1951

FERNALD ENVIRONMENTAL MANAGEMENT PROJECT
FERNALD, OHIO

RTRAK APPLICABILITY STUDY

JANUARY 1999

U.S. DEPARTMENT OF ENERGY
FERNALD AREA OFFICE

INFORMATION ONLY

(20701-RP-0003)
REVISION 2

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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 RTRAK data quality parameters. This report, Revision 1 of the RTRAK Applicability Study, incorporates information contained in Revision 0 of the same study that was issued in July 1997, as well as information contained in an addendum to Revision 0 (issued in September 1997, entitled "RTRAK Applicability Measurements in Locations of Elevated Radionuclide Concentrations"). Revised RTRAK calibration equations provide improved compensation for interferences and better represent system response in high activity areas. Additionally, the report includes refinements in the estimation of the total uncertainty of RTRAK measurements and a discussion of the effects of gamma photon interferences on calibration and data quality. Finally, this report incorporates responses to U.S. EPA and OEPA comments on Revision 0 of the July 1997 RTRAK report, and the September 1997 addendum.

A series of studies were conducted in order to evaluate optimum RTRAK operating conditions and the quality of data generated by the RTRAK. Three key data quality elements were examined: precision, minimum detectable concentration (MDC), and accuracy. These studies were conducted in areas of both low and high radionuclide activity concentrations. As a result of these studies, the preferred RTRAK operating conditions are a 4-second data acquisition time with a travel speed of 1.0 mph. These operating conditions offer the best compromise between acceptable analytical data quality and practical field implementation.

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 in the USID are where the contamination pattern is relatively uniform. This is the case for both static (not moving) and dynamic (moving) measurements. Agreement was not as good for measurements in the Drum Baling area. This is attributed to incomplete coverage of the HPGe field of view by the RTRAK and the high degree of heterogeneity in this area. The guideline for radiation scanning instrumentation, provided in the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM), is that the minimum

detectable concentrations (MDC) detection limits should be between 10% and 50% of the applicable action limit. Detection limits are a function of precision. Consequently, the large standard deviations (poor precision) for individual RTRAK measurements preclude the use of individual measurements to quantify uranium at concentration levels near the Final Remediation Levels (FRL). However, the precision of individual measurements are adequate to allow individual measurements to be used for hot spot and waste acceptance criteria (WAC) measurements, except for uranium hot spots in areas where the applicable FRL is 10 or 20 ppm. In order to achieve MDCs that meet MARSSIM guidelines for FRLs, multilpe consecutive measurements must be aggregated. For a 4 second acquisition time, the number of measurements that must be aggregated are: 18 for uranium-238, for the 82 ppm FRL, 3 for radium-226, and 3 for thorium-232. For individual measurements with a four second data acquisition time, the individual-measurement MDCs are:63 ppm for uranium-238, 1.08 pCi/g for radium-226, and 0.91 pCi/g for thorium-232.

Improving the precision of RTRAK results and associated MDCs can be accomplished by spatially averaging the measurements (aggregating) over an area larger than that of the individual measurements. The issue with spatial averaging is how large an averaging area is required to reduce measurement error and MDCs to acceptable levels without sacrificing required spatial resolution. For example, 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 ten feet to one of 20 feet would be equivalent to increasing the acquisition time to 32 seconds.

A new calibration study extended the calibration range by about a factor of three for total uranium and by about a factor of ten for radium-226 (higher concentrations of thorium-232 were not encountered in the new calibration locations). The agreement between the new and the old calibrations is good over the full range of concentrations evaluated for thorium-232 and radium-226. For uranium-238, the agreement between the two calibrations is poorer at low concentrations. This in part is a consequence of a large intercept for the uranium calibration equation. The intercept appears to reflect an overcompensation for interfering photons from radium-226 and thorium-232. At low uranium-238 concentrations, particularly where thorium-232 and radium-226 concentrations are near background, uranium-238 results may be biased high. At present, uranium-238 measurements below approximately

50 ppm should be considered questionable, although, because of the bias, they can be viewed as representing the upper limit of the concentration. The revised calibration equations appear to better correct for interferences and their use reduces the number of large negative concentrations that were obtained using the previous equations.

Because the new calibration measurements included much higher radionuclide concentrations than were used in the old calibration, interference effects had to be addressed. Spectrum interferences increase as the concentrations of thorium-232 and radium-226 increase. All three analytes of interest (uranium-238, thorium-232, and radium-226) are subject to interferences from one or more of the other analytes. Uranium-238 is the most severely affected. In areas where thorium-232 or radium-226 are of the order of tens of pCi/g, the uranium-238 results are questionable and spectra need to be carefully examined to determine whether the interferences preclude their use. Radium-226 results may also be affected when thorium-232 is in the range of 30 pCi/g and again spectra must be examined to determine the impact of the interferences. At high radium-226 concentrations, thorium-232 may be biased low; data are not yet available to quantify the level at which these latter interferences become significant.

The Radiation Scanning System (RSS) is a system similar to the RTRAK but smaller and more maneuverable. The RSS electronics and detector are identical to the RTRAK, but they are mounted on a smaller platform fabricated by modifying a three-wheeled jogging stroller. Other than the size, the primary differences are that the RSS is not motorized and the detector is oriented parallel to the direction of travel, rather than perpendicular as on the RTRAK. The RSS was calibrated in a manner similar to the RTRAK, by making a series of co-located measurements with the RSS in a static mode and the HPGe at a height of 31 cm. The calibration equations were derived by performing multiple linear regressions on these data. The forms of the equations are the same as those obtained for the RTRAK. Repeated profile measurements were made in the USID and Drum Baling Areas using both the RSS and the RTRAK to allow direct comparisons of the responses of the two systems. In addition, specific measurements were made to determine whether the detector orientations would be likely to contribute to differences in system responses. The evaluations demonstrated that the results of the RSS and RTRAK exhibit acceptable agreement. Consequently, the quality parameters derived using RTRAK data and discussed in this report are applicable to the RSS. This simplifies the logistics of using these systems by avoiding the need for multiple sets of operational criteria.

Specific RTRAK and RSS user guidelines, data interpretation guidelines, and measurement strategies and approaches are addressed in the "User's Manual" (DOE 1998a). The reader should consult this document for specifics of how the RTRAK will be used in the soil remediation process.

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LIST OF ACRONYMS AND ABBREVIATIONS

ALARA	as low as reasonably achievable
COC	constituent of concern
cps	counts per second
DGPS	differential global positioning system
DOE	U.S. Department of Energy
FEMP	Fernald Environmental Management Project
FRL	final remediation level
FWHM	full width half maximum
GPS	global positioning system
HPGe	high-purity germanium detector
IRDP	Integrated Remedial Design Package
keV	kiloelectrovolt
MCA	multichannel analyzer
MDC	minimum detectable concentration
mph	miles per hour
NaI	sodium iodide
NIST	National Institute of Standards and Technology
pCi/g	picocuries per gram
PHA	pulse height analysis
PMT	photomultiplier tube
ppm	parts per million
PSP	project specific plan
PVC	polyvinylchloride
QA/QC	Quality Assurance/Quality Control
RI/FS	Remedial Investigation/Feasibility Study
ROI	region of interest
RTRAK	Radiation Tracking System
sec	second
SEP	Sitewide Excavation Plan
USID	Uranium in Soils Identification Demonstration
WAC	waste acceptance criteria

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. Because thorium-228 and radium-228 have been shown to be in secular equilibrium with thorium-232 (letter from J. Craig to J. Saric and T. Schneider, 1997), only total uranium, radium-226, and thorium-232 are of analytical concern.

A number of 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:

- Complete coverage of areas to assess the spatial patterns of contaminant distribution in pre-design investigations;
- Rapid identification of areas potentially exceeding Waste Acceptance Criteria (WAC) during soil excavation activities;
- Complete coverage and rapid identification of areas potentially exceeding final remediation levels (FRLs), hot spot criteria, and WAC exceedances in pre-certification activities;
- Rapid attainment of data that allows high purity germanium (HPGe) measurements or physical samples to be focused on specific areas; and
- Support 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 based on a mobile sodium iodide (NaI) detector-based system for measuring gamma rays. This technique is currently being deployed in two configurations: (1) a system known as the Radiation Tracking System (RTRAK) which is mounted on a John Deere tractor and (2) a smaller system known

as the Radiation Scanning System (RSS) which is mounted on a three-wheeled cart. The detectors and electronics are identical for both systems; the differences are in the mobile platform.

1.2 BRIEF DESCRIPTION OF RTRAK AND RSS SYSTEMS

The RTRAK system is a gamma-ray measurement system mounted on a tractor. The RSS is a similar system which has detector and electronics mounted on a lightweight, three-wheeled cart. The RSS is designed for use in areas inaccessible to the RTRAK. Each vehicle has a measurement system consisting 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 RTRAK and RSS are each 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.

On the RTRAK, the detector is positioned on the tractor horizontal to the ground and perpendicular to the direction of travel at a height of approximately 31 cm above the ground. The detector on the RSS is mounted horizontal to the ground and parallel to the direction of travel at a height of approximately 31 cm. The normal operation of the RTRAK and RSS consists of moving the systems 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 8.8 m^2 for a single measurement when the system is moving at one mile per hour, with a 4-second data acquisition time (typical operating parameters). Table 1-1 gives RTRAK/RSS single measurement fields of view as a function of speed and data acquisition time. Figure 1-1 depicts how the field of view is determined (a 1.2 meter radius for the RTRAK stationary field of view is the basis for determining the moving RTRAK field of view). The travel speed of the RTRAK can be continuously monitored by the tractor's speedometer and so it can be controlled reasonably well. The travel speed of the RSS is estimated by noting the time it takes for the operator to cover a known distance. The operator then attempts to maintain a constant pace. Consequently, the RTRAK travel speed is better controlled than that of the RSS and so has a more consistent field of

view. The variations in the RSS field of view do not create serious difficulties in evaluating the data because the actual position is monitored using the GPS and because typically, the RSS is used to monitor small areas.

The RTRAK/RSS collects data which are used to generate a gamma photon energy spectrum. This spectrum may be processed to generate total activity or radionuclide-specific activities. In the total activity 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 system can be used to generate qualitative and quantitative results for uranium-238, radium-226, and thorium-232. 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 the NaI detectors, and how gamma photons are measured and quantified is provided in Appendix A. The RSS is described in Appendix C.

1.3 PREVIOUS STUDIES

In 1997, a series of method validation studies pertaining to *in-situ* gamma spectrometry were issued. These studies addressed analytical aspects of *in-situ* gamma spectrometry such as precision, accuracy, detection limits, robustness, comparability with laboratory analytical data, and data quality levels. One report and three addenda concerned HPGe detectors, and one report; Revision 0 of this report and one addendum dealt with the RTRAK. These reports and addenda are:

- Comparability of *In-Situ* Gamma Spectrometry and Laboratory Data, 20701-RP-0001, Revision 1, December 1998.
- RTRAK Applicability Study, Revision 0, July 1997
- RTRAK Applicability Study, Revision 1, April 1998
- RTRAK Applicability Measurements in Locations of Elevated Radionuclide Concentrations, September 1997 (Addendum #1)

The July 1997 "Comparability of *In-Situ* Gamma Spectrometry and Laboratory Data" (DOE 1997a) is referred to in this study as the HPGe Comparability Study. The July 1997 "RTRAK Applicability Study" is referenced in this document as DOE 1997b.

1.4 SCOPE OF THE REPORT

This report describes the results of a series of six studies conducted at the FEMP to assess the usefulness and applicability of the RTRAK to support soil remediation. An initial calibration study (1)

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 (2) and the South Field area study (3) were conducted to optimize data acquisition parameters and to delineate key data quality elements. Data were collected in the Drum Baling Area (4) to extend the characterization of the RTRAK to areas with elevated levels of radioactivity. A second calibration study (5) was conducted to extend the calibration range of the RTRAK using data from higher activity locations. The deployment of the RSS required a separate study (6) to calibrate and determine whether the quality parameters defined for the RTRAK were applicable to the RSS. The first three studies are described in the July 1997 RTRAK Applicability Study (DOE 1997b), while the fourth study was described in the September addendum to the July 1997 study. The fifth and sixth studies are described in this report. These six studies set the basis for this report's analysis and discussion.

As noted above, three of the five primary COCs, total uranium, thorium-232, and radium-226, are the contaminants of analytical 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 in pCi/g 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.**

1.5 OBJECTIVES

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

1. Describe the RTRAK and RSS systems and their component subsystems;
2. Document the calibration process for RTRAK and RSS 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 analytical parameters that affect the known quality of data for the RTRAK and RSS systems;

6. Establish values for these key parameters such that levels of uncertainty for various analyte concentrations can be estimated; and

7. Recommend guidelines for reviewing data.

1.6 RELATION TO OTHER DOCUMENTS

Figure 1-2 shows the relationship between the RTRAK Applicability Study and other key documents in the soil remediation process. The RTRAK Applicability Study is a method validation study, and thus forms the basis for analytical information to be incorporated into the User's Manual (DOE 1998a) and into the Real-Time Instrumentation Measurement Program QA/QC Plan (DOE 1998c, 1998d). Applications, strengths and limitations of the RTRAK and RSS, and other user-related information can be found in the User's Manual and are not included in this report. A detailed perspective of how the RTRAK and RSS fit into soil remediation operations is provided in the Sitewide Excavation Plan (SEP; DOE 1998b).

1.7 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). The data discussed in Section 4 was obtained from RTRAK measurements. However, as discussed in Appendix C, the quality parameters are applicable to RSS as well. Section 5 recommends guidelines for reviewing RTRAK and RSS data (Objective 7), and Section 6 provides a summary and conclusions.

Supporting data and technical details are provided in Appendices A, B, and 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). Appendix B contains tables and figures used as the

basis for data discussion and interpretation in Section 4.0. Appendix C discusses the calibration or the RSS and studies demonstrating that the RSS and RTRAK exhibit comparable quality parameters such as precision and accuracy.

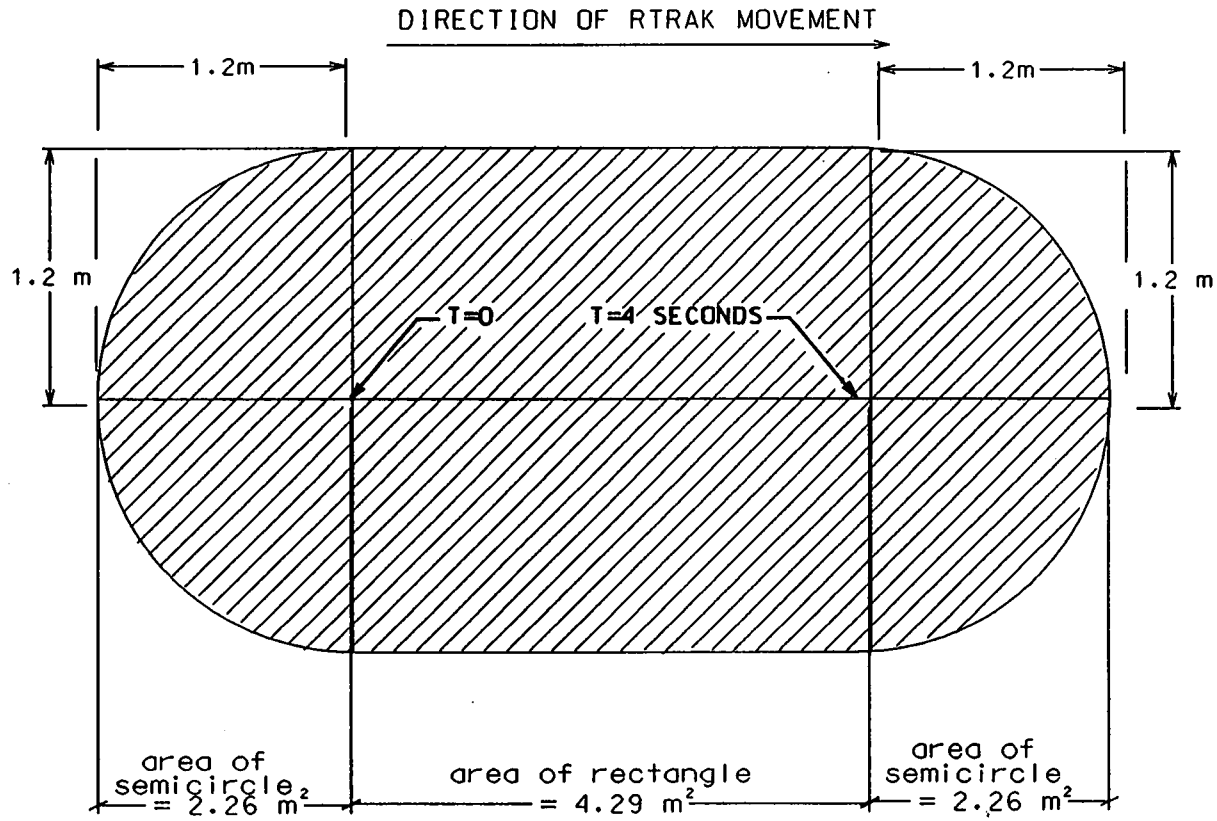
TABLE 1-1
RTRAK/RSS FIELD OF VIEW
AS A FUNCTION OF SPEED AND DATA ACQUISITION TIME

Speed	Data Acquisition Time		
(mph)	2 Seconds	4 Seconds	8 Seconds
0.5	5.6*	6.7	8.8
1.0	6.7	8.8	13.1
2.0	8.8	13.1	21.7

* Numbers represent the area of the field of view in square meters.

FIGURE 1-1.

FIELD OF VIEW OF A SINGLE RTRAK MEASUREMENT AT 1.0 MPH WITH A 4.0 SECOND DATA ACQUISITION TIME



FIELD OF VIEW OF MEASUREMENT

FIELD OF VIEW
= 2.26 + 4.29 + 2.26
= 8.81 M

RTRAK STARTS AT T=0 AND MEASUREMENT ENDS AT T=4 SECONDS. 1.0 MPH = 0.447 M/SEC. IN 4.0 SECONDS THE RTRAK TRAVELS 1.787 METERS.

