in the former USID study area. This surface was created using a grid with a spacing of 10 feet between nodes, and a moving average window with a radius of 20 feet for calculating the average thorium-232 value at each node. The resulting grid was then contoured using a triangulated irregular network routine, and the contour map was converted into a color-coded 2D surface, with the color-coding corresponding to thorium-232 concentration levels.

5.2 SPATIALLY AVERAGED CONCENTRATIONS

The variability present in RTRAK measurements for a specific isotope from a given area is a combination of measurement error and the natural spatial variability present for that isotope. Sections 4.1.1.1 through 4.1.1.4 clearly demonstrate that increasing the counting time can significantly decrease the standard deviation of the individual measurements. Because the counting uncertainty is the primary source of uncertainty for uranium-238 and radium-226 at low concentrations, the standard deviations for uranium and radium should decrease by the square root of the factor of any increase in acquisition time. In fact, data from the repeated profile measurements showed that the standard deviations of uranium-238 and radium-226 were reduced by approximately a factor of two by increasing the acquisition time from two to eight seconds. A significant improvement was also realized for thorium, although it was not as large.

Another means of reducing the effect of the measurement standard deviation is to spatially average RTRAK measurements over a larger area than the individual measurements and then to determine the standard deviation of the means of those larger areas. Aggregation of measurements over an area has a "smoothing" effect by averaging out variability. The larger the averaging area, the greater the "smoothing" effect will be. Thus, increasing averaging area sizes reduces the uncertainty associated with a concentration value, but also reduces the spatial resolution of the measurements by averaging the data over a larger area of spatial variability. The latter effect is not necessarily desirable because it

limits the ability to identify small localized areas of contamination. Whether this is a problem or not depends on the use of RTRAK data. For example, if the objective is to determine during data collection in soil excavation whether a certification unit will pass or fail certification, a spatially averaged RTRAK result that may cover an area as large as an acre in extent and include more than 1,000 RTRAK data points may be utilized. On the other hand, if the objective is to locate hot spots, spatial averaging must be minimized.

The standard deviation of the mean of an aggregation measurement is an inverse function of the square root of the number of values contributing to the spatial average. For example, the resulting average from four RTRAK measurement points will have only half of the standard deviation of the individual points contributing to the average. If nine measurements points are included in the average, the resulting average will have only one third the measurement error of the individual points. In the case of a 2 second acquisition time collected at 2 mph and a 4 second acquisition time collected at 1 mph, the viewing window of the RTRAK is approximately 86 square feet. Because the viewing window extends beyond the physical footprint of the RTRAK, sequential RTRAK measurements overlap. For a given acquisition time, the slower the speed, the greater the overlap of viewing windows. In the case of data collected at 2 mph with a 2 second acquisition time, averaging 10 sequential measurements results in a read area of 477 square feet, which is approximately 5 times as great as the read area for an individual measurement. Figure 5-5 shows the relationship between relative standard deviation of the mean and the number of points contributing to a spatial average for the 2 second acquisition time, 2 mph case.

The issue with spatial averages is how large an averaging area is required to reduce the standard deviation to acceptable levels. As indicated in Section 2.2.2.1, 100% of the USID area was characterized by the RTRAK at three different combinations of tractor speed and data acquisition time. One objective of carrying out such detailed coverage was to delineate the effects of spatially averaging measurements over areas of varying size.

In the discussion below, the mean and standard deviation associated with individual measurements of all two-second and eight-second measurements times are presented under the "Raw Data" heading in Table 5-1. The approximately one-acre portion of the USID area was subdivided into circular areas having 10, 15, 20, 30, and 40 feet areas. The mean of all two second and eight second measurement

points falling within those areas was computed. Then the grand mean and the standard deviation of the grand mean were calculated for each size circular area. The results of these calculations are also shown in Table 5-1.

Table 5-1 and Figures 5-6 through 5-8 show how the data variability decreases as averaging area sizes are increased for the 2 mph/2 sec acquisition time runs and the 0.5 mph/8 sec acquisition time runs. The effects of increasing the averaging radius or aggregating measurements are as noted above; when the averaging radius is increased by a factor of two (i.e., the area increases by a factor of four), the standard deviation of the mean decreases by a factor of two.

As shown in Table 5-1, the size of the averaging area that is required to reduce measurement error is isotope-specific. For example, RTRAK thorium-232 measurements have significantly less measurement error than RTRAK radium-226 measurements, and consequently RTRAK thorium-232 spatial averages require a smaller averaging window than radium-226 averages to attain the overall standard deviations. Table 5-2 illustrates this concept for thorium-232, radium-226 and total uranium at concentrations equal to their FRL and three times their FRL assuming measurement errors associated with individual measurements using a 2 second acquisition time at 2 mph. Here, for the purposes of illustration, acceptable error has been defined as a standard deviation or standard deviation of the mean that is less than 10% of the FRL for concentrations at the FRL, or less than 10% of three times the FRL for concentrations that are three times the FRL.

Spatial averages can be constructed in a variety of ways. The most straightforward are block averages, where a region of interest that has been surveyed with the RTRAK is broken into blocks, and an average RTRAK value is assigned to each block based on the RTRAK points contained within that block. The disadvantage of this approach is that all detail within each block is lost, which can be a significant handicap if blocks are large. The approach used in this document makes use of moving window averages. This approach defines a grid over the region of interest, and then for each grid node calculates an average using all of the points within a specified distance from the node. The advantages of this approach are that the result has the same spatial resolution as provided by the grid and that each grid node can be assigned multiple averages, i.e., one for a window radius of 5 feet, one for 10 feet, etc. The disadvantage of this approach is that it tends to be more computationally intensive than a straight block average. There are more sophisticated averaging techniques, such as point or block

kriging. With data as dense and regular as the RTRAK data, however, they provide little benefit in exchange for significantly greater computational burdens.

TABLE 5-1
EFFECT OF AGGREGATING MEASUREMENTS - USID AREA

2 mph/2 sec Acquisition Time							
		Radium-226 (pCi/g)		Thorium-232 (pCi/g)		Total Uranium (ppm)	
	No. Meas.	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
Raw Data	846	0.76	0.88	0.75	0.37	37	79
10' Radius	6	0.77	0.41	0.75	0.22	37	48
15' Radius	12	0.77	0.31	0.75	0.18	37	33
20' Radius	25	0.76	0.23	0.75	0.14	37	25
30' Radius	45	0.76	0.15	0.74	0.11	36	18
40' Radius	90	0.76	0.11	0.74	0.09	36	13
0.5 mph/8 sec Acquisition Time							
		Radium-226 (pCi/g)		Thorium-232 (pCi/g)		Total Uranium (ppm)	
	No. Meas.	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
Raw Data	682	0.79	0.38	0.73	0.21	51	41
10' Radius	6	0.78	0.24	0.72	0.16	51	28
15' Radius	12	0.79	0.16	0.73	0.12	51	21
20' Radius	25	0.79	0.12	0.73	0.10	51	16
30' Radius	45	0.79	0.08	0.73	0.07	50	10
40' Radius	90	0.79	0.06	0.73	0.06	51	7

TABLE 5-2
NUMBER OF RTRAK POINTS REQUIRED FOR AVERAGING TO ATTAIN
A PRE-SPECIFIED ERROR CRITERIA AT THE FRL AND THREE TIMES THE FRL

	Radium-226 (pCi/g)			Thorium-232(pCi/g)			Total U (ppm)		
	Error (pCi/g)	Averaging Radius (ft)	# of Points	Error (pCi/g)	Averaging Radius (ft)	# of Points	Error (ppm)	Averaging Radius (ft)	# of Points
FRL:	0.17	20	25	0.15	10	6	8	37	100
3xFRL	0.51	9	4	0.45	7	2	24	15	13