000021

- 1951

29-APR-1998

v:\5cra3\dgn\bmp\calc-005.dgn

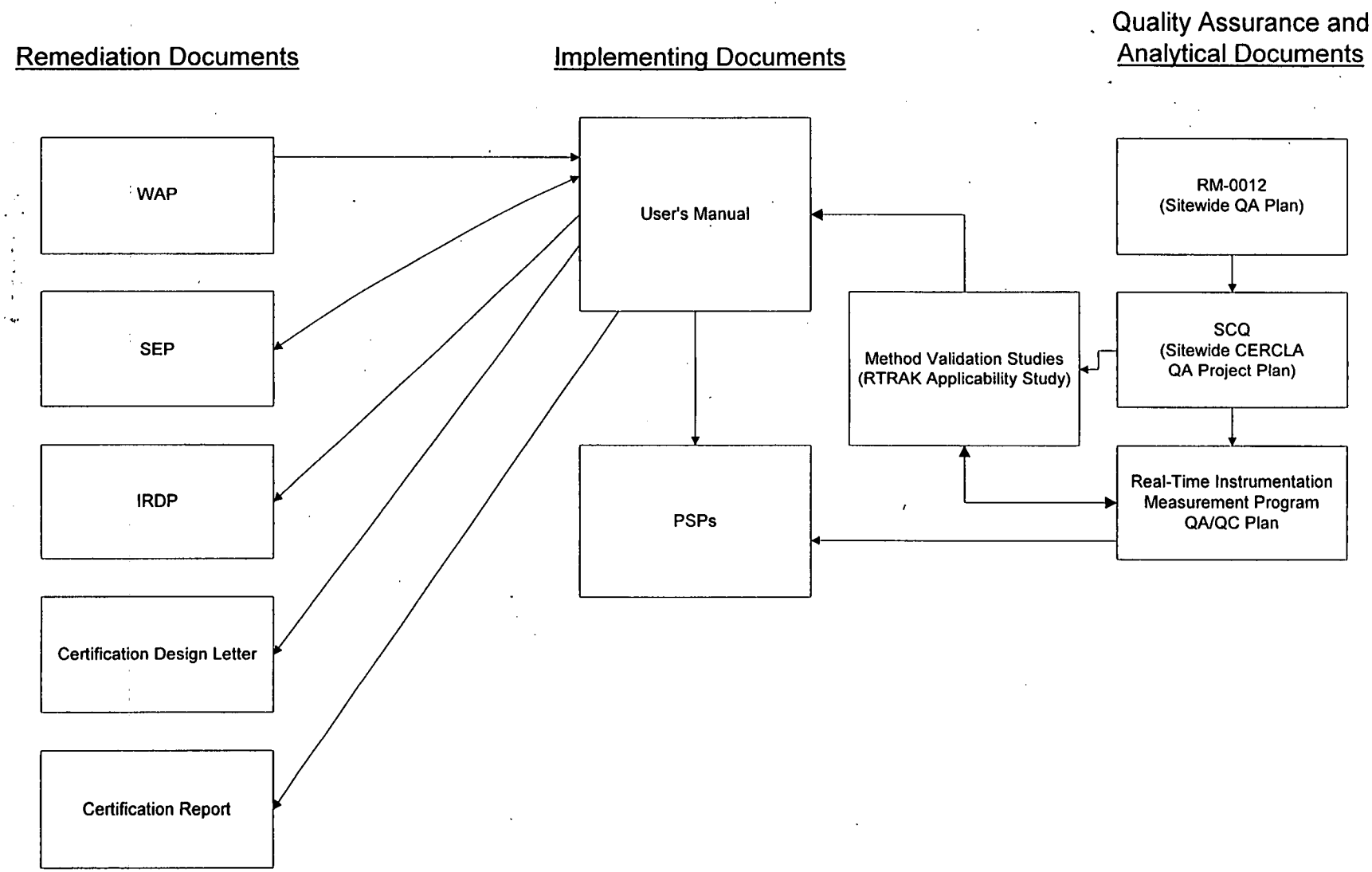


FIGURE 1-2 DOCUMENT RELATIONSHIPS

2.0 STUDY DESIGN

2.1 TYPES OF STUDIES AND LOCATIONS

As noted in Section 1.3, the discussions and conclusions in this report are based on six separate studies. The initial calibration study involved RTRAK measurements at each of the ten locations designated for collection of HPGe *in-situ* gamma spectrometry data and physical samples for the HPGe Comparability Study (DOE 1997a). These ten locations are noted in Figure 2-1.

The USID and South Field area studies (Figure 2-1), the second and third studies, 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.

The studies in the Drum Baling Area (DBA) were conducted because of a recognized need to obtain data in locations with uranium concentrations approaching or exceeding the waste acceptance criteria (WAC) limit and in which radium and thorium concentrations were elevated significantly above background. One of the principal goals of this study was to evaluate the applicability of the RTRAK for WAC screening.

The fifth study was conducted to extend the calibration range of the RTRAK to higher radionuclide concentrations. New static RTRAK measurements and new HPGe measurements were performed in the DBA, the South Field, and the USID study areas to provide calibration points across a wide concentration range. Other static RTRAK and HPGe measurements were made to provide data to be used for calibration assessment. This study is discussed in more detail in the following sections.

The sixth study which is also described in this report focused on the RSS. Static measurements were made with the RSS in the same locations as the RTRAK and HPGe measurements in the fifth study. These measurements were used to develop the RSS calibration curve. In addition, repeated profile measurements were made using the RTRAK and the RSS in the USID area and the DBA. Both systems followed the same path for the measurements. The results were used to determine whether the quality parameters of the RSS were comparable to those of the RTRAK. This study is discussed in Appendix C of this report.

2.2 CALIBRATION STUDIES

The objective (Section 1.4) of describing the calibration studies 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 both RTRAK and RSS involved making measurements at several soil locations with a wide range of radionuclide concentrations and then correlating the results to the concentrations of various radionuclides in the soils as measured by HPGe.

The ten areas used for the initial calibration study for the RTRAK were the same ten areas used to collect HPGe data and physical samples for the HPGe Comparability Study (DOE 1997a). 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. Soils in low contamination areas (Areas 1, 8 and 9) were believed to contain less than 80 ppm total uranium; soils in moderate contamination areas (Areas 2, 4, 5, and 6) were believed to contain between 80 and 200 ppm total uranium; and soils in high contamination areas (Areas 3, 7 and 10) were believed to contain more than 200 ppm total uranium. However, as shown in Table 2-1, based upon physical samples collected for the HPGe Comparability Study (DOE 1997a), actual total uranium concentrations were generally lower than believed.

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

The original RTRAK calibration was based on data collected during the HPGe Comparability Study (DOE 1997a). These data had limited concentration ranges; thorium-232 and radium-226 were all near FEMP background levels, and the maximum uranium-238 concentration was approximately 284 ppm (Table 2-1). Because of a desire to use the RTRAK and the RSS to survey for WAC exceedances, it was considered necessary to extend the calibration range to higher radionuclide concentrations. For this extension, a second calibration study was conducted in Fall 1997. This study included measurements for the calibration of RSS as well as the RTRAK. Static RTRAK, RSS, and HPGe measurements were made in the DBA, the South Field, and the USID Study Area. A total of eight new calibration measurements were made in these three areas. The locations were selected on the basis of preliminary RTRAK scans conducted in these areas. At each calibration location, measurements were made using the RTRAK and RSS in a static mode (five-minute data acquisition times) and the HPGe (15-minute data acquisition times). The data from these measurements were combined with the initial calibration data to generate calibration equations that span a wide range of activities. Details of the calibration are described in Section 3.3 of this report for the RTRAK and Appendix C for the RSS.

The additional data points and the wider range of analyte concentrations resulted in calibration equations that were more representative than the initial calibration. The data reported in Revision 0 of the Applicability Study were reprocessed using the revised calibration equations. As a general rule, data are not reprocessed whenever a calibration is improved. However, the previous RTRAK studies were conducted to quantify the system's quality parameters and the purpose of this version of the report is to improve upon and expand those efforts. Consequently, it was considered appropriate to use the revised calibration equations to process all data included in this revision of the Applicability Study. The results of the repeated profile measurements calculated using the revised calibration equations were compared with those using the original calibration equations. The segment means remained unchanged, but the segment standard deviations and ranges of results within each segment were smaller. One important aspect of this change is that the number of large negative values for individual measurements was reduced. This improvement is attributed to a better representation of the effects of interfering gamma rays. This conclusion is supported by the fact that the uranium-238 data, which are subject to the most severe interference, showed the most improvement, while the thorium-232 data, which have the least interference problems, had the least improvement.

Full area scans (approximately 100% coverage) of the USID area and a portion of the DBA were made using the RTRAK and the HPGe. These data were collected for assessment of the RTRAK calibrations in the dynamic mode. These two areas were selected for this assessment because they offer a wide range of analyte concentrations. The analyte concentrations in the USID area are low with a homogeneous distribution, while in the DBA, the concentrations are higher and the distribution heterogeneous. In the dynamic mode, the field of view of the RTRAK or RSS is constantly changing and it is not practical to exactly match the fields of view of a series of measurements with a single HPGe measurement. This makes direct comparisons between individual HPGe measurements and a set of dynamic RTRAK measurements difficult. However, because the analyte distribution in the USID area is reasonably homogeneous, a good comparison can be made. The DBA has the more heterogeneous distribution and HPGe and RTRAK would not be expected to agree as well in such an area, but the comparison provides some useful information for data evaluation.

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).

2.3.1 USID Study Area

A series of repeated profile runs were performed in the USID area north of the incinerator (see Figure 2-1) to determine the preferred combination of vehicle travel speed and data acquisition time. 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 analyzed. To determine the preferred RTRAK operating parameters, three combinations of travel speed and data 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.

Approximately 100% of the USID study area was characterized by the RTRAK. The objective of these full-coverage measurements 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 approximately 100% of the 1-acre area, as shown schematically in Figure 2-2. The coordinates of each measurement point were determined using GPS. Soil moisture and density measurements were performed in conjunction with each HPGe measurement to assess the soil physical conditions.

Replicate static measurements using the RTRAK NaI system were performed at four selected locations on the grid: these locations represented 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 replicate 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 assess 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.

Finally, a single track RTRAK measurement profile was selected based on the above 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.

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 path intersecting the center of the circular Area 13, and the eastern portion of the RTRAK path 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. RTRAK runs were not all conducted on the same days, so there were different moisture conditions than on the days that HPGe data and physical samples were collected. To allow proper correction for soil moisture content, Troxler moisture/density readings were re-collected at Area 13, Location 1, and at Area 16, Location 1 each day that the RTRAK runs were conducted. Soil and air temperature and humidity readings were also recorded at the beginning of each day of RTRAK measurements.

2.4 DRUM BALING AREA

RTRAK measurements were conducted in a location known as the DBA. Past surveys in this area revealed that elevated uranium, radium-226, and thorium-232 activities could be expected. Repeated profile measurements were performed to gain a measure of the method precision (total system precision, not just precision based upon counting statistics), using three combinations of acquisition time and travel speed: 2 sec/2 mph, 4 sec/1 mph, and 8 sec/0.5 mph. The DBA profile paths are shown in Figures 2-4 through 2-6. In addition, static RTRAK measurements and HPGe measurements were performed at three specific locations within the DBA. The static RTRAK measurements and the

collocated HPGe measurements were made to assess the accuracy of the RTRAK at higher analyte concentrations. The static RTRAK data were collected as several series of short measurements which had individual acquisition times of 2 and 8 seconds. The total acquisition period for each series of measurements was 300 seconds (summing a series of individual 2 or 8 second acquisition times for a total of 300 seconds is equivalent to a single 300 second count time).

TABLE 2-1
TOTAL URANIUM CONCENTRATIONS IN TEN AREAS
USED FOR ORIGINAL RTRAK CALIBRATION

Area	Number of Samples *	Average and Standard Deviation of Total Uranium Concentration (ppm) Based upon Alpha Spectrometry
PBC-01	6	7.4 ± 0.9
PBC-02	10	26 ± 5
PBC-03**	14	284 ± 69
PBC-04	10	55 ± 10
PBC-05	10	46 ± 18
PBC-06	10	88 ± 13
PBC-07	15	179 ± 56
PBC-08	6	5.0 ± 1.4
PBC-09	6	6.3 ± 0.7
PBC-10	15	54 ± 14

* excluding duplicates
** excluding PBC-03-1

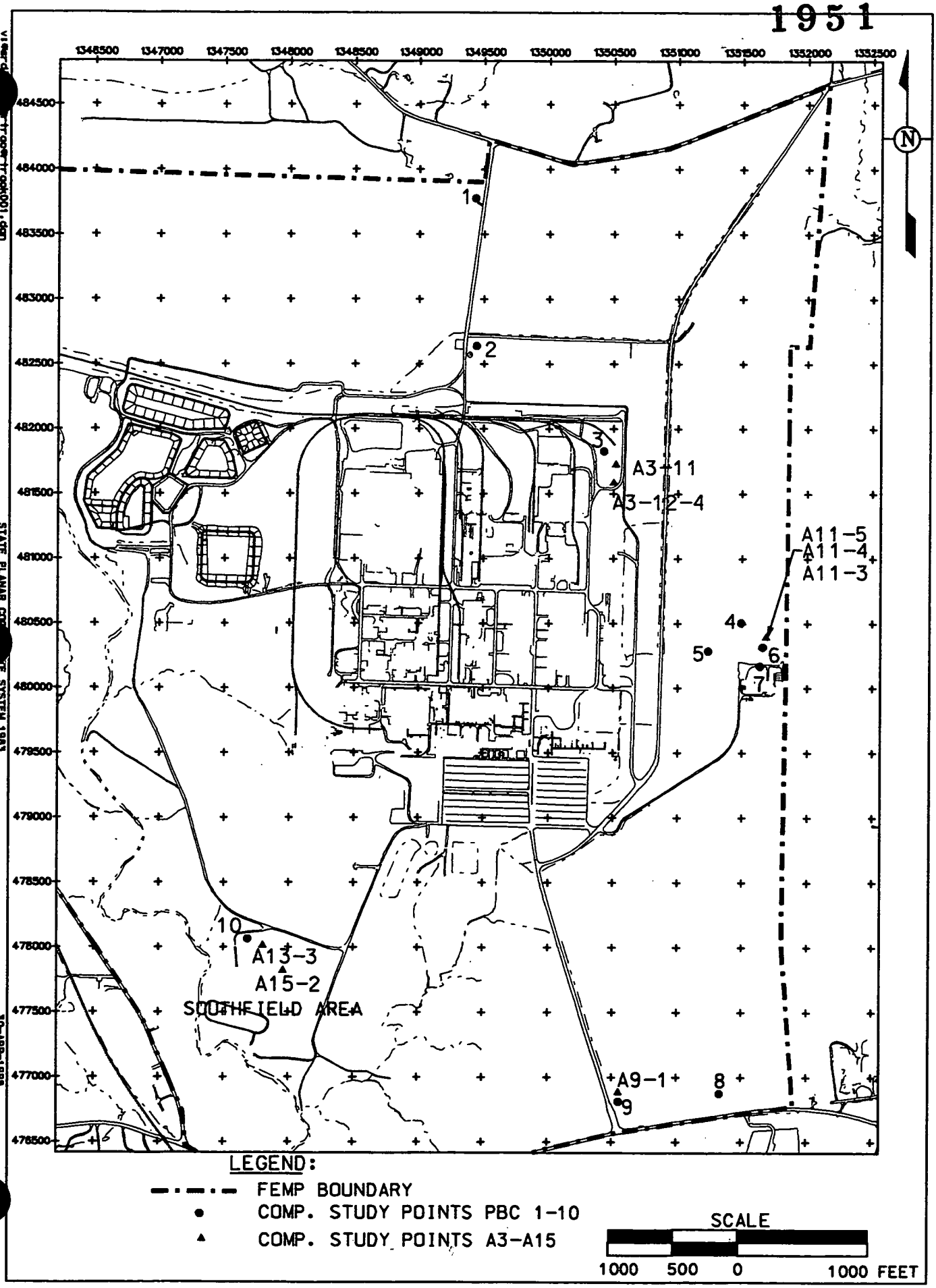


FIGURE 2-1. RTRAK CALIBRATION LOCATIONS

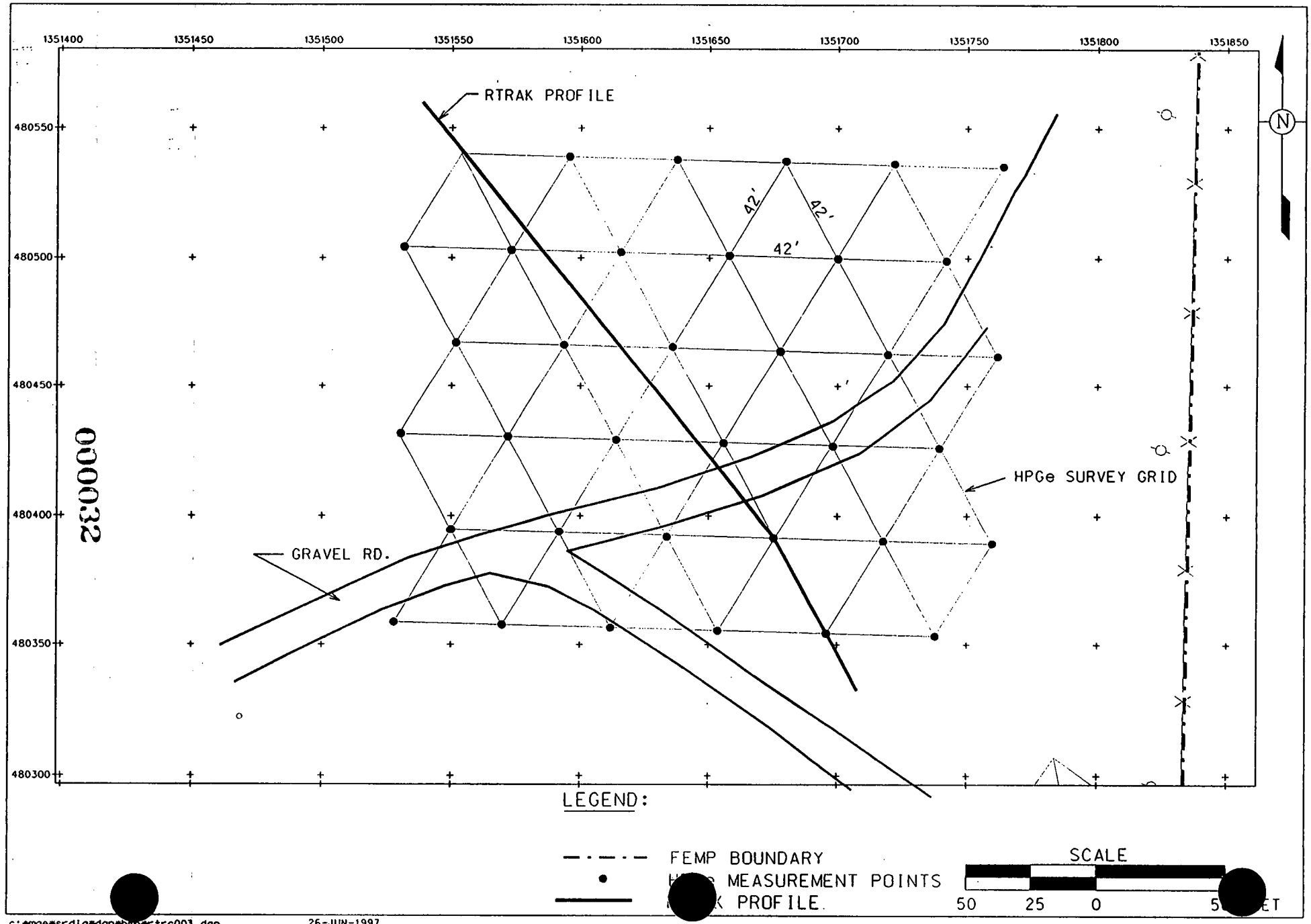
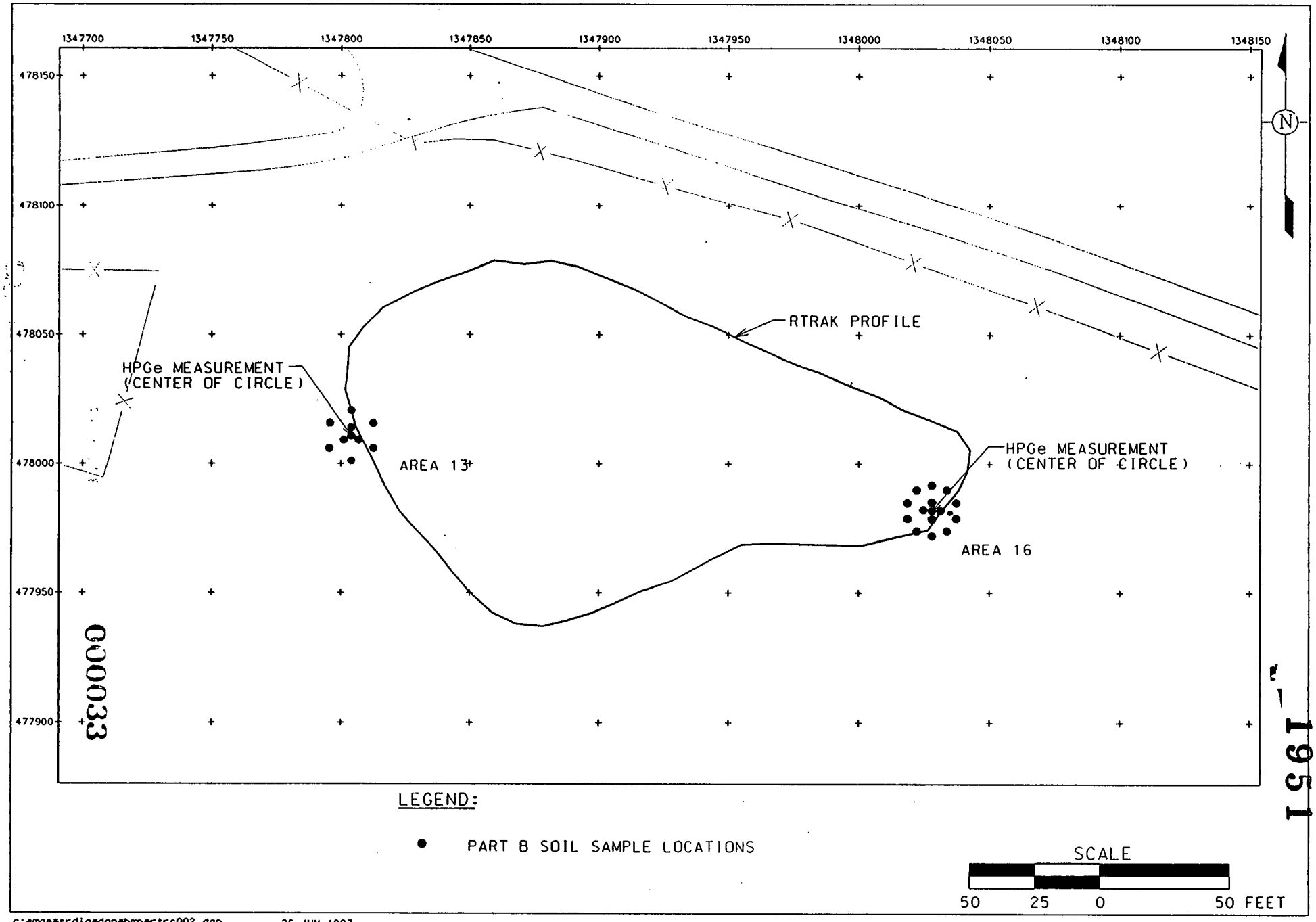


FIGURE 2-2. RTRAK AND USID TEST AREA

000032



000033

1951

c:\mga\srdlg\dgn\bmp\rtrc002.dgn
STATE PLANAR COORDINATE SYSTEM 1983

26-JUN-1997

FIGURE 2-3. RTRAK PROFILE RUN IN THE SOUTHFIELD

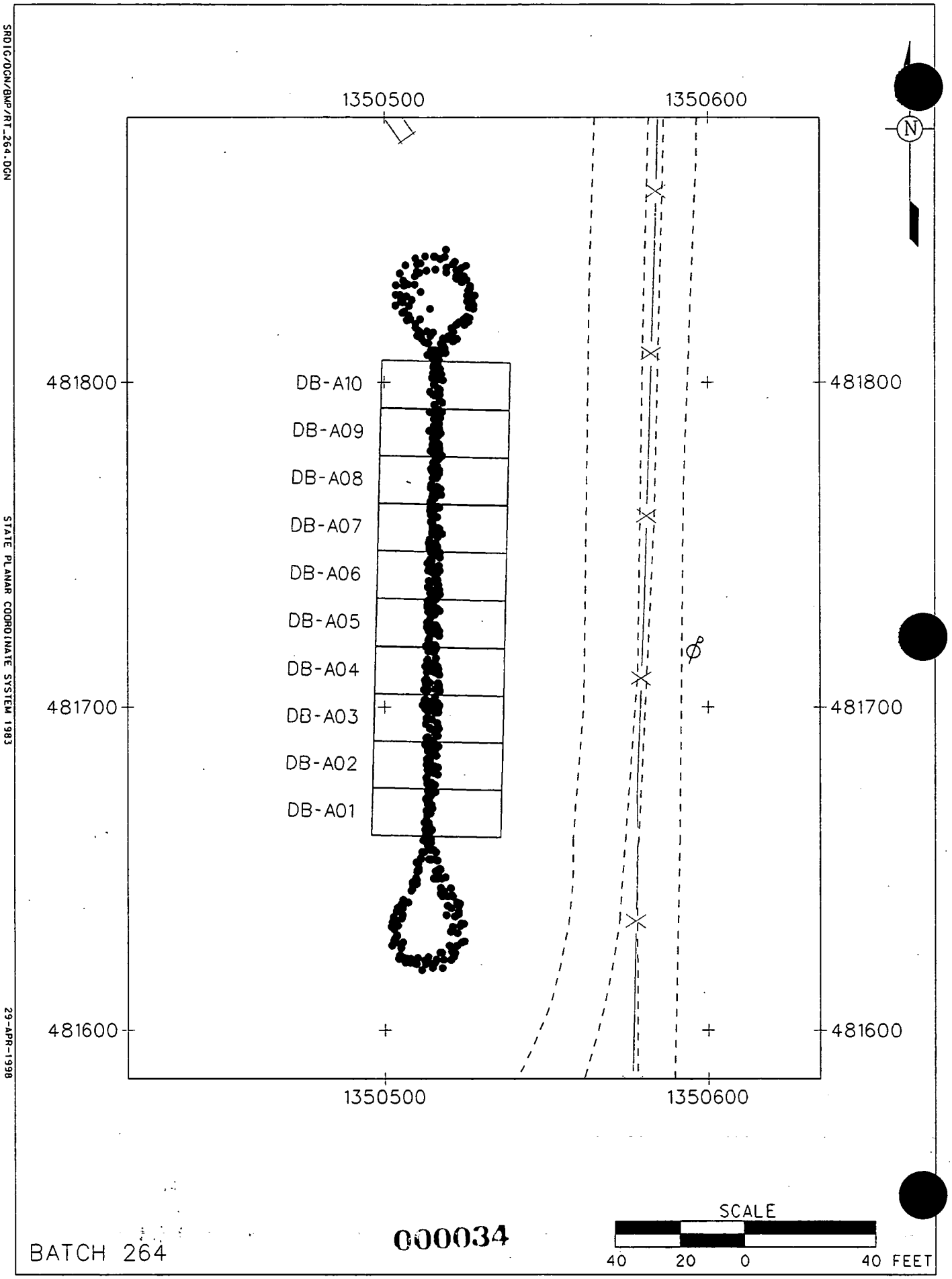
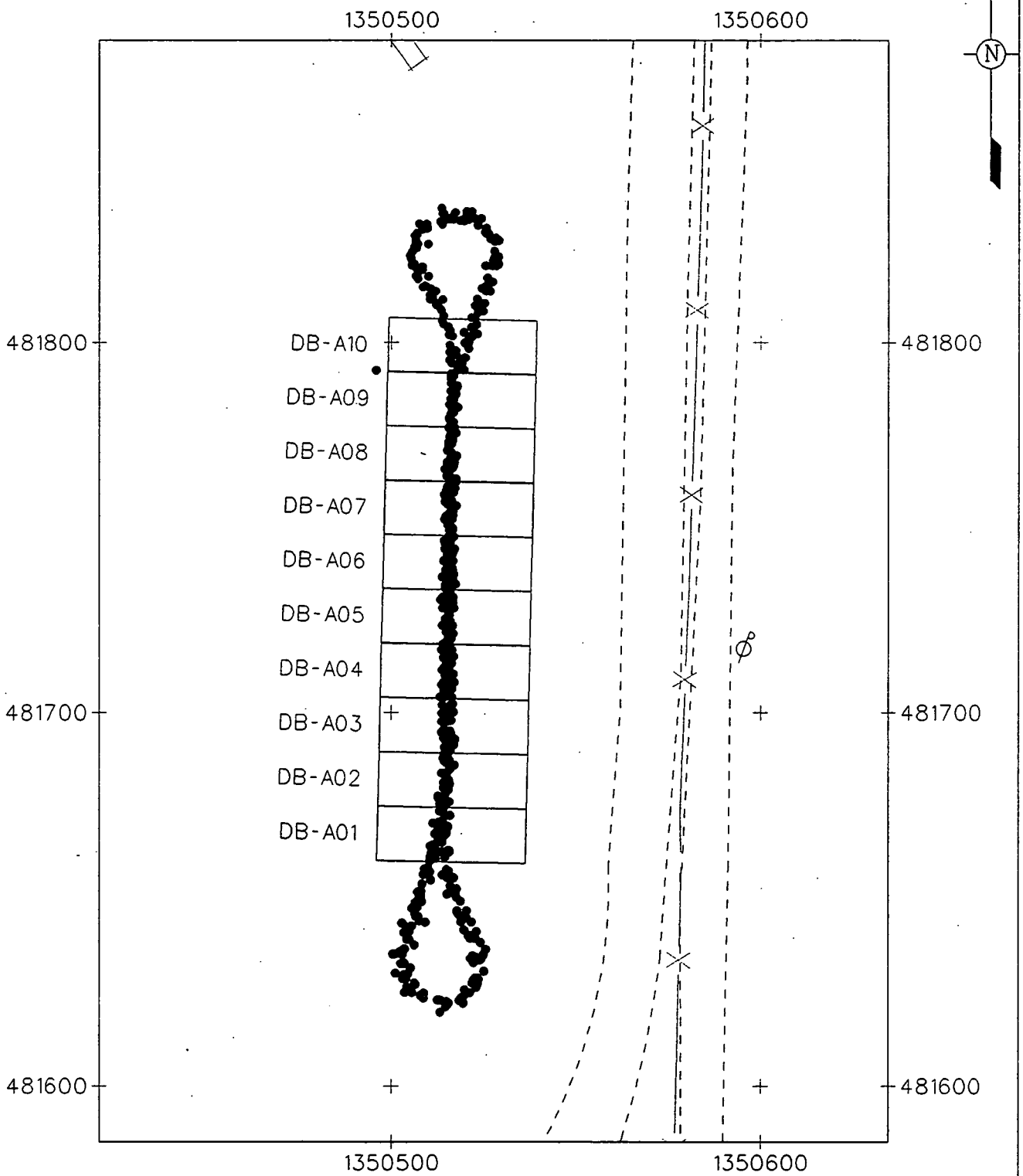


FIGURE 2-4. CONFIGURATION AND MEASUREMENTS IN PROFILE SEGMENTS FOR DRUM BALING AREA - 2 M.P.H./ 2 SEC. ACQUISITION



SCALE

40 20 0 40 FEET

BATCH 266

FIGURE 2-5. CONFIGURATION AND MEASUREMENTS IN PROFILE SEGMENTS FOR DRUM BALING AREA - 1 M.P.H./ 4 SEC. ACQUISITION

SR01G/0 P/RT_266.DGN
STATE PLANAR COORDINATE SYSTEM 1983
29-APR-1998

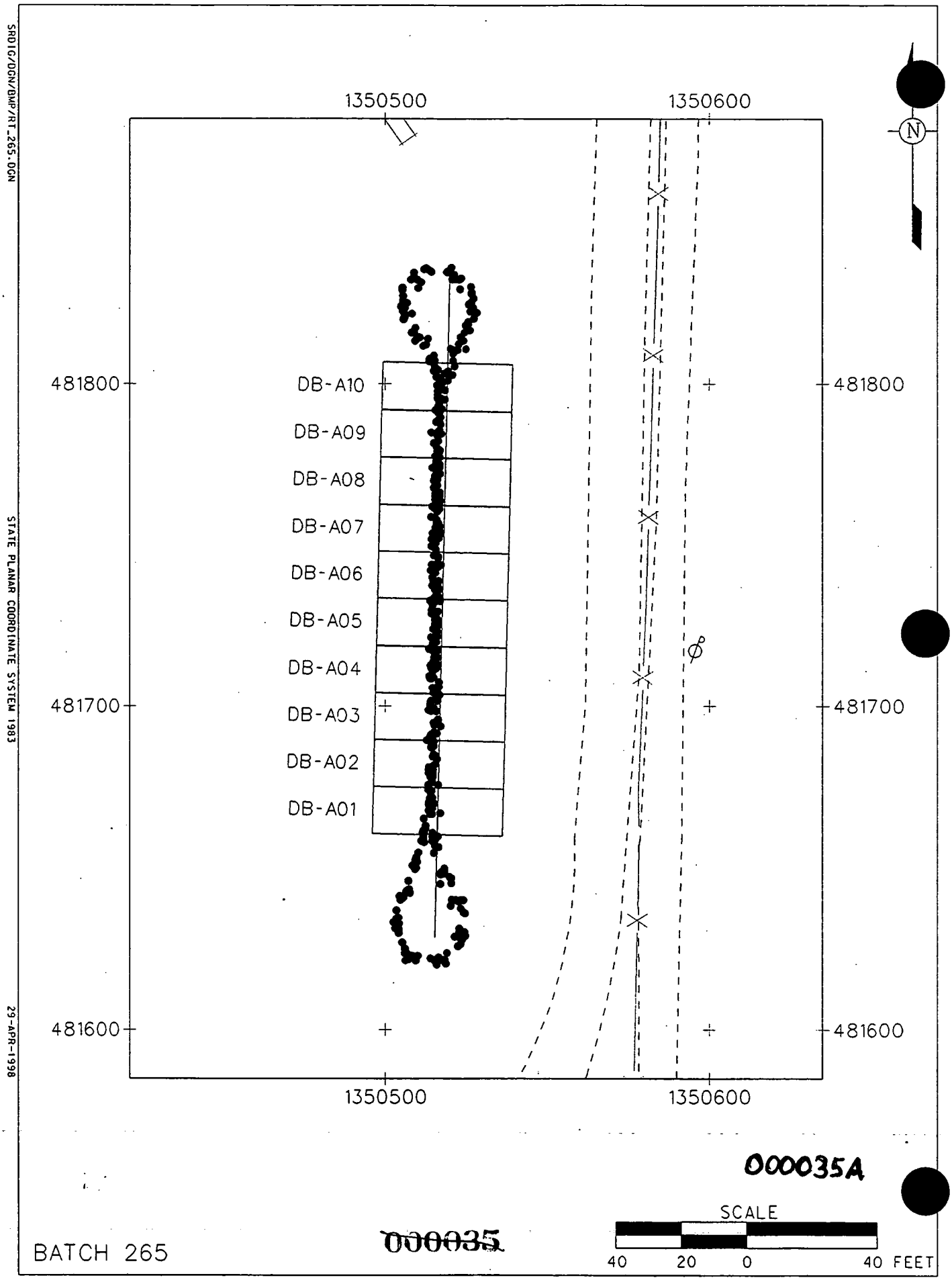


FIGURE 2-6. CONFIGURATION AND MEASUREMENTS IN PROFILE SEGMENTS FOR DRUM BALING AREA - 0.5 M.P.H./ 8 SEC. ACQUISITION

3.0 CALIBRATION OF RTRAK SODIUM IODIDE DETECTORS

3.1 DETECTOR CALIBRATIONS

This section describes the process by which the NaI gamma ray detector mounted on the RTRAK vehicle is calibrated. It also presents the "calibration equations" which are the end result of the calibration process. With these calibration equations, the net counts registered by the sodium iodide detector from a particular isotope may be used to calculate the concentration, i.e. the activity per unit mass, of that radionuclide in the soil which was scanned by the RTRAK. One of the reasons for updating the July 1997 RTRAK Applicability Study was to extend the calibration range to higher analyte concentrations. The results of this process will be discussed.

Two calibrations are required on a gamma-ray counting system in order to qualitatively and quantitatively evaluate the spectrum. These two calibrations are (1) 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 (2) an efficiency calibration, which converts the relative counts in the spectrum to activity concentrations in pCi/g. 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 system amplifier is adjusted so that the 238.6 keV photon is assigned to channel 40 in the multichannel analyzer, and so that 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 channel 40 $\pm$ 2 and channel 447 $\pm$ 2, respectively. Refer to Appendix A for more detail about the energy calibration process.

3.3 EFFICIENCY CALIBRATION

After properly completing an energy calibration, the NaI detector can be used to determine the identity of the radioisotopes in the soil scanned by the RTRAK provided that the photon energies are at least 70 keV apart (see Appendix A). However, in order to use the RTRAK to also determine the quantity of each radionuclide which is present, the number of gamma ray counts of a particular energy registered by the counter must be related to the amount of that radionuclide present in the soil. This process is called efficiency calibration.

Because the RTRAK was designed as an *in-situ* measurement system, it is not practical to use certified standard reference materials to calibrate the detector as one would in a laboratory setting. Therefore, the RTRAK efficiency calibration procedure involved making comparative RTRAK and HPGe measurements at eighteen different soil areas containing known concentrations of radionuclides and performing multiple linear regression analyses of the soil concentration (as measured by HPGe) versus the net RTRAK gamma count rates. At each measurement location, the RTRAK and the HPGe detectors were placed at the same position coordinates within the accuracy limits of the GPS satellite positioning system. Fifteen minute HPGe spectra and five minute RTRAK spectra were acquired at each location. HPGe measurements were conducted at detector heights of 15 cm, 31 cm, and 1 meter. Regression analyses were performed on all three sets of data to determine the best calibration correlations. The 31 cm data yielded the best correlations, so it was concluded that the data provided the best match with the static RTRAK field of view. The HPGe detector was positioned at height of 31 cm to approximate the RTRAK detector field of view. The data which were used to develop RTRAK calibration equations are shown in Appendix A, Table A-2. It consists of data collected at the ten field locations used in the HPGe Comparability Study (DOE 1997a) plus an additional eight locations in the Drum Baling, South Field, and USID areas of the FEMP. The measurement locations in the DBA were chosen to extend the calibration range to higher radionuclide concentrations. In most cases the RTRAK and HPGe data displayed in Table A-2 are averages of two or more measurements. Since HPGe measurements were shown by a series of reports issued in 1997 (Section 1.3) to be accurate and comparable to laboratory analyses, the HPGe measurements were used as the basis for "known" concentrations of uranium-238, thorium-232, and radium-226.

In Revision 0 of the RTRAK Applicability Study issued in July 1997 (DOE 1997b), only simple linear regressions were required to derive radium-226 and thorium-232 calibration equations, whereas

multiple linear regression was necessary to accurately represent the uranium data. When higher radionuclide concentrations are present, interferences not evident in the earlier study became apparent, and it became necessary to use multiple linear regressions to derive the calibration equations for all three isotopes. In general, the multiple linear regression equation will have the form:

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

where x_1, x_2, and x_3 are RTRAK net count rates for the three isotopes of interest and b_0, b_1, b_2, and b_3 are the coefficients derived from the multiple linear regression analysis which give the "best fit" to the data in Table A-2. For uranium-238 it is necessary to use all three variables (x_i terms) in the equation above; but thorium-232 and radium-226 require the use of only two variables. Each isotope will be discussed separately below.

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 associated with each analyte. 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 data acquisition time.

Thorium-232 Calibration Equation

The thorium-232 calibration equation involves a radium term as well as a thorium term because emissions from radium-226 daughters effect the RTRAK thorium result by contributing counts to the thorium signal window. This interference becomes important at higher radium concentrations. Multiple linear regression analysis involving thorium-232 and radium-226 net count rates versus HPGe thorium-232 measurements yields the following calibration equation:

$$\text{RTRAK Th-232 pCi/g} = 0.05725481*Th_{NCPS} - 0.0044179*Ra_{NCPS} + 0.09624421$$

The radium term in this equation is negative to compensate for contributing non-thorium counts in the signal window. When both radium-226 and thorium-232 counts are zero, the equation has an intercept of 0.096 pCi/g, which is acceptably close to zero.