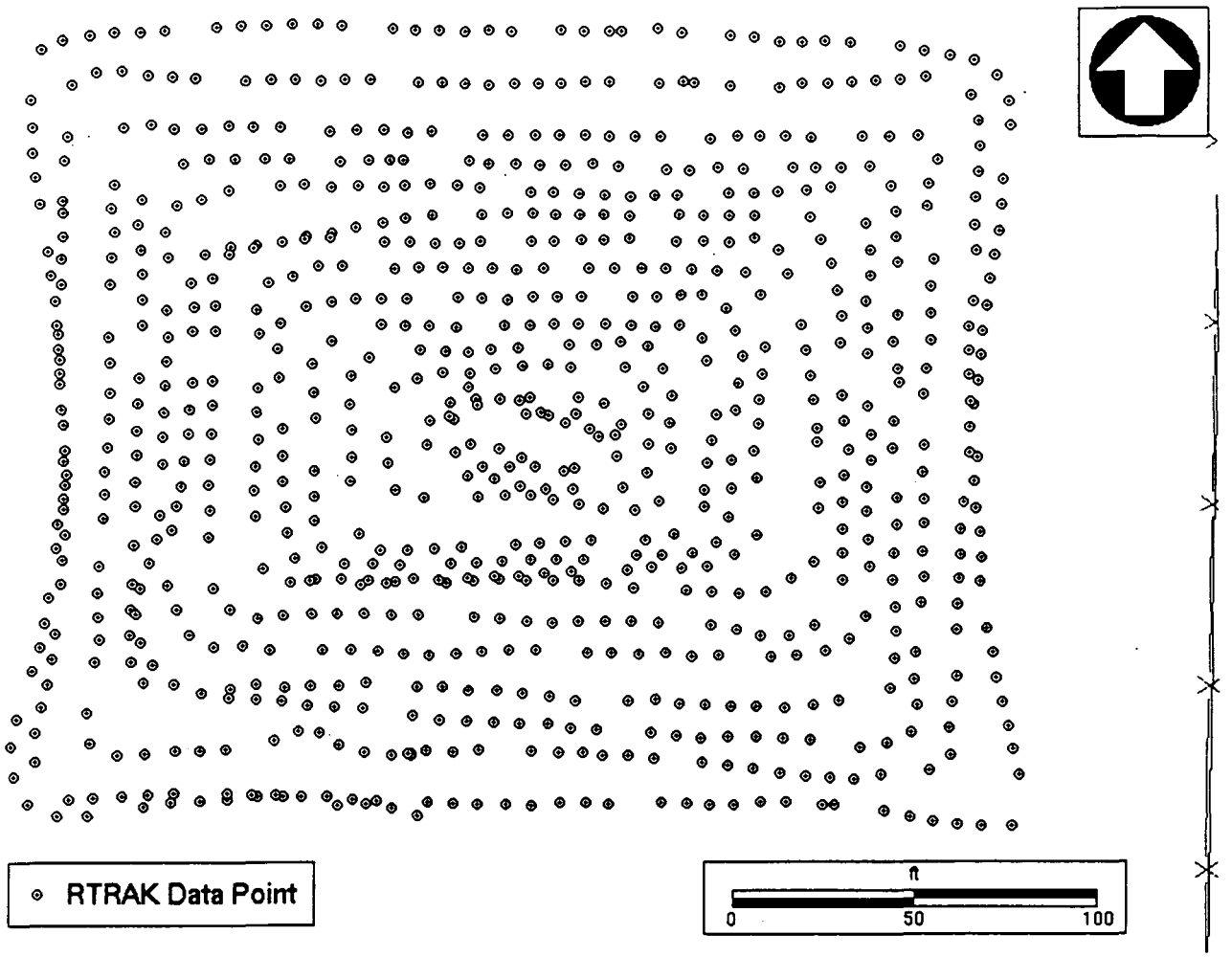


FIGURE 5-1
EXAMPLE RTRAK FOOTPRINT FOR THE USID STUDY AREA

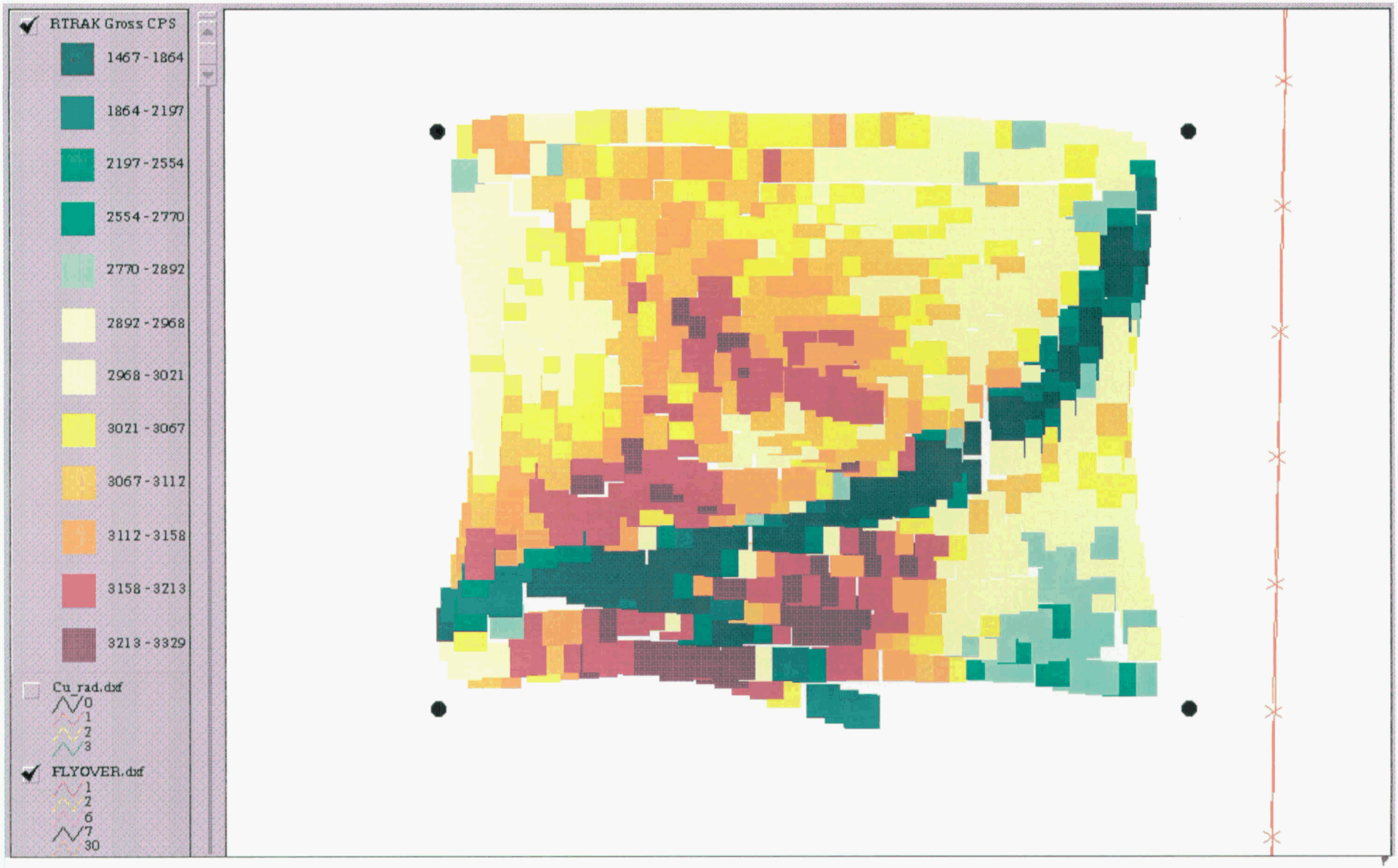


Figure 5-2 Example RTRAK Point CPS Values for the USID Area

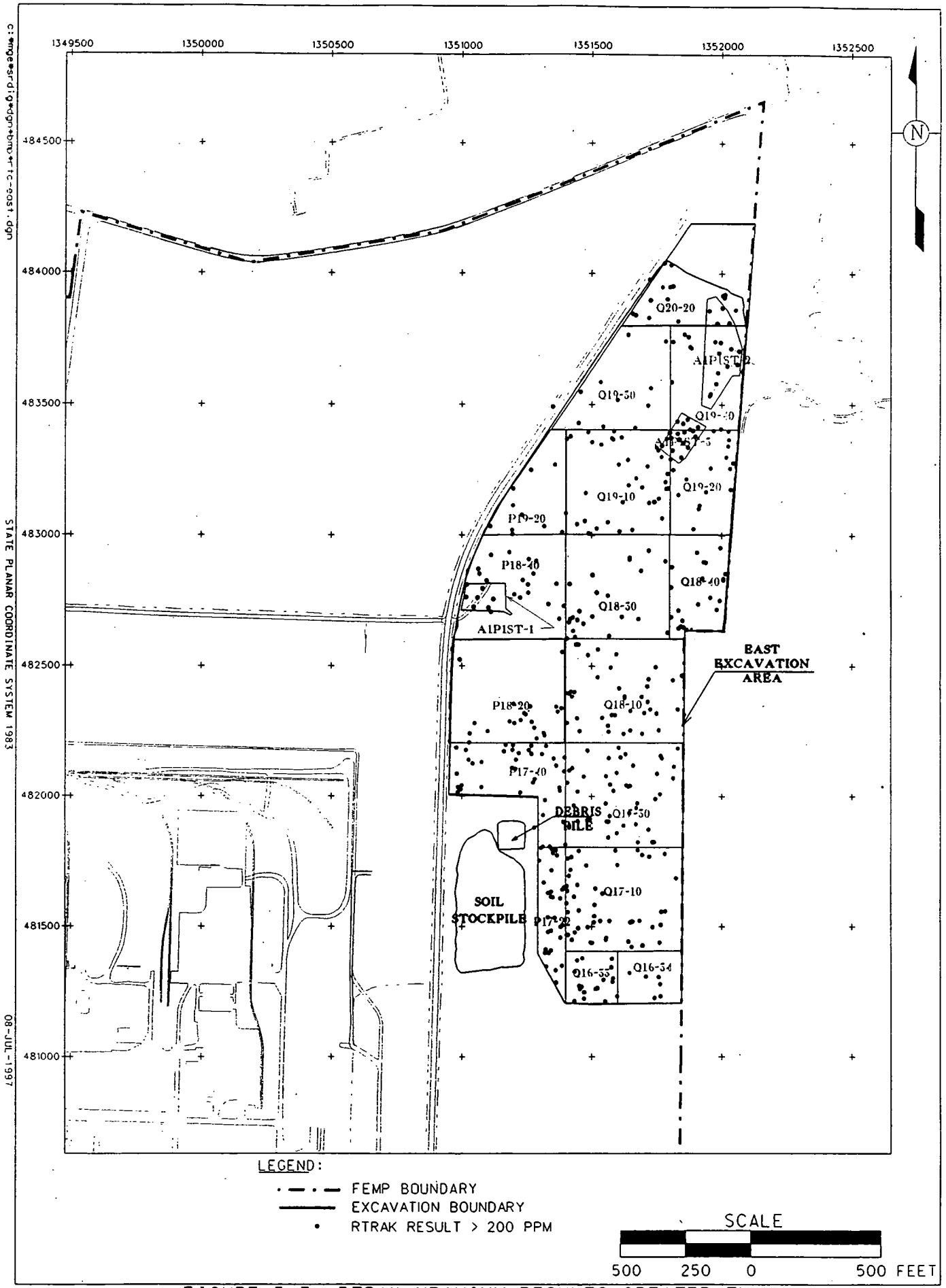


FIGURE 5-3. RTRAK URANIUM RESULTS GREATER THAN 200 PPM - AREA1, PHASE I EAST

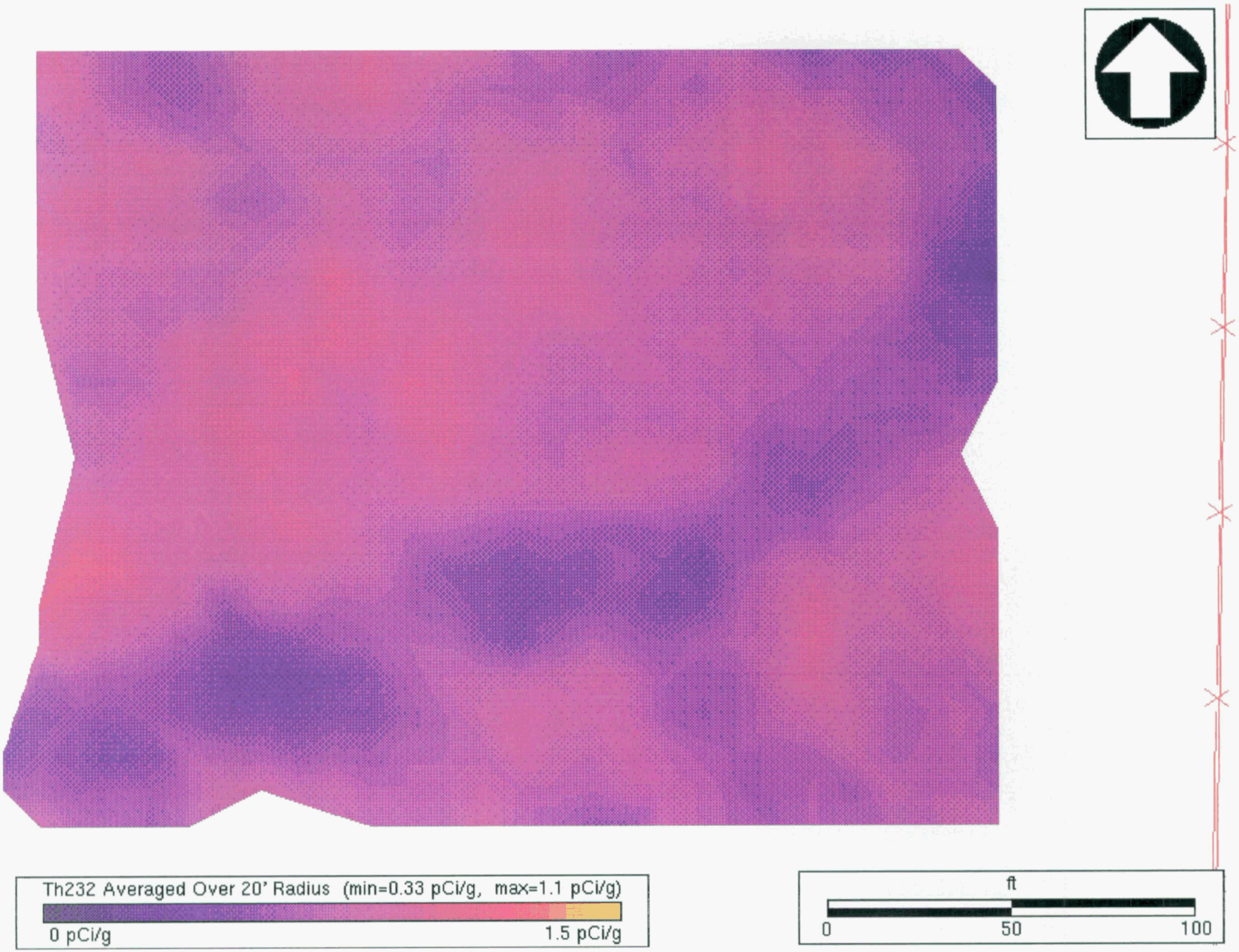


Figure 5-4 RTRAK Spatially Averaged Data for Th232 in USID Area

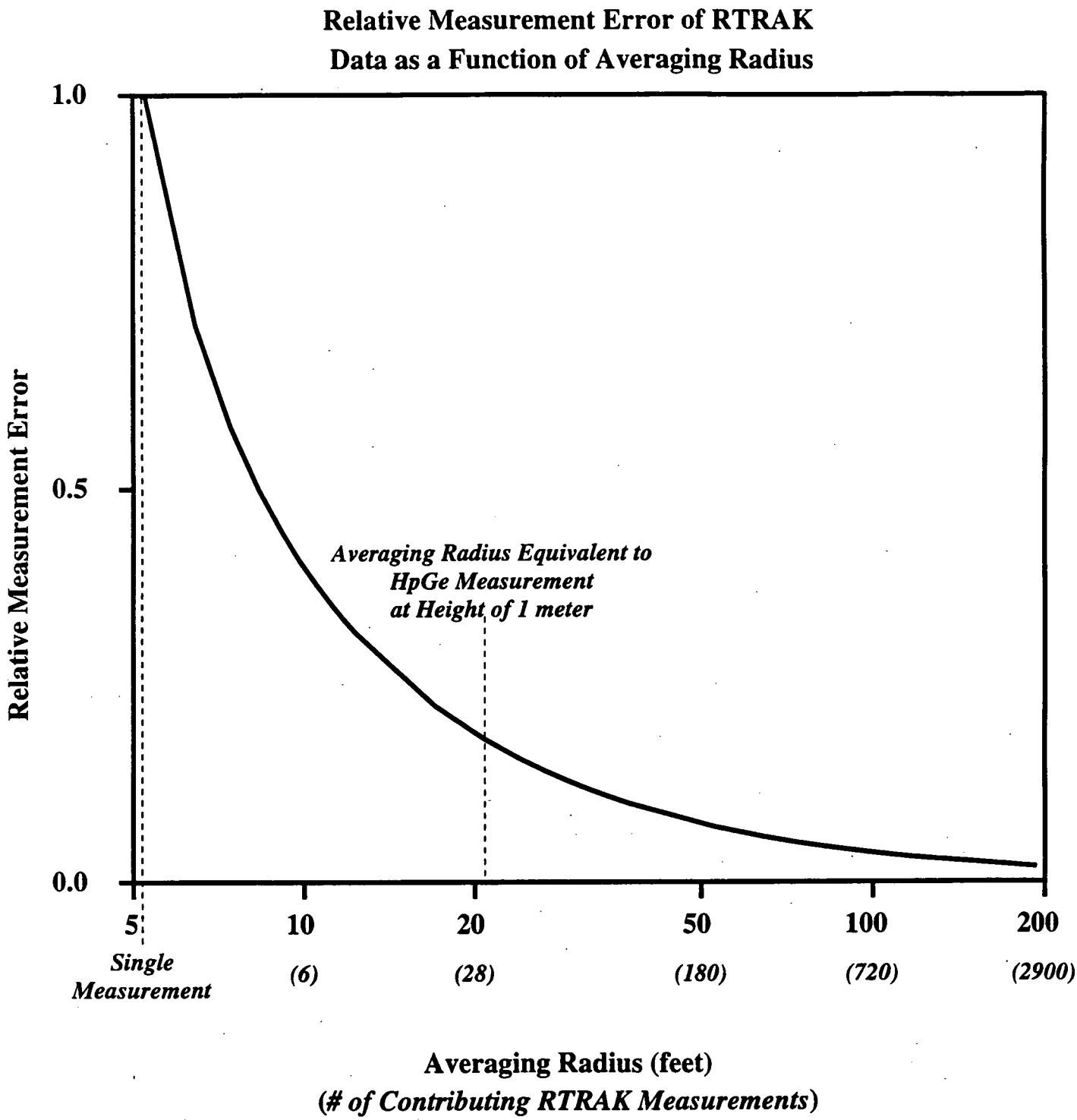


FIGURE 5-5
RELATIONSHIP BETWEEN MEASUREMENT ERROR AND
AVERAGING RADIUS FOR RTRAK DATA

080000

FIGURE 5-6
TOTAL URANIUM VARIABILITY AS A FUNCTION OF AVERAGING RADIUS

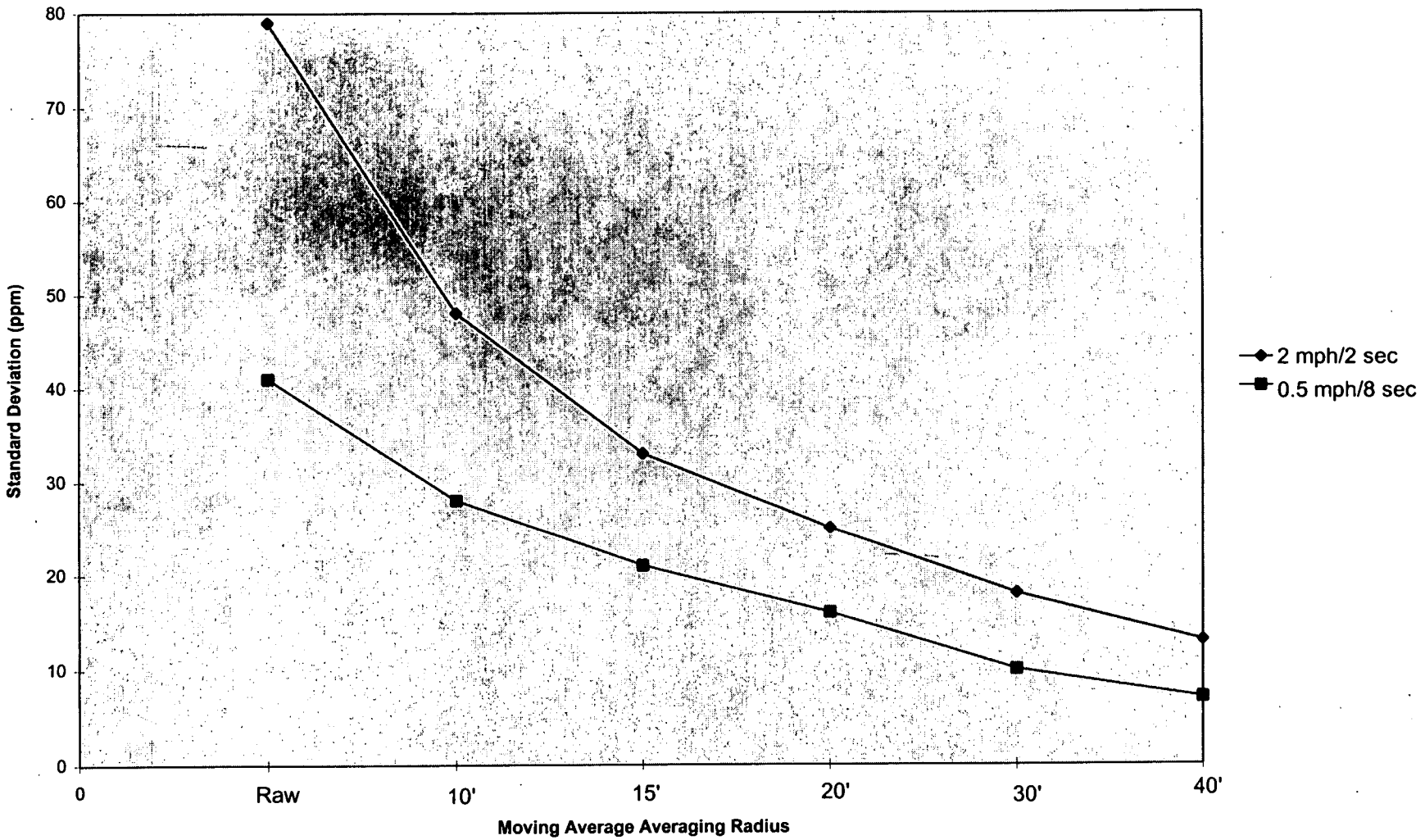


FIGURE 5-7
THORIUM-232 VARIABILITY AS A FUNCTION OF AVERAGING RADIUS

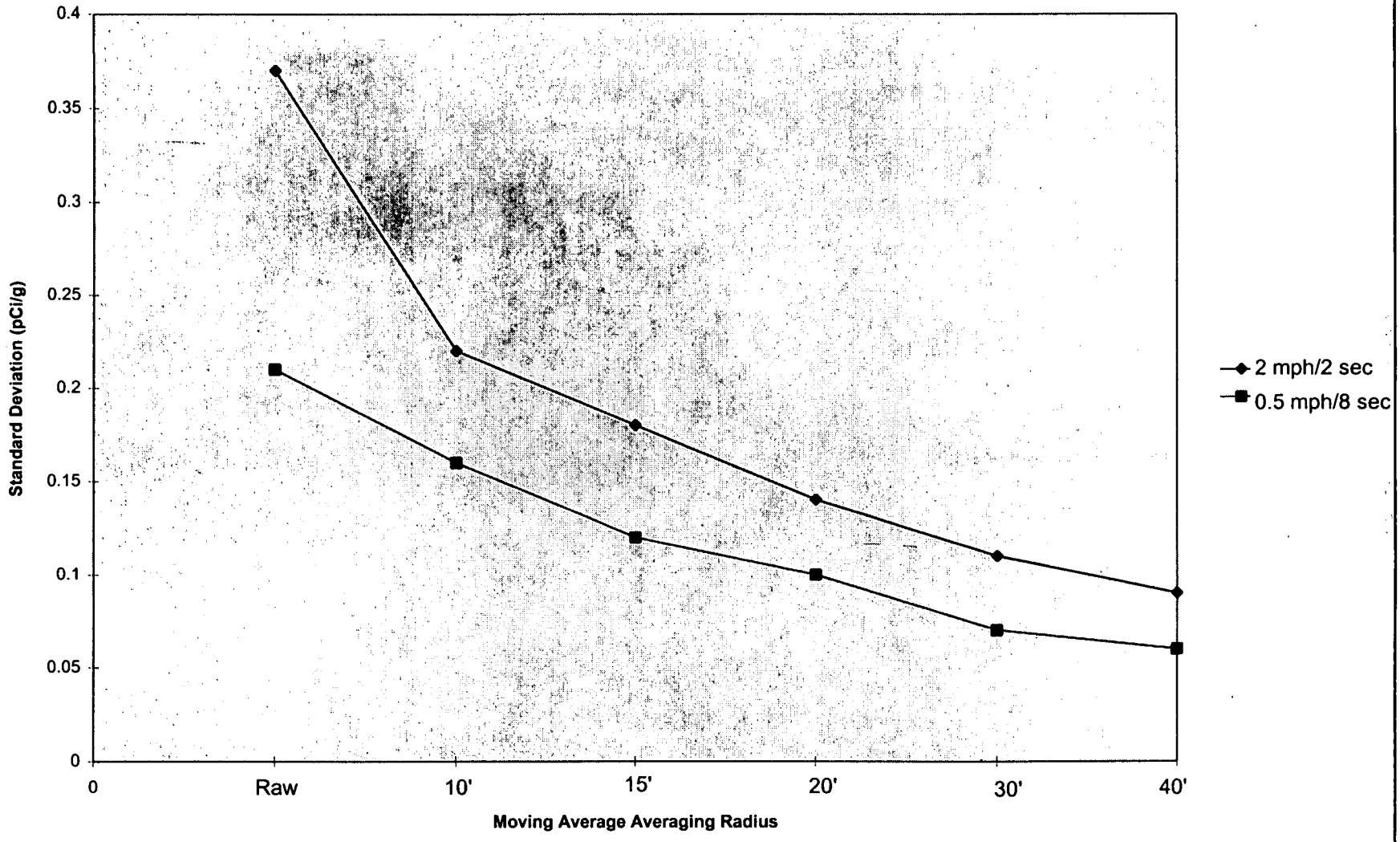
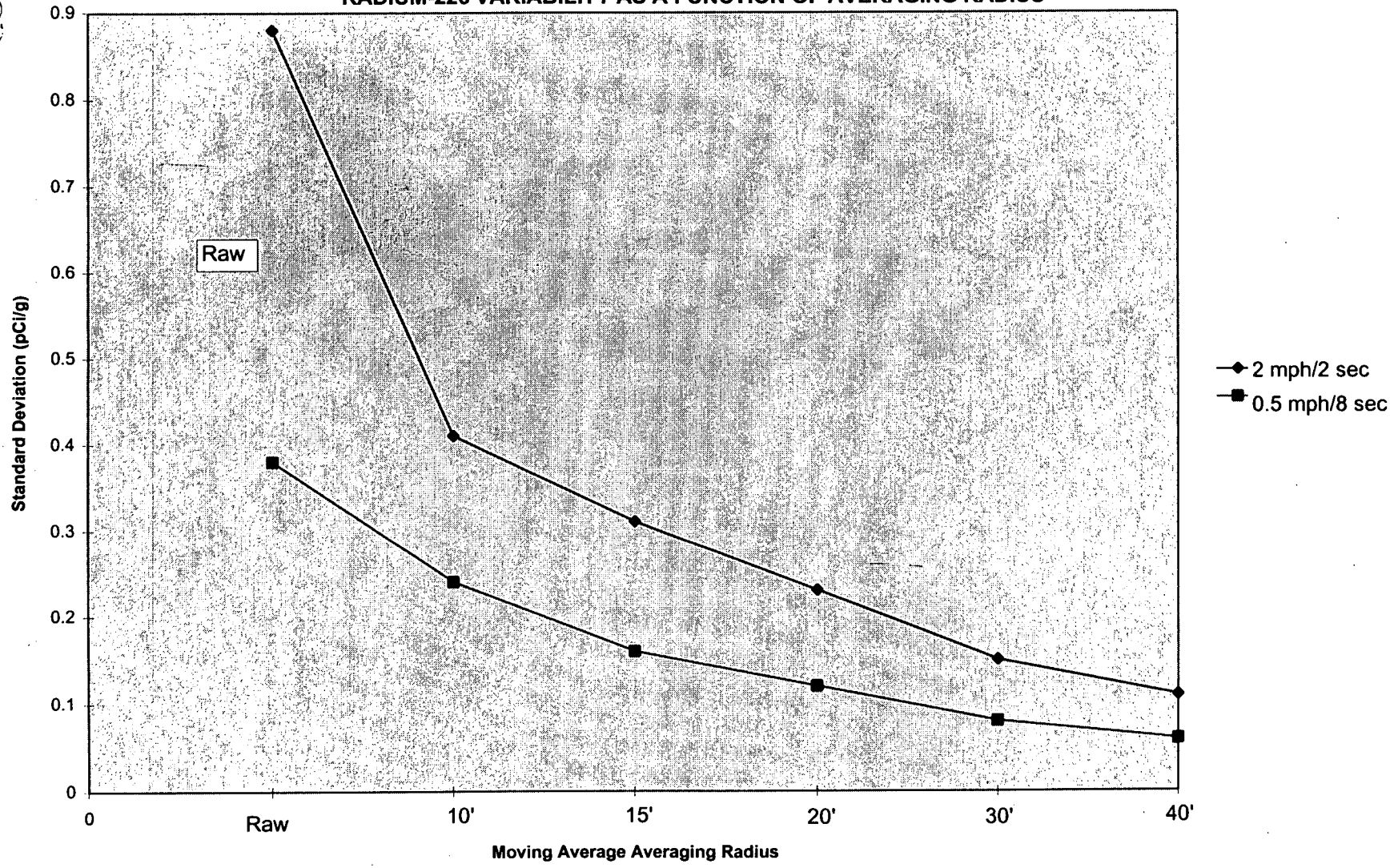


FIGURE 5-8
RADIUM-226 VARIABILITY AS A FUNCTION OF AVERAGING RADIUS



SECTION 6.0
RTRAK APPLICATIONS

The RTRAK system has several potential uses at the FEMP. These are summarized in Section 1.0. This section discusses the implications of the results of the data collected in this study as they relate to five general RTRAK applications.

6.1 APPLICATION OF RTRAK DATA TO DISCERNING GENERAL PATTERNS OF CONTAMINATION

RTRAK measurements can be used to develop an understanding of the general distribution of gamma-emitting radionuclide contamination across an area in two ways. The first makes use of gross activity levels measured by the RTRAK. The second makes use of spatially averaged RTRAK isotopic values. In all of the RTRAK data sets collected to date, gross cps levels have proven to be the most stable and reproducible data collected by the RTRAK, exhibiting very small relative measurement errors. The implication of this is that mapping raw RTRAK gross cps values provides an excellent means for determining the general spatial patterns of contamination for a given area. Figure 5-2 (in the preceding section) provides this type of map derived for the former USID study area. Note that in this graphic the presence of a road is clearly discernable, as are areas of generally elevated activity, despite the fact that activity levels for all three primary isotopes are below their respective FRLs. In this mode, the RTRAK is functioning in a manner very similar to traditional gamma walk-over surveys, with three important distinctions: 1) a much larger crystal is being used, providing for higher efficiencies than might be expected from a hand-held device, 2) the data are recorded and stored electronically for later processing, and 3) the integrated use of a differential GPS allows for accurate mapping of the measurements taken.

The primary shortcoming with this form of analysis is that it provides no information about which radionuclides are contributing to the activity or their probable concentrations. A good example of this shortcoming is found in the RTRAK profile data collected from the South Field area. The elliptical RTRAK path in that area identified 3 distinct peaks measured by gross cps activity (see Figure C-22). A review of the RTRAK isotope data showed that two of the peaks were almost solely attributable to thorium-232 (see Figure C-10), with concentration levels less than approximately 2 times the thorium-232 FRL, but that the third peak was attributable almost solely to radium-226 (see Figure C-16) with a

16) with a maximum concentration that was almost four times the radium-226 FRL. The gross count measurements could provide no information on the radionuclides responsible for the three peaks.

The ability of the RTRAK to resolve gross activity information into isotopic concentrations for radium-226, thorium-232 and total uranium, while at the same time providing almost 100% areal coverage, is perhaps its greatest strength. As discussed in Sections 5.1 and 5.2, because of the "noisiness" of point RTRAK isotopic information, some level of spatial averaging is required to control the level of measurement error. However, in the context of determining general patterns of contamination, the amount of spatial averaging required to obtain good isotopic estimates is not significant. For example, for levels of contamination that are at or below FRLs, a spatial averaging radius of 10, 20, and 40 feet for thorium-232, radium-226 and total uranium, respectively, are sufficient to bring measurement error to levels that are less than 10% of their respective FRLs when data are collected with a 2 second acquisition time at 2 mph. Figures 6-1, 6-2, and 6-3 provide color-coded maps of isotope concentrations for the former USID study area using averaging radii of 10, 15, and 20 feet for thorium-232, radium-226, and total uranium, respectively, with the RTRAK data collected at 0.5 mph with an 8 second acquisition time. In all three maps, the road traversing the area is clearly visible. The patterns of contamination suggested by the gross cps data appear to be reflecting trends in total uranium and thorium-232 concentrations for this area.

6.2 APPLICATION OF RTRAK DATA TO THE IMPLEMENTATION OF ALARA GOALS

The FEMP Sitewide Excavation Plan (SEP, DOE 1997b) defines the implementation of ALARA for the soils remediation project at Fernald as pursuing excavation, once excavation has been initiated, until total uranium levels are reduced in general to levels less than 50 ppm. For the RTRAK to support the implementation of ALARA as defined by the SEP, the RTRAK must be capable of resolving total uranium concentrations around 50 ppm over the typically large areas that would be involved with excavation. For total uranium averaging areas with radius of 40 feet, the standard deviation to be expected is on the order of 8 ppm. For total uranium averaging areas with radius of 70 feet, the standard deviation to be expected is less than 5 ppm. In other words, for an averaging area with radius 40 feet., the 95% confidence interval for a 50 ppm average ranges between approximately 34 ppm and 66 ppm. For an averaging area with radius 70 ft., the 95% confidence interval for a 50 ppm average ranges between approximately 41 ppm and 59 ppm. Note that an averaging area of 70 feet is approximately equal to one third of an acre.

6.3 APPLICATION OF RTRAK DATA TO DETERMINING CU PASS/FAIL STATUS

DOE has the responsibility for certifying that areas have achieved FRL goals before those areas are released for other uses. This certification process entails two steps: (1) establishing that the average level of contaminants of concern are less than the FRL over areas of specified sizes known as certification units (CUs); and (2) that, for primary radionuclides, there are no "hot spots" that exceed three times the appropriate FRL. The application of the RTRAK to hot spot concerns is addressed in Section 6.4. This section focuses on the use of the RTRAK to rapidly verify, prior to soil excavation, data collection that an area will pass the certification process for thorium-232, radium-226 and total uranium. This capability is particularly important because certification failure can be expensive and result in delays of the overall soils remediation program. Certification failure requires at least one subsequent round of additional remediation and certification sampling.

To verify that a particular CU is ready for certification on an average FRL basis for thorium-232, radium-226 and total uranium requires an accurate assessment of what the average contamination concentration is across that CU. For a CU that is 250 ft. by 250 ft., on average there will have been more than 1,300 RTRAK measurements taken with a 2 second acquisition time at 2 mph. For a CU that is 500 ft. by 500 ft., on average there will have been more than 5,300 RTRAK measurements taken with a 2 second acquisition time at 2 mph. With these large numbers of measurements, the 95% confidence intervals for RTRAK based averages over a whole CU that are at or below the FRLs are less than ± 0.03 pCi/g for thorium-232, less than ± 0.04 pCi/g for radium-226, and less than ± 4 ppm for total uranium. In short, when RTRAK measurements are averaged over areas the size of certification units, because of the large numbers of RTRAK measurements involved, the resulting averages are extremely precise. Figures 6-4, 6-5 and 6-6 contain scatter plots that compare certification unit averages based on discrete samples and based on RTRAK data for thorium-232, radium-226 and total uranium in Area 1 Phase I, respectively. The RTRAK data in these figures were corrected for moisture using a correction factor of 1.35. Note from these figures that for both radium-226 and thorium-232, agreement is excellent. For total uranium, the RTRAK is biased high.

For thorium-232, radium-226 and total uranium, the RTRAK data not only can provide an accurate pre-certification assessment of average COC levels, they can also provide information about the level of spatial variability present in the residual contamination. This can be extremely important from the perspective of allocating certification sample numbers to certification units. For example, given two

certification units with the same average thorium-232 value (less than the FRL) but significantly different spatial variabilities associated with thorium-232, the CU with higher variability would require a larger sample size than its counterpart to establish FRL compliance.

When initially evaluating whether a CU is likely pass or fail certification, it may be desirable to consider measurements with better spatial resolution than is obtained by averaging over a 250 ft x 250 ft CU. Doing so provides valuable information about the variability of concentrations across the CU and can indicate areas of sufficiently elevated activity that might potentially lead to certification failure. In addition, in cases when a CU does fail, RTRAK data with a smaller spatial resolution can provide valuable information about why it failed and what corrective action must be taken to pass certification. It is clear from the discussion in Section 5.2 that the RTRAK can provide data with adequate precision to allow the use of much smaller averaging areas. Table 5.2 shows that a standard deviation of 10 percent of the total uranium FRL can be achieved for a 2 second acquisition time by spatially averaging over a 37 ft. radius. For thorium-232 and radium-226, the averaging radii are 7 ft. and 9 ft., respectively. The averaging radii can be reduced by increasing the acquisition time for the measurements. The averaging radii needed to achieve a given standard deviation will change approximately in proportion to the inverse square root of the change in acquisition time(i.e., with a factor of four increase in the acquisition time, the averaging radius can be reduced by a factor of two). From a certification program design perspective, the RTRAK can not only be used to ascertain whether average thorium-232, radium-226 and total uranium levels are below FRLs, it can also provide data for use in determining the number of discrete samples that would be required to statistically establish that this is the case.

6.4 APPLICATION OF RTRAK DATA TO HOT SPOT IDENTIFICATION

Prior to releasing areas as remediated for soil contamination at the FEMP, DOE will need to show for thorium-232, radium-226 and total uranium that "hot spots", i.e., areas that exceed three times the FRL, do not exist. Hot spots can be extremely difficult to locate and quantify using a discrete sampling approach. A rather extensive body of literature has been developed towards this end; the general conclusions are always the same---verifying the absence of hot spots using discrete samples requires exhaustive, gridded sampling. Technologies such as the RTRAK can potentially provide significant benefits when applied to hot spot identification because the RTRAK provides complete areal coverage for an area of concern.

Soil hot spot evaluation at the FEMP takes place after an area has either been excavated sufficiently that DOE is confident that average FRL goals have been attained, or if there is sufficient evidence that existing average contaminant levels do not pose FRL concerns. This sequence of events suggests that when hot spot evaluation is undertaken, existing general residual contaminant levels should be around or below FRLs for the area that is being surveyed. When a hot spot evaluation using the RTRAK is conducted, there are two types of errors the RTRAK could make. The first is incorrectly categorizing a measurement (or an average based on a set of measurements) as being below the hot spot criteria when in fact it exceeds three times the FRL. This error would result in somewhat elevated human health risk. The second is incorrectly categorizing a measurement (or an average based on a set of measurements) as being a "hot spot" when in fact it is below three times the FRL. This error results in unnecessary excavation.

When applying the RTRAK system to hot spot identification, there are three parameters that can be adjusted---the "trigger level" for a particular isotope (i.e., the level above which an RTRAK reading would require hot spot action), the area over which this trigger level applies, and the combined acquisition time/speed at which the RTRAK is being driven. Tables 6-1 and 6-2 compare the effects of these three parameters on the ability of the RTRAK to avoid the second type of error (false positive) given a goal of only a 5% false negative error rate. Table 6-1 performs this analysis for RTRAK measurements collected with a 2 second acquisition time at 2 mph. Table 6-2 performs this analysis for RTRAK measurements collected with a 4 second acquisition time at 1 mph. A 20 foot averaging radius is approximately the viewing area of an HPGe measurement at a height of 1 meter.

Figure 6-7 illustrates conceptually how the numbers in these tables are derived for radium-226 using single point measurements collected with a 2 second acquisition time at 2 mph. For a Group 1 certification unit, there can be more than 1,300 RTRAK measurements that are collected. If these measurements are spatially averaged using moving window averages to a grid with 5 foot grid spacings, there would be 2,500 grid nodes per CU. Whether one is working with spatial averages or individual measurement points, the false positive rates need to be kept preferably to levels less than 0.001. A false positive rate of 0.001 for a Group 1 CU translates into, on average, one false "hot spot" reading per CU for individual RTRAK measurement points, and 2 to 3 false "hot spot" readings per CU for spatially averaged RTRAK readings.

As these two tables make clear, the RTRAK provides an excellent hot spot screen for thorium-232. At an acquisition time of 2 seconds and a speed of 2 mph, and at an acquisition time of 4 seconds and a speed of 1 mph, trigger levels can be set for thorium-232 that provide a minimal probability of missing hot spots and basically no false positives with point RTRAK measurements. For radium-226, the RTRAK also provides good performance. For an acquisition time of 4 seconds and a speed of 1 mph, trigger levels can be set that provide a minimal probability of missing hot spots and basically no false positives with point RTRAK measurements. For an acquisition time of 2 seconds and a speed of 2 mph, using a spatial averaging radius of 10 feet, trigger levels can be set that provide excellent hot spot identification with basically no false positive errors. Even for total uranium, for both combinations of speeds and acquisition times, a 10 foot averaging radius allows for trigger levels that provide excellent hot spot identification with basically no false positives.

Table 6-3 explores the relationship between false negative rates, trigger levels and false positive rates for the three isotopes using point RTRAK measurements collected with a 4 second acquisition time at a speed of 1 mph. At this speed/data acquisition rate, trigger levels can be set with point measurements for thorium-232 that basically force both types of errors to zero. For radium-226, false positive errors can be controlled with a false negative rate of only 5%; this translates into catching radium-226 hot spots at least 95% of the time. For total uranium, however, with point measurements there are no trigger levels that both provide acceptable false negative rates and reasonable false positive rates.

The HPGe is available for validating RTRAK hot spot analyses. At a height of one meter, the HPGe viewing window captures an area that is 15 times as big as that viewed by one RTRAK measurement. A comparable set of RTRAK reads would include approximately 30 RTRAK data points with either a 2 second acquisition time at 2 mph or a 4 second acquisition time at 1 mph. In contrast, an HPGe reading at a height of one foot would yield a viewing window that captures an area that is approximately twice the size of one RTRAK measurement.

6.5 APPLICATION OF RTRAK DATA TO WAC ATTAINMENT VERIFICATION

The application of the RTRAK to WAC attainment verification is exactly the same type of application as the identification of hot spots. The differences are that one is only concerned with total uranium, and the contaminant level of WAC concern is significantly higher than even hot spot concerns. The issue of whether averaging areas is required, the selection of false negative error criteria, the

calculation of appropriate trigger levels, and the determination of false positive error rates can be accomplished in exactly the same fashion as was done for hot spots. The key questions for WAC attainment are the precision of the RTRAK total uranium data at WAC levels, and the degree to which other isotopes, namely thorium-232 and radium-226, might potentially interfere with the accuracy of RTRAK data if they are present at significant levels. Unfortunately, there currently exists no RTRAK field data from areas that might constitute WAC concerns.

TABLE 6-1
RELATIONSHIP BETWEEN AVERAGING AREA, ISOTOPES, AND HOT SPOT FALSE POSITIVE RATES FOR A FALSE NEGATIVE RATE OF 5% AND DATA ACQUIRED AT 2 SECOND/2 MPH

Averaging Radius (ft)	Radium-226 (pCi/g)		Thorium-232 (pCi/g)		Total Uranium (ppm)	
	Trigger Level	Expected False Positive Rate[a]	Trigger Level	Expected False Positive Rate[a]	Trigger Level	Expected False Positive Rate[a]
Single Pt. (6 ft. equiv.)	3.4	0.018	3.7	0.000	105	0.390
10	4.6	0.000	4.2	0.000	201	0.000
15	4.7	0.000	4.3	0.000	209	0.000
20	4.7	0.000	4.3	0.000	215	0.000

a Decimal factor of total number of measurements expected to exceed trigger level

TABLE 6-2
RELATIONSHIP BETWEEN AVERAGING AREA, ISOTOPES, AND HOT SPOT FALSE POSITIVE RATES FOR A FALSE NEGATIVE RATE OF 5% AND DATA ACQUIRED AT 4 SECOND/1 MPH

Averaging Radius (ft)	Radium-226 (pCi/g)		Thorium-232 (pCi/g)		Total Uranium (ppm)	
	Trigger Level	Expected False Positive Rate[a]	Trigger Level[a]	Expected False Positive Rate	Trigger Level[a]	Expected False Positive Rate
Single Pt. (6 ft. equiv.)	3.9	0.000	3.9	0.000	146	0.132
10	4.7	0.000	4.3	0.000	214	0.000
15	4.8	0.000	4.3	0.000	220	0.000
20	4.8	0.000	4.4	0.000	224	0.000

a Decimal factor of total number of measurements expected to exceed trigger level

TABLE 6-3
RELATIONSHIP BETWEEN TRIGGER LEVELS, EXPECTED FALSE POSITIVE RATES, AND FALSE NEGATIVE RATES WITH RTRAK DATA COLLECTION AT 4 SECOND ACQUISITION TIME/SPEED OF 1 MPH

False Negative Rates (%)	Radium-226 (pCi/g)		Thorium-232 (pCi/g)		Total Uranium (ppm)	
	Trigger Level	Expected False Positive Rate[a]	Trigger Level	Expected False Positive Rate[a]	Trigger Level	Expected False Positive Rate[a]
1	3.4	0.002	3.7	0.000	105	0.347
5	3.9	0.000	3.9	0.000	146	0.132
10	4.2	0.000	4.0	0.000	168	0.066
20	4.5	0.000	4.2	0.000	195	0.024
30	4.7	0.000	4.3	0.000	214	0.011

a Decimal fraction of total number of measurements expected to exceed trigger level

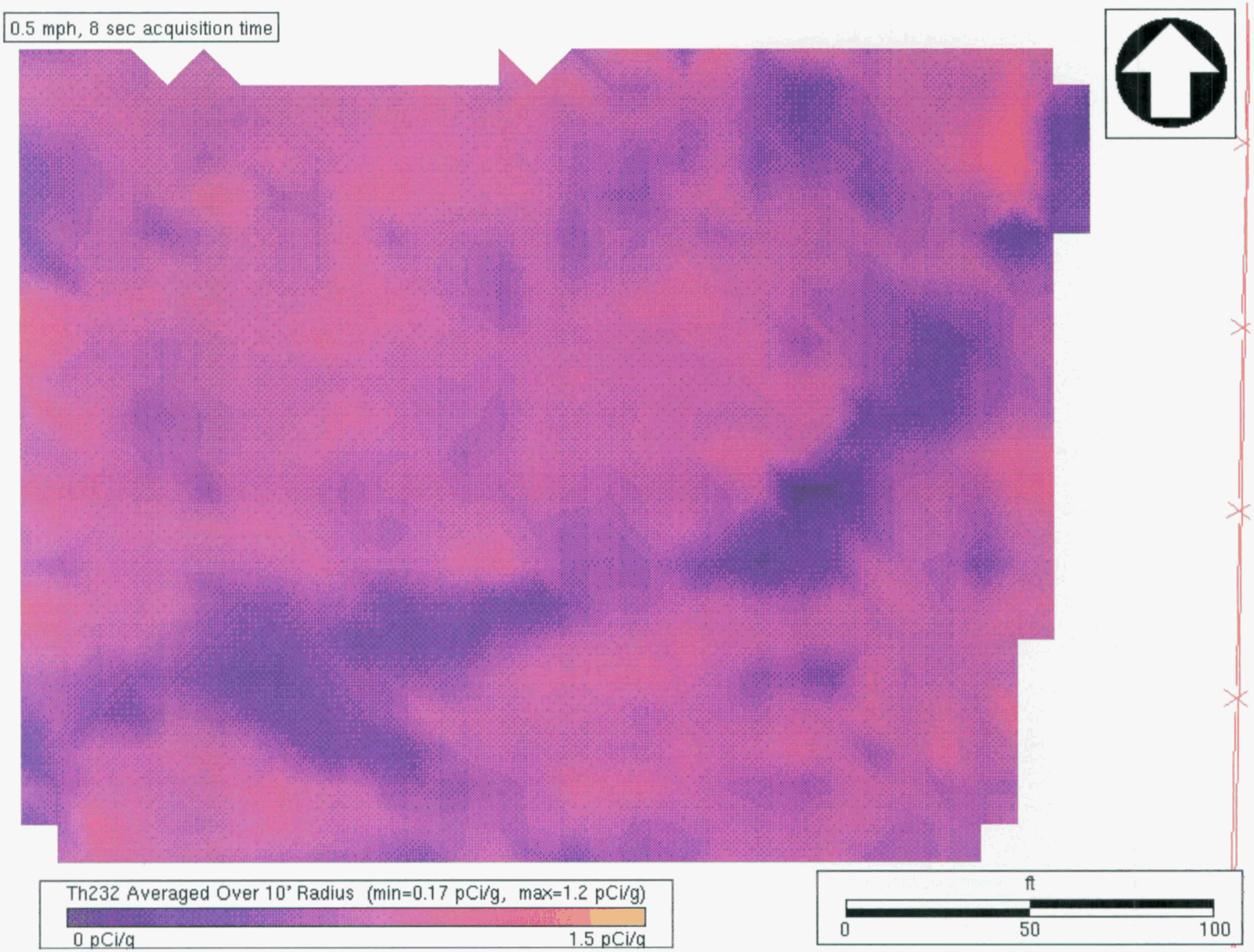


Figure 6-1 RTRAK Th232 Results for the USID Area Using a Spatial Averaging Radius of 10 ft.