Radium-226 Calibration Equation

Low abundance gamma rays from thorium-232 daughters contribute counts to the background windows for radium-226. If this interference was ignored, the normal mode of background correction would overcompensate, thus yielding radium-226 results biased low. Multiple linear regression analysis involving thorium-232 and radium-226 net count rates versus HPGe radium-226 measurements yields the following calibration equation:

$$\text{RTRAK Ra-226 pCi/g} = 0.12145634*Ra_{NCPS} + 0.01735413*Th_{NCPS} + 0.13277316$$

The thorium term in the radium-226 equation is positive to compensate for the overcorrection of the background. When both radium-226 and thorium-232 counts are zero, the equation has an intercept of 0.13 pCi/g for radium-226, which is acceptably close to zero.

Uranium Calibration Equation

Two equations are provided for uranium, thereby allowing uranium to be calculated as either pCi/g of uranium-228 or as ppm of total uranium. The second equation is derived from the first by making use of known constants and weight to activity conversion factors, and further assuming that the uranium encountered in the soil will be of normal enrichment.

Uranium experiences interferences in both the signal window and the background windows. Thorium-232 daughter gamma rays at 969 keV contribute to the signal window, while radium-226 daughter gamma rays at 1120 keV contribute to the background window. Thus a term proportional to the thorium-232 activity must be subtracted from the counts in the signal window, while a term proportional to the radium-226 activity must be added back in to compensate for the overcorrection due to the elevated background counts. Multiple linear regression analysis involving uranium-238, thorium-232 and radium-226 net count rates versus HPGe Uranium-238 measurements yields the following equations:

$$\text{RTRAK U-238 pCi/g} = 0.95562898*U_{NCPS} - 0.4031465*Th_{NCPS} + 1.01951125*Ra_{NCPS} + 9.408$$

$$\text{RTRAK Total U ppm} = 2.86307076*U_{NCPS} - 1.20782959*Th_{NCPS} + 3.05446247*Ra_{NCPS} + 28.186$$

Figures 3-1 through 3-3 display the results of the multiple linear regression analyses for thorium-232, radium-226 and uranium-238 respectively. In each figure, HPGe results are plotted on the x-axis and the calculated RTRAK results based on the multiple linear regression calibration equation for the corresponding isotope are plotted on the y-axis. The calibration equation is displayed on each graph along with the square of the correlation coefficient for the multiple linear regression. Values of R^2 near one indicate the degree to which the equation represents the data. For all three isotopes, R^2 exceeds 0.95 which indicates excellent correlation. In addition to using R^2 as a gauge of the reasonableness of the calibration equation, the intercept is also important. This tells what the calibration equation would predict for the soil activity when all the net count rates in a given equation are zero. Ideally, this intercept should be zero. So, a calibration equation having an intercept near zero is another criterion that can be used to judge reasonableness. All three calibration equations satisfy this criterion also. The uranium calibration equations have the largest intercept of the three: 9.4 pCi/g or 28.2 ppm. While these values are not ideal, they will not effect the use of RTRAK in any practical way because they are approximately one third of the uranium FRL of 82 ppm, and are far below the WAC of 1030 ppm. In any event, the RTRAK will not be used to decide if a given area is below FRL.

If there were perfect agreement between the HPGe results and the RTRAK results based on the calibration equations, all the plotted points would fall on a straight line which had a slope of one. A solid line with a slope of one has been added to each graph (Figure 3-1 through 3-3). This line does not represent a best fit or regression line. It was added to help the reader judge the goodness of the calibration. One can see that while the data on each graph spans a fairly wide range, most of the data points fall near the "slope of one" line. On a percentage basis, the differences between HPGe and RTRAK results are no larger at high analyte concentrations than they are at low concentrations.

In order to assess the uncertainty associated with the new calibrations, one can look at the differences between the measured HPGe isotopic concentrations and the values calculated by use of the new RTRAK calibration equations. The absolute differences display variations from point to point, but the differences in pCi/g become successively larger from thorium-232 to radium-226 and then to uranium-238. This same trend holds true when evaluating the data on a percentage basis, using the HPGe results as the known values. For each isotope, there are instances where the RTRAK calibration yields larger results than the corresponding HPGe values, and other instances where the RTRAK equation predicts values lower than the HPGe measurement. To make an overall assessment of the

differences, the average percent difference between RTRAK and HPGe has been computed. This has been done for the three isotopes of concern. Whether the differences are positive or negative is immaterial; therefore, the averages of the absolute values of the percent differences were computed. For thorium-232, radium-226 and uranium-238 respectively, the percent differences are 9.0%, 14.8% and 23.8%. The RTRAK uranium-238 equation will not agree with HPGe results below 9.4 pCi/g, the intercept of the RTRAK equation; therefore, data points with HPGe readings below this value were omitted before computing the average absolute percent difference for uranium-238. The values for the average absolute percent differences stated above may be considered estimates for each isotope of the overall uncertainty associated with the calibration process. In agreement with material presented elsewhere in this report, it can be stated that thorium-232 measurements are most accurate, followed next by radium-226 measurements and then by uranium-238 measurements.

3.4 COMPARISON TO PREVIOUS RTRAK CALIBRATION EQUATIONS

In a radioanalytical laboratory, it is considered good practice to compare old and new calibrations to see if they agree with one another. If they are significantly different, the causes of the discrepancies should be investigated to assure that the new calibration is valid. This was done with the old and new RTRAK calibrations, and indeed, the new calibration equation for each isotope did closely resemble the old equation. It is possible to give plausible explanations for the differences that were noted. Some of these details are discussed below.

The new thorium calibration equation has an extra term which was not present in the old equation. This is a term which is proportional to the radium-226 net count rate. Correspondingly, the new radium calibration equation has an extra term involving the thorium-232 net count rate. One of the reasons for recalibrating the RTRAK system was to extend the calibration to higher analyte concentrations. In doing this, we entered a domain where interferences became more evident, and the analysis of the data revealed that it was necessary to include additional variables in order to accurately explain the variations in the data. Although the thorium and radium calibration equations have a slightly different form than the old equations, the reasons for the differences are understandable and plausible. The old and new uranium calibration equations have basically the same form, although the new equations are formulated in a different manner. That is, both sets of equations have four first order terms, and both require knowledge of the uranium, thorium and radium net count rates to predict the uranium-238 activity.

Even though, as noted above, the thorium and radium equations have terms which were not present in the old calibration equations, the magnitudes of most of the corresponding "best fit" coefficients are similar. For example, the slope of the old thorium calibration equation was 0.06817, and the corresponding coefficient in the new equation is 0.05825481. For the radium calibration equation, the new radium-226 coefficient of 0.12145634 corresponds to an old slope value of 0.19243. The largest changes in the "best fir" coefficients were noted for the intercept of the uranium calibration equation. The old intercept of 1.9 pCi/g uranium-238 changed to 9.4 pCi/g. But this is not surprising in light of the fact that eight additional data points were added to the calibration data set.

In summary, the new RTRAK calibration equations were compared to the old equations to provide some assurance of their validity. The new equations were similar in form to the old equation and the numerical values of constants did not change a great deal, in most cases. There were plausible explanations for the differences that were noted.

3.5 USE OF CALIBRATION EQUATIONS

In a traditional laboratory setting, the normal practice is to recalibrate gamma spectrometry systems either on a routine basis or when process control charts indicate that the system is out of control and cannot be brought back into control by making minor adjustments. Before using the new calibration, it is good practice to compare the old and new calibration equations to see if they agree with one another. If they are significantly different, the causes of the discrepancies should be investigated to assure that the new calibration is valid. After approving the new calibration, the laboratory discontinues use of the old calibration. Unless errors in the old calibration are discovered, the laboratory does not use the new calibration equation to recalculate results that were originally generated with the old equation.

An analogous situation exists with the RTRAK calibration equations. A new calibration was performed and compared to the previous one. As described in Section 3.4, the differences were investigated and found to be reasonable under the circumstances surrounding the new calibration. The new calibration equations were placed into service once the validity of the equations was confirmed.

As would typically be done with laboratory data, there are no plans to reprocess all previous RTRAK data using the new equations. However, as a part of an effort to refine the total uncertainty estimate, RTRAK raw data for the repeated profile measurements discussed in Section 4.0 of this report were

reprocessed using the revised equations and compared with the results obtained using the original equations. It was found that the standard deviations of the individual segments were smaller for the revised equations than for the original ones. This was especially pronounced for uranium-238. A closer review of the data revealed that the original equations resulted in a large number of negative concentrations, particularly for uranium-238 and radium-226. Use of the revised equations eliminated most of the negative concentrations which in turn reduced the range of concentrations seen within the segments. This improvement is attributed to the revised equations better correcting for interferences. The improvement was best for the uranium-238 because it is most severely affected by interferences. It was concluded that overall, the revised equations better represent the RTRAK response. Because the purpose of this report is to establish quality parameters to be used in the interpretation of future RTRAK data, all results have been generated using the revised calibration equations. Consequently, the evaluations of system precision, accuracy, total measurement uncertainty, spatial averaging and minimum detectable activity are all based on the revised equations.

3.6 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 multiple linear 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.

Figure 3-1
COMPARISON OF RTRAK & HPGE Th-232 RESULTS

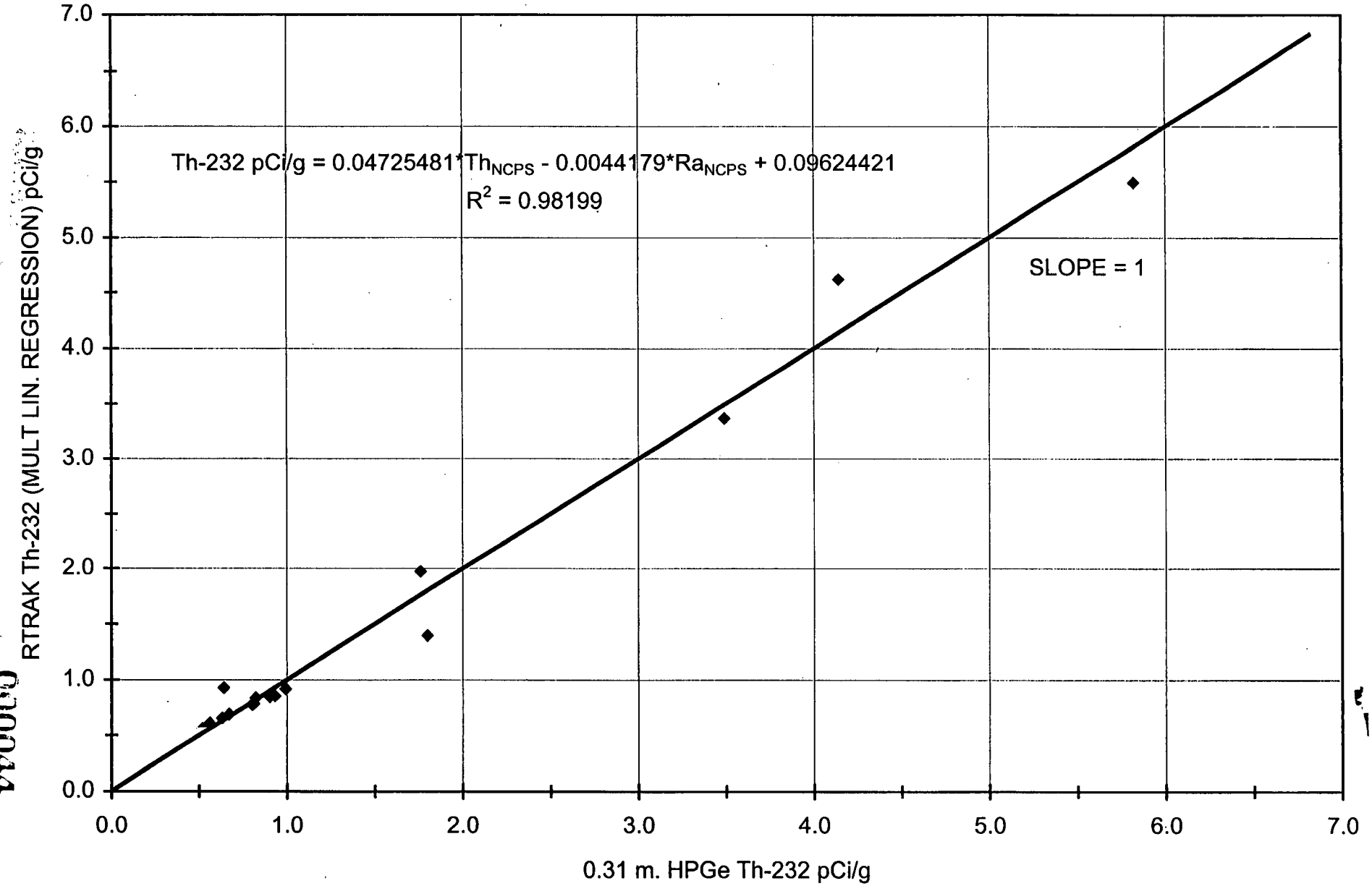


Figure 3-2
COMPARISON OF RTRAK & HPGe Ra-226 RESULTS

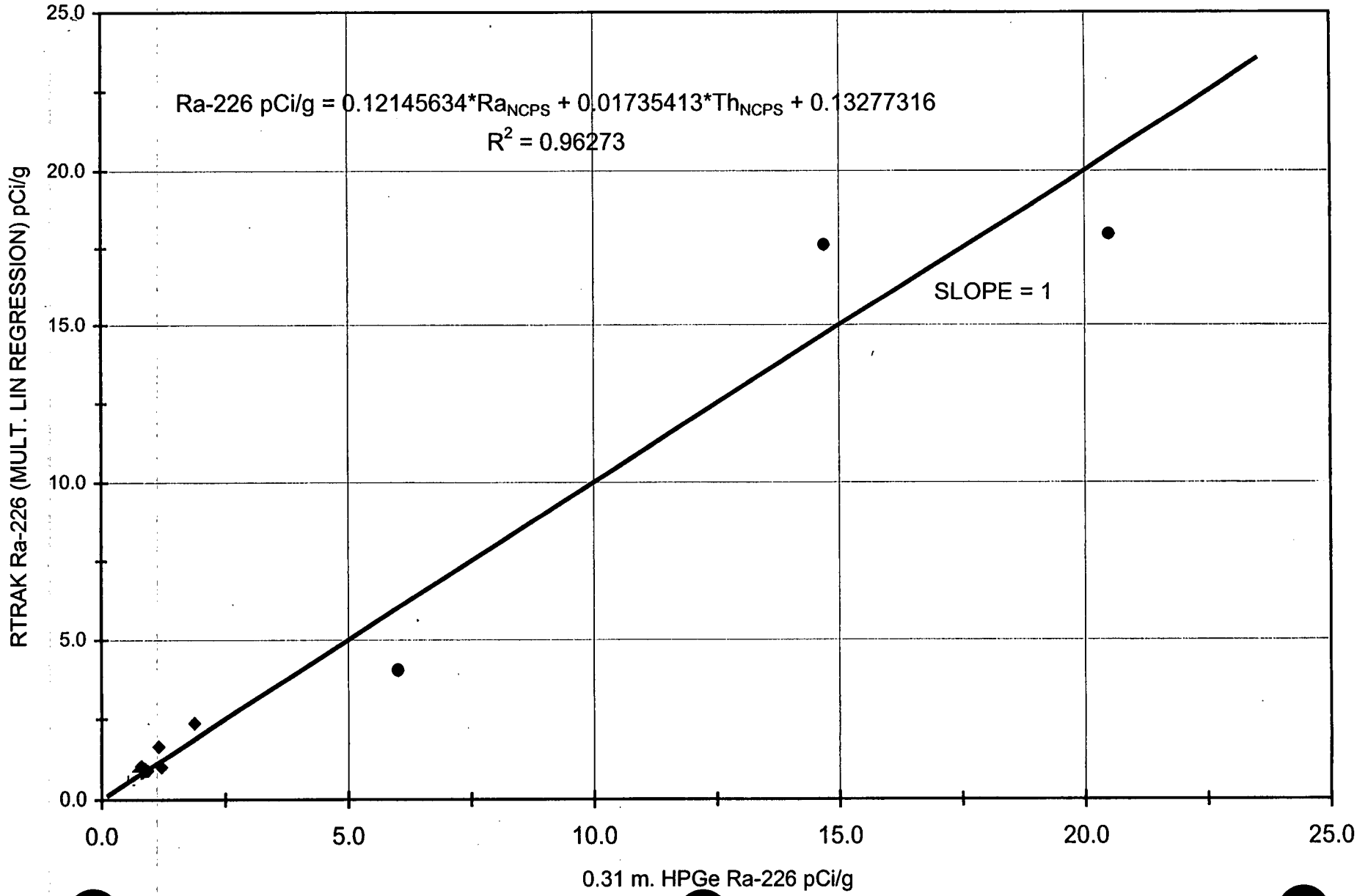


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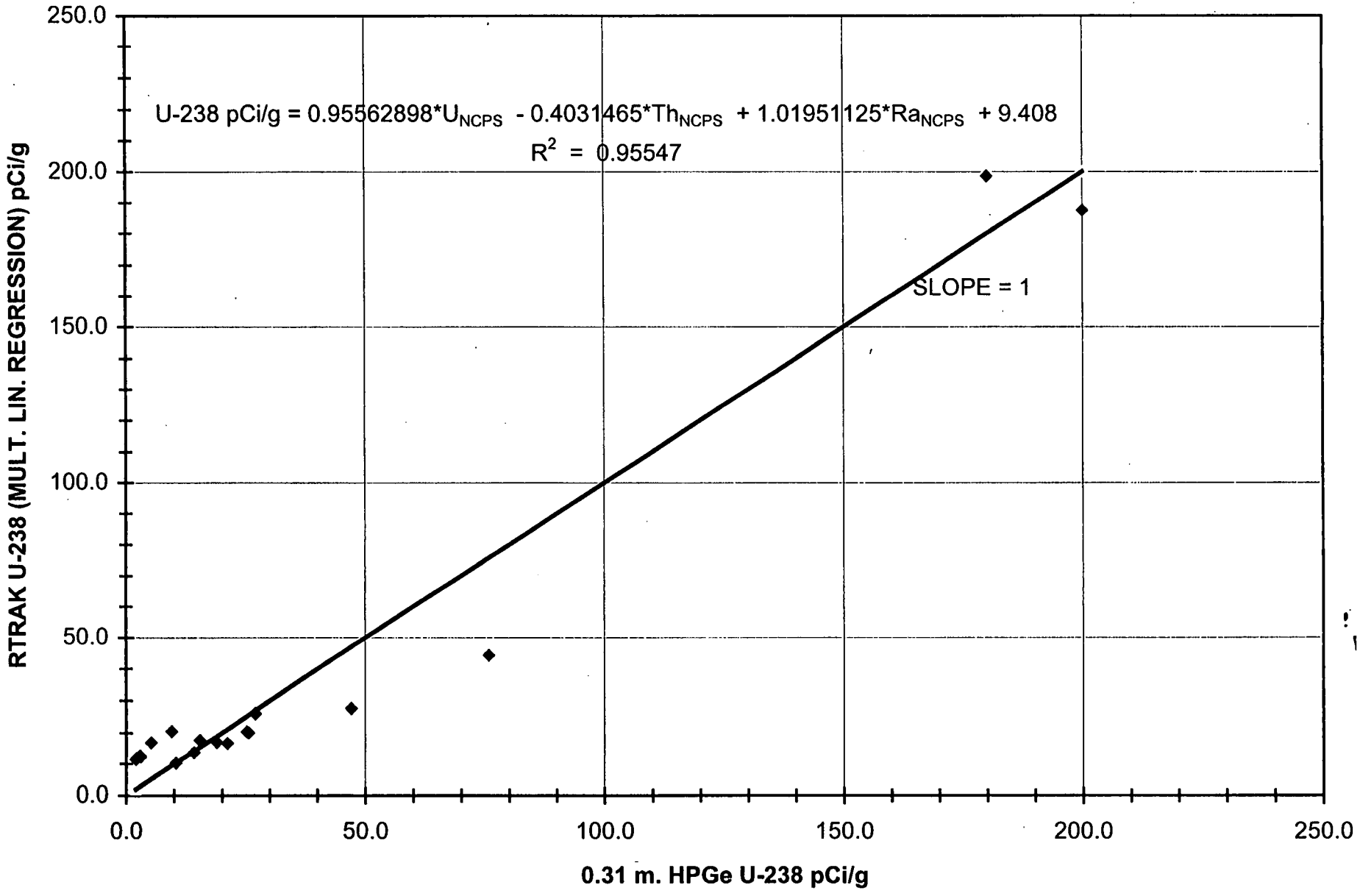
Figure 3-3
COMPARISON OF RTRAK & HPGe U-238 RESULTS



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. A series of measurements were made using the RTRAK in areas of differing analyte concentrations to obtain data which could be used to quantify these parameters. Different combinations of RTRAK travel speed and data acquisition time were evaluated in order to determine the analyte precision and MDCs for each combination. This information was used along with logistical considerations to determine the preferred operating parameters. 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 three profiles in three areas (one profile per area) and HPGe measurements made in those same areas. The results and their interpretations are discussed below.

4.1 SYSTEM PRECISION

4.1.1 Contributions to Precision

Precision may be defined as the closeness in agreement of replicate measurements. In most of the discussion that follows, precision is addressed in terms of uncertainty (expressed as a standard deviation): the higher the degree of uncertainty (larger the standard deviation), the poorer the precision. Evaluating the precision of the RTRAK measurements requires identifying sources of uncertainty, quantifying the individual sources, and calculating their combined effects. Potential sources of uncertainty include both systematic and random uncertainties.

The total uncertainty calculated for the RTRAK includes the contributions from both random and systematic sources. The preferred approach to handling systematic uncertainties is to identify and eliminate them from the process. Unfortunately, this is currently not practical for the RTRAK, so the approach taken for this study is to estimate systematic uncertainties and propagate them with random uncertainties using the relationship (ANSI N42.14-1991):

$$U^2 = \sigma^2_{random} + 1/3(\Sigma(\delta_{systematic})^2) \qquad (1)$$

where:

U = The total uncertainty of the measurement, including the sources of maximum estimated systematic uncertainties and random uncertainties.
σ_{random} = The standard deviations of random sources of uncertainty
$\delta_{systematic}$ = The estimated maximum systematic uncertainties

For techniques based on measuring radiation, there are two general categories of random uncertainties: (1) uncertainties associated with the nature of radioactive decay (typically called counting uncertainty) and (2) instrument and operational uncertainties. Systematic uncertainties identified relate to the calibration of the system and the agreement of measurements with laboratory analyses. The potential uncertainty sources are listed below. Analyte heterogeneity within the study areas is not included as an uncertainty source; the rationale behind this is discussed in Section 4.1.3. Each of the uncertainty terms is discussed in the report section identified in parentheses..

- Random Uncertainties
  - counting uncertainty (Section 4.1.5)
  - instrument/operational uncertainties (Section 4.1.5)
  - environmental effects (Section 4.1.6)

- Systematic Uncertainties (Section 4.1.7)
  - comparability between HPGe and laboratory data
  - regression uncertainty

Incorporating these into Equation 1, the total uncertainty for the RTRAK can be explicitly expressed as:

$$U = [\sigma^2_{Inst/Oper} + \sigma^2_{Counting} + \sigma^2_{Env} + 1/3(\delta^2_{Comparability} + \delta^2_{Regression})]^{1/2} \qquad (2)$$

where:

$\sigma_{counting}$ = counting uncertainty.
$\sigma_{Inst/Oper}$ = uncertainty associated with instrument and operational parameters.
σ_{Env} = uncertainty associated with variations in environmental conditions.
$\delta_{Comparability}$ = estimated systematic uncertainty associated with the agreement between laboratory data and *in-situ* measurements.
$\delta_{Regression}$ = estimated systematic uncertainty associated with the multiple regression analysis used to generate the calibration equations.

Section 4.1 addresses the approach taken to assess each of the contributors to the RTRAK uncertainty and combine them to provide an estimate of the total uncertainty assigned to measurements. A series of repeated profile measurements were made in three study locations. The purpose of these measurements was to obtain a measure of the short-term random contributors to the precision of the RTRAK

measurements which could be used to quantify specific contributors to the total measurement uncertainty. The counting uncertainty ($\sigma_{counting}$) and instrument/operational uncertainty ($\sigma_{Inst/Oper}$) are the principal contributors to the measured standard deviations of the repeated measurements. The counting uncertainty can be readily calculated from the results of the individual measurements. Analyte concentrations are obtained by inserting the net counts per second observed in the appropriate spectral regions of interest. The counting uncertainties are then derived by applying propagation of uncertainty relationships to this calculation. The calculated counting uncertainties and the measured standard deviations are used to calculate the instrument/operational uncertainties. The repeated profile measurements are described in Section 4.1.2 and an overview of the results is presented in Section 4.1.4. The details of the calculations of the counting uncertainties and the instrument/operational uncertainties are shown in Section 4.1.5.

The counting uncertainty and the instrument/operational uncertainty are short-term random effects. That is, they can result in differences between two measurements in the same location that are made within a very short time period. A longer term random uncertainty source (σ_{Env}), is the effect of variations in environmental conditions such as ambient temperature and humidity. Environmental variables were addressed in a study reported separately in, "Effect of Environmental Variables Upon *In-Situ* Gamma Spectrometry Data," Addendum 3, 20701-RP-0001, Revision A, December 1997. The variations in analyte measurements at a field quality control station determined in this study are used to estimate the uncertainty from environmental effects. The details of this are provided in Section 4.1.6.

The two systematic uncertainties identified for the RTRAK are associated with the comparability of *in-situ* measurements with laboratory measurements ($\delta_{Comparability}$) and the linear regressions used to derive the RTRAK calibration equations. The former is obtained from the results of HPGE comparability studies reported in "Comparability of *In-Situ* Gamma Spectrometry and Laboratory Data," 20701-RP-0001, Revision 1-Draft, December 1998. The regression uncertainty is derived from the regression statistics for the calibration equations. The calibrations are discussed in Section 3.0 and Appendix A. Section 4.1.7 provides details on estimating the comparability and regression systematic uncertainties.

The various uncertainty contributors are combined using Equation 2. This provides an estimate of the total uncertainty of the RTRAK measurements, incorporating those sources of uncertainty that have been identified to date. Section 4.1.8 explains how this is done and provides estimates of the total uncertainty for the RTRAK at various analyte concentrations. If future studies identify additional sources of uncertainty, they can be added to the estimates by modification of Equation 2. The total uncertainty estimates are used in subsequent sections to determine the minimum detectable concentrations and establish "trigger" levels to be used in the field evaluation of measurements.

4.1.2 Repeated Profile Measurements

The data from the repeated profile measurements (single tracks in the USID area and the DBA; an elliptical track in the South Field) were evaluated to provide an indication of the overall measurement precision of the RTRAK system. A segment within the USID area that crosses a gravel road was used to estimate RTRAK MDCs. 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 concentration, 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 entire USID area, but not for portions of the South Field or DBAs. The standard deviations for the set of data within each segment represent the precision associated with the individual measurements.

USID Area

The profile for the USID area is a straight-line path that traverses locations where activity concentrations are low but elevated above background and a gravel-covered road. The road was covered with gravel and other fill material after other portions of the area were contaminated, so it is considered near the background levels for FEMP soils. 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.

South Field Area

The 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 and DBAs because the elliptical path is longer than the straight-line path and because a high degree of variability was observed in the data. The use of larger segments was evaluated. A review of the individual measurements within those segments revealed that in many cases, one or more measurements were much 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 total measurements per segment). The segments selected for the South Field area are shown in Figures 4-2A and 4-2B. It can be seen by inspection of Figure 4-2B, that two of the segments (A-35 and A-36) along the profile path for the 1 mph/4 sec runs have only a few measurements. The 0.5 mph/8 sec runs also have only a few measurements in these segments. This results from many measurements having to be discarded due to GPS signal errors (see Appendix A). Trees and terrain in the South Field partially obstructed the satellite signal near segments A-35 and A-36 during the 0.5 mph/8-second runs. The 2 mph/2-second run was conducted at a time when the satellite position was favorable, so measurements were not affected by this problem. Therefore, the 2 mph/2sec run has a full complement of measurements. Data from segments A-35 and A-36 are not included in data tables or used in quantifying quality parameters.

Drum Baling Area

The profile for the DBA is also a straight-line path. This profile was divided into 10 segments. The locations of the profile segments were adjusted to exclude the portion of the path where the RTRAK was turned at the end of a pass. A total of 20 passes was made over the profile. The profile segments are shown schematically in Figures 2-4, 2-5, and 2-6.

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

1. Total activity (gross counts per second) in the spectrum with no energy differentiation;
2. Gross, background, and net counts in analyte regions of interest;

3. Activity concentrations for uranium-238, thorium-232, and radium-226; and
4. Uncertainty for the individual results, based on counting uncertainty.

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 individual measurement in the segment), average counting uncertainty, and the RTRAK minimum detectable concentration. The standard deviation of the distribution provides a measure of the precision for individual measurements within the area from short-term random sources of uncertainty. The precision of the individual measurements is an important consideration in evaluating the usability of RTRAK data in specific applications.

4.1.3 Heterogeneity

Although heterogeneity of the analytes in a study areas is important with regard to data interpretation, it is not included in this discussion as a contributor to the RTRAK measurement uncertainty. The effects of heterogeneity are analogous to the effects of non-representative sampling design on the results of a set of discrete samples collected from an area. Representative sampling is important when a limited number of samples is being used to represent the concentration of analytes throughout the entire area of interest. However, in practice, the RTRAK covers 100 percent of the area of interest, so there are no unmonitored locations that need to be represented by other measurements. While heterogeneity might make it difficult to exactly replicate each individual measurement obtained during a large area scan, the full set of measurements would be representative of the overall distribution of contamination. As is described in "User Guidelines, Measurement Strategies, and Operational Factors for Deployment of *In-Situ* Gamma Spectrometry at the Fernald Site," 20701-RP-0006, Revision A, the RTRAK is being used as a screening instrument to provide full coverage of a study area, and the results of single measurements will not be used alone. The result of a single measurement may indicate the possible presence of a hot spot or a WAC exceedance, but HPGe measurements will then be made to confirm the activity concentration and to delineate the area of exceedance. Consequently, it is not necessary to be able to precisely replicate either the activity concentration or location of any single measurement.

4.1.4 Overview of Repeated Profile Data

4.1.4.1 Uranium-238

The uranium-238 measurements display the lowest degree of precision of the three radionuclides of interest. This limits the usability of the data for low-concentration measurements. The low degree of

precision (high uncertainty) occurs because of the low photon yield at the energy of interest, the high spectrum background, and from thorium-232 and radium-226 interferences. Uranium-238 is quantified using the 1001 keV gamma ray from its decay product protactinium-234m which has as gamma photon yield of 0.0085 gamma rays for each disintegration. By contrast, the gamma rays used to quantify radium and thorium have gamma yields of about 0.16 and 0.35 gamma rays per disintegration, respectively. That means that for equal activity concentrations, uranium-238 will exhibit far fewer gamma rays of interest than either radium-226 or thorium-232. The uranium-238 region of interest (943.1 - 1058.9 keV) is at the lowest energy region of interest of the three radionuclides, and at that low energy, the spectrum background under the uranium-238 peak is relatively high because of the high Compton continuum resulting from the presence of higher energy gamma rays. The presence of thorium-232 and radium-226 result in interferences because of the detector's inability to resolve gamma rays with energies near the uranium-238 region of interest. These gamma rays increase the apparent background under the uranium-238 peak. In areas where the concentrations of all analytes of interest are low, the fractional uncertainty is dominated by the Compton continuum. In locations where thorium-232 or radium-226 concentrations are high, they can dominate the uncertainty and in some cases make quantification of the uranium-238 impractical. The effects of interferences are discussed further in Section 5.1.

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 repeated profile measurements for the study areas are presented in Appendix B. The data can be found in Table B-1, and in Figures B-1 through B-3 for the USID Area, Table B-2 and Figures B-4 through B-6 for the South Field, and Table B-3 and Figures B-7 through B-9 for the DBA. The data in Tables B-1 through B-3 are presented as a function of RTRAK operating speed and data acquisition time and are summarized in Table 4-1.

It can be seen by inspection of the tables and the figures cited above that the mean uranium-238 concentrations of the profile segments are in good agreement across the various combinations of operating parameters for each study area. The segment means all agree within one standard deviation. Within each study area though, the uranium-238 concentrations vary between individual segments along the profiles. The overall average uranium-238 concentrations for the USID area and the South Field are similar, both near 15 pCi/g. Within the USID area, the segment means range between about 15 and 18 pCi/g, excluding the road, for the 8 sec/0.5 mph measurements. However, the segment

means vary more over the South Field with a range of between about 9 and 30 pCi/g for the 8 sec/0.5 mph measurements. The uranium-238 concentrations in the DBA are higher than the other two areas, averaging about 93 pCi/g. The variability across the DBA is high ranging between about 45 and 177 pCi/g for the 8 sec/0.5 mph measurements.

The standard deviations for the USID area and the South Field are similar, typically near 5 pCi/g or about 30% of the mean activity for the 8 sec/0.5 mph measurements. For the DBA, the average standard deviation is about 26 pCi/g or about 30% of the mean for the same operating conditions. The fact that the percent standard deviations are nearly identical might be interpreted as meaning that the variability of the uranium-238 contamination within the three areas is similar. However, as is discussed in Section 4.1.5, the counting uncertainty is a large contributor to the uncertainty of each individual measurement and will consequently contribute to the standard deviation of the measurements within a segment. As the activity increases, the percent counting uncertainty would decrease, as would the segment standard deviation, if there were not a comparable increase in another source of uncertainty, so the data clearly show that an additional source is present. The primary additional uncertainty source is believed to be analyte heterogeneity. These measurements are consistent with general knowledge of the contamination pattern in these areas; heterogeneity is expected to be the least for the USID area and the greatest for the DBA. As discussed above, while the heterogeneity does affect the observed standard deviation of repeated profile measurements, it is not a component of the uncertainty of an individual measurement

In all three study areas the 8 second/0.5 mph measurements have the lowest standard deviations of the various combinations of operating parameters. This is a direct consequence of the longer data acquisition time. For a single measurement, the standard deviation related to counting uncertainty 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. This is consistent with the relationship seen between the measured segment standard deviations and the acquisition times. Counting uncertainty is discussed in more detail in Section 4.1.5.

4.1.4.2 Thorium-232

The thorium-232 measurements display the highest degree of precision of the three radionuclides of interest. The high degree of precision (small uncertainty) occurs because of a relatively high photon

yield at the energy of interest, the low spectrum background, and because of only limited interference from a low intensity radium-226 peak. Thorium-232 is quantified using the 2615 keV gamma ray from its decay product thallium-208, which results in a gamma photon yield of 0.35 gamma rays for each thorium-232 disintegration. By contrast, the gamma rays used to quantify radium and uranium have gamma yields of about 0.16 and 0.0085 gamma rays per disintegration, respectively. That means that for equal activity concentrations, thorium-232 will generate more gamma rays of interest than either radium-226 or uranium-238. The thorium-232 region of interest (2405.4 - 2823.8 keV) is the highest energy region of interest of the three radionuclides, and at that high energy, the spectrum background under the thorium-232 peak is relatively low because there are few gamma rays of higher energy to contribute to the Compton continuum. The presence of radium-226 in high concentrations could result in interferences because of the detector's inability to resolve gamma rays with energies near the thorium-232 region of interest. These gamma rays would increase the apparent background under the thorium-232 peak. However, the radium-226 concentrations in the study areas are low enough that interferences with the thorium-232 peaks are minor. The effects of interferences are discussed further in Section 5.1.

The thorium-232 means, standard deviations, and percent standard deviations (standard deviation as a percentage of the mean) for each of the segments in the repeated profile measurements for the study areas are presented in Appendix B. The data can be found in Table B-4, and in Figures B-10 through B-12 for the USID Area, Table B-5 and Figures B-13 through B-15 for the South Field, and Table B-6 and Figures B-16 through B-18 for the DBA. The data in Tables B-4 through B-6 are presented as a function of RTRAK operating speed and data acquisition time and are summarized in Table 4-2.

It can be seen by inspection of the tables and the figures cited above that the mean thorium-232 concentrations of the profile segments are in good agreement across the various combinations of operating parameters for each study area. The segment means all agree within one standard deviation. Within each study area, though, the thorium-232 concentrations vary between individual segments along the profiles. The overall average thorium-232 concentrations for the USID area and the South Field are similar, both near 0.8 pCi/g. Within the USID area, the segment means range between about 0.7 and 0.8 pCi/g, excluding the road, for the 8 sec/0.5 mph measurements. However, the segment means vary more for the South Field with a range of between about 0.5 and 3 pCi/g for the 8 sec/0.5 mph measurements. The thorium-232 concentrations in the DBA are higher than the other

two areas, averaging about 3 pCi/g. The variability across the DBA is also high, ranging between about 1.8 and 6.8 pCi/g for the 8 sec/0.5 mph measurements.

The standard deviations for the USID area and the South Field are similar, typically less than 0.2 pCi/g or about 20% of the mean activity for the 8 sec/0.5 mph measurements. For the DBA, the average standard deviation for the same operating conditions is about 0.6 pCi/g or about 20% of the mean. The fact that the percent standard deviations are nearly identical might be interpreted as meaning that the variability of the thorium-232 contamination within the three areas is similar. However, the counting uncertainty is a large contributor to the uncertainty of each individual measurement and will consequently contribute to the standard deviation of the measurements within a segment. As the activity increases, the percent counting uncertainty would decrease, as would the segment standard deviation, if there were not a comparable increase in another source of uncertainty. These measurements are consistent with general knowledge of the contamination pattern in these areas; heterogeneity is expected to be the least for the USID area and the greatest for the DBA.

As was seen for the uranium-238 measurements, in all three study areas the 8 second/0.5 mph measurements have the lowest standard deviations of the various combinations of operating parameters. This is a direct consequence of the longer data acquisition time. For a single measurement, the standard deviation related to counting uncertainty 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. This is consistent with the relationship seen between the measured segment standard deviations and the acquisition times. Counting uncertainty is discussed in more detail in Section 4.1.5.

4.1.4.3 Radium-226

The radium-226 measurements display a degree of precision between that of the other two radionuclides of interest. This is in part because both the photon yield and the detection efficiency at the energy of interest fall between those of the thorium and uranium. Radium-226 is quantified using the 1765 keV gamma ray from its decay product bismuth-214, which results in a gamma photon yield of 0.16 gamma rays for each radium-226 disintegration. By contrast, the gamma rays used to quantify uranium and thorium have gamma yields of about 0.0085 and 0.35 gamma rays per disintegration, respectively. That means that for equal activity concentrations, radium-226 will generate fewer gamma rays of interest than thorium-232 but more than uranium-238. Similarly, the differences in detection

efficiencies mean that a lower higher percentage of uranium-238 gamma rays and a lower percentage of thorium-232 gamma rays are detected than are the radium-226 gamma rays. This results in a larger number of net counts in the4 region of interest and consequently a lower counting uncertainty.

Another factor influencing the uncertainty is that the radium-226 region of interest (1699.3 - 1850.9 keV) is between the regions of interest of uranium-238 and thorium-232. At that energy, the spectrum background under the radium-226 peak is lower than for the uranium-238 region because there are fewer gamma rays at higher energies to contribute to the Compton continuum. However, the Compton continuum is higher than for the thorium region of interest. The Compton continuum is a large portion of the spectrum background, so the uncertainty of the net counts in the region of interest is a function of the continuum's magnitude. In addition, the radium-226 peak has more severe interference than the thorium-232 region but less than the uranium-238 region. Thorium-232 interferes with the radium-226 region of interest, although the interference is not as severe as those that effect uranium-238. Interfering gamma rays increase the apparent background under a peak, which contributes to the uncertainty. The effects of interferences are discussed further in Section 5.1.