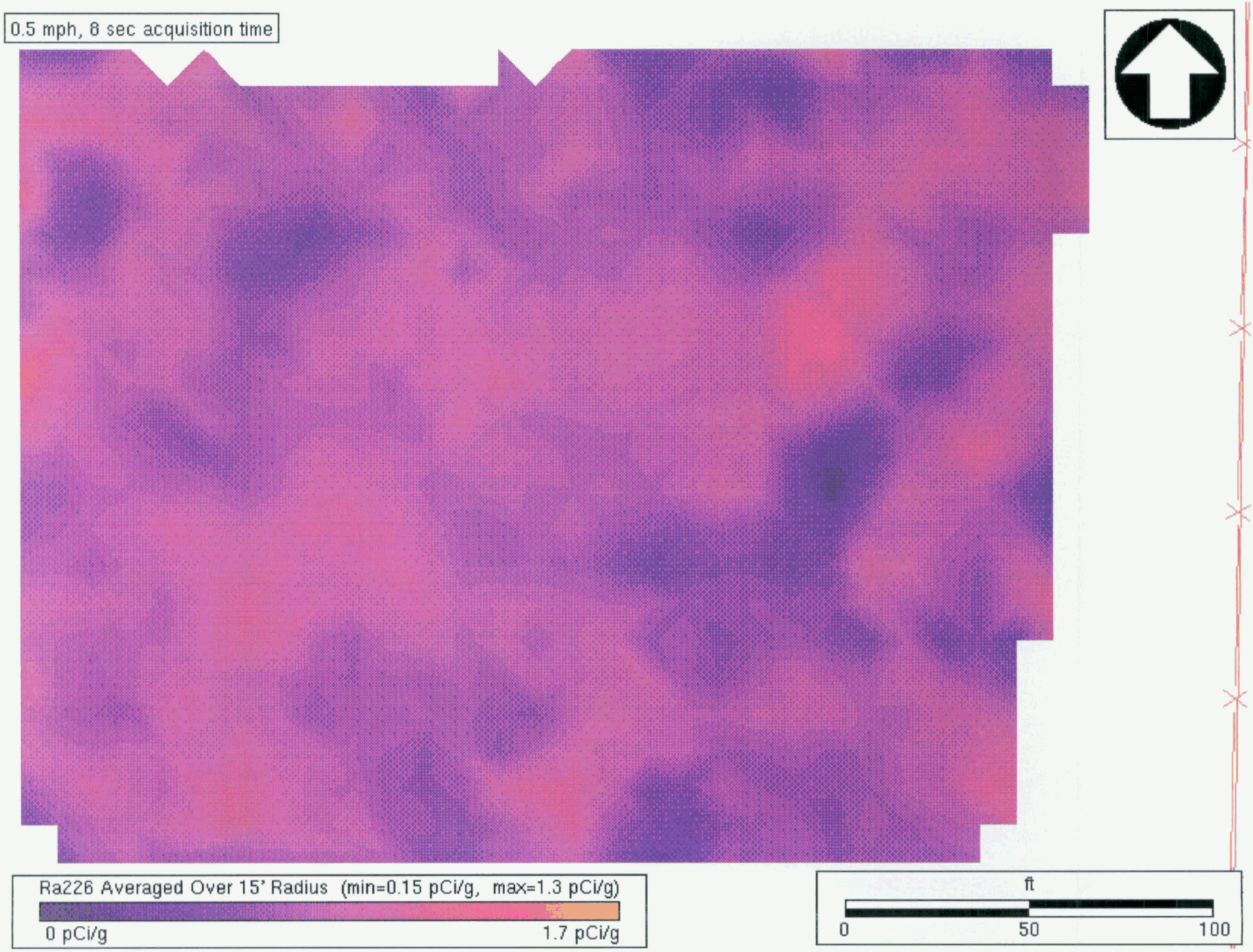


Figure 6-2 RTRAK Radium-226 Results for the USID Area Using a Spatial Averaging Radius of 15 Feet

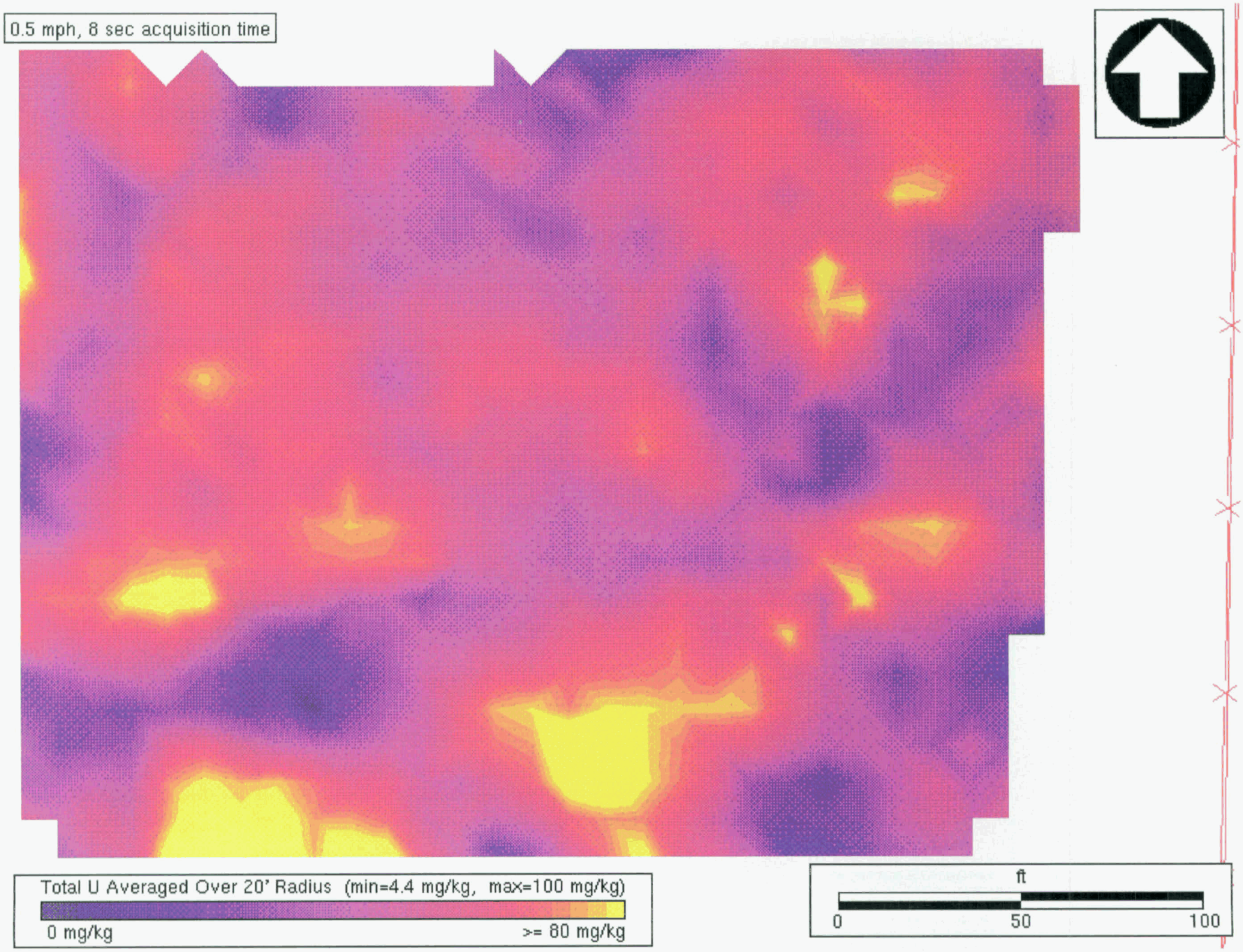


Figure 6-3 RTRAK Total Uranium Results for the USID Area Using a Spatial Averaging Radius of 20 Feet

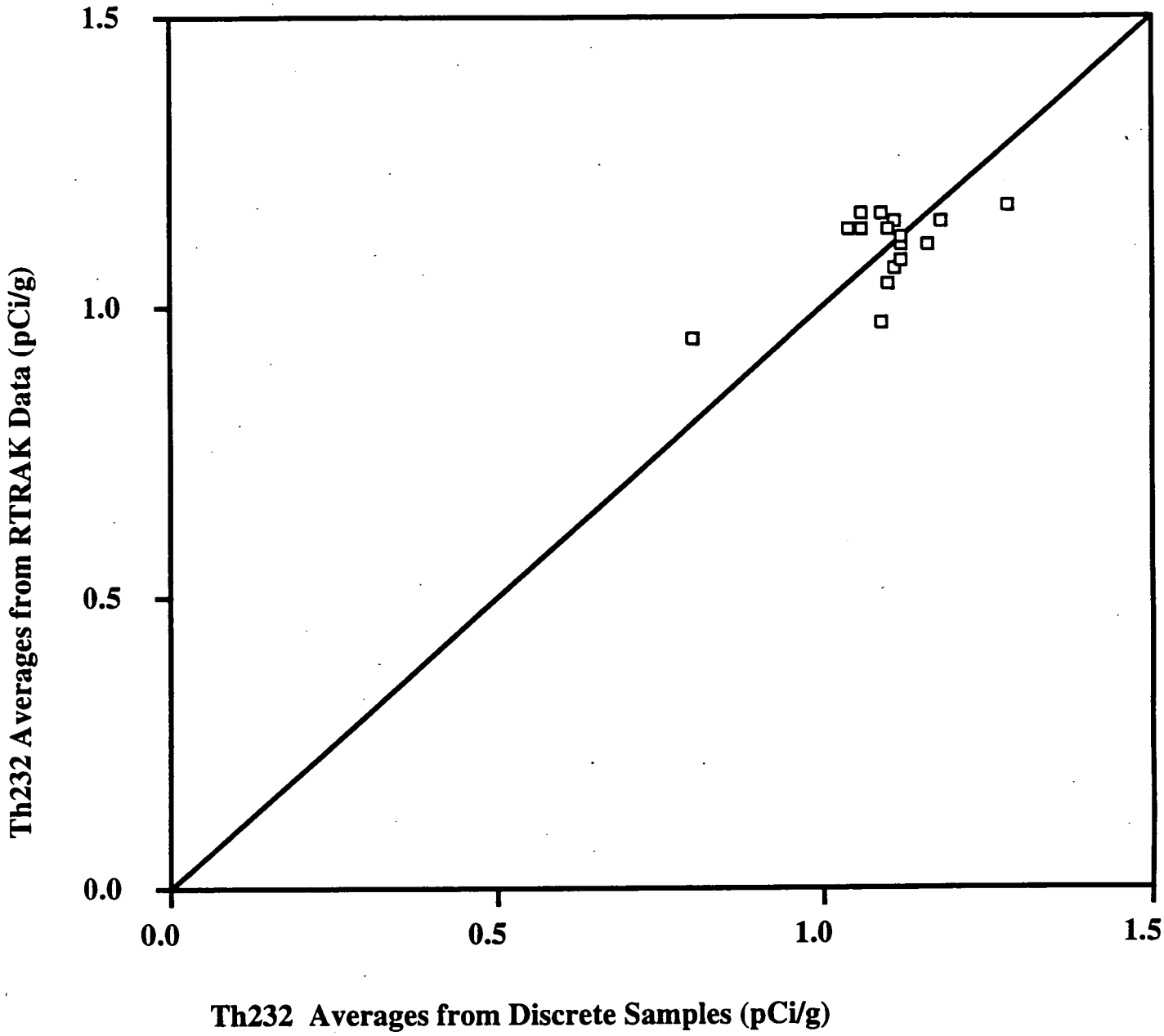


FIGURE 6-4
COMPARISON OF CU AVERAGE THORIUM-232 LEVELS
DEVELOPED FROM DISCRETE SAMPLE DATA AND RTRAK DATA

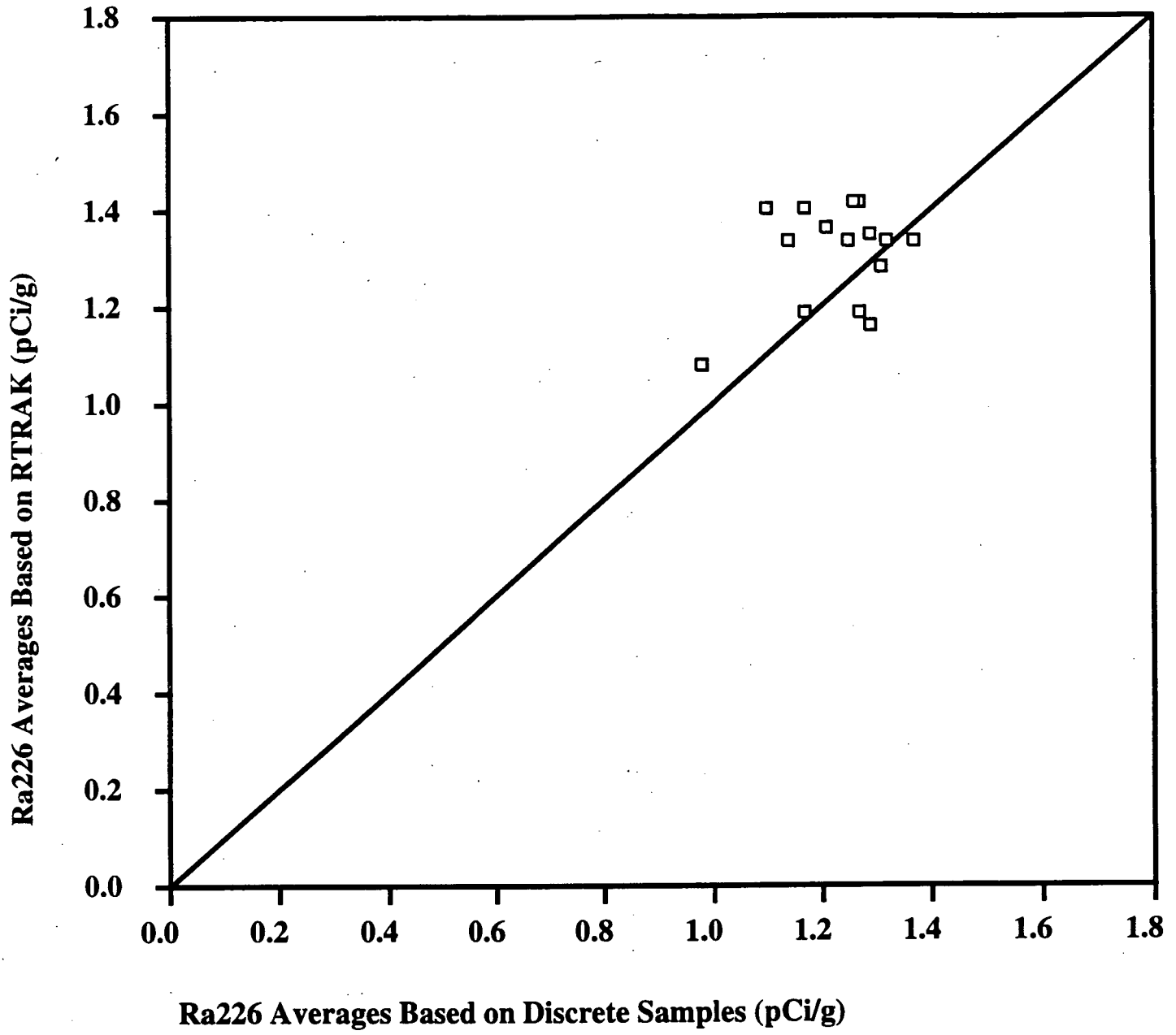


FIGURE 6-5
COMPARISON OF CU AVERAGE RADIUM-226 LEVELS
DEVELOPED FROM DISCRETE SAMPLE DATA AND RTRAK DATA

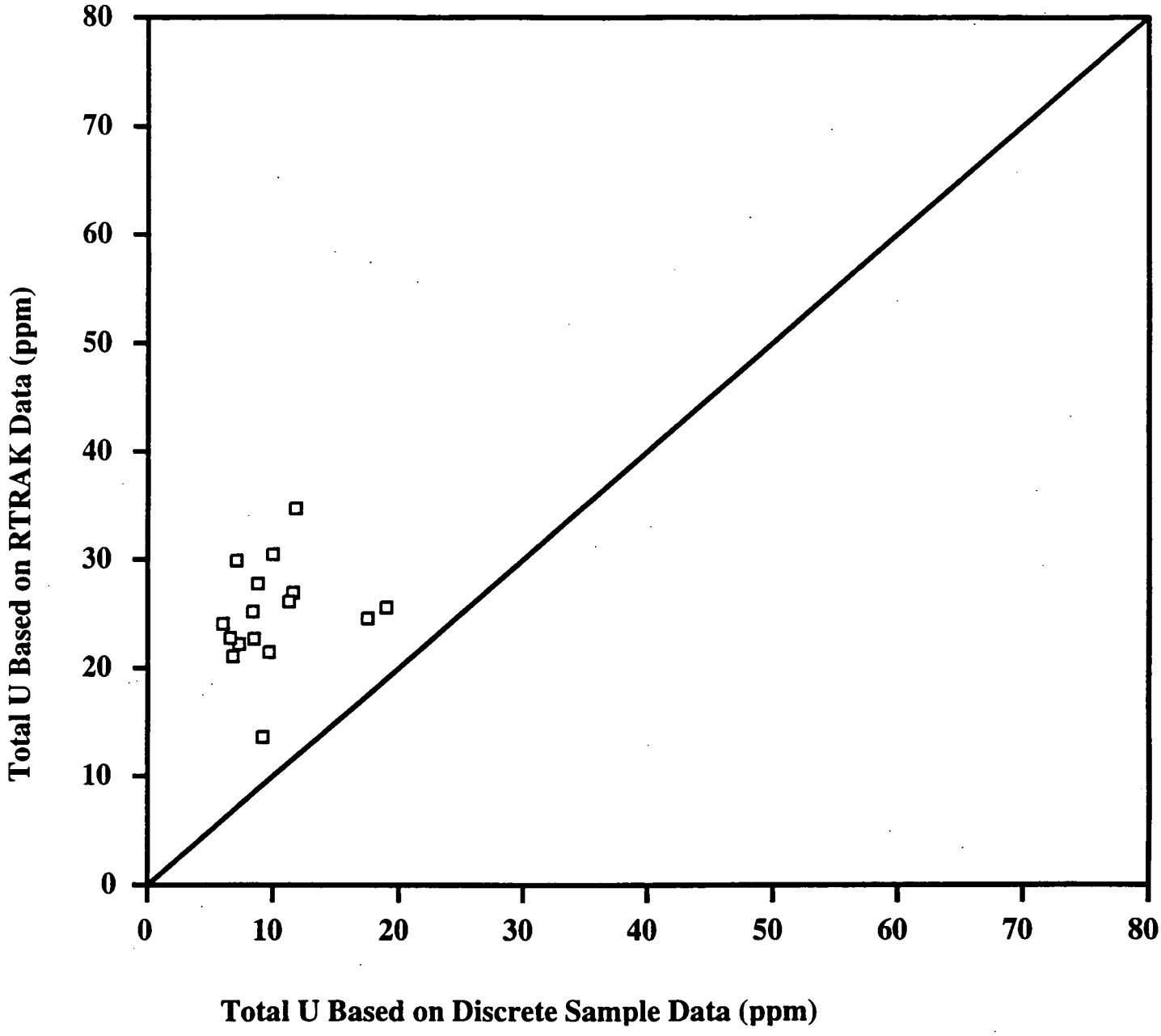


FIGURE 6-6
COMPARISON OF CU AVERAGE TOTAL URANIUM LEVELS
DEVELOPED FROM DISCRETE SAMPLE DATA AND RTRAK DATA

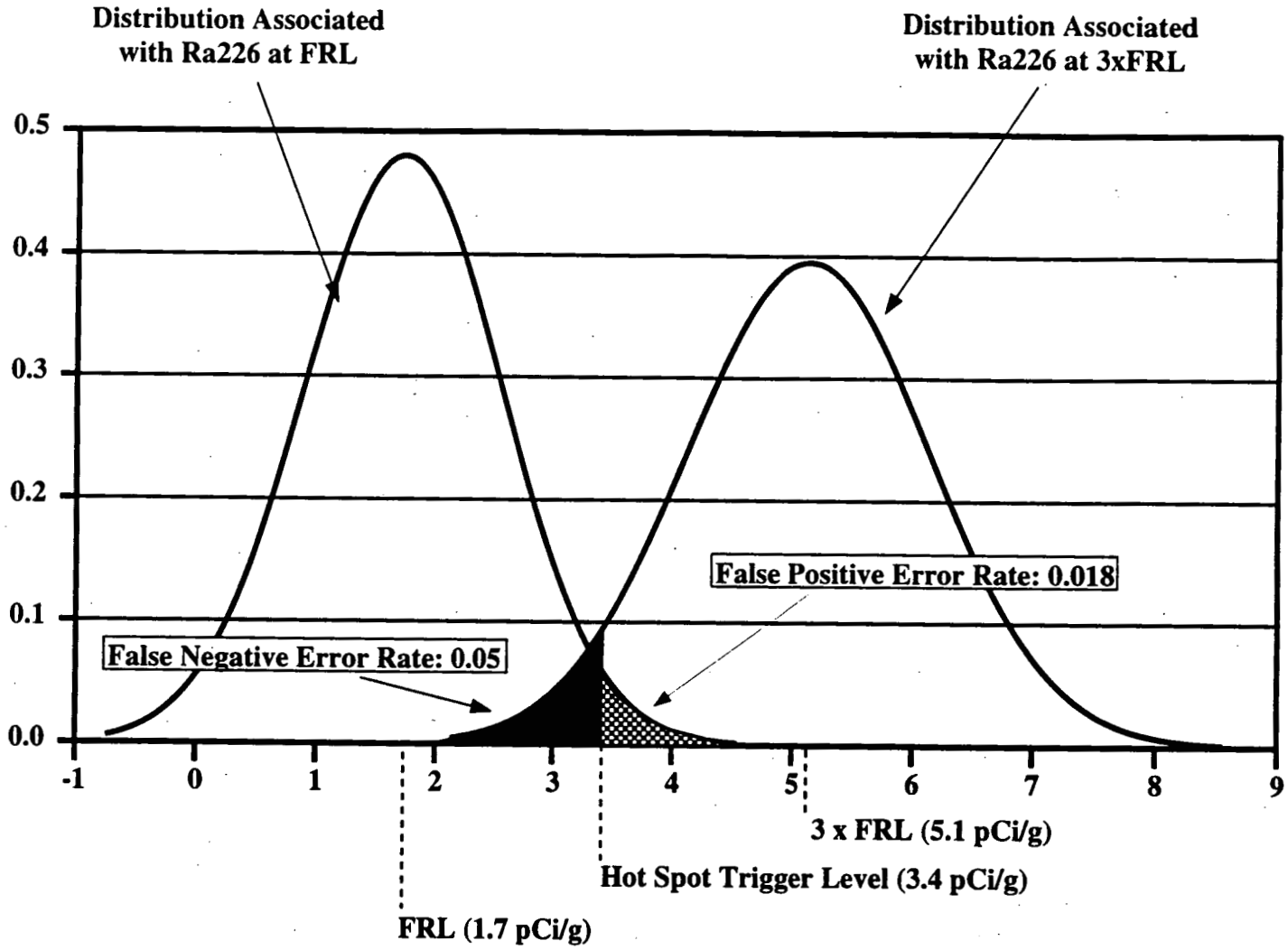


FIGURE 6-7
CONCEPTUAL DEVELOPMENT OF TRIGGER LEVELS AND ERROR RATES FOR RADIUM-226 HOT SPOTS

SECTION 7.0
STRATEGY AND PATH FORWARD FOR FUTURE USE OF THE RTRAK SYSTEM

7.1 STRATEGY FOR USE OF THE RTRAK

7.1.1 Strengths and Limitations of the RTRAK

The strengths of the RTRAK system are enumerated below. It effectively provides complete coverage of an area which is being investigated. The RTRAK is superior to typical "walk-over" surveys in that it can provide quantitative isotopic information as well as quantitative gross activity measurements. It also provides an electronic record of all measurement results and their locations to allow mapping and subsequent contamination location. Because the system is mobile, it can cover an area rapidly and completely. Data quality can be improved by changing RTRAK speeds and data acquisition times. These characteristics make the RTRAK invaluable as a survey tool.

The RTRAK has a number of limitations; precision is limited for individual measurements. As a result, individual measurements cannot be used to precisely quantify quantify total uranium and radium-226 at concentrations near their FRLs. Thorium-232 may be quantified at concentrations near its FRL. However, data variability can be reduced by aggregating measurements. At concentrations well above the FRL, the precision of individual measurements is sufficient for valid data.

The RTRAK is also susceptible to interference from other radionuclides as well as from elevated radiation fields. Thus, elevated concentrations of thorium-232 and radium-226 can result in falsely high uranium-238 results.

A potentially significant interference, called "shine," can result from elevated radiation fields that contain gamma radiation from uranium, thorium, or radium. Such fields can occur near large quantities of radioactive materials. If the gamma rays originate from the material being surveyed, the RTRAK will detect them and report a falsely high result. When used in such locations, high results must be considered suspect and would require confirmation by HPGe or discrete sampling. HPGe measurements are also susceptible to shine; however, the excellent energy resolution of gamma photons provided by the HPGe detector allows shine problems to be recognized more easily than with the RTRAK NaI detector.

Table 7-1 summarizes the strengths, limitations, and data quality and related parameters of the RTRAK system. These items dictate the usage and applications of the RTRAK system, as discussed below.

7.1.2 Potential Uses of RTRAK in Soil Remediation

There are three broad categories in which the RTRAK can be used to support soil remediation:

1. Operations Prior to Soil Remediation:

   - Conduct surveys in accessible areas to develop a general sense for contamination patterns and for general engineering planning and design.
   - Conduct surveys to identify potential WAC exceedance areas.
   - Conduct surveys to identify potential hot spot problems.
   - Conduct surveys to determine heterogeneity within CUs to help determine how many physical samples or HPGe readings must be taken for certification

2. Soil Remediation Operations:

   - Conduct surveys to help establish excavation footprints
   - Conduct surveys to assist in assessing whether specific CUs are likely to fail.
   - Support Implementation of ALARA

3. Operations Following Soil Remediation:

   - Conduct surveys to determine if potential hot spot or FRL problems exist after remediation

Table 7-2 lists potential RTRAK uses and indicates the degree of confidence in the data generated by RTRAK in performing the proposed operation.

7.2 RELATION BETWEEN RTRAK AND HPGe USAGE

The RTRAK and HPGe systems complement each other. The RTRAK is able to provide rapid, 100% coverage of an area. Its precision and detection limits are sufficient to determine the degree of homogeneity and heterogeneity of a given area with respect to total uranium, thorium-232 and radium-226. Its data output is amenable to mapping and spatial averaging. The latter attribute makes RTRAK very useful for applications in which knowledge of average concentrations of soil contaminants are desirable. Finally, the RTRAK is ideal as a front-end survey tool to help focus and guide the use of HPGe.

The strengths of the HPGe are its ability to accurately quantify a variety of isotopes, its high degree of energy resolution (which makes interferences less likely), its ability to average data over a large area, thereby minimizing sampling error and maximizing data representativeness, and its capability to delineate hot spot footprints or WAC exceedances by lowering the detector height to focus in on smaller areas. These characteristics dictate the HPGe's use in providing high quality data for certification/verification activities relative to remediation of soils for hot spots, WAC exceedances, and FRLs. Additionally, the HPGe's strength in footprint delineation indicates that it should be used as a confirmatory tool to evaluate potential hot spot and WAC exceedance areas noted by RTRAK surveys.

7.3 ADDITIONAL RTRAK METHOD DEVELOPMENT

Based upon discussions and conclusions presented in Sections 4 and 5 and upon information presented in Table 7-2, several additional method development studies are required to complement those already performed.

- Most of the data discussed in Sections 4 and 5 have been collected in areas of relatively low contamination. However, additional data are needed from high contamination areas, particularly high uranium contamination, to provide a better understanding of precision and measurement errors at elevated concentrations. This will permit RTRAK data to be used with confidence for WAC and hot spot applications.

- The RTRAK is calibrated against the HPGe; however, as discussed in Section 3.3, the correlation of the RTRAK measurement to HPGe activity concentrations is anchored by low and high data points with few, if any, intermediate data points. Further, even the high points are not indicative of significantly elevated contamination. For RTRAK data to be useful across the contamination levels likely to be encountered at the FEMP, the calibration range must be extended. Therefore, identify areas where radium-226 and thorium-232 concentrations exceed 6 pCi/g and perform HPGe and RTRAK measurement to extend the RTRAK calibration curve. Also, additional areas where total uranium exceeds 300 ppm would extend the calibration toward WAC levels.

- Determine if an empirical relationship can be identified between gross counts per second and isotope specific results to allow gross counts to be interpreted in a manner that could provide isotope specific information. Because all radioactive isotopes contributable to gross counts, a universal relationship may not be possible, but area-specific ones may be.

- Investigate methods for mitigating interferences from elevated radiation fields (shine) and develop quality control indicators that "shine" (may be present) and that data and spectra need to be evaluated and interpreted accordingly.

These activities will be completed as soon as feasible. Activities relating to the first bullet have already been initiated, while activities relating to the second bullet are in the planning stages. As these additional method development studies are completed, separate, stand-alone memoranda will document and summarize the results. These stand-alone memoranda will constitute addenda to this report and should be regarded as incremental method development improvements.