The radium-226 means, standard deviations, and percent standard deviations (standard deviation as a percentage of the mean) for each of the segments in the repeated profile measurements for the study areas are presented in Appendix B. The data can be found in Table B-7, and in Figures B-19 through B-21 for the USID Area, Table B-8 and Figures B-22 through B-24 for the South Field, and Table B-9 and Figures B-25 through B-27 for the DBA. The data in Tables B-7 through B-9 are presented as a function of RTRAK operating speed and data acquisition time and are summarized in Table 4-3.

It can be seen by inspection of the tables and the figures cited above that the mean radium-226 concentrations of the profile segments are in good agreement across the various combinations of operating parameters for each study area. The segment means all agree within one standard deviation. Within each study area though, the radium-226 concentrations vary between individual segments along the profiles. The mean segment radium-226 concentrations are lowest for the USID area, ranging between about 0.7 and 0.9 pCi/g with an overall mean for the area of about 0.8 pCi/g. In the South Field, mean radium-226 concentrations of many of the segments are similar to those in the USID area, but there are others with much higher concentrations, ranging between about 0.7 and 4.5 pCi/g with an

overall area mean near 1.2 pCi/g. The average segment concentrations in the DBA are much higher, averaging about 6.4 pCi/g and ranging between about 2.6 and 11.8 pCi/g.

The average of the segment standard deviations for the USID area is 0.26 pCi/g or 32% of the mean activity for the 8 sec/0.5 mph measurements. For the South field, the average of the segment standard deviations is 0.30 pCi/g or 27% of the mean activity for the 8 sec/0.5 mph measurements. In the DBA, the average standard deviation for the 8 sec/0.5 mph measurements is about 1.6 pCi/g or about 25% of the mean. The fact that the percent standard deviations are slightly lower for the South Field and the DBA are nearly identical might be interpreted as meaning that the variability of the radium-226 contamination in these areas is less than in the USID area. However, the counting uncertainty is a large contributor to the uncertainty of each individual measurement and will consequently contribute to the standard deviation of the measurements within a segment. As the activity increases, the percent counting uncertainty would decrease, as would the segment standard deviation, if there were not a comparable increase in another source of uncertainty, such as heterogeneity. These measurements are consistent with general knowledge of the contamination pattern in these areas; heterogeneity is expected to be the least for the USID area and the greatest for the DBA.

As was seen for the uranium-238 and the thorium-232 measurements, in all three study areas the 8 sec/0.5 mph measurements have the lowest standard deviations of the various combinations of operating parameters. This is a direct consequence of the longer data acquisition time. For a single measurement, the standard deviation related to counting uncertainty 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. This is consistent with the relationship seen between the measured segment standard deviations and the acquisition times. Counting uncertainty is discussed in more detail in Section 4.1.5.

4.1.4.4 Total Activity

Total activity (gross counts per second) results are obtained from the RTRAK by simply summing all of the counts seen in the RTRAK gamma spectrum and dividing by the data acquisition time. 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 an 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.

The means, standard deviations, and percent standard deviations for the total activity data are presented in Appendix B in Table B-10 and Figures B-28 through B-30 for the USID Area, in Table B-11 and Figures B-31 through B-33 for the South Field, and in Table B-12 and Figures B-34 through B-36 for the DBA. The data in Tables B-10 through B-12 are presented as a function of RTRAK operating speed and data acquisition time and are summarized in Table 4-4.

The total activity measurements show 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 fractional counting uncertainty. For the isotopic measurements, the counting uncertainties are all high at low concentrations. As an example, the lowest average percent standard deviation for the isotopic data is for thorium in the USID and DBAs, at approximately 20% for an 8 second measurement. However, for total activity, 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. In the DBA, the percent standard deviations average about 14%. The higher standard deviation in the DBA is probably a consequence of greater analyte heterogeneity. The standard deviations for the individual measurements are also comparable for the three combinations of speed/time in all three areas. This occurs despite the fact that the acquisition times range over a factor of four. It would generally be expected that the measurements with the longer acquisition times would consistently have smaller standard deviations because, as explained previously, the counting uncertainty is proportional to the square root of the acquisition time. Consequently, when acquisition times differ by a factor of four, the uncertainties should differ by a factor of two. 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 total activity 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 fractional 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.

The average gross counts per second for the segment means across the full DBA profile are more than a factor of 5 larger than those for the other study areas. This is consistent with the higher concentrations observed for the uranium-238, thorium-232, and radium-226. The average segment means are 15666, 15796, and 15703 cps, respectively, for 2, 4, and 8 sec acquisition times. Four of the individual segments have total activity which are approximately a factor of two higher than the others: DB-A01, DB-A02, DB-A04, and DB-A05. These are the same segments that have elevated concentrations of uranium-238 and radium-226. The segment with the lowest total activity is DB-A07; this segment has the lowest concentrations of uranium-238 and thorium-232 and a lower than average radium-226 concentration. The total activity results are consistent with the analyte-specific data previously discussed in this report.

For the total activity, 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 total activity measurements can be useable to provide general indications of elevated activity. Because total activity measurements provide no radionuclide-specific information their use is limited to general radiological screening.

4.1.5 Short-term Random Uncertainties

As noted in Sections 4.1.4.1 through 4.1.4.3, both the USID area and the South Field have moderately uniform distributions of contamination for uranium-238, thorium-232, and radium-226. while the DBA is much more heterogeneous. The average measured standard deviations for the repeated profile measurements in the USID area and South Field are being used to represent the short-term random uncertainty associated with the RTRAK for subsequent calculations to estimate the overall uncertainty of the RTRAK measurements. These average standard deviations are presented in Tables 4-5 through 4-7.

Sources which contribute to the measured standard deviations of the profile measurements are counting uncertainties, the heterogeneity of contamination within the study areas, and miscellaneous random uncertainties associated with the RTRAK instrumentation and operation. The counting uncertainty will vary with the activity concentration within an area, as will analyte heterogeneity. The instrument/operational uncertainty can be expected to be relatively constant for all measurements and it can be obtained from the profile standard deviations. In doing so, it would be preferable to accurately determine the contributions from analyte heterogeneity to the measured standard deviations. However, this would require the collection and analysis of a large number of discrete samples and it was concluded that this was not warranted. Instead, the data are being treated as if there are no contributions from the heterogeneity and the measured standard deviations are a result of counting uncertainties and instrument/operational uncertainties. With this simplification, the measured standard deviations can be represented by the relationship:

$$\sigma_{measured} = \sqrt{\sigma^2_{counting} + \sigma^2_{instoper}} \qquad (3)$$

where:

$\sigma_{measured}$ = the average measured standard deviation calculated by averaging the standard deviations for the individual segments of the repeated profile measurements

$\sigma_{counting}$ = the average counting uncertainty for the individual profile measurements

$\sigma_{inst/oper}$ = the uncertainty contribution associated with the RTRAK instruments and operational parameters

The counting uncertainty can be easily calculated from the gross counts and background counts determined for each region of interest. The counting uncertainty for either the gross counts or the background counts in a region of interest can be represented by the relationship:

$$\sigma = \sqrt{N} \qquad (4)$$

where:

σ = the uncertainty associated with the number of counts
N = the number of gross or background counts in a region of interest

The net number of counts, which is directly related to the activity concentration, is obtained by simply subtracting the background counts from the gross counts. The uncertainty of the net counts is given by the relationship:

$$\sigma_{net} = \sqrt{\sigma_{gross}^2 + \sigma_{back}^2} \qquad (5)$$

where:

σ_{net} = the uncertainty associated with the number of net counts
σ_{gross} = the uncertainty associated with the number of gross counts
σ_{back} = the uncertainty associated with the number of background counts

Typically, the counting uncertainty is calculated using Equations 4 and 5. However, for the RTRAK system, the calibration equations take into account interferences from gammas emitted by other radionuclides. Consequently, the counting uncertainties are calculated by applying standard propagation of uncertainty relationships and Equations 4 and 5 to the calibration equations defined in Section 3.0 and Appendix A. The counting uncertainty for the three nuclides of interest are given by the following relationships:

$$\sigma_U = \frac{\sqrt{0.956^2(N_{Ugross}+N_{Uback})+0.403^2(N_{Thgross}+N_{Thback})+1.019^2(N_{Ragross}+N_{Raback})}}{t^2} \quad (6)$$

$$\sigma_{Th} = \frac{\sqrt{0.0474^2(N_{Thgross}+N_{Thback})+0.004^2(N_{Ragross}+N_{Raback})}}{t^2} \quad (7)$$

$$\sigma_{Ra} = \frac{\sqrt{0.121456^2(N_{Ragross}+N_{Raback})+0.01735^2(N_{Thgross}+N_{Thback})}}{t^2} \quad (8)$$

where:

σ_U	=	the counting uncertainty of the uranium-238 concentration in pCi/g
N_{Ugross}	=	the number of gross counts in the uranium-238 region of interest
N_{Uback}	=	the number of background counts in the uranium-238 region of interest
σ_{Th}	=	the counting uncertainty of the thorium-232 concentration in pCi/g
$N_{Thgross}$	=	the number of gross counts in the thorium-232 region of interest
N_{Thback}	=	the number of background counts in the thorium-232 region of interest
σ_{Ra}	=	the counting uncertainty of the radium-226 concentration in pCi/g
$N_{Ragross}$	=	the number of gross counts in the radium-226 region of interest
N_{Raback}	=	the number of background counts in the radium-226 region of interest

The numerical coefficients in these equations are the coefficients for the corresponding terms from the linear regressions used to derive the calibration equations (see Section 3.0 and Appendix A). Equivalent equations for the counting uncertainty of the RSS measurements can be derived using the calibration equations presented in Appendix C.

The counting uncertainties for the individual repeated profile measurements were calculated using Equations 6 through 8. These were averaged over the entire profile to obtain an overall average counting uncertainty. These values and the measured standard deviations for the segments were then inserted into Equation 3 which was rearranged to solve for the instrument/operational uncertainty. The

instrument/operational uncertainties for each acquisition time were used to calculate a nominal average which was used for all general estimates of precision-related quality parameters such as minimum detectable concentration and trigger levels. The nominal average is simply the calculated average rounded to one figure for uranium-238 and two figures for thorium-232 and radium-226. Tables 4-5 through 4-7 summarize these calculations.

4.1.6 Environmental Effects

The uncertainties discussed in the previous section are a consequence of short-term factors that can change rapidly and are likely to affect the precision of a number of measurements made over a short time period such as a few hours. Environmental effects involve long-term changes that would be likely to affect the precision of measurements collected over a long time period such as days or weeks. Environmental variables that might affect measurements include weather conditions such as ambient temperature, humidity, precipitation, winds, and soil moisture content. The magnitude of these effects can be estimated by making a series of measurements in one location over an extended period of time. Such measurements have been made at a field quality control station using HPGe systems. The results of these studies are reported in "Comparability of *In-Situ* Gamma Spectrometry and Laboratory Data," 20701-RP-0001, Revision 1, December 1998. The measurements reported in that document were used to establish control charts with statistically based limits that represent the effect of the environmental variables on the long-term precision of *in-situ* measurements. Because both the RTRAK and HPGe systems are based on the detection of gamma rays, these studies are applicable to both systems. The percent standard deviations for the nuclide-specific data from the field quality control stations are considered to represent the contributions of the environmental effects to the overall uncertainty of the measurement. The uncertainties are calculated by applying the percentages to the measured values. The percentage uncertainties are shown in Table 4-8.

4.1.7 Systematic Uncertainties

Systematic uncertainties are sources of uncertainty that cannot assessed by statistical techniques. These may be sources of bias such as calibration errors or uncertainties that are random in nature but still cannot be assessed statistically. The preferred approach to handling systematic uncertainties is to evaluate and eliminate them. However, this is not practical when the causes of the systematic uncertainties cannot be readily defined, they comprise contributions from multiple sources, they result from sources that cannot be readily controlled, or the sign and magnitude cannot be accurately

determined. In such cases, it is appropriate to estimate the effects of the systematic uncertainties and propagate them with the random uncertainties.

Two systematic uncertainties have been identified for the RTRAK, both of which are related to the calibration of the system. The RTRAK is calibrated against HPGe measurements. The HPGe calibration is based on a combination of detector calibrations using point-geometry radionuclide sources and mathematical modeling. The HPGe calibration was validated by demonstrating comparability with laboratory analysis of discrete samples. This was documented in, "Comparability of *In-Situ* Gamma Spectrometry and Laboratory Data, 20701-RP-0001," Revision 1, December 1998. The degree of agreement between the HPGe measurements and the laboratory data was used to define an uncertainty contribution related to the comparability of *in-situ* and laboratory analyses. This factor is intended to account for the fundamental differences between *in-situ* techniques and the analysis of discrete samples. The contributions to the uncertainty are calculated by multiplying the measured analyte concentration by the relative percent differences (RPD) for HPGe vs. laboratory analyses, as reported in the referenced documents. The RPDs are 11% for uranium-238, 6.7% for thorium-232, and 15% for radium-226. This uncertainty source is called the comparability uncertainty and is denoted by the symbol, $\delta_{Comparability}$. The Greek letter delta is often used to distinguish systematic uncertainties from random uncertainties which are denoted by the Greek letter sigma, σ.

The RTRAK calibration was based on a series of measurements made using both the RTRAK and the HPGe in a series of locations where the analyte concentrations covered a wide range. The calibration equations were derived by performing multiple linear regressions on the results of the measurements. The RTRAK calibration is discussed in detail in Section 3.0. The uncertainty for the regression was calculated by multiplying the measured analyte concentration by the average percent residuals for each analyte. For thorium-232 and radium-226, the percentages were based on the average of residuals over the full calibration range. The uranium-238 calibration has a high intercept, so the residuals were averaged over only those concentrations exceeding the intercept concentration. The average residuals are 24% for uranium-238, 9% for thorium-232, and 15% for radium-226. This contribution is called the regression uncertainty and is denoted by the symbol, $\delta_{Regression}$.

4.1.8 Total Uncertainty of RTRAK Measurements

The final step in assessing the precision of the RTRAK measurements is to calculate the total uncertainties. The total uncertainty is important because it provides the basis for establishing confidence intervals, determining how data are to be displayed, determining when and in what manner data should be combined, and defining detection limits. To summarize the previous discussions, the total uncertainty for the RTRAK comprises three random and two systematic sources of uncertainty:

- Random Uncertainties
  - counting uncertainty
  - instrument/operational uncertainties
  - environmental effects
- Systematic Uncertainties
  - comparability between HPGe and laboratory data
  - regression uncertainty

As was noted previously, it is not practical to remove or accurately define the magnitude or sign of systematic uncertainties, so they are being propagated with the random uncertainties to provide an overall estimate of the uncertainty of the RTRAK measurements. This is done using Equation 2 which, for convenience, is repeated below:

$$U = [\sigma^2_{Inst/Oper} + \sigma^2_{Counting} + \sigma^2_{Env} + 1/3(\delta^2_{Comparability} + \delta^2_{Regression})]^{1/2} \qquad (2)$$

The total uncertainty can be calculated by inserting the appropriate terms in Equation 2. There will be a unique uncertainty for each individual measurement because each term, with the exception of the instrument/operational uncertainty, will vary depending upon the activities of the analytes present within the field of view and factors such as the spectrum background and interferences. In practice, this means that it is not possible to make a highly accurate *a priori* determination of the total uncertainty for an analyte at a given concentration. The exact total uncertainty can only be determined *a posteriori*. However, for the purposes of planning and assessing the applicability of the RTRAK, it is possible to estimate the expected uncertainty by making assumptions of the concentrations at which other interfering analytes are present. Whether the determinations are *a posteriori* determinations or *a priori* estimates, the calculations are handled in the same manner. The counting uncertainties are calculated from the gross peak and gross background counts for the measurement using Equations 6, 7, and 8. The instrument/operational uncertainties are dependent upon the acquisition time and the analyte of interest and can be obtained from Tables 4-5 through 4-7. The terms associated with

environmental effects and the calibration-related comparability and regression uncertainties are expressed as percentages of the measured concentrations; these are found in Table 4-8.

Total uncertainties were estimated for analyte concentrations near action limits of interest at the FEMP. These include the FRLs, hot spot criteria, and the uranium-238 waste acceptance criteria (WAC). These were calculated for 2, 4, and 8 sec acquisition periods. For uranium-238, values are provided for FRLs equal to 10, 20, 50 and 82 ppm to cover the FRLs for all remediation areas. The results are presented in Tables 4-9 through 4-11, along with the magnitudes of the uncertainty contributors. The estimates were based on the following assumptions:

1. The spectrum backgrounds that are unrelated to interfering gamma rays are constant and equal to the spectrum backgrounds measured in the USID area.

2. Instrument-related uncertainties were obtained from the repeated profile measurements described in this report.

3. The concentrations of analytes having gamma rays which interfere with other analytes (e.g., thorium-232 and radium-226 gamma rays interfering with uranium-238) or contribute to their background are equal in concentration to their corresponding FRLs.

4.1.9 Summary

The Studies discussed in this section provide the data necerssary to characterize the quality parameters of the RTRAK system. The repeated profile studies can be used along with an evaluation of other sourtces of uncertainty to estimate the total uncertainty of RTRAK measurements. For the three analytes of interest, uranium-238, thorium-232, and radium-226, the counting uncertainty associated with the spectrum backgrounds are major contributors to the total uncertainty. Other uncertainty sources that have been identified are the random uncertainties associated with instrument/operational variations and environmental effects and two systematic sources associated with the derivation of the calibration equations, comparability and regression uncertainties.

The identified sources of uncertainty can be combined using conventional techniques for the propagation of uncertainty to determine the total uncertainty for any measurement. By making assumptions concerning the concentrations of interfering analytes, the total uncertainties for the three analytes of interest were calculated for selected concentrations. The results of these calculations, presented in Tables 4-9 through 4-11 demonstrate that the relative uncertainty of individual RTRAK

measurements is large at low analyte concentrations. This limits the applicability of the RTRAK at concentrations near background. However, at higher concentrations, such as hot spot criteria or WAC, the relative uncertainty decreases and the measurements are adequate to support such activities as excavation control and precertification.

4.2 SPATIAL AVERAGING AND AGGREGATION

The uncertainty of individual RTRAK measurements is large enough to limit the value of the data at analyte concentrations near background. For some applications, it may be desirable to appreciably reduce the uncertainty. As was discussed in Section 4.1, one way to reduce the uncertainty is to increase the acquisition time. This would result in a decrease of the counting uncertainty equivalent to the square root of the increase in time and a consequent decrease of the total uncertainty. However, operational and logistical considerations limit the practicality of increasing the acquisition time and the desired uncertainty may not be achievable. Another means of reducing the effect of the measurement standard deviation is to spatially average or aggregate 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 number of measurements averaged or aggregated, the greater the "smoothing" effect will be. Aggregating measurements is comparable to increasing the acquisition time, because in both cases, the total number of photons detected over the acquisition period increases. Thus, increasing the number of measurements averaged reduces the uncertainty associated with a measured analyte concentration, but it also reduces the spatial resolution of the measurements by averaging the data over that 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 intended use of RTRAK data. For example, assume that the objective is to collect data during pre-certification to determine whether a certification unit is likely to pass or fail the actual certification process. In this scenario, it may be acceptable to use 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. On the other hand, if the objective is to locate hot spots or WAC exceedances, such large-area spatial averaging would be inappropriate.