TABLE 7-1
SUMMARY OF RTRAK QUALITY PARAMETERS

Quality Parameters	2 mph/2 sec				0.5 mph/8 sec			
	Uranium-238	Radium-226	Thorium-232	Gross Counts	Uranium-238	Radium-226	Thorium-232	Gross Counts
Rapid Coverage?	yes	yes	yes	yes	yes	yes	yes	yes
Isotopic Information?	yes	yes	yes	no	yes	yes	yes	no
Minimum Standard Deviation	26 pCi/g 81 ppm[a]	0.8 pCi/g	0.4 pCi/g	142 cps	14 pCi/g 42 ppm[a]	0.4 pCi/g	0.2 pCi/g	142 cps
MDC	72 pCi/g 216 ppm[a]	2.2 pCi/g	1.1 pCi/g	NA	47 pCi/g 141 ppm[a]	1.4 pCi/g	0.8 pCi/g	NA
Matrix Interference	thorium radium	thorium	none	NA	thorium radium	thorium	none	NA
"Shine" Interference?	yes	yes	yes	yes	yes	yes	yes	yes

a ppm refer to total uranium

TABLE 7-2
USE OF RTRAK DATA IN SOIL REMEDIATION OPERATIONS

Application	Gross Counts (cps)	Isotopic Concentrations		
		Radium-226	Thorium-232	Total Uranium
Operations Prior to Soil Remediation: • Contamination Patterns	Provides clearly discernable evidence of contamination patterns even at low radionuclide concentrations without the need for data averaging 1 mph/4 sec operating conditions	Provides usable maps of contamination patterns when 1 mph/4 sec data are averaged over a 10 ft radius	Provides usable maps of contamination patterns when 1 mph/4 sec data are averaged over a 10 ft radius	Provides usable maps of contamination patterns when 1 mph/4 sec data are averaged over a 10 ft radius
• Potential WAC Exceedance Areas	May be usable if coupled with HPGe data. Need to better define relationship between gross counts and isotopic data. Need additional data in areas of higher contamination 1 mph/4 sec operating condictions	Not Applicable	Not Applicable	Usable except in areas of high thorium or high radium. Operating conditions of 1 mph/ 4 sec and data average over a 10 ft radius

TABLE 7-2
(continued)

Application	Gross Counts (cps)	Isotopic Concentrations		
		Radium-226	Thorium-232	Total Uranium
Operations Prior to Soil Remediation (cont'd): • Potential Hot Spot Areas	May be usable if coupled with HPGe data. Need to better define relationship between gross counts and isotopic data. Need additional data in areas of higher contamination 1 mph/4 sec operating condictions	Usable with aggregated measurements. Individual measurements may be acceptable if precision levels satisfy project requirements 1 mph/4 sec and data averaged over a 10 ft radius	Usable with aggregated measurements. Individual measurements may be acceptable if precision levels satisfy project requirements 1 mph/4 sec and data averaged over a 10 ft radius	Usable with aggregated measurements. Individual measurements may be acceptable if precision levels satisfy project requirements. May not be usable in areas with high thorium or high radium. 1 mph/4 sec and data averaged over a 10 ft radius
• Homogeneity Within CUs	Provides usable homogeneity information about total activity. Provides no isotope-specific information. 1 mph/4 sec operating conditions	Usable. May require aggregation of measurements depending on required precision and threshold levels. 1 mph/4 sec and data averaged over a 10 ft radius	Usable. May require aggregation of measurements depending on required precision and threshold levels. 1 mph/4 sec and data averaged over a 10 ft radius	Usable but will probably require aggregation of measurements. 1 mph/4 sec and data averaged over a 10 ft radius
Soil Remediation Operations • Excavation Footprints	May be usable if coupled with HPGe data. Need to better define relationship between gross counts and isotopic data. 1 mph/4 sec operating conditions	Usable with aggregated measurements. 1 mph/4 sec and data averaged over a 10 ft radius	Usable with aggregated measurements. 1 mph/4 sec and data averaged over a 10 ft radius	Usable with aggregated measurements except in areas of high thorium or high radium. 1 mph/4 sec and data averaged over a 10 ft radius

TABLE 7-2
(continued)

Application	Gross Counts (cps)	Isotopic Concentrations		
		Radium-226	Thorium-232	Total Uranium
• Potential CU Pass/Fail	Not usable because it provides no isotopic data. 2 mph/2 sec operating conditions	Useable if measurements are aggregated. Spatial resolution is degraded by aggregation. 2 mph/2 sec operating conditions with data averaged over 40 ft radius	Useable if measurements are aggregated. 2 mph/2 sec operating conditions with data averaged over 40 ft radius	Usable if measurements are aggregated, except in areas with high thorium or high radium. 2 mph/2 sec operating conditions with data averaged over 40 ft radius
• Support ALARA Implementation	Potentially usable but need to better define relationship between gross counts and isotopic data. 2 mph/2 sec operating conditions	Not Applicable.	Not Applicable.	Usable, although need to aggregate measurements. A 40 ft. averaging radius at 2 mph/2 sec should provide adequate precision and accuracy.
Operations Following Soil Remediation: • Determine if Potential Hot Spot or FRL Exceedances Remain after Excavation	Can provide information or elevated contamination. Should be followed by HPGe for confirmation. 1 mph/4 sec operating conditions	Usable if measurements are aggregated. Spatial resolution is degraded by aggregation. 1 mph/4 sec operating conditions with data averaged over a 10 ft radius	Usable if measurements are aggregated. Spatial resolution is degraded by aggregation. 1 mph/4 sec operating conditions with data averaged over a 10 ft radius	Usable if measurements are aggregated, except in areas of high thorium or high radium. Spatial resolution is degraded by aggregation. 1 mph/4 sec operating conditions with data averaged over a 10 ft radius

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APPENDIX A

THE RTRAK SYSTEM

APPENDIX A
THE RTRAK SYSTEM

A.1 GENERAL DESCRIPTION

The RTRAK is a gamma-ray measurement system mounted on a four wheel drive John Deere tractor which serves as a mobile counting platform. This platform carries a low resolution 4 x 4 x 16 inch sodium iodide (NaI) detector connected to a high speed pulse height analysis (PHA) counting system. The counting system is mounted in and operated from the climate controlled tractor cab. The NaI detector with its associated photomultiplier tube (PMT) is insulated and mounted into a sealed 8" PVC pipe to protect it from thermal and physical shock during field use. This pipe containing the NaI detector is suspended from the rear of the tractor and is at a height of 31 centimeters (1 foot) above ground level when in the measurement position.

A.2 SODIUM IODIDE DETECTOR

The sodium iodide (NaI) detector is a 4 x 4 x 16 inch NaI scintillation crystal connected to a photomultiplier tube (PMT). When radiation particles or rays strike the NaI scintillation crystal, the crystal emits light or scintillates. This light emission is proportional to the energy of the radiation that caused the scintillation.

To be measured, the light emission must be converted to an electronic signal. This process occurs in the photomultiplier tube (PMT). Sodium iodide (NaI) detectors emit light that is too high a frequency to be seen in most PMTs. To shift the light to a region visible by the PMT, an additive called an activator is added to the scintillation crystal. In NaI detectors the added activator is Thallium (Tl). When Tl is added to a NaI detector, it is more properly written as NaI(Tl).

The PMT is optically coupled to the NaI(Tl) detector. Light from the detector strikes a photosensitive surface of the PMT called the photocathode where the light is converted to one or more electrons. These generated electrons strike electron multiplier plates inside the PMT called dynodes and the signal is amplified to a level that can be registered by readout circuitry such as a pulse height analysis system.

In the NaI(Tl) detector the minimum energy required to record a radiation event is quite high compared to that required by a HPGe detector. In order for a signal to be generated, an electron in the crystal

must move from the valence band to the conduction band and result in a light emission. For NaI(Tl) this evolution requires about 30 eV of energy. By comparison, the HPGe detector requires approximately 0.6 eV to move from the valence band to the conduction band and generate a signal. Because the NaI(Tl) requires so much more energy, its energy resolution is much poorer than a HPGe detector. When a NaI(Tl) detector and a HPGe detector with a rated resolution (FWHM, rated at the 1332 keV peak of Co-60) of 2.0 measure a Cs-137 standard (energy = 661.6 keV), the Ge detector will produce a peak with a resolution (FWHM) of about 1.8 keV, whereas the NaI(Tl) resolution for the peak will be about 55 keV. This means the HPGe detector is superior for resolving and identifying nuclides.

A.3 COUNTING SYSTEM

Whenever an output pulse from a detector is proportional to the energy deposition in the detector, the measurement of pulse heights is a useful tool for energy determinations. This is the basis of pulse height analysis (PHA). PHA is more versatile if it is coupled to a multichannel analyzer (MCA) in which the pulses are sorted according to size and simultaneously recorded in many consecutive channels. The MCA technique permits the identification of many nuclide decay energies during a single analysis. The RTRAK PHA counting system is coupled to a computer containing MCA software. Presently, the counting system is using EG&G Maestro II MCA software to provide gamma spectrum display and peak identification. Gamma peaks displayed in the spectrum are identified by comparing the peak energies to known peak energies contained in a "reference library." For gamma-emitting nuclides, the net peak area is divided by the counting time and multiplied by a conversion or counting efficiency factor to quantitatively determine the concentration of an identified nuclide. The RTRAK counting system may also be used as a gross survey instrument by summing the total net counts in the spectrum. This feature is useful in identifying "hot spots" during the measurement process.

A.4 GLOBAL POSITIONING SYSTEM

The physical location of spectrum acquired by the system is determined using a global positioning system (GPS). The GPS system used at the FEMP utilizes two receivers, a Pathfinder ProXL system and an Omnistar 6300A. These receivers are mounted in the climate controlled tractor cab and antennae for the systems are mounted on the cab roof. The Omnistar receiver is used to provide real-time differential correction to the Pathfinder receiver, increasing position accuracy. In essence, the Omnistar receiver acts as a "virtual base station". Operating in the differential mode allows sub-meter

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position accuracy. (Note: Without the differential processing capability, position errors up to approximately 100 meters can exist). When counting is performed using the RTRAK system, special software developed for RTRAK called MULTIACQ tags the spectrum with location coordinates provided by the GPS system.

A.4.1 Operation of the GPS

The GPS is started and checked before the RTRAK unit proceeds to the field for measurements. The technique for start-up and checking is as follows:

- Turn on the GPS and differential GPS (DGPS) receivers.
- Allow five minutes for the receivers to warm up.
- Ensure that the GPS and DGPS antennae mounted on the tractor cab are intact and undamaged.

After startup, the GPS will automatically lock onto satellites during the warm-up. The unit is designed to lock onto US Defense Department satellites named "NAVSTAR." There are 24 NAVSTAR satellites in polar orbit that make up the GPS constellation. Twenty-one of these are in operation at all times and three are spares. To ensure optimal location information the FEMP uses a Differential Global Positioning System (DGPS), a second GPS receiver which acts as a "virtual base station". The DGPS provides signal corrections to the GPS receiver that reduce the uncertainty in location. In a system operating without DGPS, signal degradation from the satellites provide location values within about 100 meters of the true location.

The GPS information is read out to a Magellan NAV 5000 Receiver. This receiver displays location information and, if the station is moving, also displays the rate of speed. The GPS rate of speed in miles per hour is used to control the survey speed of the RTRAK (ie. ½ or 2 mph).

A.4.2 Determination of the Detector Field of View

From a theoretical perspective, the field of view for the detector can be considered to be infinity. However, for field measurements, this is an impractical concept. For practical considerations, the field of view for the RTRAK is defined as the circumference of the circle which encompasses 90% of the gamma photon flux emanating from a radioactive source. At the FEMP, a U_3O_8 point calibration source

was measured at various angles to the center of the NaI detector at distances of 1 meter and 2 meters. From calculations based upon these measurements, the following results were obtained:

Distance in meters	Fraction of Source Strength
1.12	0.8987
1.2	0.9102

As a matter of practice, the value of 1.2 meters is used as the radius value for the detector's field of view. This field of view permits evaluation of an approximately 10 m^2 area when the tractor is moving at 2 miles per hour and a 2 second count is acquired.

A.4.3 Detector Calibrations

Normally two calibrations are required on a gamma-ray counting system in order to qualitatively and quantitatively evaluate the spectrum. These calibrations are an energy calibration which permits nuclide identification of peaks in the spectrum on the basis of their energies, and an efficiency calibration which corrects the relative counts in the spectrum to absolute counts by determining the system measurement efficiency at fixed and defined measurement geometries using traceable efficiency calibration sources. The efficiency calibrations are discussed in detail in Section 3.3.

A.4.3.1 RTRAK Energy Calibration

The RTRAK detector system is calibrated for energy before each use. Calibration is performed by placing thorium-bearing lantern mantles in the center of the detector housing and counting the mantles for 120 seconds. Two energy calibration checks are performed before each use. The first check at 2615 keV is performed to adjust the counting system amplifier to the correct gain and to ensure the counting system is functioning correctly before proceeding to the field. A second energy calibration is performed when the RTRAK arrives at the measurement location. This energy calibration is accomplished by using the 238.6 keV (at display channel 40) and 2615 keV (at display channel 447) gamma peaks generated by the Thorium lantern mantles to create an energy line or curve between the two energy points. This provides an energy calibration factor for the counting system of about 5.84 keV/channel of the display. Once the MCA has been calibrated, any radionuclides with gamma energies lying between the two energy extremes can be identified on the basis of their decay energies.

A.4.3.2 RTRAK Efficiency Calibration

In the RTRAK, efficiency calibrations cannot be done in the "normal fashion" because the geometry of field measurements cannot be appropriately reproduced with traceable efficiency calibration sources. RTRAK measurement efficiency factors were determined by comparison of HPGe data with static 300 second RTRAK data at 10 sampling locations. The resultant data were used to generate the following equations for quantifying RTRAK net counting data:

Thorium-232 Correction Factor

$$C_{Th}\ pCi/g = (\ 0.06817\ pCi/g\ x\ N_{Th}\ cps\ ) - 0.041\ pCi/g$$

Radium-226 Correction Factor

$$C_{Ra}\ pCi/g = (\ 0.19243\ \frac{pCi/g}{cps}\ x\ N_{Ra}\ cps\ ) + 0.08805\ pCi/g$$

Potassium-40 Correction Factor

$$C_K = 0.21\ pCi/g\ x\ N_K\ cps$$

Uranium-238 Correction Factor

$$C_U\ pCi/g = 2.994\ \frac{pCi/g}{cps}\ (\ N_U\ cps - (\ \frac{C_{Th}\ pCi/g}{0.135\ \frac{pCi/g}{cps}}\ ) + (\frac{C_{Ra}\ pCi/g}{0.271\ \frac{pCi/g}{cps}}\ )\ ) + 0.481\ pCi/g$$

Note: In the equation for uranium-238 the concentration for thorium must be subtracted out because there is a contribution from a thorium daughter peak (Ac-228 @ 969.11 keV) that contributes to the uranium-238 (protactinium-234m) window. The concentration for radium is added back in because the background subtraction for the Compton scatter etc. also subtracts counts due to radium that are within the background window but not part of the background. If the radium correction is not made, the spectrum background will be overcompensated.

A.5 RTRAK OPERATION

The RTRAK may be operated in the static mode or the mobile mode. In the static mode, i.e. the RTRAK vehicle remaining stationary, the operator initiates a count for a specified amount of time. At

the end of the counting period, the collected spectrum is saved to electronic media for later data reduction.

In the mobile mode, a special computer program called MULTIACQ is used to provide a continuous collection of spectra once the counting time is set and the GPS coordinate data are incorporated. When this program is initiated, spectra will continue to be consecutively collected at the specified counting time until the operator stops the counting process. The counting times presently used for RTRAK spectrum collection range from two to eight seconds.

Standard mobile operation of the RTRAK consists of driving the tractor at approximately two miles per hour (~ 3 ft/s) over an area to be measured and collecting, GPS tagging and storing a spectrum every two seconds. Each two second measurement integrates the concentration over ~ 10 m^2. Alternatively, the tractor may be operated at a speed of one half mile per/hr (~ 0.75 ft/s) while collecting data every two seconds or every eight seconds. Slowing the RTRAK down, counting longer, adding detectors or averaging over a larger area reduces the relative error of the data collected by roughly the square root of the change in counting time.

Windows or regions of interest for those nuclides of interest are noted in the RTRAK spectra, and then the net counting data determined from these windows are quantified. The windows used for RTRAK spectra are given in Table A-1.

The signal windows for each of the nuclides shown in this table are very wide. This is necessary because of the poor energy resolution of NaI crystals compared to HPGe. With a NaI detector, the signal window is set wide to ensure that all the counts associated with the peak are captured. Except for thallium-208 (thorium-232) peak at 2614 keV, the signal that the windows show range from ~116 to 234 keV wide to collect as many counts from the measured nuclide as possible without undue interference from other peaks in the spectrum. The thallium-208 signal window is set wider because there are no close interfering peaks at this energy and peaks are wider at the higher energies because the resolution increases with increasing energy. Except for uranium-238, these energy windows yield reasonable results for the nuclides of interest. The analysis for uranium-238 (protactinium-234) requires two corrections. First, there is interference from both thorium and radium near the signal window

energy. Second, the branching ratio of the measured nuclide, protactinium-234m, is very low, resulting in low counts and a correspondingly larger uncertainty in the result.

A.5.1 Quantification of Nuclide Data

To obtain net counts for each of the measured nuclide signal windows, the integrated counts of the two background windows are summed and then normalized to the width of the signal window. The normalized value is subtracted from the integrated signal window counts. This technique is illustrated in Figure A-1. The normalized "counting backgrounds" for each signal window are shown as cross hatching under each of the peak (signal window) areas. The upper black area of the peak is the resultant net counts for each peak. Figure A-1 also illustrates the large uncertainty in RTRAK counts where the "counting background" is substantially larger than the measured net peak counts. These large uncertainties occur as a result of short spectrum count times (2 or 8 seconds) and measuring activity that is at or just above background concentrations.

The resulting net counts are divided by the counting time (2 or 8 seconds) yielding a result for the signal window of counts per second (cps). The signal net cps are then inserted into appropriate equation to yield a quantified activity concentration in pCi/g. These data are also saved to electronic media for later data reduction.

TABLE A-1
WINDOWS USED FOR RTRAK SPECTRUM

Measured Nuclide	Measured Nuclide Energy, keV	Branching Ratio	Nuclide of Interest	Low Backgd Window, keV	Signal Window, keV	High Backgd Window, keV
Pa-234m	1001.0	0.00845	U-238	836.6-865.8	943.1-1058.9	1064.7-1093.8
Tl-208	2614.44	0.998	Th-232	2370.3-2399.5	2405.4-2823.8	2829.6-2858.9
Bi-214	1764.49	0.158	Ra-226	1644.2-1693.4	1699.3-1850.9	1856.7-1886.0
K-40	1460.81	0.1067	K-40	1308.8-1338.0	1343.9-1577.7	1583.5-1612.8

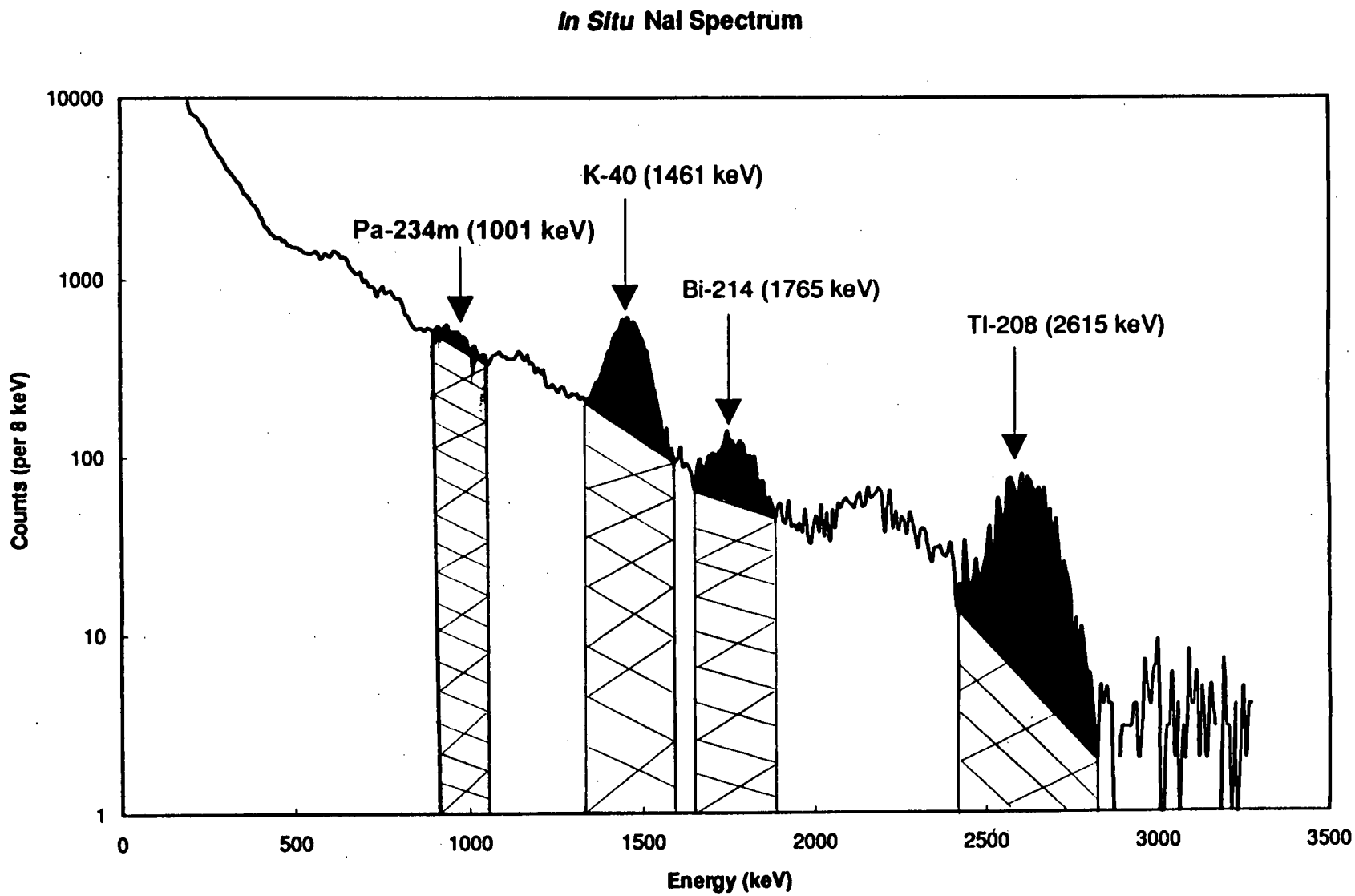
In Situ NaI Spectrum
Pa-234m (1001 keV)
K-40 (1461 keV)
Bi-214 (1765 keV)
Tl-208 (2615 keV)
Counts (per 8 keV)
10000
1000
100
10
1
0
500
1000
1500
2000
2500
3000
3500
Energy (keV)

Figure A-1

APPENDIX B

CALCULATING HOT SPOT AND WAC TRIGGER LEVELS

APPENDIX B
CALCULATION OF HOT SPOT AND WAC TRIGGER LEVELS

The soils remediation project at the FEMP requires that DOE identify and remediate any primary radionuclide (i.e., thorium-232, radium-226, and total uranium) that exceeds three times the appropriate FRL. In addition, to satisfy the WAC for total uranium, DOE is committed to identifying and segregating soils that contain total uranium in excess of 1,030 ppm. The RTRAK is a valuable tool for both identifying potential hot spot concerns and for locating soils that might exceed the WAC for total uranium because the RTRAK provides 100% areal coverage and quantitative isotopic concentrations for the thorium-232, radium-226, and total uranium.

When the RTRAK is deployed to locate potential hot spot and/or WAC concerns, there is a practical question of what "trigger level" should be used to initiate action. "Trigger levels" can be defined as concentrations that, if exceeded by an RTRAK measurement, result in some further action---for example, follow-up analyses with the HPGe and/or discrete samples, or immediate remediation. Because of the measurement error associated with individual RTRAK measurements, to be confident at a pre-specified certainty level that all hot spot/WAC concerns have been identified, trigger levels are typically set at values below the actual hot spot or WAC criteria. How far below the hot spot or WAC criteria is a function of how confident one wishes to be that a true hot spot or WAC problem is identified, and the size of the measurement error associated with the particular isotope of concern at the hot spot and/or WAC level. Because measurement error is a function of isotope, RTRAK speeds/acquisition times, and the amount of spatial averaging that is being used with the RTRAK measurements, all of these factors will also have a direct impact on the trigger level.

Once a trigger level has been set, there are two potential errors that might be made in the field. The first error (false negative) is missing a hot spot/WAC problem, i.e., the RTRAK returns a concentration that is below the trigger level even though the actual concentration for the read area is above the hot spot/WAC criteria. The second error is identifying a hot spot or WAC concern even though none actually exists, i.e., the RTRAK returns a concentration that is above the trigger level, even though actual concentrations are below the relevant hot spot/WAC criteria. Whenever

measurement error is present, there will always be some probability that one of these errors will be made, no matter what trigger level is selected. The best trigger level keeps both errors below some acceptable level. For the first type of mistake, traditionally an error rate of at most 5% has been deemed acceptable, i.e., for a given set of trigger levels, if a hot spot or WAC concern exists, the RTRAK will catch it at least 95% of the time. For the second type of mistake, given the large number of RTRAK measurements that are made in a typical characterization effort, the error rate must be kept on the order of 0.1% or less. Error rates larger than this will generate a significant number of "false positives" per acre that would require unnecessary action.

The calculation of trigger levels and their accompanying error rates is straightforward from a statistical perspective. For the sake of illustration, assume that one is specifying a hot spot trigger level for a particular isotope. Since false negative errors are considered to be the worse of the two types of errors, one typically prespecifies the false negative rate that will be tolerated, α. One also requires the hot spot criteria, 3xFRL, the measurement error or standard deviation expected from the RTRAK for the isotope of concern at the hot spot criteria, σ_{3xFRL}, the concentration at which making false positive statements becomes important (for hot spots, assumed to be the FRL), and finally the standard deviation or measurement error associated with RTRAK values at that concentration, σ_{FRL}. Using the assumption that measurement error is normally distributed, a trigger level can then be calculated:

$$\text{Trigger} = 3\text{xFRL} - z_{1-\alpha} \cdot \sigma_{3xFRL}$$

This trigger level guarantees that at the prespecified false negative error rate α, hot spots will be missed at a rate of at most $(1 - \alpha)$. The only question that remains is what the false positive error rate, β, will be given this trigger level. Again, this can be calculated using the assumption that measurement error is normally distributed, and is simply:

$$\beta = \text{Prob(RTRAK measurement} > \text{trigger level} \mid \text{actual concentration} = \text{FRL)}$$

This says that the false positive error rate β is equal to the probability that the RTRAK will return a value greater than the trigger level when in fact the actual concentration is at the FRL. Figure 6-7 illustrates these concepts graphically.

APPENDIX C

PROFILE RUNS FOR USID AND SOUTH FIELD AREAS

APPENDIX C
PROFILE RUNS FOR USID AND SOUTH FIELD AREAS

Appendix C contains tables and figures presenting data obtained from repeated measurements along pathways in the USID and South Field areas. Tables C-1, C-3, C-5, and C-7 present data for the USID area, while Tables C-2, C-4, C-6, and C-8 present data for the South Field area. Each table shows the number of segments into which the pathway is subdivided, as well as the number of measurements for each segment. The mean, standard deviation, and percent standard deviation (relative to the mean) of the measurements in each segment are also shown. Grand averages of the mean, standard deviation, and percent standard deviation are also calculated for each pathway.

Figures C-1 through C-24 are graphical presentations of the means, standard deviations, and standard deviations as a percentage of the means contained in Tables C-1 through C-8.

TABLE C-1

URANIUM-238 - REPEATED PROFILE RUNS IN USID AREA

	2 sec - 2 mph				2 sec - 0.5 mph				8 sec - 0.5 mph			
AREA	NO. MEASURMENTS	MEAN*	STD DEV*	% STD DEV	NO. MEASURMENTS	MEAN*	STD DEV*	% STD DEV	NO. MEASURMENTS	MEAN*	STD DEV*	% STD DEV
A-01	41	11.50	25.36	220.52	129	5.61	27.76	494.83	27	16.33	12.80	78.38
A-02	71	8.57	25.76	300.58	217	9.97	27.11	271.92	52	11.92	12.53	105.12
A-03	73	14.58	26.20	179.70	206	14.43	26.73	185.24	44	16.80	12.77	76.01
A-04	72	16.41	25.76	156.98	205	13.73	24.58	179.02	50	20.09	14.84	73.87
A-05	76	15.51	25.59	164.99	216	18.37	25.98	141.43	47	16.97	14.53	85.62
A-06	73	17.04	26.18	153.64	225	11.54	27.71	240.12	43	17.01	15.07	88.59
A-07	69	13.91	23.27	167.29	200	17.65	28.69	162.55	46	19.78	13.31	67.29
A-ROAD	52	13.21	21.82	165.18	120	6.46	21.34	330.34	28	8.49	14.21	167.37
A-08	75	24.47	28.02	114.51	231	19.01	26.45	139.14	49	20.47	16.01	78.21
A-09	84	29.00	28.34	97.72	232	21.78	28.04	128.74	53	22.01	15.02	68.24
A-10	80	23.83	24.08	101.05	240	20.03	29.53	147.43	55	21.33	13.27	62.21
A-11	73	12.76	29.5	231.19	193	13.96	25.95	185.89	44	14.70	14.82	100.82
Averages		16.73	25.82	171.11		14.38	26.66	217.22		17.16	14.10	87.65

* activity concentration units are pCi/g

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TABLE C-2

URANIUM-238 - REPEATED PROFILE RUNS - SOUTH FIELD

	2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph			
AREA	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV
A-01	42	1.13	25.07	2218.58	15	17.41	18.36	105.46	16	-5.55	15.31	275.86
A-02	38	11.82	29.77	251.86	15	11.53	18.57	161.06	14	8.70	12.07	138.74
A-03	43	22.26	26.38	118.51	16	9.84	19.20	195.12	17	9.83	14.27	145.17
A-04	44	4.62	31.36	678.79	17	16.09	25.47	158.30	15	16.73	17.51	104.66
A-05	42	17.11	38.03	222.27	17	13.59	19.69	144.89	16	17.24	19.07	110.61
A-06	43	20.72	31.47	151.88	19	17.38	15.38	88.49	16	10.64	11.86	111.47
A-07	44	11.03	27.92	253.13	10	10.62	23.40	220.34	17	8.68	18.08	208.29
A-08	37	18.24	35.53	194.79	17	29.30	28.85	98.46	17	29.60	14.71	49.70
A-09	42	27.73	43.49	156.83	14	37.18	29.32	78.86	15	25.90	24.78	95.68
A-10	40	14.11	23.57	167.04	16	5.81	17.27	297.25	15	8.61	15.52	180.26
A-11	42	9.74	24.58	252.36	13	14.96	14.57	97.39	14	7.62	13.29	174.41
A-12	43	5.35	27.44	512.90	13	5.58	22.76	407.89	15	5.06	15.39	304.15
A-13	35	9.84	26.50	269.31	15	-0.92	19.13	2079.35	10	12.80	16.10	125.78
A-14	41	8.37	33.27	397.49	16	8.21	22.30	271.62	15	9.91	19.83	200.10
A-15	42	9.38	25.28	269.51	17	10.78	16.30	151.21	19	7.82	12.48	159.59
A-16	41	11.40	31.42	275.61	14	6.21	25.27	406.92	15	-0.28	16.33	5832.14
A-17	39	15.58	22.63	145.25	16	6.42	21.43	333.80	13	9.37	13.45	143.54
A-18	51	12.25	23.49	191.76	13	17.26	20.83	120.68	19	6.23	12.96	208.03
A-19	53	9.89	25.10	253.79	17	13.90	16.80	120.86	14	11.83	12.74	107.69
A-20	42	4.47	29.94	669.80	15	10.32	15.04	145.74	17	5.54	15.04	271.48
A-21	35	2.39	28.43	1189.54	17	5.09	18.47	362.87	14	9.83	6.45	65.62
A-22	45	7.14	27.37	383.33	13	5.08	19.78	389.37	15	6.84	14.83	216.81
A-23	43	10.57	27.54	260.55	13	4.49	21.55	479.96	15	7.80	8.96	114.87
A-24	43	4.00	23.84	596.00	17	3.43	18.11	527.99	17	5.53	6.76	122.24
A-25	38	5.88	20.90	355.44	15	5.72	11.28	197.20	15	8.31	12.42	149.46
A-26	45	-2.80	30.04	1072.86	16	-11.89	30.37	255.42	16	-12.13	21.87	180.30
A-27	42	1.49	28.90	1939.60	14	-7.15	18.39	257.20	15	9.97	13.30	133.40
A-28	36	5.89	24.88	422.41	16	4.67	19.26	412.42	17	10.10	14.52	143.76
A-29	45	15.69	33.95	216.38	18	21.11	26.12	123.73	19	17.20	16.08	93.49
A-30	47	29.27	34.25	117.01	17	21.35	23.10	108.20	19	26.17	11.59	44.29
A-31	43	25.28	38.99	154.23	20	31.64	31.40	99.24	17	26.23	24.70	94.17
A-32	42	17.34	35.99	207.55	19	23.33	23.11	99.06	18	21.44	21.09	98.37
A-33	34	14.46	28.78	199.03	17	11.76	21.14	179.76	16	13.01	11.88	91.31
A-34	39	5.69	23.56	414.06	14	7.04	20.66	293.47	20	4.89	14.79	302.45
A-37	48	1.31	22.52	1719.08	1	3.31	19.92	601.81	8	12.10	12.46	102.98
A-38	37	10.78	18.76	174.03	5	3.52	17.89	508.24	1	6.98	9.89	141.69

TABLE C-2

(continued)

		2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph		
AREA	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV
A-39	42	6.27	19.67	313.72	18	16.15	16.89	104.58	14	6.02	11.22	186.38
A-40	38	4.16	20.81	500.24	15	7.21	13.27	184.05	14	10.48	10.59	101.05
A-41	48	10.02	25.60	255.49	21	6.97	14.92	214.06	16	6.99	11.95	170.96
A-42	46	4.14	22.48	543.00	17	10.90	15.80	144.95	15	8.57	10.85	126.60
A-43	45	4.35	25.11	577.24	16	13.61	17.14	125.94	16	5.28	18.73	354.73
A-44	33	2.68	26.18	976.87	16	7.35	22.44	305.31	20	6.95	12.63	181.73
A-45	43	12.76	22.33	175.00	18	11.81	22.31	188.91	14	7.88	14.52	184.26
A-46	45	3.37	26.48	785.76	14	17.06	14.20	83.24	18	8.22	11.47	139.54
A-47	45	8.73	21.92	251.09	18	6.97	20.70	296.99	17	11.10	11.00	99.10
A-48	41	5.26	23.01	437.45	17	6.40	17.73	277.03	14	6.47	12.72	196.60
A-49	52	9.29	21.64	232.94	14	11.49	26.89	234.03	16	5.31	13.61	256.31
A-50	38	3.63	23.14	637.47	18	-2.74	16.43	599.64	16	2.08	14.09	677.40
Averages		9.88	27.28	474.14		10.57	20.19	277.88		9.71	14.29	285.78

* activity concentration units are pCi/g

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TABLE C-3

THORIUM-232 - REPEATED PROFILE RUNS IN USID AREA

	2 sec - 2 mph											
AREA	NO. MEASURMENTS	MEAN*	STD DEV*	% STD DEV	NO. MEASURMENTS	MEAN*	STD DEV*	% STD DEV	NO. MEASURMENTS	MEAN*	STD DEV*	% STD DEV
A-01	41	0.75	0.33	44.00	129	0.75	0.31	41.33	27	0.73	0.16	21.92
A-02	71	0.83	0.35	42.17	217	0.78	0.37	47.44	52	0.78	0.18	23.08
A-03	73	0.74	0.34	45.95	206	0.76	0.32	42.11	44	0.82	0.16	19.51
A-04	72	0.76	0.33	43.42	205	0.82	0.37	45.12	50	0.76	0.19	25.00
A-05	76	0.78	0.33	42.31	216	0.73	0.35	47.95	47	0.79	0.17	21.52
A-06	73	0.76	0.42	55.26	225	0.77	0.34	44.16	43	0.79	0.17	21.52
A-07	69	0.86	0.36	41.86	200	0.79	0.37	46.84	46	0.78	0.18	23.08
A-ROAD	52	0.35	0.34	97.14	120	0.43	0.35	81.40	28	0.52	0.25	48.08
A-08	75	0.87	0.38	43.68	231	0.76	0.40	52.63	49	0.77	0.22	28.57
A-09	84	0.78	0.33	42.31	232	0.76	0.38	50.00	53	0.80	0.20	25.00
A-10	80	0.76	0.33	43.42	240	0.73	0.37	50.68	55	0.76	0.17	22.37
A-11	73	0.71	0.32	45.07	193	0.75	0.34	45.33	44	0.66	0.21	31.82
Averages		0.75	0.35	48.88		0.74	0.36	49.58		0.75	0.19	25.95

* activity concentration units are pCi/g

TABLE C-4

THORIUM-232 - REPEATED PROFILE RUNS - SOUTH FIELD

	2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph			
AREA	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV
A-01	42	0.79	0.30	37.97	15	0.97	0.21	21.65	16	0.93	0.20	21.51
A-02	38	0.97	0.31	31.96	15	0.88	0.24	27.27	14	0.90	0.15	16.67
A-03	43	0.80	0.36	45.00	16	0.90	0.34	37.78	17	1.09	0.34	31.19
A-04	44	1.73	0.76	43.93	17	2.22	0.76	34.23	15	1.92	0.56	29.17
A-05	42	1.69	0.87	51.48	17	1.52	0.77	50.66	16	1.30	0.52	40.00
A-06	43	1.02	0.41	40.20	19	0.94	0.24	25.53	16	0.96	0.22	22.92
A-07	44	1.00	0.35	35.00	10	0.96	0.35	36.46	17	1.16	0.32	27.59
A-08	37	1.50	0.54	36.00	17	2.18	0.46	21.10	17	1.97	0.51	25.89
A-09	42	2.53	0.86	33.99	14	3.50	0.50	14.29	15	2.71	0.61	22.51
A-10	40	1.42	0.70	49.30	16	1.00	0.39	39.00	15	1.02	0.46	45.10
A-11	42	0.74	0.30	40.54	13	0.72	0.26	36.11	14	0.71	0.14	19.72
A-12	43	0.69	0.36	52.17	13	0.75	0.34	45.33	15	0.77	0.11	14.29
A-13	35	0.87	0.37	42.53	15	0.84	0.38	45.24	10	0.72	0.17	23.61
A-14	41	0.98	0.50	51.02	16	0.75	0.37	49.33	15	0.78	0.20	25.64
A-15	42	0.70	0.33	47.14	17	0.70	0.22	31.43	19	0.73	0.20	27.40
A-16	41	0.65	0.33	50.77	14	0.63	0.17	26.98	15	0.68	0.16	23.53
A-17	39	0.65	0.33	50.77	16	0.68	0.24	35.29	13	0.63	0.15	23.81
A-18	51	0.63	0.28	44.44	13	0.61	0.27	44.26	19	0.65	0.16	24.62
A-19	53	0.58	0.35	60.34	17	0.69	0.24	34.78	14	0.62	0.15	24.19
A-20	42	0.69	0.35	50.72	15	0.66	0.23	34.85	17	0.62	0.15	24.19
A-21	35	0.74	0.36	48.65	17	0.75	0.20	26.67	14	0.67	0.16	23.88
A-22	45	0.60	0.28	46.67	13	0.53	0.20	37.74	15	0.51	0.12	23.53
A-23	43	0.59	0.29	49.15	13	0.60	0.19	31.67	15	0.66	0.16	24.24
A-24	43	0.57	0.26	45.61	17	0.59	0.19	32.20	17	0.53	0.16	30.19
A-25	38	0.50	0.30	60.00	15	0.52	0.24	46.15	15	0.52	0.19	36.54
A-26	45	0.96	0.59	61.46	16	1.09	0.62	56.88	16	1.46	0.47	32.19
A-27	42	0.78	0.42	53.85	14	0.87	0.43	49.43	15	0.71	0.20	28.17
A-28	36	0.65	0.24	36.92	16	0.60	0.27	45.00	17	0.65	0.15	23.08
A-29	45	0.67	0.36	53.73	18	0.67	0.27	40.30	19	0.69	0.17	24.64
A-30	47	0.74	0.43	58.11	17	0.69	0.38	55.07	19	0.96	0.23	23.96
A-31	43	1.09	0.58	53.21	20	1.21	0.34	28.10	17	1.11	0.26	23.42

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TABLE C-4

(continued)

		2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph		
AREA	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV
A-32	42	1.03	0.42	40.78	19	1.00	0.42	42.00	18	0.96	0.25	26.04
A-33	34	0.88	0.40	45.45	17	0.83	0.25	30.12	16	0.76	0.24	31.58
A-34	39	0.75	0.29	38.67	14	0.68	0.28	41.18	20	0.60	0.16	26.67
A-37	48	0.61	0.29	47.54	1	0.53	0.33	62.26	8	0.53	0.12	22.64
A-38	37	0.54	0.29	53.70	5	0.64	0.18	28.13	1	0.54	0.12	22.22
A-39	42	0.51	0.32	62.75	18	0.60	0.17	28.33	14	0.54	0.11	20.37
A-40	38	0.62	0.26	41.94	15	0.61	0.22	36.07	14	0.51	0.18	35.29
A-41	48	0.53	0.28	52.83	21	0.50	0.23	46.00	16	0.59	0.15	25.42
A-42	46	0.47	0.36	76.60	17	0.43	0.21	48.84	15	0.47	0.16	34.04
A-43	45	0.62	0.40	64.52	16	0.66	0.12	18.18	16	0.64	0.20	31.25
A-44	33	0.69	0.35	50.72	16	0.77	0.32	41.56	20	0.73	0.19	26.03
A-45	43	0.72	0.34	47.22	18	0.64	0.26	40.63	14	0.67	0.11	16.42
A-46	45	0.63	0.32	50.79	14	0.65	0.23	35.38	18	0.59	0.17	28.81
A-47	45	0.60	0.27	45.00	18	0.68	0.22	32.35	17	0.59	0.13	22.03
A-48	41	0.45	0.34	75.56	17	0.50	0.16	32.00	14	0.59	0.16	27.12
A-49	52	0.54	0.35	64.81	14	0.41	0.25	60.98	16	0.55	0.12	21.82
A-50	38	0.55	0.31	56.36	18	0.72	0.28	38.89	16	0.72	0.21	29.17
Averages		0.82	0.39	49.54		0.86	0.30	37.58		0.83	0.22	26.13

* activity concentration units are pCi/g

TABLE C-5

RADIUM-226 - REPEATED PROFILE RUNS IN USID AREA

	2 SEC - 2 MPH				2 SEC - 0.5 MPH				8 SEC - 0.5 MPH			
AREA	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV	NO. MEASURMENTS	MEAN*	STD DEV*	% STD DEV	NO. MEASURMENTS	MEAN*	STD DEV*	% STD DEV
sec/2 mp	2 sec/2 mph	2 sec/2 mph	2 sec/2 mph	2 sec/2 mph	2 sec/0.5 mph	sec/0.5 mp	sec/0.5 mp	sec/0.5 mp	8 sec/0.5 mph	sec/0.5 mp	sec/0.5 mp	sec/0.5 mph
A-01	41	0.76	0.82	107.89	129	0.7	0.79	112.86	27	0.74	0.36	48.65
A-02	71	0.61	0.75	122.95	217	0.8	0.8	100.00	52	0.74	0.41	55.41
A-03	73	0.80	0.73	91.25	206	0.86	0.74	86.05	44	0.74	0.44	59.46
A-04	72	0.76	0.82	107.89	205	0.73	0.83	113.70	50	0.81	0.41	50.62
A-05	76	0.78	0.86	110.26	216	0.86	0.84	97.67	47	0.83	0.36	43.37
A-06	73	0.79	0.87	110.13	225	0.75	0.81	108.00	43	0.92	0.39	42.39
A-07	69	0.77	0.7	90.91	200	0.81	0.84	103.70	46	0.92	0.35	38.04
A-ROAD	52	0.69	0.68	98.55	120	0.62	0.67	108.06	28	0.8	0.43	53.75
A-08	75	0.78	0.84	107.69	231	0.85	0.92	108.24	49	0.86	0.48	55.81
A-09	84	0.96	0.62	64.58	232	0.94	0.79	84.04	53	0.83	0.38	45.78
A-10	80	0.88	0.78	88.64	240	0.78	0.75	96.15	55	0.88	0.42	47.73
A-11	73	0.68	0.71	104.41	193	0.77	0.78	101.30	44	0.64	0.39	60.94
Averages		0.77	0.77	100.43		0.79	0.80	101.65		0.81	0.40	50.16

* activity concentration units are pCi/g

TABLE C-6

RADIUM-226 - REPEATED PROFILE RUNS - SOUTH FIELD

	2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph			
AREA	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV
A-01	42	1.05	0.81	77.14	15	1.23	0.49	39.84	16	1.01	0.37	36.63
A-02	38	0.88	0.91	103.41	15	1.12	0.48	42.86	14	1.10	0.41	37.27
A-03	43	1.16	1.00	86.21	16	1.18	0.44	37.29	17	1.12	0.49	43.75
A-04	44	0.80	1.23	153.75	17	0.90	0.98	108.89	15	0.63	0.43	68.25
A-05	42	0.93	0.98	105.38	17	1.01	0.68	67.33	16	1.27	0.59	46.46
A-06	43	1.09	0.86	78.90	19	1.39	0.66	47.48	16	1.23	0.36	29.27
A-07	44	1.02	0.83	81.37	10	1.43	0.35	24.48	17	0.82	0.33	40.24
A-08	37	0.71	1.08	152.11	17	0.81	0.83	102.47	17	0.49	0.54	110.20
A-09	42	0.64	1.20	187.50	14	0.39	0.95	243.59	15	0.47	0.70	148.94
A-10	40	0.48	0.99	206.25	16	0.96	0.74	77.08	15	0.90	0.48	53.33
A-11	42	1.04	0.65	62.50	13	0.85	0.35	41.18	14	0.97	0.39	40.21
A-12	43	0.95	0.69	72.63	13	1.09	0.67	61.47	15	0.95	0.41	43.16
A-13	35	1.33	0.67	50.38	15	0.96	0.68	70.83	10	0.90	0.28	31.11
A-14	41	1.38	0.95	68.84	16	1.28	0.72	56.25	15	1.62	0.51	31.48
A-15	42	1.38	0.73	52.90	17	1.56	0.50	32.05	19	1.38	0.34	24.64
A-16	41	1.23	0.91	73.98	14	1.21	0.63	52.07	15	1.03	0.37	35.92
A-17	39	1.22	0.66	54.10	16	1.28	0.45	35.16	13	1.22	0.38	31.15
A-18	51	1.07	0.79	73.83	13	1.10	0.57	51.82	19	1.07	0.54	50.47
A-19	53	0.98	0.87	88.78	17	1.05	0.54	51.43	14	1.24	0.46	37.10
A-20	42	0.99	0.84	84.85	15	1.08	0.44	40.74	17	0.91	0.36	39.56
A-21	35	1.06	0.75	70.75	17	1.22	0.47	38.52	14	0.93	0.37	39.78
A-22	45	0.94	0.85	90.43	13	1.24	0.82	66.13	15	1.08	0.40	37.04
A-23	43	1.17	0.78	66.67	13	1.02	0.42	41.18	15	1.11	0.42	37.84
A-24	43	1.02	0.83	81.37	17	1.08	0.76	70.37	17	0.96	0.23	23.96
A-25	38	0.95	0.74	77.89	15	0.88	0.58	65.91	15	1.09	0.45	41.28
A-26	45	1.20	0.82	68.33	16	0.75	0.90	120.00	16	1.50	0.52	34.67
A-27	42	1.47	0.95	64.63	14	1.44	0.38	26.39	15	1.50	0.36	24.00
A-28	36	1.70	1.04	61.18	16	1.69	0.67	39.64	17	1.65	0.35	21.21
A-29	45	2.94	1.55	52.72	18	2.89	1.75	60.55	19	3.02	1.11	36.75
A-30	47	4.30	1.50	34.88	17	3.72	1.07	28.76	19	5.27	1.65	31.31
A-31	43	5.75	1.79	31.13	20	6.30	1.39	22.06	17	6.48	0.68	10.49

TABLE C-6

(continued)

AREA	2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph			
	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV
A-32	42	4.53	1.42	31.35	19	4.20	1.94	46.19	18	4.20	0.84	20.00
A-33	34	2.94	1.35	45.92	17	2.89	0.89	30.80	16	2.51	0.76	30.28
A-34	39	1.69	1.05	62.13	14	1.47	0.57	38.78	20	1.40	0.39	27.86
A-37	48	0.70	0.72	102.86	1	0.75	0.62	82.67	8	0.92	0.46	50.00
A-38	37	0.61	0.74	121.31	5	0.96	0.45	46.88	1	0.78	0.39	50.00
A-39	42	0.67	0.82	122.39	18	0.96	0.66	68.75	14	0.95	0.36	37.89
A-40	38	0.86	0.74	86.05	15	1.01	0.50	49.50	14	1.09	0.23	21.10
A-41	48	1.29	0.79	61.24	21	0.91	0.61	67.03	16	0.91	0.38	41.76
A-42	46	1.06	0.65	61.32	17	1.15	0.61	53.04	15	1.10	0.31	28.18
A-43	45	0.98	0.76	77.55	16	0.94	0.56	59.57	16	0.98	0.31	31.63
A-44	33	0.80	0.85	106.25	16	0.89	0.51	57.30	20	0.88	0.43	48.86
A-45	43	1.24	0.68	54.84	18	0.98	0.64	65.31	14	0.82	0.35	42.68
A-46	45	1.04	0.71	68.27	14	1.26	0.51	40.48	18	0.99	0.39	39.39
A-47	45	0.99	1.00	101.01	18	1.00	0.43	43.00	17	1.15	0.31	26.96
A-48	41	1.07	0.68	63.55	17	1.18	0.53	44.92	14	1.15	0.32	27.83
A-49	52	1.16	0.81	69.83	14	1.03	0.46	44.66	16	0.87	0.52	59.77
A-50	38	0.82	0.73	89.02	18	0.92	0.48	52.17	16	0.80	0.47	58.75
Averages		1.36	0.91	82.08		1.39	0.67	57.39		1.38	0.47	40.84

* activity concentration units are pCi/g

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TABLE C-7

GROSS COUNTS/SECOND - REPEATED PROFILE RUNS IN USID AREA

	2 sec - 2 mph				2 sec - 0.5 mph				8 sec - 0.5 mph			
AREA	NO. MEASURMNTS.	MEAN (CPS)	SDEV (CPS)	%SDEV	NO. MEASURMNTS.	MEAN (CPS)	SDEV (CPS)	% SDEV	NO. MEASURMENTS	MEAN (CPS)	SDEV (CPS)	% SDEV
A-01	41	2781.26	113.10	4.07	129	2772.21	142.50	5.14	27	2813.86	118.42	4.21
A-02	71	2926.83	62.03	2.12	217	2931.66	66.24	2.26	52	2954.16	64.78	2.19
A-03	73	2964.07	64.75	2.18	206	2946.46	64.29	2.18	44	2969.10	52.87	1.78
A-04	72	3034.49	66.41	2.19	205	3026.71	68.54	2.26	50	3043.23	56.49	1.86
A-05	76	3089.30	71.24	2.31	216	3076.30	72.64	2.36	47	3102.44	63.17	2.04
A-06	73	3035.76	76.69	2.53	225	3027.69	71.73	2.37	43	3060.92	62.16	2.03
A-07	69	3097.12	187.25	6.05	200	3100.84	120.09	3.87	46	3025.28	258.90	8.56
A-ROAD	52	2075.35	479.74	23.12	120	2007.89	524.35	26.11	28	2307.47	568.46	24.64
A-08	75	3140.69	301.54	9.60	231	3049.69	430.32	14.11	49	3028.87	471.32	15.56
A-09	84	3183.90	79.15	2.49	232	3192.32	75.59	2.37	53	3210.17	64.72	2.02
A-10	80	3065.56	121.91	3.98	240	3084.15	111.38	3.61	55	3118.10	136.80	4.39
A-11	73	2850.26	84.31	2.96	193	2867.51	79.06	2.76	44	2838.33	199.18	7.02
Averages		2937.05	142.34	5.30		2923.62	152.23	5.78		2955.99	176.44	6.36

TABLE C-8

GROSS COUNTS/SEC - REPEATED PROFILE RUNS - SOUTH FIELD

	2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph			
AREA	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV	NO. MEASURMNTS.	MEAN*	STD DEV*	% STD DEV
A-01	42	2628.14	136.69	5.20	15	2768.40	162.85	5.88	16	2751.01	114.78	4.17
A-02	38	2886.04	85.21	2.95	15	2935.32	64.10	2.18	14	2942.71	49.32	1.68
A-03	43	3017.47	129.37	4.29	16	3192.61	126.84	3.97	17	3218.07	170.01	5.28
A-04	44	3710.57	544.22	14.67	17	4106.04	516.68	12.58	15	3959.26	622.55	15.72
A-05	42	3726.29	639.01	17.15	17	3491.99	621.71	17.80	16	3297.55	541.65	16.43
A-06	43	3158.94	137.30	4.35	19	3065.26	127.52	4.16	16	2979.40	126.98	4.26
A-07	44	2826.91	137.14	4.85	10	2829.38	78.76	2.78	17	2958.47	203.45	6.88
A-08	37	3178.31	201.28	6.33	17	3762.81	445.79	11.85	17	3745.56	402.00	10.73
A-09	42	4107.85	653.62	15.91	14	5078.32	307.34	6.05	15	4586.56	480.05	10.47
A-10	40	3169.19	755.65	23.84	16	2899.78	378.93	13.07	15	2870.53	436.31	15.20
A-11	42	2540.73	58.76	2.31	13	2554.10	41.39	1.62	14	2562.29	35.19	1.37
A-12	43	2533.90	99.59	3.93	13	2558.35	49.34	1.93	15	2560.64	32.62	1.27
A-13	35	2756.94	207.17	7.51	15	2695.93	119.13	4.42	10	2636.15	130.37	4.95
A-14	41	2988.33	145.58	4.87	16	2975.88	104.60	3.51	15	2884.16	120.29	4.17
A-15	42	2664.61	121.09	4.54	17	2675.09	88.96	3.33	19	2639.94	113.52	4.30
A-16	41	2546.12	42.38	1.66	14	2585.66	25.31	0.98	15	2566.31	20.95	0.82
A-17	39	2521.17	48.80	1.94	16	2538.91	43.69	1.72	13	2540.38	35.65	1.40
A-18	51	2526.23	76.45	3.03	13	2538.60	74.68	2.94	19	2538.55	81.30	3.20
A-19	53	2412.09	61.70	2.56	17	2398.68	41.71	1.74	14	2449.26	35.78	1.46
A-20	42	2486.77	61.40	2.47	15	2502.18	65.59	2.62	17	2542.66	85.73	3.37
A-21	35	2663.60	60.49	2.27	17	2658.35	71.87	2.70	14	2638.17	70.99	2.69
A-22	45	2359.81	142.85	6.05	13	2334.08	76.22	3.27	15	2318.43	43.73	1.89
A-23	43	2401.81	76.30	3.18	13	2419.60	65.25	2.70	15	2424.02	40.00	1.65
A-24	43	2277.48	113.52	4.98	17	2316.32	105.32	4.55	17	2226.23	99.85	4.49
A-25	38	2162.83	151.71	7.01	15	2202.70	161.34	7.32	15	2324.09	164.87	7.09
A-26	45	2921.77	490.38	16.78	16	3134.81	610.87	19.49	16	3444.35	412.10	11.96
A-27	42	2803.29	356.89	12.73	14	2926.16	394.05	13.47	15	2767.81	208.18	7.52
A-28	36	2731.35	170.51	6.24	16	2784.13	133.32	4.79	17	2874.38	122.42	4.26
A-29	45	3621.93	587.57	16.22	18	3496.76	639.16	18.28	19	3683.53	508.71	13.81
A-30	47	4881.83	632.49	12.96	17	4603.65	584.16	12.69	19	5292.45	945.46	17.86
A-31	43	6076.42	250.96	4.13	20	6365.26	276.89	4.35	17	6329.93	404.82	6.40

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TABLE C-8

(continued)

AREA	NO. MEASURMNTS.	2 sec - 2 mph MEAN*	STD DEV*	% STD DEV	NO. MEASURMNTS.	4 sec - 1 mph MEAN*	STD DEV*	% STD DEV	NO. MEASURMNTS.	8 sec - 0.5 mph MEAN*	STD DEV*	% STD DEV
A-32	42	5026.76	331.15	6.59	19	4721.18	1045.58	22.15	18	4665.24	524.55	11.24
A-33	34	3814.10	521.72	13.68	17	3631.47	489.34	13.48	16	3352.57	350.93	10.47
A-34	39	2927.86	182.13	6.22	14	2930.64	173.93	5.93	20	2810.93	206.47	7.35
A-37	48	2243.93	74.91	3.34	15	2279.65	78.89	3.46	14	2206.01	57.16	2.59
A-38	37	2118.85	32.12	1.52	15	2160.17	29.03	1.34	14	2158.10	25.84	1.20
A-39	42	2172.04	40.49	1.86	18	2200.21	36.80	1.67	16	2217.81	24.47	1.10
A-40	38	2237.45	142.73	6.38	15	2229.12	24.23	1.09	15	2216.87	22.06	1.00
A-41	48	2159.66	49.90	2.31	21	2217.67	114.42	5.16	16	2167.01	42.95	1.98
A-42	46	2060.37	72.94	3.54	17	2070.99	119.78	5.78	20	2060.31	57.89	2.81
A-43	45	2238.98	227.54	10.16	16	2294.80	182.05	7.93	14	2359.67	139.60	5.92
A-44	33	2516.55	52.08	2.07	16	2553.73	27.83	1.09	18	2557.17	34.92	1.37
A-45	43	2554.52	44.04	1.72	18	2575.18	42.39	1.65	17	2549.51	42.23	1.66
A-46	45	2460.80	59.47	2.42	14	2461.43	50.79	2.06	14	2432.74	46.50	1.91
A-47	45	2334.78	46.27	1.98	18	2331.99	34.98	1.50	16	2315.73	34.78	1.50
A-48	41	2196.40	96.71	4.40	17	2206.32	69.52	3.15	16	2200.21	41.62	1.89
A-49	52	2152.91	39.78	1.85	14	2201.98	28.98	1.32	16	2187.17	31.77	1.45
A-50	38	2254.30	111.39	4.94	18	2407.15	134.86	5.60	13	2398.31	98.19	4.09
Averages		197.95	6.29	2893.10	193.47	5.90	2883.50	180.03	5.34			