The standard deviation of the mean of an aggregated 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 cases of data collected with either a 2 second acquisition time at a 2 mph travel speed or with a 4 second acquisition time at 1 mph, the viewing window of the RTRAK will be approximately 8.8 m^2 (94.7 ft^2). Because the viewing window extends beyond the physical footprint of the RTRAK, sequential RTRAK measurements overlap and the averaging area is smaller than would be estimated by simply multiplying the area of a single measurement by the number of measurements aggregated. The aggregated area is a function of the travel speed, acquisition time, and, for multiple passes, the overlap between passes. In the case of data collected at 4 mph with a 1 second acquisition time, averaging 25 sequential measurements results in an aggregate field of view of about 112 m^2, which is approximately 13 times as great as the read area for an individual measurement. If the twenty five measurements are clustered, such as would occur for five sequential measurements in each of 5 passes, the aggregate field of view would be slightly larger, at about 115 m^2. For comparison, the field of view of the HPGe is approximately 113 m^2 at a height of 1 m and 19.6 m^2 at a height of 1 ft. RTRAK field of view is discussed in detail in "User Guidelines, Measurement Strategies, and Operational Factors for Deployment of *In-Situ* Gamma Spectrometry at the Fernald Site," 20701-RP-0006, Revision A.

The issue with spatial averaging is the size of the averaging area that 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 all of the individual 2 and 8 second measurements are presented under the "Raw Data" heading in Table 4-12 The "raw data" quantities represent the data without the effects of aggregating or spatially averaging measurements. The approximately one-acre portion of the USID area was subdivided into circular areas having radii of 10, 15, 20, 30, and 40 feet. The mean of all 2 second and 8 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 4-12.

Table 4-12 and Figures 4-3 through 4-5 show how the data variability decreases as the size of the averaging area is increased for the 2 and 8 second measurements. 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 can be seen from Table 4-12 and in Figures 4-3 through 4-5, 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 would require a smaller averaging window than radium-226 averages to attain small standard deviations.

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 measurements 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.

Care must be taken when aggregating RTRAK measurements to ascertain that the area represented by the aggregated measurements is not significantly larger than the hot spot of interest. This can be a practical limitation to the use of RTRAK to detect hot spots. Section 4.3-1 of the User's Manual (DOE 1998a) provides a method for determining the approximate size of an area represented by a number of aggregated measurements.

4.3 MINIMUM DETECTABLE CONCENTRATIONS

4.3.1 Calculation of *a priori* MDCs

MDC refers to the statistically determined minimum quantity of a radionuclide that can be measured at a preselected confidence level. The MDC is the *a priori* activity concentration that a specific instrument and technique can be expected to detect 95% of the time. When stating the detection capability of an instrument, this value should be used. The MDC is the detection limit L_D, multiplied by an appropriate conversion factor to give units of activity concentration (MARSSIM 1997). The magnitude of the MDC is a function of instrument parameters, radiological background levels, and the measurement procedure.

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 lowest 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:

$$L_D = 2ks, \qquad (9)$$

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 uncertainty of the measurement when the net measurement is near the background

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

The repeat profile runs in the USID area were used as the basis of calculating 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 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 deviation of the distribution is equivalent to the standard deviations of the individual measurements. These standard deviations represent the combined counting uncertainty and the instrument/operational

uncertainties. They were combined with the systematic uncertainties to calculate the total uncertainty for the measurements using Equation (2). The total uncertainty was used to calculate *a priori* MDCs for the three combinations of acquisition time and travel speed. Because the combination of 4 sec/1 mph was not run in the USID area, the MDC was estimated from the 8-second data. 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 *a priori* MDCs are presented in Table 4-13. The values in the table represent MDCs in areas where all analytes of interest are in concentrations near background. MDCs will be higher in areas of elevated activity because of the effects of interferences and the increased spectrum background. The calculation of location-specific MDCs for locations with elevated activity levels contributions is discussed in Section 4.3.2.

As shown in Table 4-13, increasing the acquisition time decreases the MDCs for uranium-238, thorium-232, and radium-226. If the only contribution to the uncertainty were the counting uncertainty, the MDCs would decrease by the square root of the factor by which the acquisition time has changed. That means that increasing the acquisition time from 2 to 8 seconds would decrease the MDC by a factor of two. A decrease of this magnitude is not observed for any of the analytes. These smaller decreases illustrate the effects of the other contributors to the total uncertainty. Nonetheless, the uncertainty of a measurement and consequently the MDC, can be lowered appreciably by increasing the acquisition time.

It is not practical to increase the acquisition time indefinitely in order to lower the uncertainty or the MDC. As was discussed in Section 4.2, another way to decrease the relative uncertainty of a measurement is to aggregate measurements. This results because the relative uncertainty of the mean of a number of measurements is smaller than for a single measurement. Because the MDC is a function of the uncertainty, aggregation will decrease it as well. The improved MDC would be obtained at the expense of poorer spatial resolution. The MDC for aggregated measurements can be calculated by combining Equation 9 with Equation 2 and adjusting to take into consideration the effect of decreasing the random uncertainties. All the random uncertainties are decreased by a factor equal to the square root of the number of aggregated measurements. The systematic uncertainties are unchanged because they are not reduced with increasing numbers of measurements. This is expressed by the following equation:

$$MDC = 3.29\,[(\sigma^2_{Measured}+\sigma^2_{Env})/n^{1/2}+1/3(\delta^2_{Comparability}+\delta^2_{Regression})]^{1/2} \quad (10)$$

where:

$\sigma_{Measured}$ = standard deviation of repeated profile measurements in the road segment of the USID area (considered representative of background)

σ_{Env} = uncertainty associated with variations in environmental conditions.

$\delta_{Comparability}$ = estimated systematic uncertainty associated with the agreement between laboratory data and *in-situ* measurements.

$\delta_{Regression}$ = estimated systematic uncertainty associated with the multiple regression analysis used to generate the calibration equations.

n = the number of measurements that are aggregated

The greater the number of measurements that are aggregated, the smaller the MDCs. The number of measurements that should be aggregated for an application is dependent upon the required MDC and spatial resolution. MDCs obtained by aggregating 2, 5, 10, 50, and 100 measurements for the 2, 4, and 8 second acquisition times are shown in Table 4-14. The MDCs obtained for the individual measurements shown in Table 4-13 are also presented in Table 4-14 for comparison.

The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM 1997) addresses selection of instrumentation to be used for radiological surveys. MARSSIM recommends that where practical, the MDCs for survey instrumentation should be between 10 and 50% of the applicable limit. At the FEMP, the appropriate limits for comparison would be the FRL, hot spot criteria, and the WAC. Table 4-15 presents the number of measurements that must be aggregated to meet the 50% criterion. This is shown as a function of the analyte of interest and the acquisition time. For uranium-238, only the 82 ppm FRL is considered for the table. The MDCs for single RTRAK measurements satisfy the criterion for all the analytes for both the 2 x FRL and 3 x FRL hot-spot limits and for WAC, at all three acquisition times. However, the thorium-232 individual-measurements with the 8 sec acquisition time have an MDC that meets the criterion for the FRL. In order to meet the MARSSIM criterion to survey for FRLs for uranium-238 and radium-226 or for thorium with 2 or 4 second acquisition times, measurements must be aggregated.

4.3.2 Location Specific MDCs

As discussed previously, MDCs should only be used *a priori* to determine whether a system is appropriate for an intended application. However, the MDC is a function of the spectrum background, the MDCs calculated in Section 4.3.1 are applicable only in locations where the background radiation levels are low, or near natural background In locations of higher radiation levels such as would be found in highly contaminated areas or near radioactive materials storage areas, these MDCs are no longer meaningful. Locations near Silos 1, 2 and 3 and some portions of the production area fall into that category. If the elevated background consists largely of uncollided gamma rays, it is difficult to discern background from the soil being monitored. However, if the elevated background is primarily collided gamma ray flux, there will be no net contributions to the peaks but the spectrum background is increased. In such cases, a location-specific MDC can be determined, but it is not always practical to do so *a priori*. An *a posteriori* MDC can be calculated for each RTRAK measurement. They should be used only to determine whether the data obtained in a location can be used for its intended purpose, such as whether the MDC is to large to allow scanning for FRL or hot spot exceedances. The MDCs should never be used to decide if radioactive materials are present or whether activity concentrations exceed a limiting criterion. In addition, reported MDCs should not be used in calculating average concentrations within a measurement area. The *a posteriori* MDCs can be calculated by applying standard propagation of uncertainty relationships to the RTRAK calibration equations and adding uncertainty contributions form non-counting sources. To calculate the MDC for a measurement, the assumption is made that the gross number of counts is equal to the number of background counts. The contributions of the non-counting uncertainty sources are set equal to the values used in calculating the MDCs in Section 4.3.1. The following relationships can be used to calculate the *a posteriori* MDCs:

RTRAK

Uranium-238

$$MDC_{a\,posteriori}\,(pCi/g) = 3.29(A_u^2*2*UB_{cnts} + B_u^2*2*ThB_{cnts} + C_u^2*2*RaB_{cnts} + 20.75)^{0.5}/t$$

Thorium-232

$$MDC_{a\,posteriori}\,(pCi/g) = 3.29(A_{Th}^2*2*ThB_{cnts} + B_{Th}^2*2*RaB_{cnts} + 0.064296)^{0.5}/t$$

Radium-226

$$MDC_{a\,posteriori}\,(pCi/g) = 3.29(A_{Ra}^2*2*RaB_{cnts} + B_{Ra}^2*2*ThB_{cnts} + 0.044865)^{0.5}/t$$

where:

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UB_{cnts}	=	normalized background counts for the uranium-238 region
ThB_{cnts}	=	normalized background counts for the thorium-232 region
RaB_{cnts}	=	normalized background counts for the radium-226 region
A_U	=	first coefficient from RTRAK uranium-238 calibration equation.
B_U	=	second coefficient from RTRAK uranium-238 calibration equation
C_U	=	third coefficient from RTRAK uranium-238 calibration equation
A_{Th}	=	first coefficient from RTRAK thorium-232 calibration equation
B_{Th}	=	second coefficient from RTRAK thorium-232 calibration equation
A_{Ra}	=	first coefficient from RTRAK radium-226 calibration equation
B_{Ra}	=	second coefficient from RTRAK radium-226 calibration equation
t	=	live timenumerical
values	=	the numerical equivalent of the uncertainties, other than counting uncertainty, used in calculating Section 4.3.2 MDCs.

4.4 TRIGGER LEVELS

To facilitate use of the RTRAK results, "trigger levels" can be established to aid in decision making. A "trigger level" can be defined as an analyte concentration that, if exceeded by a field or laboratory measurement, provides the basis for some subsequent action to be taken. The general approach described in this report can be applied to any data set, but the tables provided are specific to the RTRAK configuration as used at the FEMP. In practice, a trigger level would be associated with a regulatory limit or internal action limit. The advantage of using a trigger level is that it provides a single value against which data can be quickly compared to screen a location for potential exceedances of a given limiting criterion. The discussion in Appendix C shows that RTRAK and RSS measurements are equivalent. Consequently, the trigger levels defined for RTRAK are applicable to RSS.

Because every RTRAK measurement will have some corresponding uncertainty, trigger levels are typically set below the actual limiting criteria to provide confidence that a regulatory or operational limit will not be exceeded, The difference between the limiting criterion and the trigger level is a function of the precision of the actual measurement value being used and the required level of confidence that a measurement at or below the trigger level will not exceed the limiting criterion. Because the precision of a measurement is analyte specific, the trigger level will also be analyte specific.

The use of aggregate measurements complicates establishing a trigger level; consequently, a practical approach to setting a trigger level is to arbitrarily define a minimum acceptable trigger level as a

percentage of the applicable regulatory limit. This percentage must be a value such that the trigger level is well above the detection limit and is also well above the radionuclide background concentration in soils. Equation 10 below, can then be solved for the corresponding number of measurements that must be aggregated in order for the standard deviation to be acceptably reduced.

$$\text{Minimum Acceptable Trigger} = L - k\sigma_{limit}/(n)^{1/2} \qquad (11)$$

where:

L = the magnitude of the limiting criterion such as the FRL, hot spot criterion, or WAC

k = the standard normal variate, a statistical factor related to the acceptable confidence level of the measurement. At the 95% confidence level, k is equal to 1.645 for a single-tailed distribution.

σ_{limit} = the standard deviation assumed for RTRAK measurements of soil concentrations numerically equal to the limit

n = the number of measurements that are aggregated

For the purposes of this discussion, the minimum acceptable RTRAK trigger level is set at 70% of the applicable regulatory limit. This is not based on a rigorous statistical or quantitative evaluation, but was chosen in part because at 70% of the limit, acceptable trigger levels can be achieved by aggregating only two measurements for uranium WAC exceedances. In addition, the Real-Time Working Group concluded that a trigger level lower than 750 ppm would be acceptable for the uranium WAC; 70% of the WAC is 721 ppm.

The trigger levels and the number of measurements that must be aggregated to achieve these levels are presented in Tables 4-16 through 4-18. These parameters were calculated using Equation 11 and the uncertainties estimated for individual RTRAK measurement in Tables 4-9, 4-10, and 4-11 Table 4-16 is for total uranium at FRLs of 10, 20, and 82 ppm respectively. Tables 4-17 and 4-18 are for thorium-232 and radium-226, respectively. Each table lists trigger levels for the FRL and WAC (total uranium only) at acquisition times of 2, 4, and 8 seconds.

The tables can be interpreted as follows:

1. The first and second columns define the applicable limiting criterion.

2. The third column is the minimum acceptable trigger level calculated as 70% of the limiting criterion.

3. Subsequent columns provide trigger level information for the three acquisition times.

4. The following information is provided for each acquisition time:

   a. The column labeled "Single Measurement Trigger" shows the trigger level that would be calculated for a single measurement. The column is annotated to indicate whether this satisfies the requirement to exceed the minimum acceptable trigger level. The notation "marginal" indicates that the single measurement trigger level is less than 10% lower than the minimum acceptable trigger level.

   b. The column labeled "No. Aggregated Measurements (Trigger)" shows the number of measurements that must be aggregated in order to reduce the uncertainty to achieve the minimum acceptable trigger level. This number is calculated using Equation 11 and rounded up to the next whole measurement. Beneath the number of measurements, in parentheses, is the actual calculated trigger level that would be obtained for the aggregated measurements.

4.5 ACCURACY

4.5.1 Calibration Assessment

As discussed in Section 3.0, the RTRAK calibration equations were developed by performing multiple linear regression analyses on the results of static RTRAK and HPGe measurements made in identical locations. To assess the validity of the calibration, additional static RTRAK and HPGe measurements were made at locations in the USID and DBAs. The results of these measurements and their calculated uncertainties are shown in Table 4-19. The RTRAK values listed in the table are the means of series of multiple measurements taken at each location. RTRAK measurements were taken for both 2 second and 8 second acquisition times for a total of 300 seconds of data acquisition time. This resulted in a total of approximately 150 measurements for the 2 second acquisitions and 38 measurements for the 8 second acquisitions. The total uncertainties for the RTRAK measurements were obtained by using the calculated standard deviations of the mean for these measurements to represent the counting and instrument/operational uncertainties and propagating them with the other uncertainty contributors discussed in Section 4.1. The HPGe measurements were single measurements at each of those

locations for 900 second acquisition periods. The HPGe uncertainties are the counting uncertainties of the measurements.

For the measurements in the USID area, the HPGe and RTRAK measurements agree within their uncertainties for all three analytes. The agreement in the DBA is poorer. At both locations in the DBA, the HPGe and RTRAK radium-226 measurements agree within the uncertainty but the uranium-238 measurements differ by over 4 times the uncertainty. The thorium-232 results agree within the uncertainty for location RBS 3-2 but differ by over 2 times the uncertainty for RBS 3-1. The lack of agreement may be attributable to the heterogeneity in the DBA and the difference in the fields of view of the HPGe and the RTRAK. In general, elevated concentrations of radionuclides are found in heterogeneous distributions, while contamination near background levels is often reasonably homogeneous. Locations in the DBA were selected for measurements so that comparisons could be made in locations of elevated radionuclide concentrations. Since the measurements were made, it has been observed that locations of elevated activity typically have heterogeneous radionuclide distributions with the elevated activity often limited to small areas, at times less than one foot in diameter. Such is the case for the DBA. The HPGe measurements were made at a height of 1 meter which has a field of view of approximately 113 square meters. By comparison, the RTRAK field of view for a static measurement is only 4.5 square meters. Given this field of view difference and the known heterogeneity of the area, it is not unexpected that the agreement appears poor for these elevated measurements. It is quite reasonable to speculate that there are multiple areas of high radionuclide concentrations within the HPGe field of view that would not be viewed by the RTRAK. It is notable that the poorest agreement is for uranium-238 which is elevated above typical backgrounds by more than an order of magnitude. Similarly, the thorium-232 agreement is worse for the higher concentration measurements than the lower ones. Within the USID area, the analyte distributions are relatively homogeneous; this can be seen in the results of the repeated profile measurements discussed in Section 4.1. Consequently, the field of view differences are of less importance and the agreement between HPGe and RTRAK is very good.

There is some question about the accuracy of the RTRAK uranium-238 measurements in low concentration areas. The intercept of the uranium-238 calibration equation is nearly 10 pCi/g or 30 ppm, so at low concentrations the RTRAK results may be biased high. However, the bias would not be as large as the intercept because of the of effect gamma rays from thorium-232 and radium-226

interfering with the uranium-238 region of interest. The large intercept results in part from the need to correct for those interferences. The bias would be equal to the intercept only in cases where there the thorium-232 and radium-226 concentrations are zero. Low uranium concentrations may be biased high, particularly in areas with very low thorium and radium concentrations. Because of the intercept, uranium-238 concentrations below approximately 50 ppm or 17 pCi/g should be considered questionable.

Given the field of view differences, the effect of the high intercept, and the good agreement seen within the homogeneous USID area, it can be concluded that the RTRAK agrees acceptably well with HPGe measurements.

4.5.2 Comparison of HPGe and Dynamic RTRAK Isotopic Results

In the HPGe Comparability Study, criteria for evaluating the closeness of HPGe and laboratory data were adopted from the Contract Laboratory Program (CLP) statements of work (SOW) and SW-846 guidelines for relative precision requirements for metals. The RPD is defined by the relationship:

$$\% \text{ Relative Deviation} = [(|\bar{x}_1 - \bar{x}_2|)/\bar{\bar{x}}] \times 100$$

where:

$\bar{x}_1$ is the weighted mean of the laboratory data corresponding to simulate HPGe measurements at a given detector height

$\bar{x}_2$ is the mean of duplicates for HPGe measurement at a given detector height

$\bar{\bar{x}}$ is the average of the two means

| | is the absolute value symbol

The CLP SOW and SW-846 state that data are considered acceptable when the percent relative difference between laboratory duplicates is less than 20% for data that are greater than five times the MDC. For data less than five times the MDC, the precision requirement is $\pm$MDC. When the RPD is greater than 20%, the data are to be qualified or reanalyzed. However, US EPA CLP National Functional Guidelines for Inorganic Data Review sets the RPD criterion for metals analysis of soils at 35% before data are to be qualified. Guidelines for comparison of field duplicates have less restrictive criteria. For metals analysis of soils, field duplicates for which RPDs exceed 50% are to be qualified. The Comparable Study used the criteria for comparing laboratory duplicates to define the criteria for

comparing HPGe and laboratory data. HPGe and laboratory data are defined as being very similar when the RPD is less than or equal to 20%; as having acceptable similarity when the RPD is greater than 20% but less than or equal to 35%; and being dissimilar when the RPD is greater than 35%. These same criteria have been adopted for comparison of RTRAK and HPGe measurements. As noted, these criteria are adopted from criteria for laboratory duplicates in which the effects of sample heterogeneity should be minimal. Because of field of view differences, area heterogeneity will have an impact on the agreement between HPGe and RTRAK measurements, so the use of the laboratory-duplicates criterion represents a conservative indicator of agreement.