* activity concentration units are pCi/g

FIGURE C-1
URANIUM-238 - USID AREA - MEAN

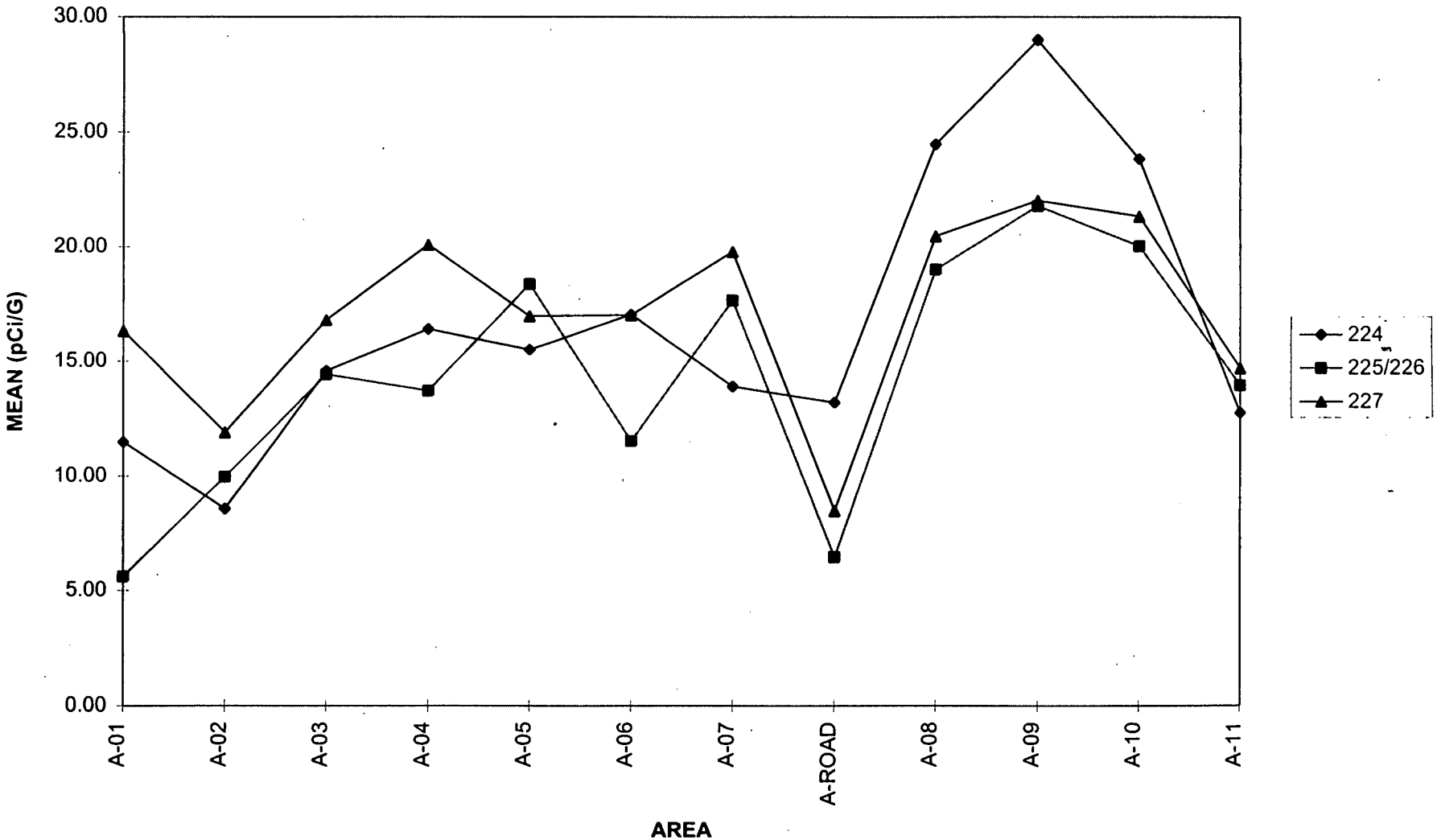

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FIGURE C-2
URANIUM-238 - USID AREA - STANDARD DEVIATION

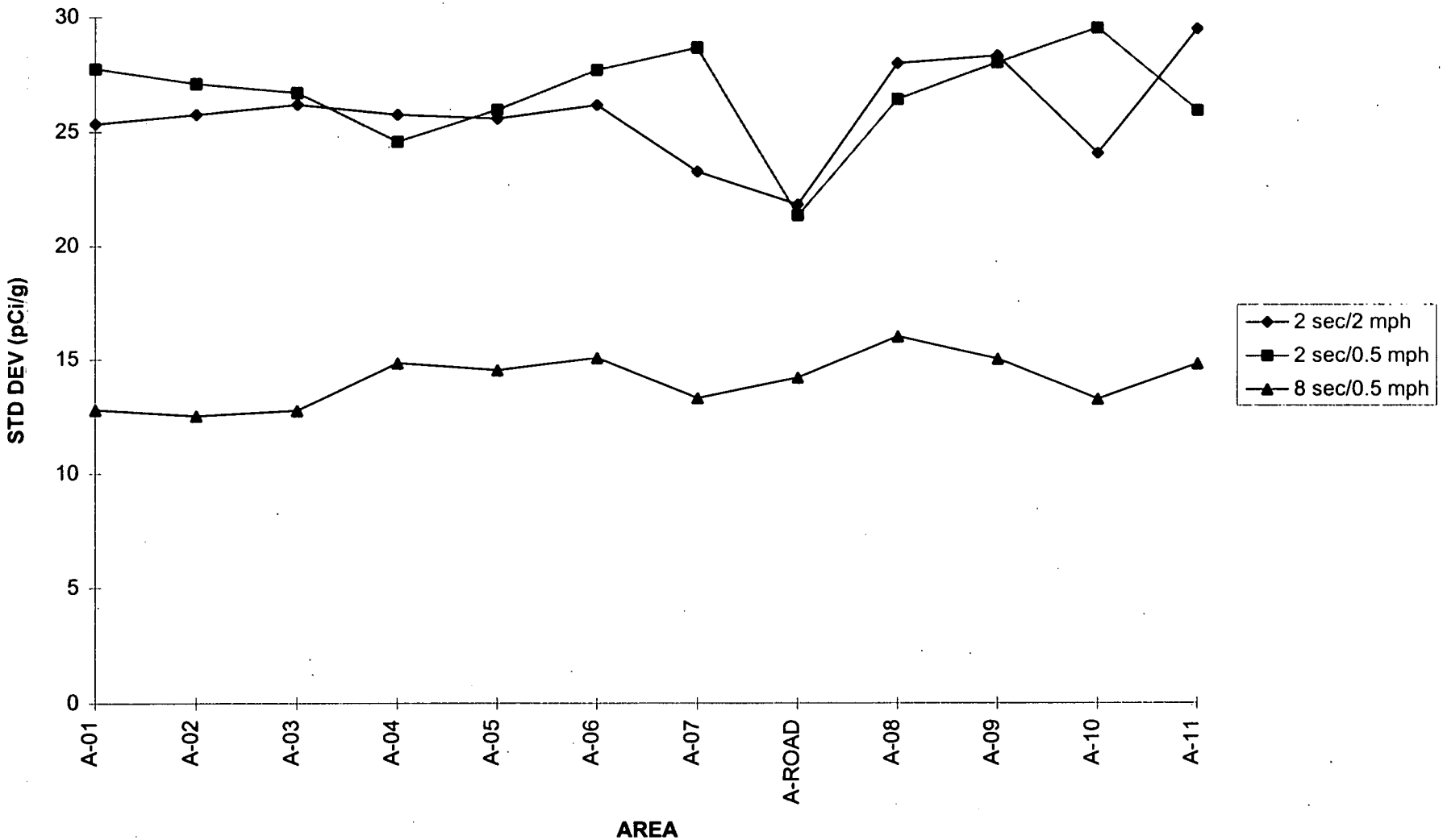

FIGURE C-3
URANIUM-238 - USID AREA - % STANDARD DEVIATION

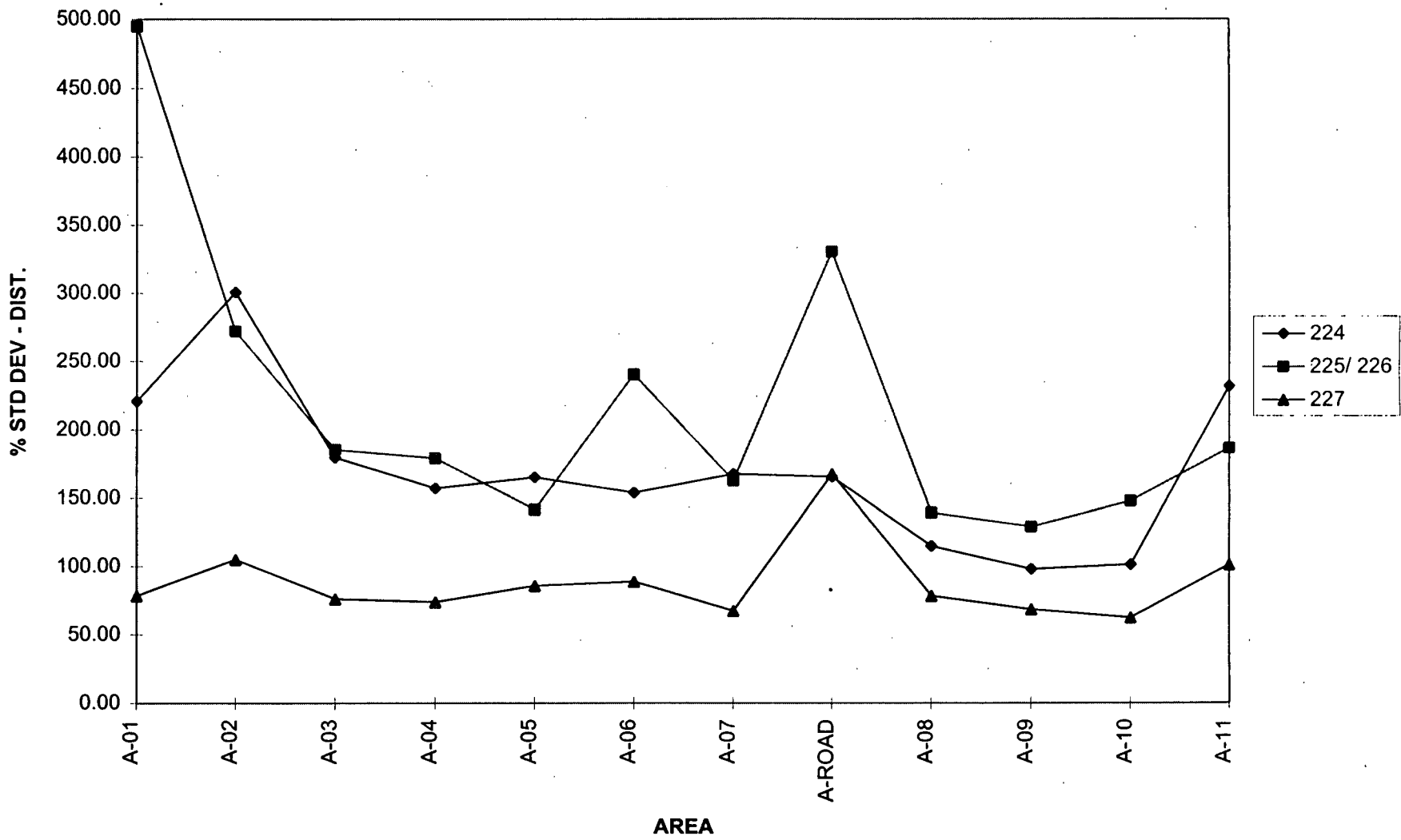

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FIGURE C-4
URANIUM-238 - SOUTH FIELD - MEAN

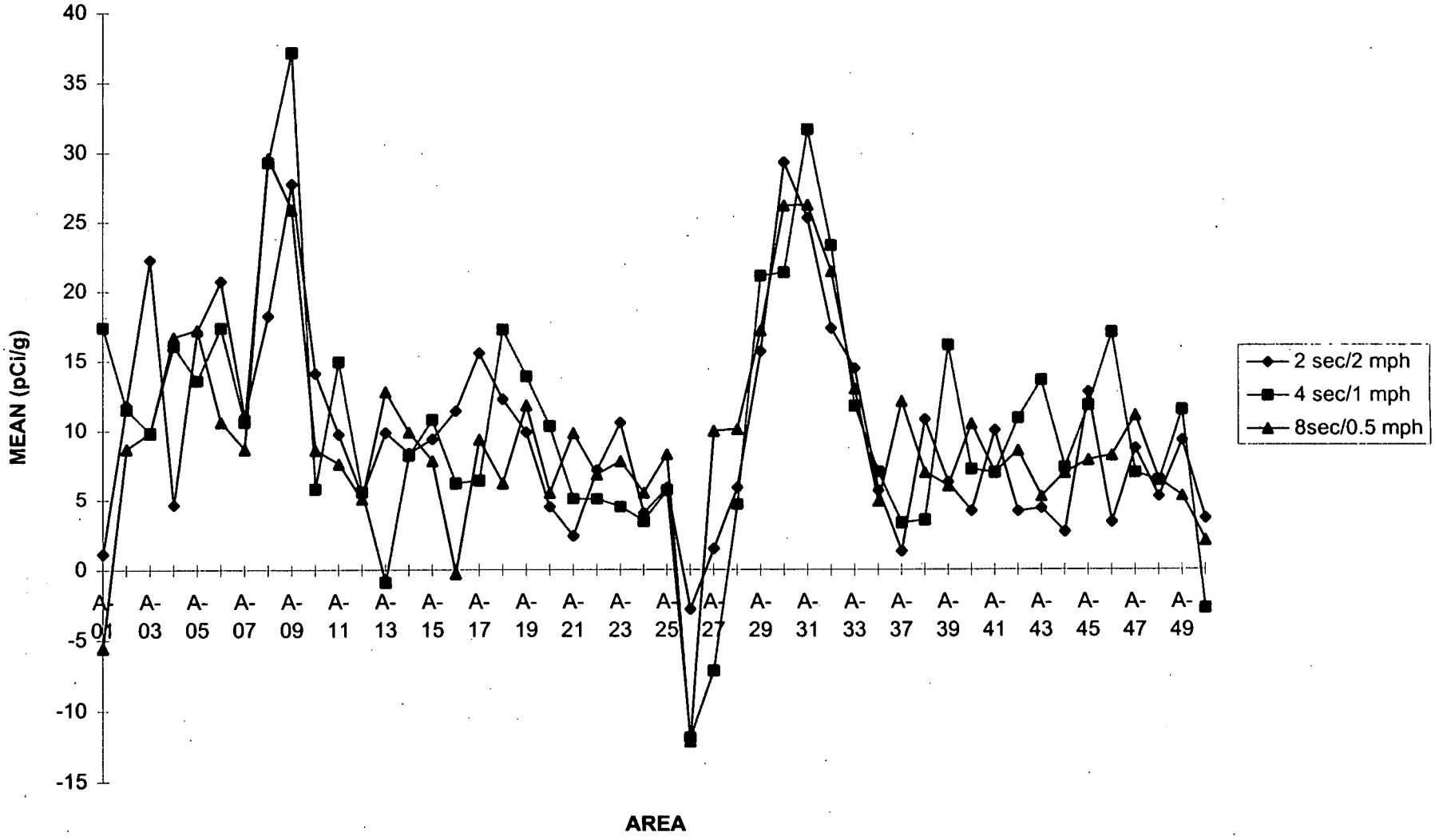

FIGURE C-5
URANIUM-238 - SOUTH FIELD - STANDARD DEVIATION

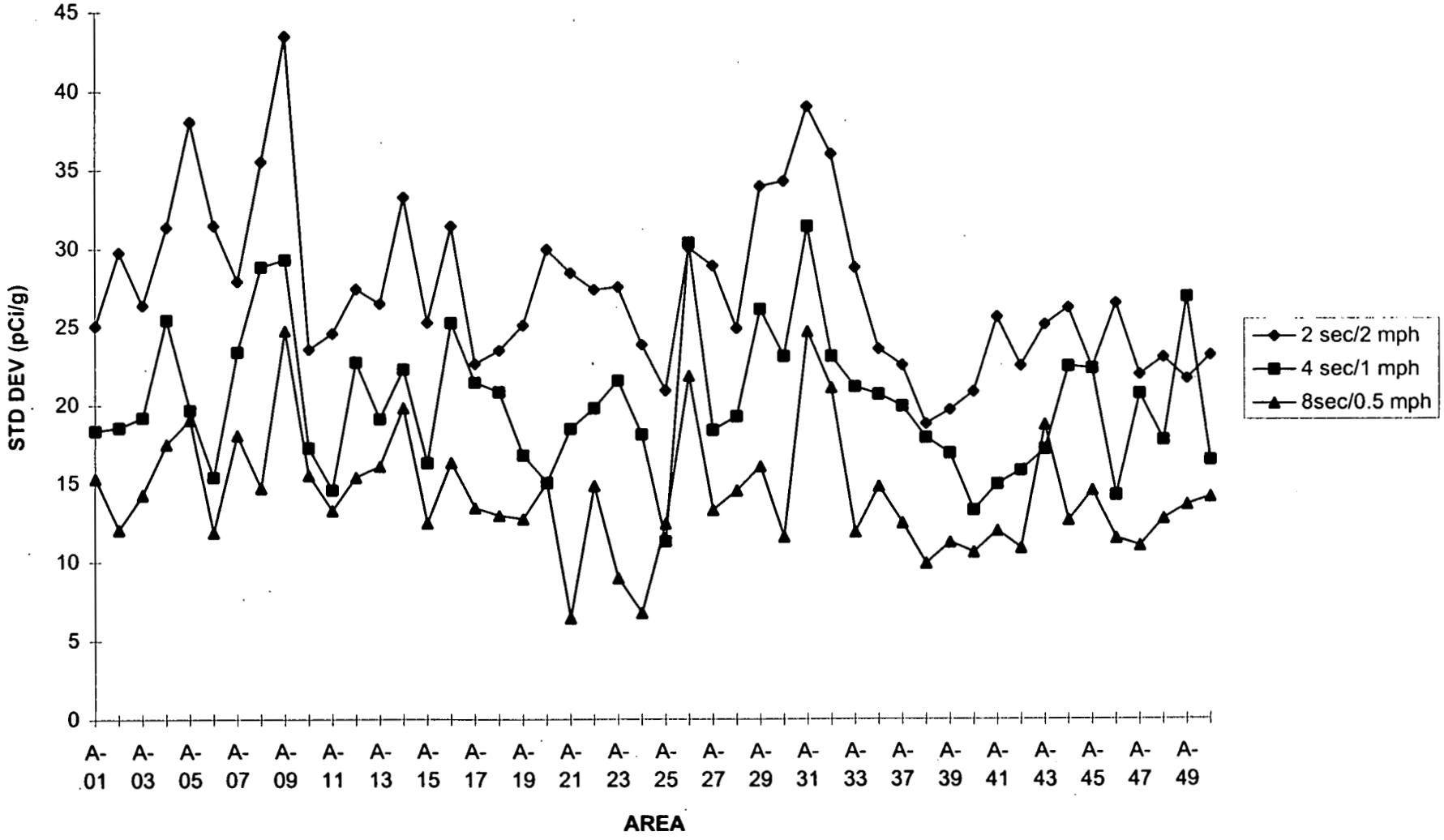

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FIGURE C-6
URANIUM-238 - SOUTH FIELD - % STANDARD DEVIATION

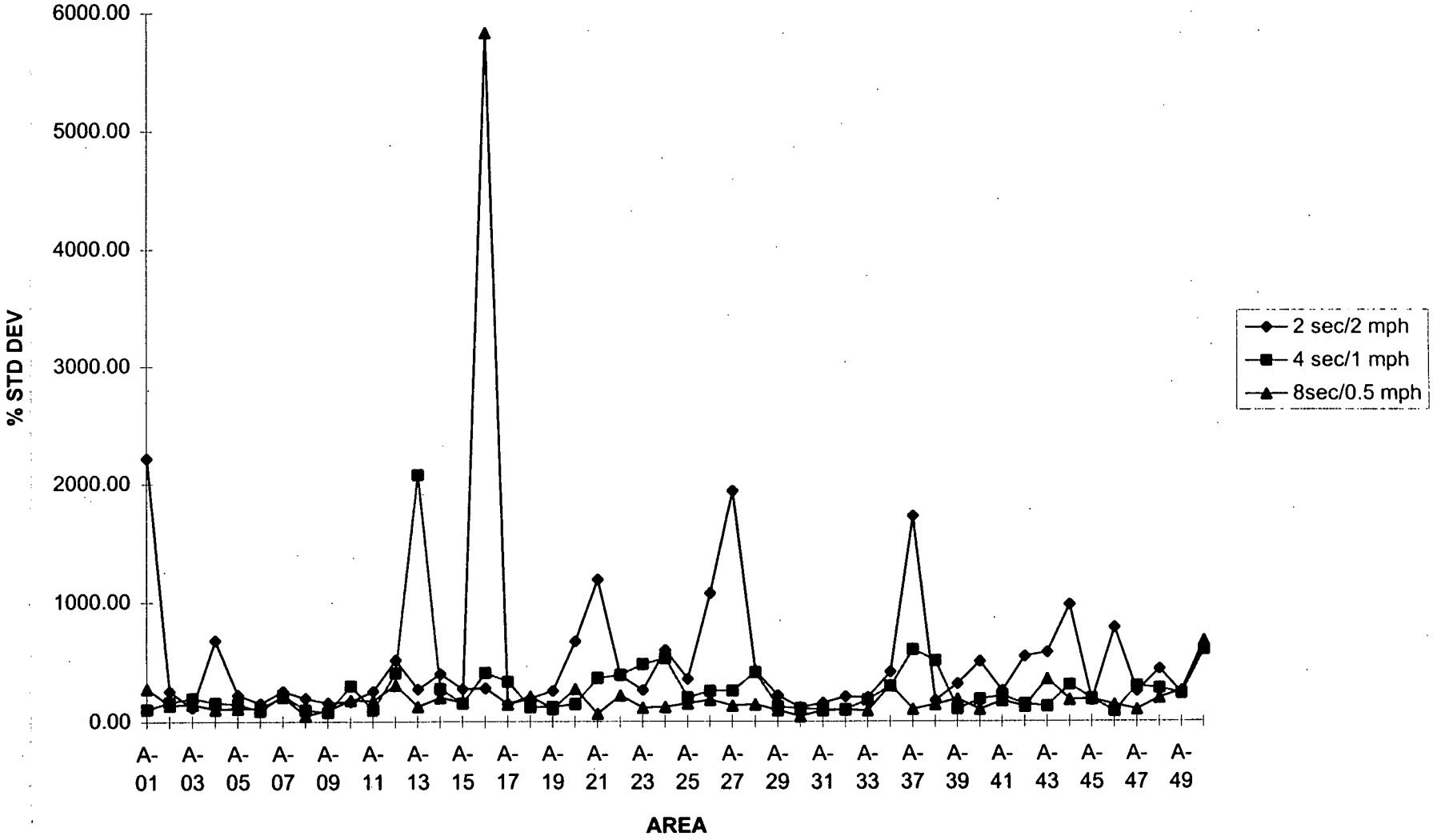

FIGURE C-7
THORIUM-232 - USID AREA - MEAN

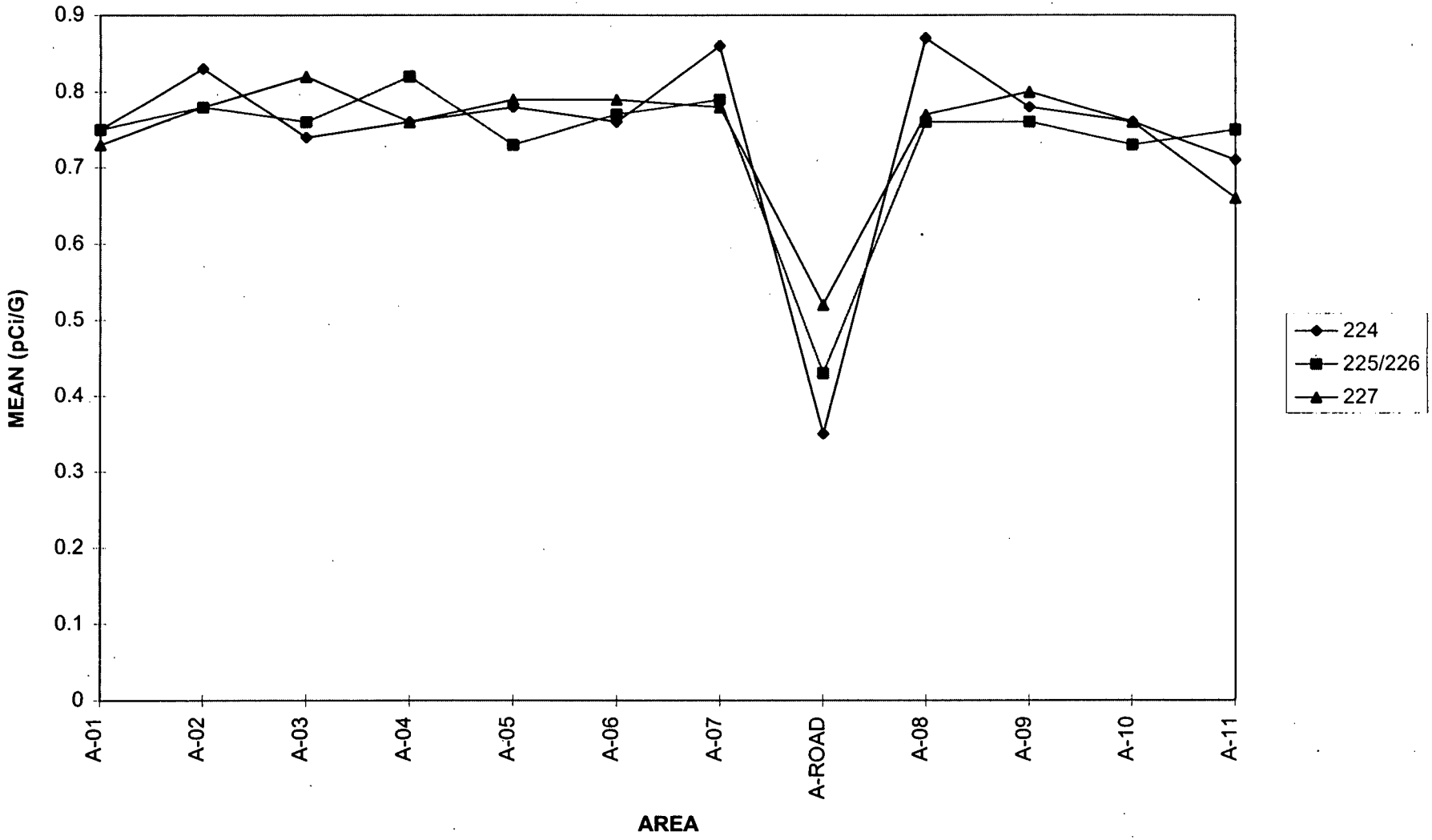

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FIGURE C-8
THORIUM-232 - USID AREA - STANDARD DEVIATION

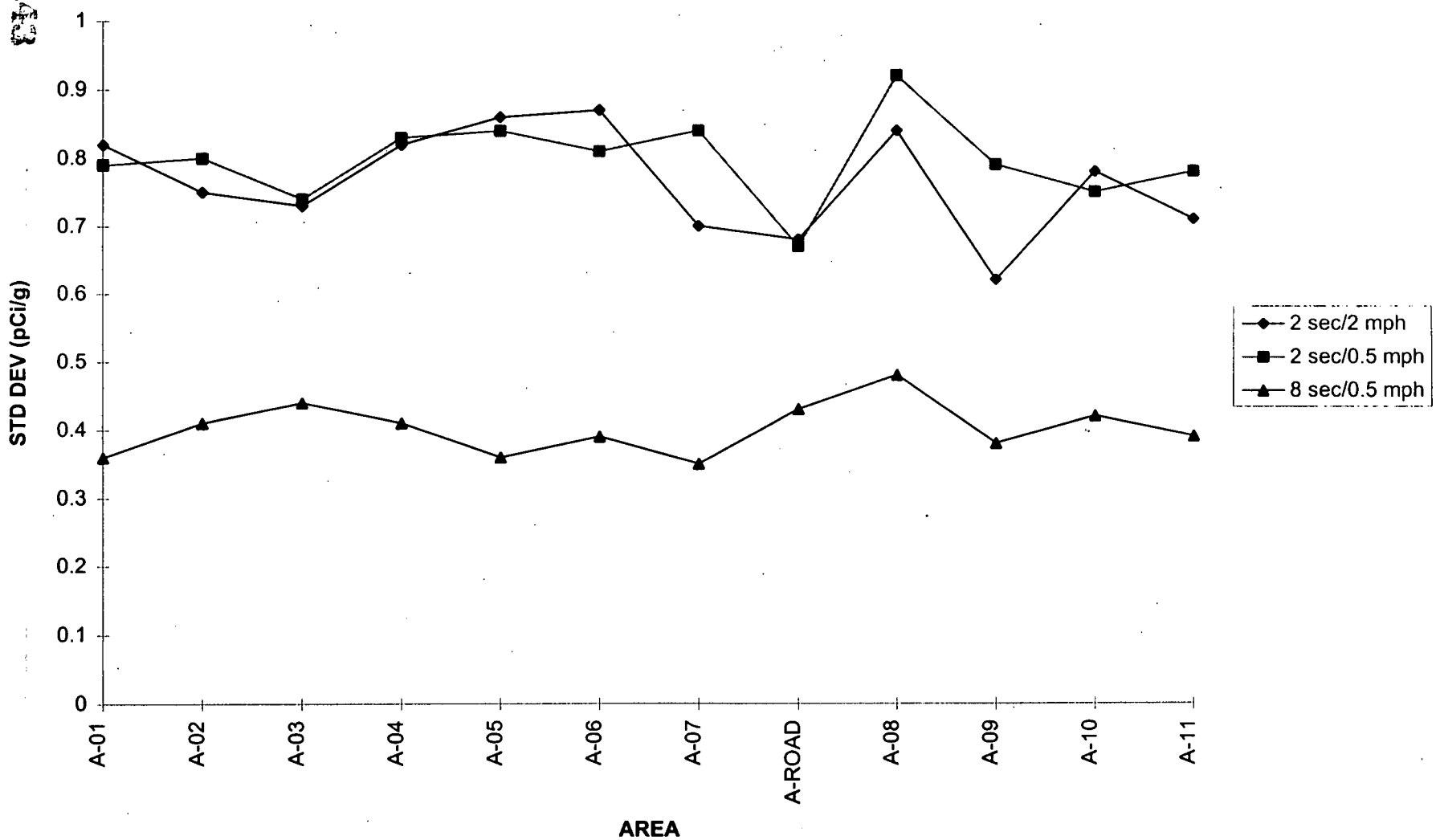

FIGURE C-9
THORIUM-232 - USID AREA - % STANDARD DEVIATION

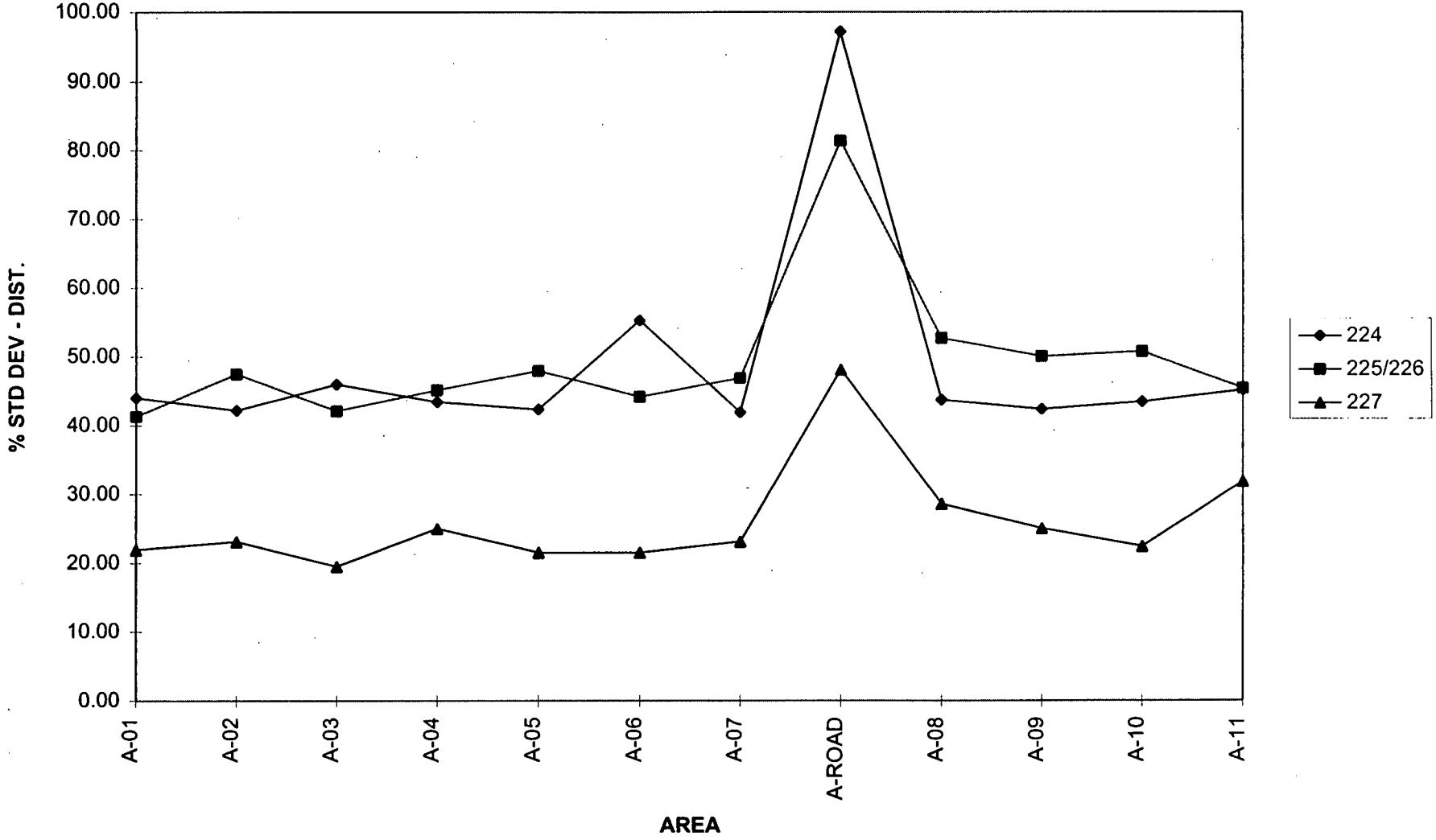

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FIGURE C-10
THORIUM-232 - SOUTH FIELD - MEAN

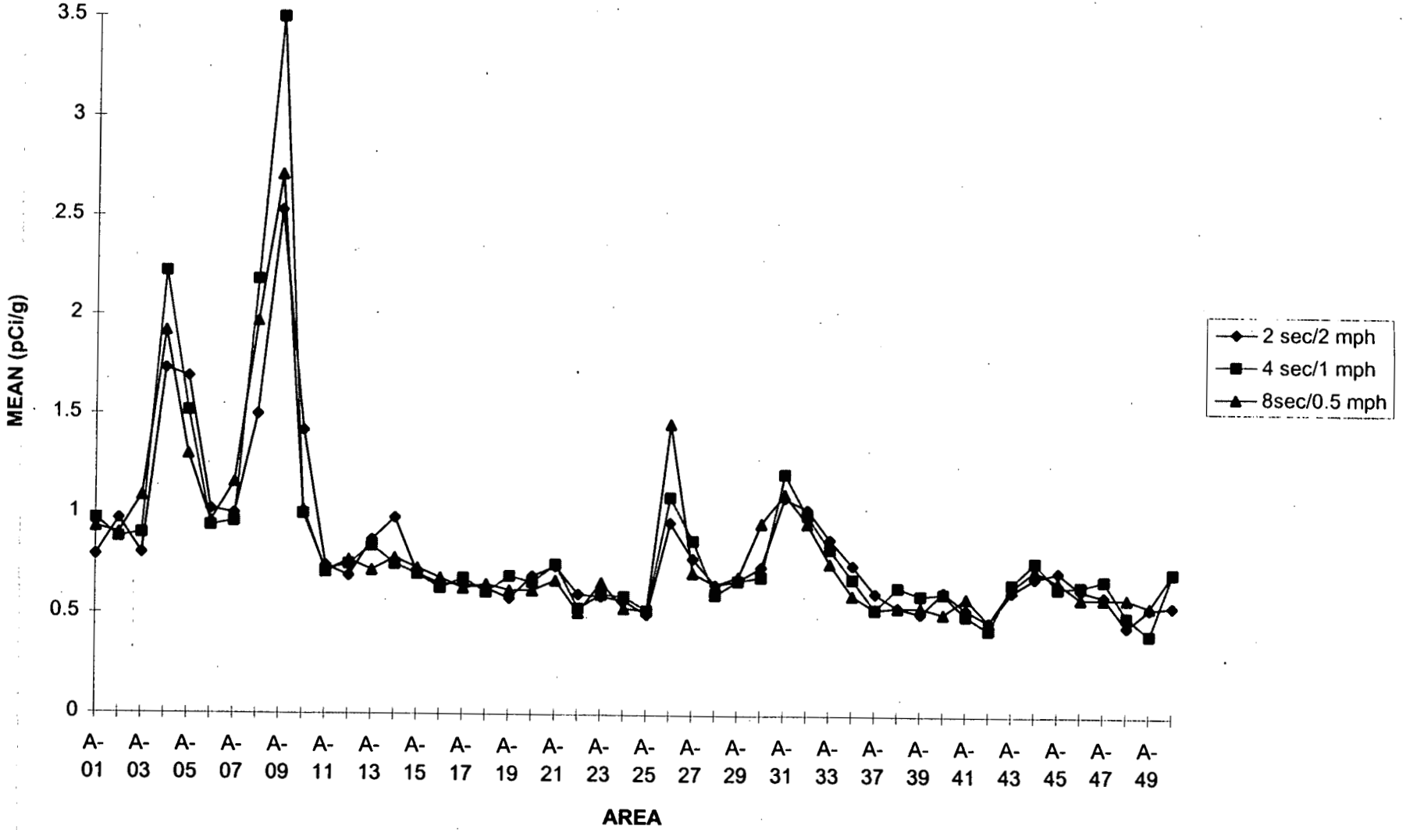

FIGURE C-11
THORIUM-232 - SOUTH FIELD - STANDARD DEVIATION

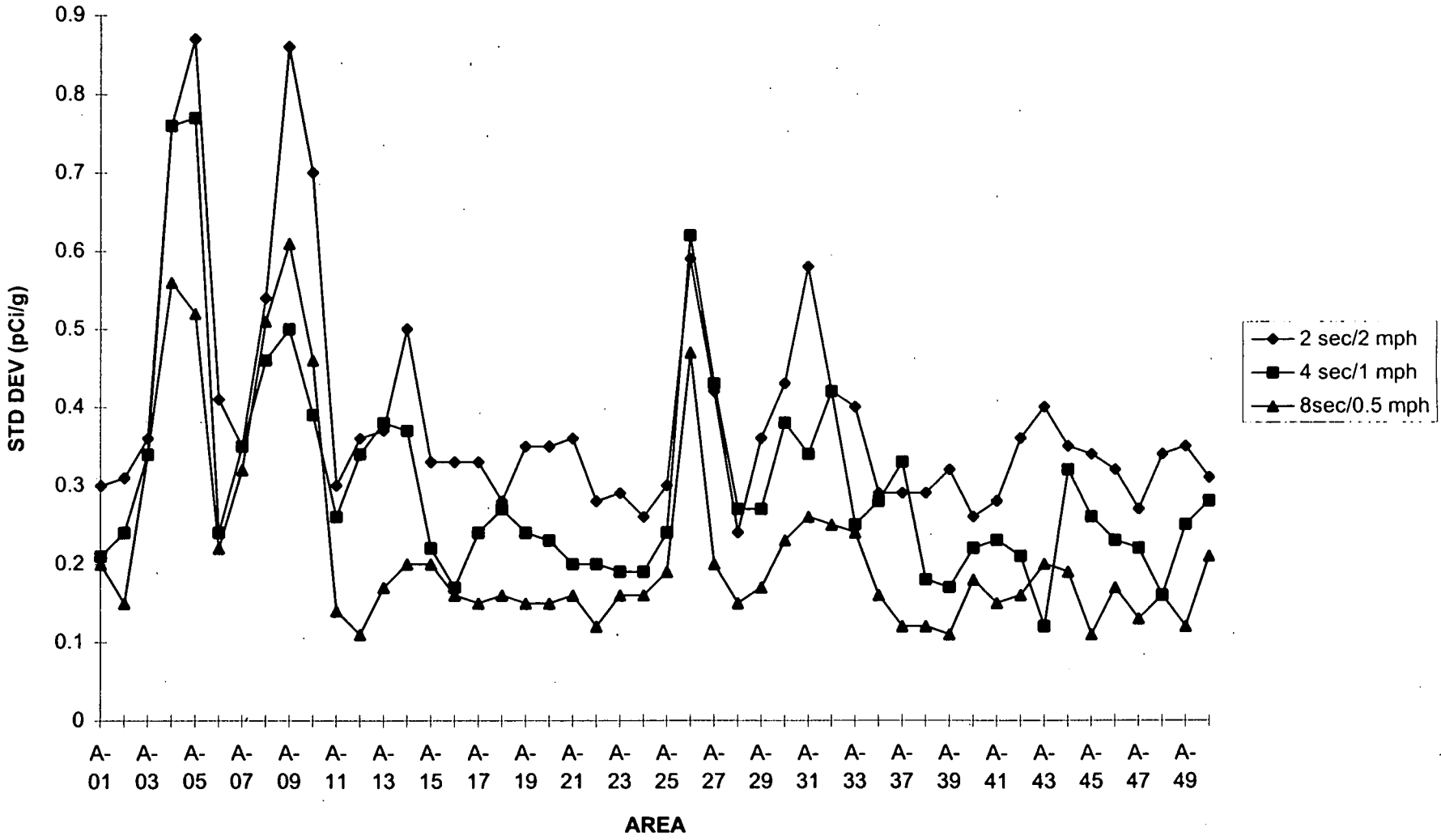

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FIGURE C-12
THORIUM-232 - SOUTH FIELD - %STANDARD DEVIATION

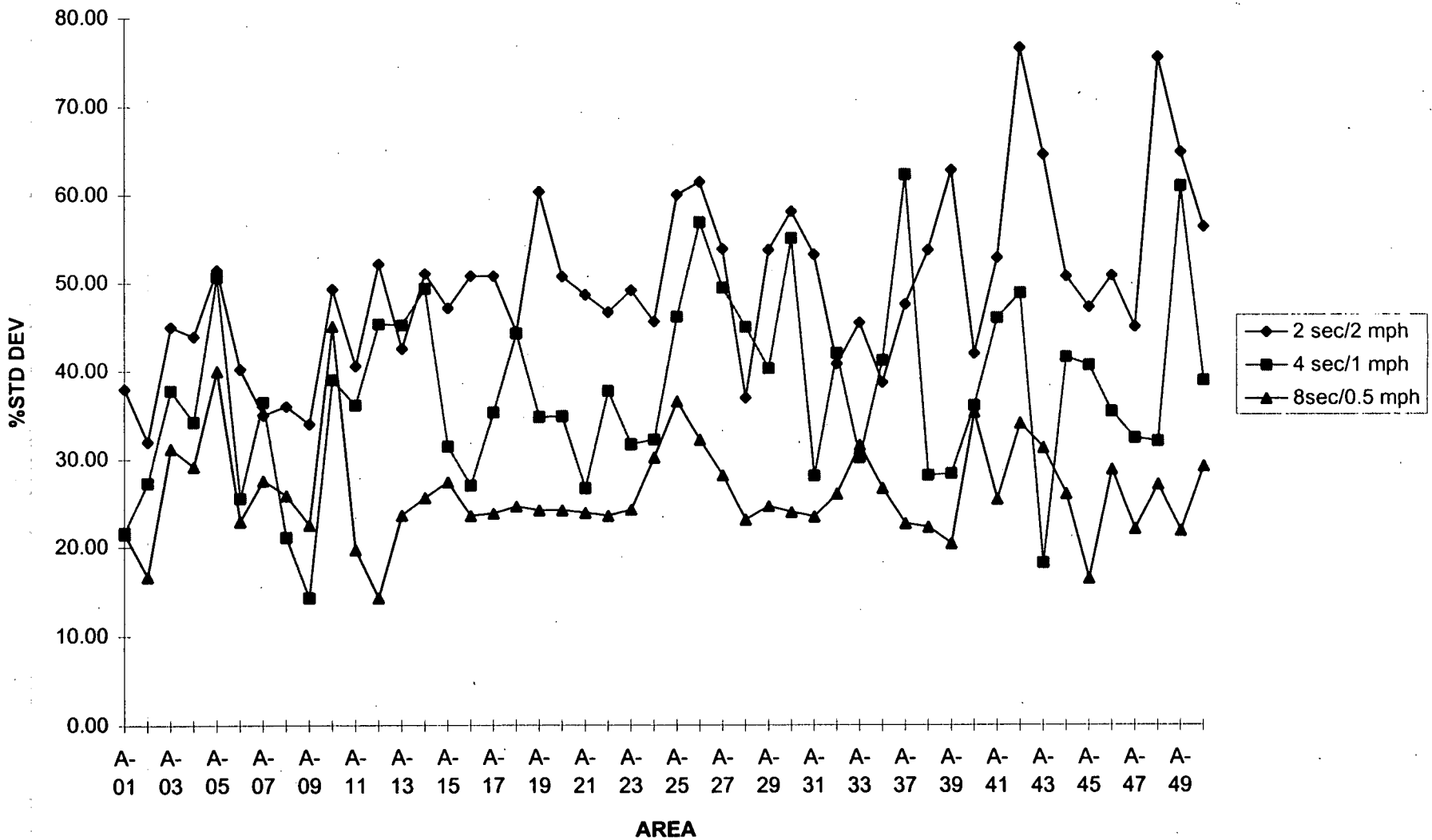

FIGURE C-13
RADIUM-226 - USID AREA - MEAN

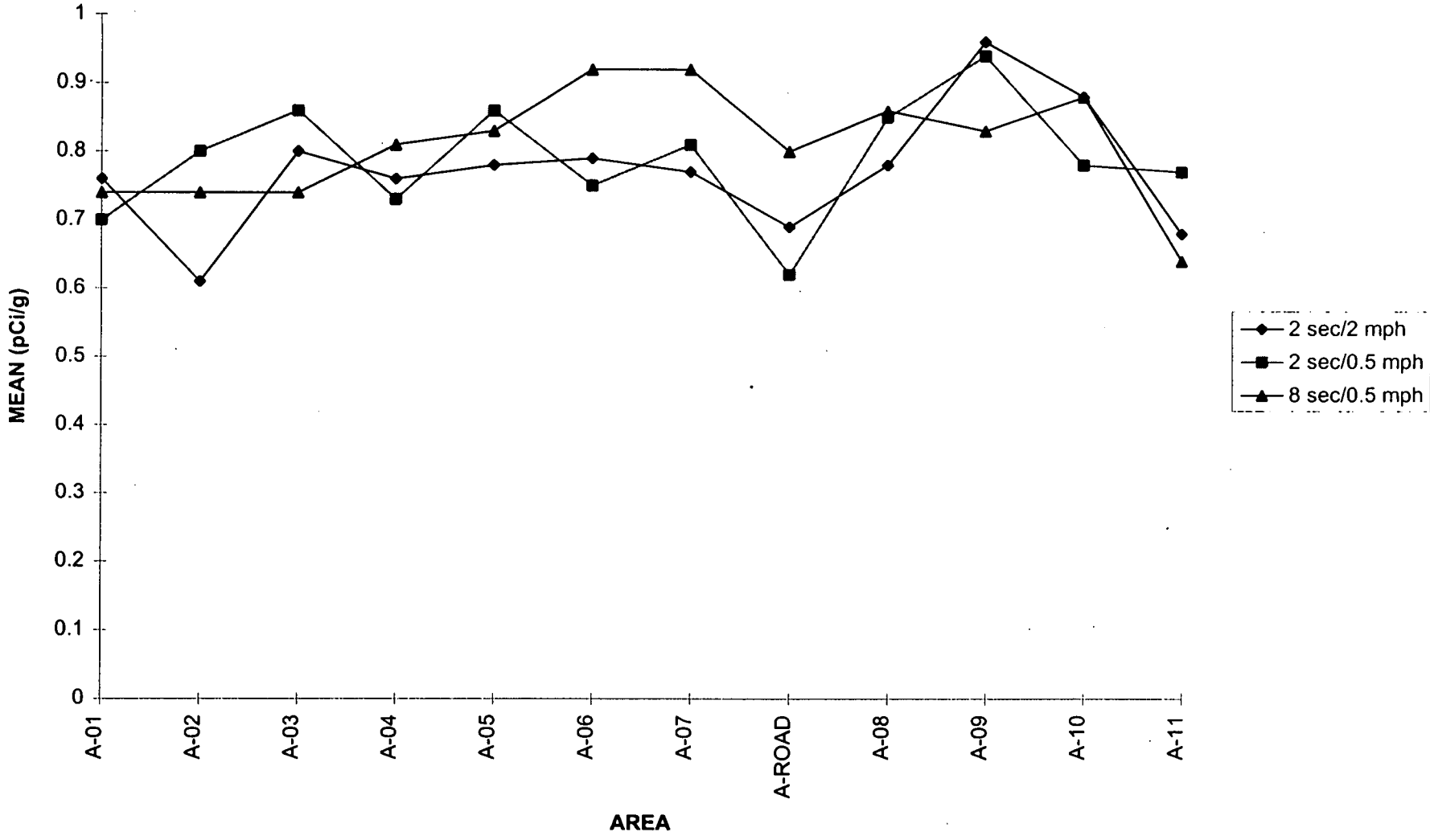

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FIGURE C-14
RADIUM-226 - USID AREA - STANDARD DEVIATION

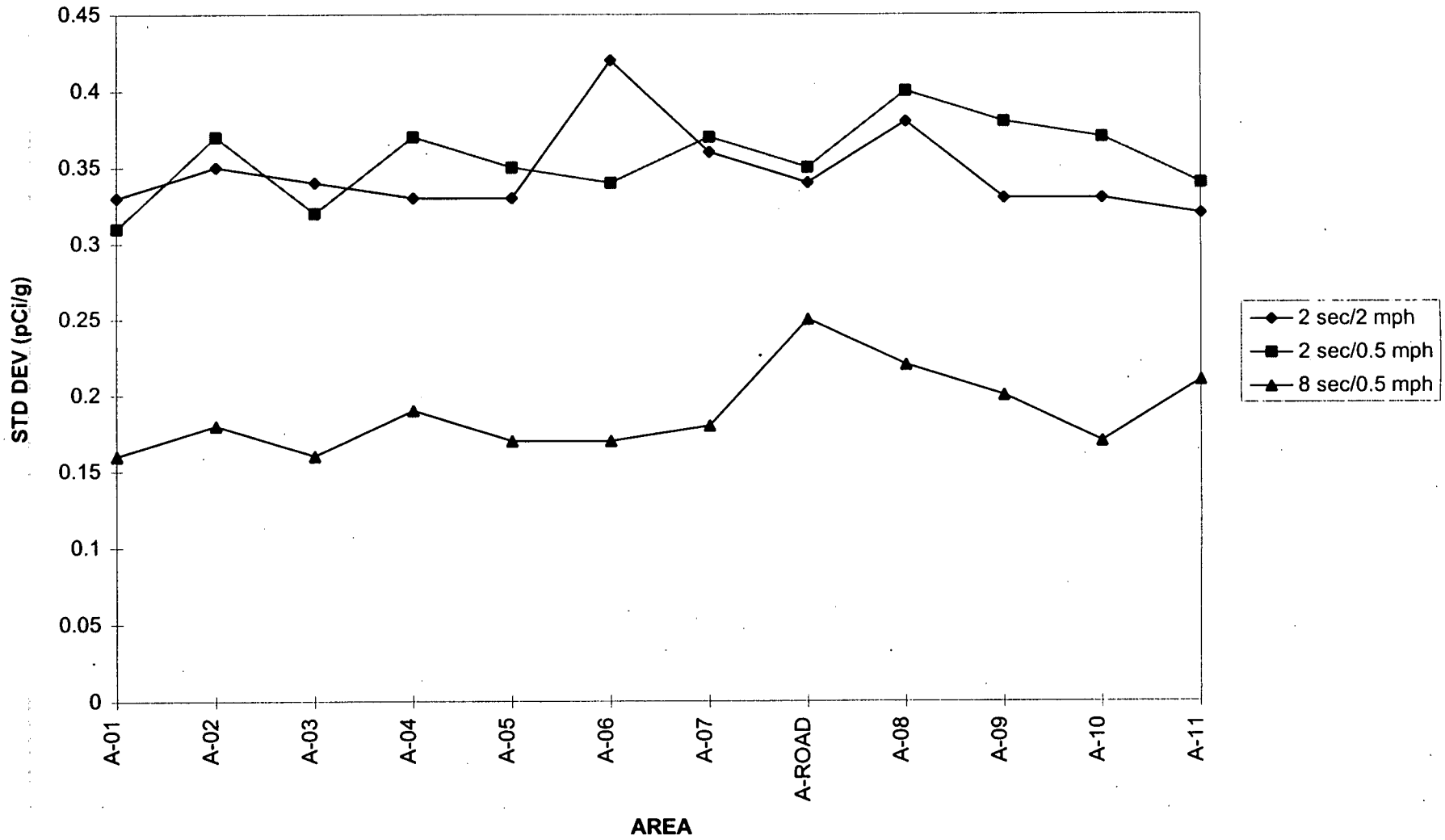

FIGURE C-15
RADIUM-226 - USID AREA - % STANDARD DEVIATION

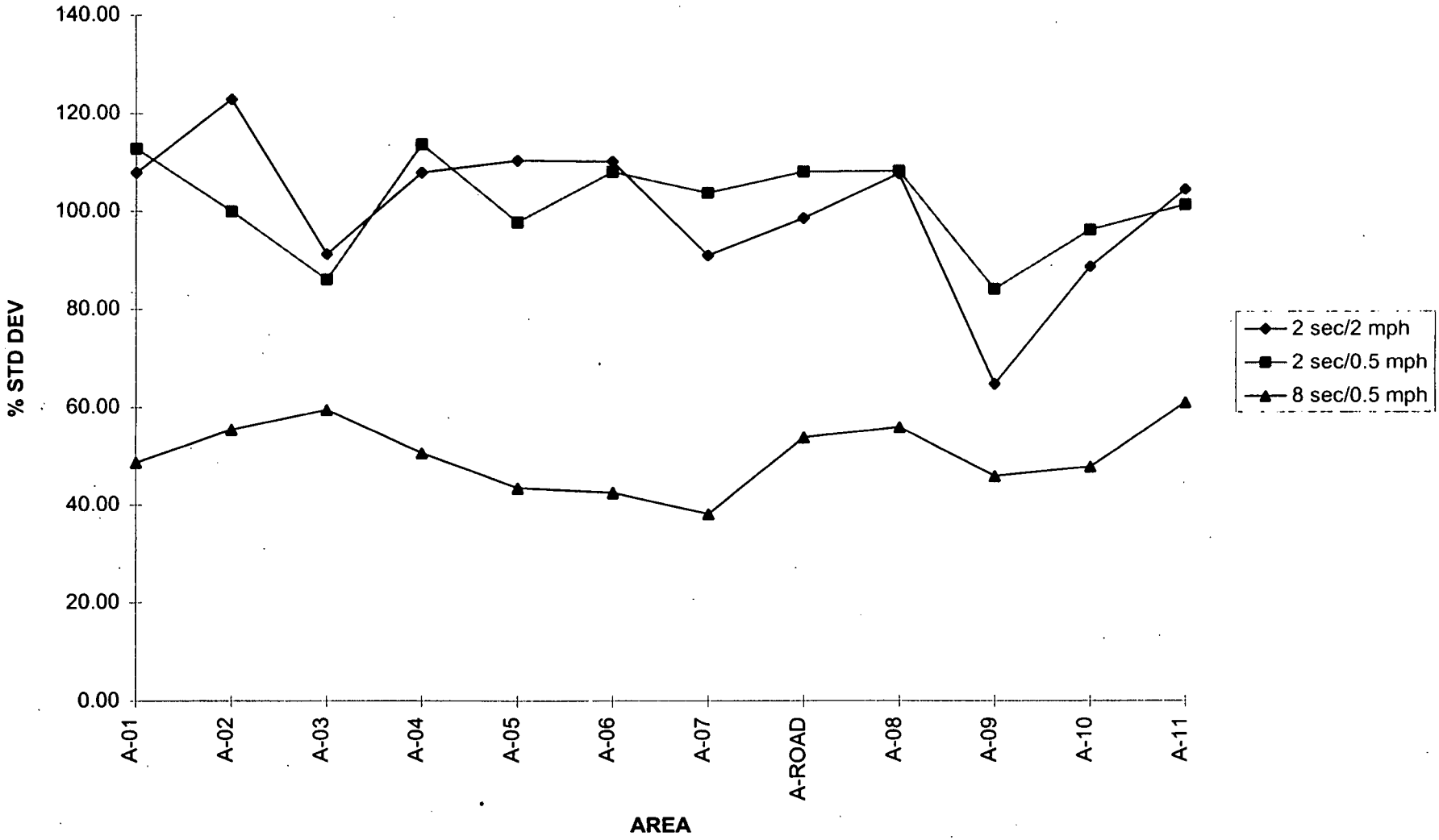

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FIGURE C-16
RADIUM-226 - SOUTH FIELD - MEAN

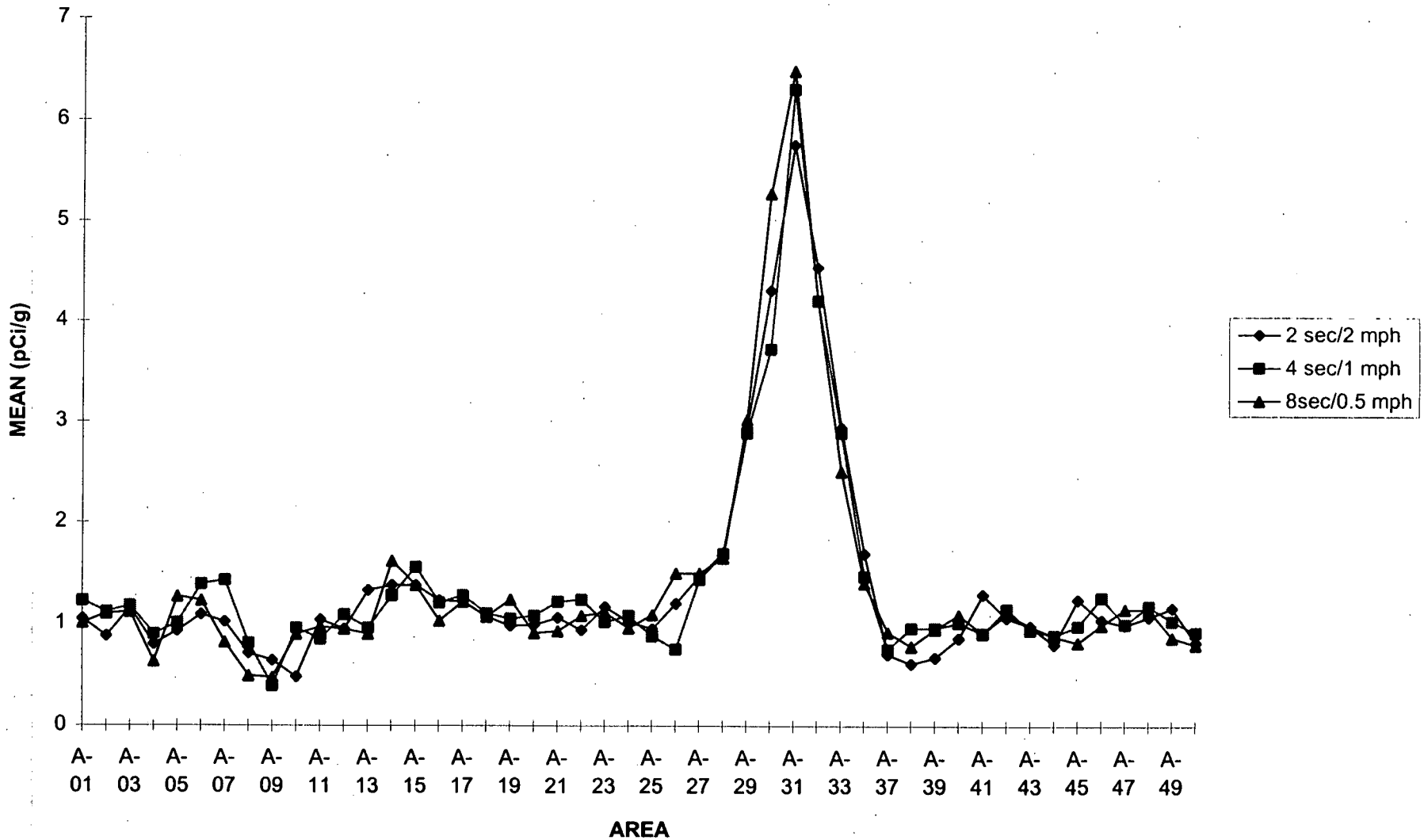

FIGURE C-17
RADIUM-226 - SOUTH FIELD - STANDARD DEVIATION

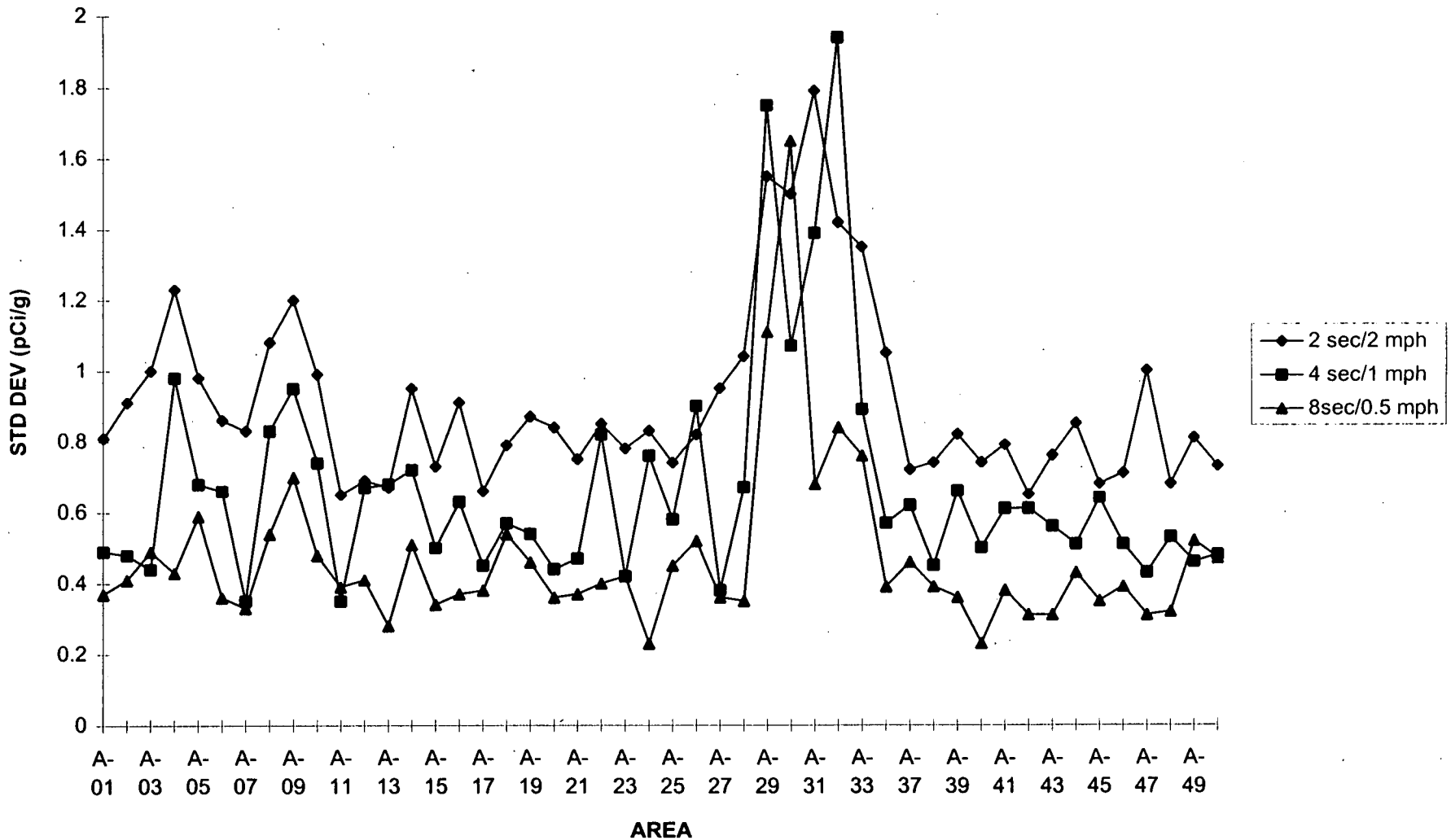

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FIGURE C-18
RADIUM-226 - SOUTH FIELD - % STANDARD DEVIATION

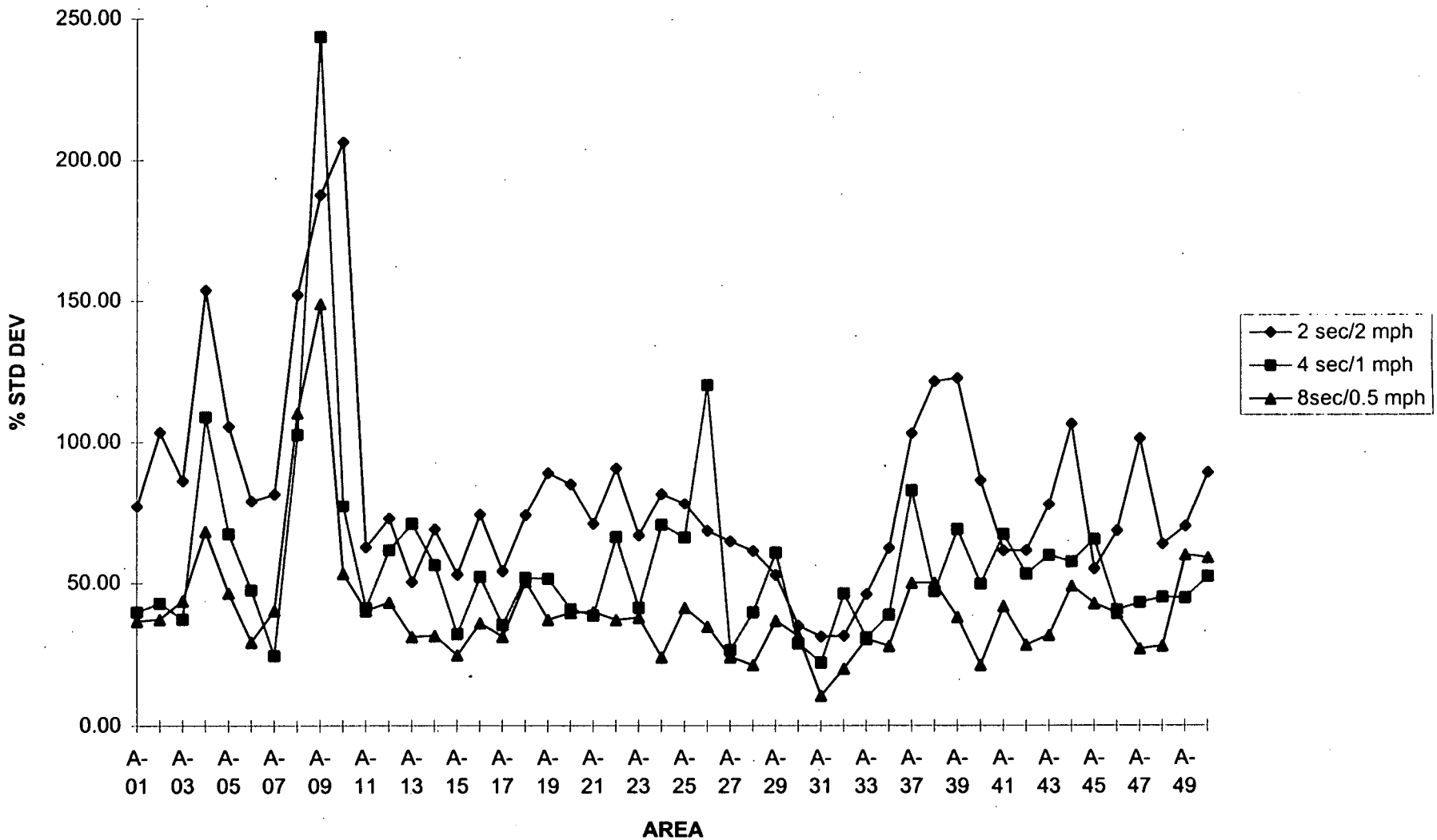

FIGURE C-19
GROSS CPS - USID AREA - MEAN

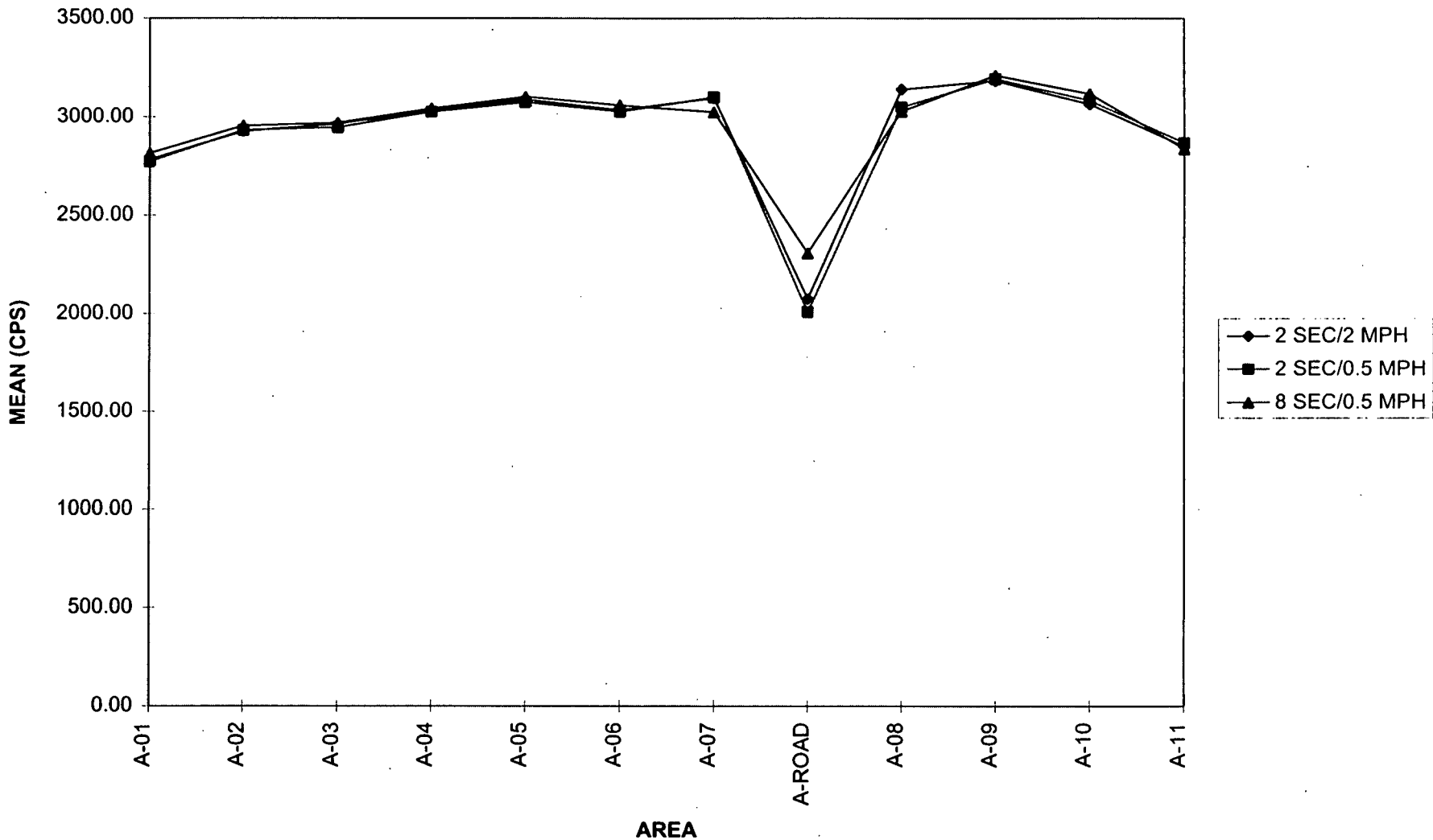

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FIGURE C-20
GROSS CPS - USID AREA - STANDARD DEVIATION

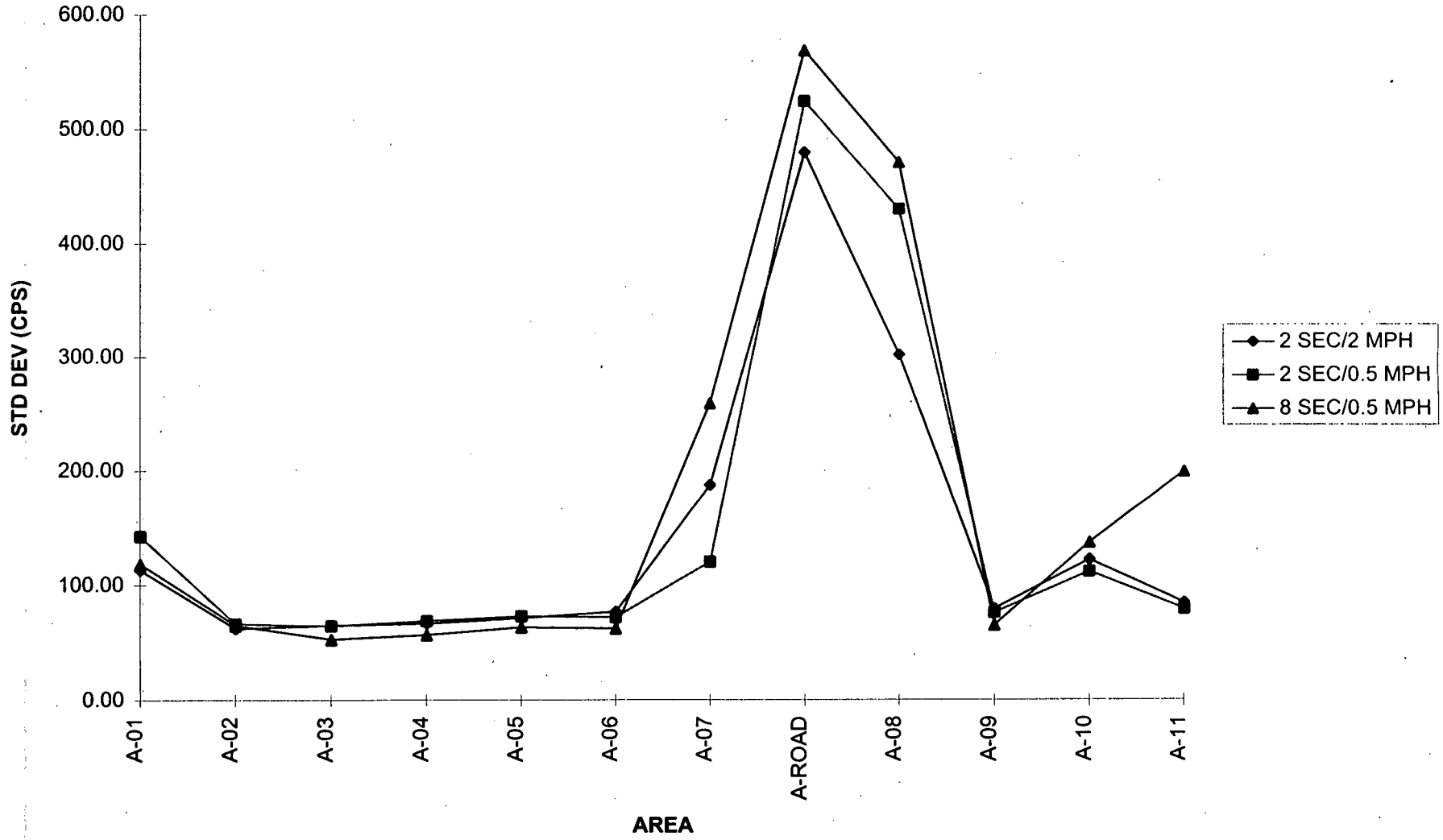

FIGURE C-21
GROSS CPS - USID AREA - % STANDARD DEVIATION

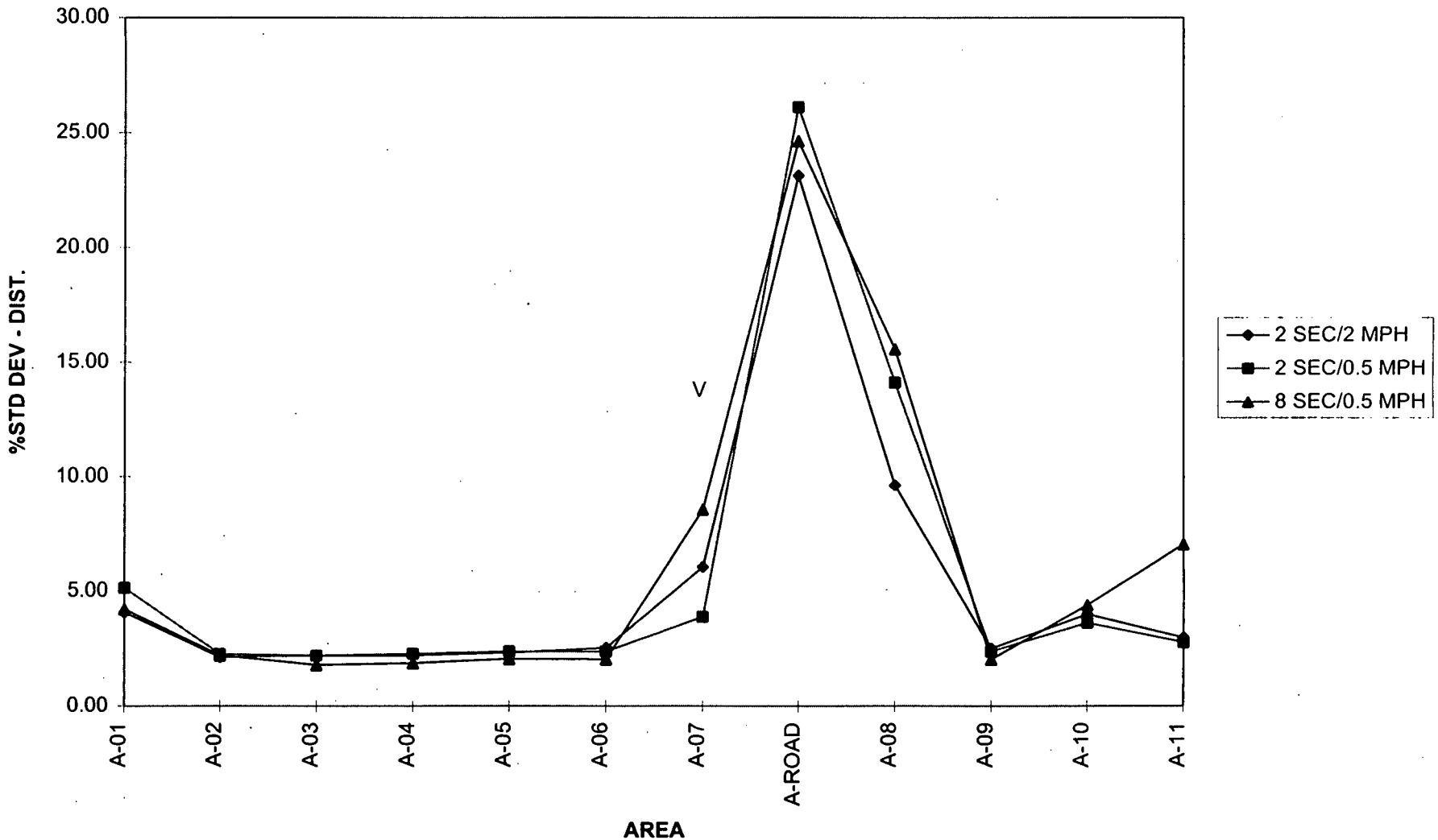

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FIGURE C-22
GROSS CPS - SOUTH FIELD - MEAN

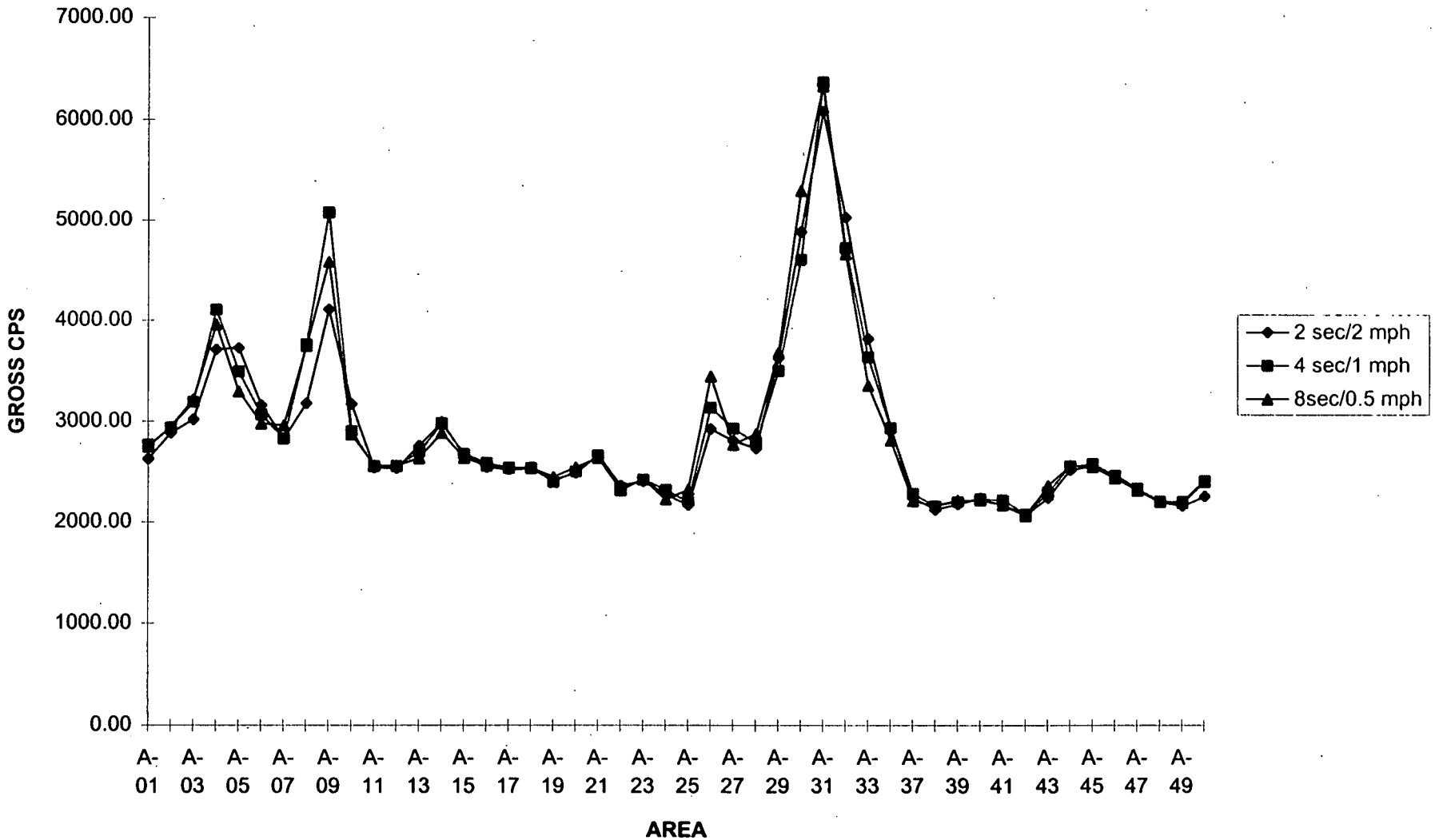
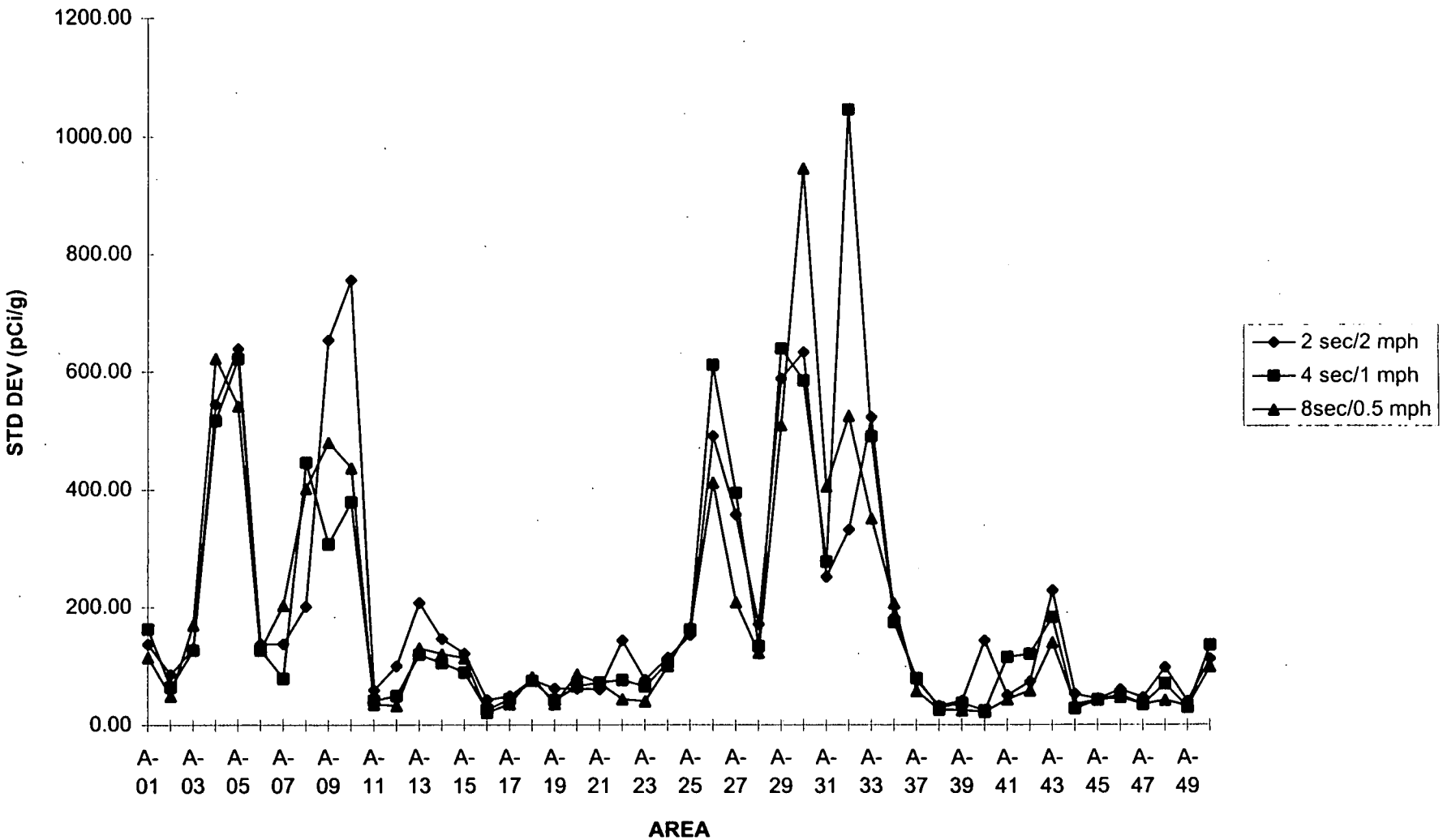


FIGURE C-23
GROSS CPS - SOUTH FIELD - STANDARD DEVIATION



000158

0001459

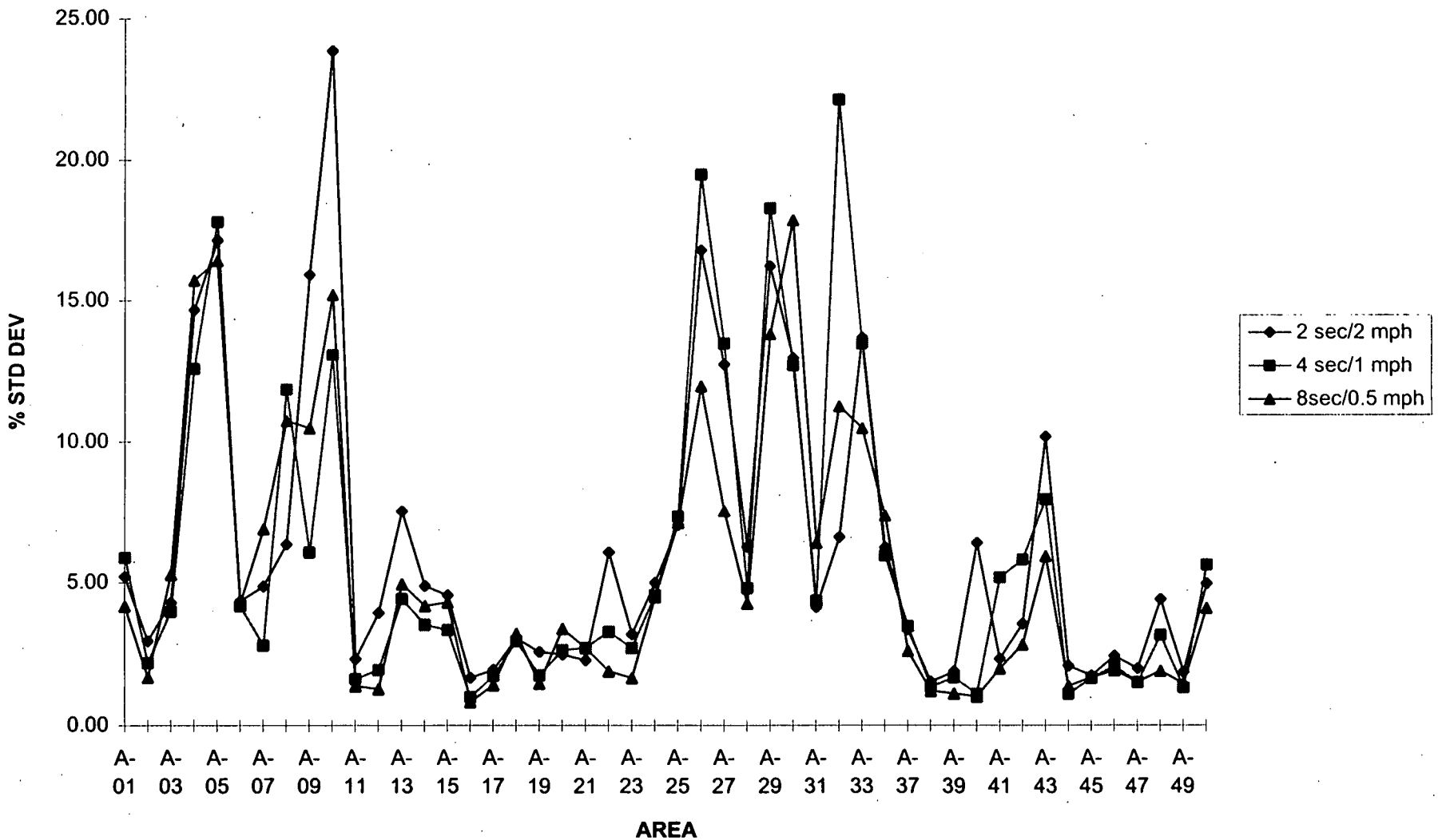



FIGURE C-24
GROSS CPS - SOUTH FIELD - %STD DEV