Tables 4-20 and 4-21 compare *in-situ* HPGe results with RTRAK isotopic values averaged over each of the individual HPGe viewing areas in the USID (36 HPGe positions) area and the DBA (8 HPGe positions). Coverage of the DBA by the RTRAK was incomplete because terrain and the presence of obstructions made much of it inaccessible to the RTRAK. For many of the HPGe measurements, less than half of the field of view was covered by the RTRAK, and none of them had 100% coverage. Data are included in Table 4-21 only for those HPGe positions for which the RTRAK cover more than 50% of the field of view. In evaluating these data, it is important to recognize that the HPGe measurements were static, while the RTRAK measurements were collected with the RTRAK in a dynamic mode. The RTRAK data in the table are the averages of measurements for which the GPS coordinates were within the filed of view of the HPGe. Consequently, the fields of view of the aggregate RTRAK measurements would approximate but not be identical to that of corresponding HPGe measurements. In addition, when averaged, the RTRAK measurements were not weighted on the basis of their locations within the HPGe field of view as was done for comparisons of HPGe measurements with laboratory data. These factors would be expected to result in some differences between the HPGe and RTRAK measurements.

Within the USID area (Table 4-20), there is excellent agreement between HPGe and RTRAK, for both 2 and 8 second acquisition times. For uranium-238, 86% of the measurements are very similar (RPDs are 20% or less) or acceptably similar (RPDs between 20% and 35%) for the 2 second acquisition times, as are 94% of the measurements at 8 seconds. RPDs exceed 35% (dissimilar) for only 5 measurements at 2 seconds and 2 measurements at 8 seconds. RPDs are between 20% and 35% (acceptably similar) for 10 measurements (28%) at 2 seconds and 5 measurements (14%) at 8 seconds. It is reasonable to characterize the overall agreement as excellent, particularly in light of field of view

differences. The contamination within the USID area is considered to be reasonably homogeneous, so the field of view effects should not be large. However, there is some variation in the contamination distribution, so minor heterogeneity effects will be present.

The thorium-232 measurements also show excellent agreement in the USID area. For the both the 2 second and the 8 second measurements, 94% are very or acceptably similar. Only 2 measurements each (6%) have RPDs exceeding 35% (dissimilar) and 2 measurements each (6%) have RPDs between 20% and 35% (acceptably similar).

The radium-226 is also very good, with 97% of the 2 second measurements and 100% of the 8 second measurements categorized as acceptably or very similar. However, a larger fraction of the RPDs fall within the 20-35% range than for the other nuclides. None of the 8 second measurements and only 1 2 second measurement (3%) have RPDs exceeding 35% (dissimilar). RPDs were between 20% and 35% (acceptably similar) for 15 measurements (42%) at 2 seconds and 8 measurements (22%) at 8 seconds.

Much of the difference between HPGe and RTRAK can be attributed to analyte heterogeneity and field of view differences. This is supported by the observation that two HPGe locations, 500349-13 and 500349-21, are responsible for two of the five exceedances of the 35% criterion for uranium-238 at 2 seconds, both exceedances at 8 seconds, and those for thorium-232 at both 2 and 8 seconds. The other two location for the 2 second uranium-238 exceedances had RPDs between 20 and 35% for the 8 second measurements. Because disagreement is seen for two analytes at both acquisition times, it can be concluded that the differences are "real," that is, they are a consequence of differences in the analyte concentrations observed by the two systems. This is consistent with the fact that the HPGe and the aggregated RTRAK measurements do not have identical fields of view. In positions 500349-13 and - 21, both uranium-238 and thorium-232 are much higher for RTRAK than for HPGe. This can be interpreted to mean that the RTRAK is viewing small areas at these locations with elevated levels of uranium-238 and thorium-232 that are not being viewed by the HPGe. This demonstrates the ability of the RTRAK, with its smaller field of view to detect "hot spots" better than HPGe which averages over a larger area.

It is clear from an examination of the data in Table 4-21 that the agreement in the DBA is not as good as in the USID area. RPDs exceed 35% for 50% or more of the measurements for all three nuclides.

This is not surprising for the set of data in question. As was noted previously, the RTRAK measurements did not provide full coverage of the fields of view for any of the HPGe measurement locations. Figure 4-6 and Figure 4-7 show the RTRAK measurements within the field of view of the HPGe measurements collected in the DBA. The figures show the positions of the HPGe and RTRAK measurements and indicate the RTRAK gross activity in counts per second. The large circles show the HPGe field of view to scale. However, the symbols showing the RTRAK positions are sized arbitrarily around the GPS positions; they are not scaled to show the RTRAK field of view. It can be seen by examining the figure that there are no HPGe measurements that have complete coverage by RTRAK measurements. Those locations that have a large percentage of the area covered exhibit a high degree of variability. As an example, HPGe location RSS-A3-25G has RTRAK measurements as low as the 5000 - 10000 cps range and as high as the 32500 - 70000 cps for both the 2 and 4 second acquisition times. In light of this, good agreement between the individual HPGe and RTRAK measurements cannot be expected. For this reason, no conclusions can be drawn using the data in Table 4-21. An evaluation of this sort would require measurements in an area of homogeneous elevated activity concentrations. Such locations have not been identified at the FEMP; elevated activity areas exhibit high heterogeneity.

Table 4-22 compares HPGe values averaged over the entire USID Area and a portion of the DBA with RTRAK values averaged over the same areas. As would be expected from the evaluation of the individual HPGe measurements shown in Table 4-20, the agreement is excellent for the USID area. The averaging over the entire area dilutes the effects of heterogeneity seen in some of the individual measurements. For the entire area, the RPDs of the HPGe and RTRAK results agree within 20% for all analytes at both acquisition times, so all measurements are categorized as very similar.

As with the individual HPGe measurements, the agreement in the DBA is not as good as in the USID area. The RPDs exceed 35% for uranium-238 at 2 seconds and for thorium-232 at 4 seconds. The RPD for thorium-232 at 2 seconds is between 20% and 35%. The RPDs for uranium-238 at 4 seconds and radium-226 at both 2 and 4 seconds are below 20%. This is likely a consequence of the incomplete coverage of the RTRAK measurements and the heterogeneity of the area. The large standard deviations of the measurements, all of which exceed 50%, illustrate the heterogeneity of the area.

TABLE 4-1
SUMMARY OF U-238 INFORMATION
FOR USID, SOUTH FIELD, AND DRUM BALING AREAS

Operating Conditions	Area	Isotope	Avg. Segment Means (pCi/g)	Avg. Segment SDs (pCi/g)	Avg. Segment % SDs
2 sec/2 mph	USID	U-238	16.3	8.8	55
2 sec/0.5 mph	USID	U-238	15.7	9.1	59
8 sec/0.5 mph	USID	U-238	16.6	4.8	29
2 sec/2 mph	SF	U-238	15.1	9.3	63
4 sec/1 mph	SF	U-238	15.4	6.8	47
8 sec/0.5 mph	SF	U-238	15.1	4.8	33
2 sec/2 mph	DBA	U-238	92.9	32.4	39
4 sec/1 mph	DBA	U-238	93.4	31.6	36
8 sec/0.5 mph	DBA	U-238	94.4	25.6	29

TABLE 4-2
SUMMARY OF THORIUM-232 INFORMATION
FOR USID, SOUTH FIELD, AND DRUM BALING AREAS

Operating Conditions	Area	Isotope	Avg. Segment Means (pCi/g)	Avg. Segment SDs (pCi/g)	Avg. Segment % SDs
2 sec/2 mph	USID	Th-232	0.77	0.29	38
2sec/0.5 mph	USID	Th-232	0.76	0.30	40
8 sec/0.5 mph	USID	Th-232	0.76	0.15	20
2sec/2 mph	SF	Th-232	0.79	0.33	42
4 sec/1 mph	SF	Th-232	0.82	0.25	32
8 sec/0.5 mph	SF	Th-232	0.80	0.18	22
2 sec/2 mph	DBA	Th-232	3.09	0.91	30
4 sec/1 mph	DBA	Th-232	3.20	0.94	28
8 sec/0.5 mph	DBA	Th-232	3.15	0.63	20

TABLE 4-3
SUMMARY OF RADIUM-226 INFORMATION
FOR USID, SOUTH FIELD, AND DRUM BALING AREAS

Operating Conditions	Area	Isotope	Avg. Segment Means (pCi/g)	Avg. Segment SDs (pCi/g)	Avg. Segment % SDs
2 sec/2 mph	USID	Ra-226	0.78	0.50	64
2 sec/0.5 mph	USID	Ra-226	0.79	0.52	66
8 sec/0.5 mph	USID	Ra-226	0.80	0.26	32
2 sec/2 mph	SF	Ra-226	1.16	0.59	55
4 sec/1 mph	SF	Ra-226	1.18	0.43	38
8 sec/0.5 mph	SF	Ra-226	1.17	0.30	27
2 sec/2 mph	DBA	Ra-226	6.52	2.09	35
4 sec/1 mph	DBA	Ra-226	6.36	1.79	29
8 sec/0.5 mph	DBA	Ra-226	6.40	1.58	25

TABLE 4-4
SUMMARY OF GROSS COUNTS INFORMATION
FOR USID, SOUTH FIELD, AND DRUM BALING AREAS

Operating Conditions	Area	Isotope	Avg. Segment Means (cps)	Avg. Segment SDs (cps)	Avg. Segment % SDs
2 sec/2 mph	USID	Gross Counts	2937	142	5.30
2 sec/0.5 mph	USID	Gross Counts	2924	152	5.78
8 sec/0.5 mph	USID	Gross Counts	2456	176	6.36
2 sec/2 mph	SF	Gross Counts	2849	198	6.29
4 sec/1 mph	SF	Gross Counts	2893	194	5.90
8 sec/0.5 mph	SF	Gross Counts	2883	180	5.34
2 sec/2 mph	DBA	Gross Counts	15666	2147	13.31
4 sec/1 mph	DBA	Gross Counts	15796	2420	15.02
8 sec/0.5 mph	DBA	Gross Counts	15703	2298	14.48

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TABLE 4-5
UNCERTAINTY CONTRIBUTORS FOR URANIUM-238 PROFILE MEASUREMENTS

Operating Conditions	Study Area	Average Profile Standard Deviation (pCi/g)	Average Counting Uncertainty (pCi/g)	Instrument/Operational Uncertainty (pCi/g)
2 sec/2 mph	USID	8.70	7.27	4.78
2 sec/0.5 mph	USID	8.98	7.26	5.28
8 sec/0.5 mph	USID	4.81	3.64	3.14
2 sec/2 mph	South Field	9.23	7.62	5.22
4 sec/1 mph	South Field	6.86	5.44	4.18
8 sec/0.5 mph	South Field	4.82	3.82	2.95
2 sec	nominal average	NA	NA	5
4 sec	nominal average	NA	NA	4
8 sec	nominal average	NA	NA	3

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TABLE 4-6
UNCERTAINTY CONTRIBUTORS FOR THORIUM-232 PROFILE MEASUREMENTS

Operating Conditions	Study Area	Average Profile Standard Deviation (pCi/g)	Average Counting Uncertainty (pCi/g)	Instrument/Operational Uncertainty (pCi/g)
2 sec/2 mph	USID	0.29	0.19	0.22
2 sec/0.5 mph	USID	0.30	0.19	0.23
8 sec/0.5 mph	USID	0.16	0.10	0.13
2 sec/2 mph	South Field	0.32	0.20	0.26
4 sec/1 mph	South Field	0.25	0.14	0.21
8 sec/0.5 mph	South Field	0.19	0.10	0.15
2 sec	nominal average	NA	NA	0.24
4 sec	nominal average	NA	NA	0.21
8 sec	nominal average	NA	NA	0.14

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TABLE 4-7
UNCERTAINTY CONTRIBUTORS FOR RADIUM-226 PROFILE MEASUREMENTS

Operating Conditions	Study Area	Average Profile Standard Deviation (pCi/g)	Average Counting Uncertainty (pCi/g)	Instrument/Operational Uncertainty (pCi/g)
2 sec/2 mph	USID	0.49	0.41	0.28
2 sec/0.5 mph	USID	0.51	0.41	0.31
8 sec/0.5 mph	USID	0.26	0.20	0.16
2 sec/2 mph	South Field	0.58	0.46	0.36
4 sec/1 mph	South Field	0.43	0.33	0.28
8 sec/0.5 mph	South Field	0.30	0.23	0.19
2 sec	nominal average	NA	NA	0.32
4 sec	nominal average	NA	NA	0.28
8 sec	nominal average	NA	NA	0.18

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TABLE 4-8
UNCERTAINTY CONTRIBUTIONS FROM ENVIRONMENTAL EFFECTS, COMPARABILITY, AND REGRESSION
(AS A PERCENTAGE OF THE MEASURED VALUE)

Nuclide	Environmental Effects	Comparability	Regression
U-238	6%	11%	24%
Th-232	6%	6.7%	9%
Ra-226	8%	15%	15%

000089

TABLE 4-9
ESTIMATED CONTRIBUTORS TO MEASUREMENT TOTAL UNCERTAINTY

ACQUISITION TIME	LIMIT TYPE	TOTAL URANIUM (ppm)						
		LIMIT ppm	$\sigma_{INST/OPER}$	$\sigma_{COUNTING}$	σ_{ENV}	$\delta_{REGRESSION}$	$\delta_{COMPARABILITY}$	U_{TOTAL}
2 SEC	U FRL=10 ppm	10	15	22	1	2	1	27
2 SEC	FRL=10 HOT SPOT (3x)	30	15	23	2	7	3	28
2 SEC	FRL=10 HOT SPOT (2x)	20	15	22	1	5	2	27
2 SEC	U FRL=20 ppm	20	15	22	1	5	2	27
2 SEC	FRL=20 HOT SPOT (3x)	60	15	24	4	14	7	30
2 SEC	FRL=20 HOT SPOT (2x)	40	15	23	2	10	4	28
2 SEC	U FRL=50 ppm	50	15	24	3	12	6	29
2 SEC	FRL=50 HOT SPOT (3x)	150	15	26	9	36	17	39
2 SEC	FRL=50 HOT SPOT (2x)	100	15	25	6	24	11	33
2 SEC	FRL=82 ppm	82	15	24	5	20	9	32
2 SEC	FRL=82 HOT SPOT (3x)	246	15	29	15	59	27	52
2 SEC	FRL=82 HOT SPOT (2x)	164	15	27	10	39	18	41
2 SEC	WAC	1030	15	44	62	247	113	175
4 SEC	U FRL=10 ppm	10	12	16	1	2	1	20
4 SEC	FRL=10 HOT SPOT (3x)	30	12	16	2	7	3	21
4 SEC	FRL=10 HOT SPOT (2x)	20	12	16	1	5	2	20
4 SEC	U FRL=20 ppm	20	12	16	1	5	2	20
4 SEC	FRL=20 HOT SPOT (3x)	60	12	17	4	14	7	23
4 SEC	FRL=20 HOT SPOT (2x)	40	12	17	2	10	4	22
4 SEC	U FRL=50 ppm	50	12	17	3	12	6	22
4 SEC	FRL=50 HOT SPOT (3x)	150	12	19	9	36	17	33
4 SEC	FRL=50 HOT SPOT (2x)	100	12	18	6	24	11	27
4 SEC	FRL=82 ppm	82	12	18	5	20	9	25
4 SEC	FRL=82 HOT SPOT (3x)	246	12	21	15	59	27	47
4 SEC	FRL=82 HOT SPOT (2x)	164	12	19	10	39	18	35
4 SEC	WAC	1030	12	31	62	247	113	172

000030

TABLE 4-9
(continued)

ACQUISITION TIME	LIMIT TYPE	TOTAL URANIUM (ppm)						
		LIMIT ppm	$\sigma_{INST/OPER}$	$\sigma_{COUNTING}$	σ_{ENV}	$\delta_{REGRESSION}$	$\delta_{COMPARABILITY}$	U_{TOTAL}
8 SEC	U FRL=10 ppm	10	9	11	1	2	1	15
8 SEC	FRL=10 HOT SPOT (3x)	30	9	12	2	7	3	15
8 SEC	FRL=10 HOT SPOT (2x)	20	9	11	1	5	2	15
8 SEC	U FRL=20 ppm	20	9	11	1	5	2	15
8 SEC	FRL=20 HOT SPOT (3x)	60	9	12	4	14	7	18
8 SEC	FRL=20 HOT SPOT (2x)	40	9	12	2	10	4	16
8 SEC	U FRL=50 ppm	50	9	12	3	12	6	17
8 SEC	FRL=50 HOT SPOT (3x)	150	9	13	9	36	17	29
8 SEC	FRL=50 HOT SPOT (2x)	100	9	13	6	24	11	23
8 SEC	FRL=82 ppm	82	9	12	5	20	9	20
8 SEC	FRL=82 HOT SPOT (3x)	246	9	15	15	59	27	44
8 SEC	FRL=82 HOT SPOT (2x)	164	9	14	10	39	18	31
8 SEC	WAC	1030	9	22	62	247	113	170

TABLE 4-10
ESTIMATED CONTRIBUTORS TO MEASUREMENT TOTAL UNCERTAINTY

		THORIUM-232 (pCi/g)						
ACQUISITION TIME	LIMIT TYPE	LIMIT (pCi/g)	$\sigma_{INST/OPER}$	$\sigma_{COUNTING}$	σ_{ENV}	$\delta_{REGRESSION}$	$\delta_{COMPARABILITY}$	U_{TOTAL}
2 SEC	FRL	1.5	0.24	0.24	0.09	0.14	0.10	0.43
2 SEC	HOT SPOT (3x)	4.5	0.24	0.38	0.27	0.41	0.30	0.76
2 SEC	HOT SPOT (2x)	3.0	0.24	0.32	0.18	0.27	0.20	0.60
4 SEC	FRL	1.5	0.21	0.17	0.09	0.14	0.10	0.37
4 SEC	HOT SPOT (3x)	4.5	0.21	0.27	0.27	0.41	0.30	0.69
4 SEC	HOT SPOT (2x)	3.0	0.21	0.23	0.18	0.27	0.20	0.52
8 SEC	FRL	1.5	0.14	0.12	0.09	0.14	0.10	0.30
8 SEC	HOT SPOT (3x)	4.5	0.14	0.19	0.27	0.41	0.30	0.64
8 SEC	HOT SPOT (2x)	3.0	0.14	0.16	0.18	0.27	0.20	0.46

TABLE 4-11
ESTIMATED CONTRIBUTORS TO MEASUREMENT TOTAL UNCERTAINTY

		RADIUM-226 (pCi/g)						
ACQUISITION TIME	LIMIT TYPE	LIMIT (pCi/g)	$\sigma_{INST/OPER}$	$\sigma_{COUNTING}$	σ_{ENV}	$\delta_{REGRESSION}$	$\delta_{COMPARABILITY}$	U_{TOTAL}
2 SEC	FRL	1.70	0.32	0.48	0.14	0.26	0.26	0.63
2 SEC	HOT SPOT (3x)	5.10	0.32	0.66	0.41	0.77	0.77	1.05
2 SEC	HOT SPOT (2x)	3.40	0.32	0.58	0.27	0.51	0.51	0.83
4 SEC	FRL	1.70	0.28	0.35	0.14	0.26	0.26	0.51
4 SEC	HOT SPOT (3x)	5.10	0.28	0.47	0.41	0.77	0.77	0.93
4 SEC	HOT SPOT (2x)	3.40	0.28	0.41	0.27	0.51	0.51	0.71
8 SEC	FRL	1.70	0.18	0.25	0.14	0.26	0.26	0.39
8 SEC	HOT SPOT (3x)	5.10	0.18	0.33	0.41	0.77	0.77	0.84
8 SEC	HOT SPOT (2x)	3.40	0.18	0.24	0.27	0.51	0.51	0.58

TABLE 4-12
EFFECT OF AVERAGING AREA ON RTRAK STANDARD DEVIATIONS

Operating Conditions - 2 sec/2 mph							
		Total Uranium (ppm)		Thorium (pCi/g)		Radium (pCi/g)	
	# Measurements Aggregated	Mean	Std Dev of Mean	Mean	Std Dev of Mean	Mean	Std Dev of Mean
Raw	1	59	36	0.99	0.41	1.01	0.69
10	5	58	17	1.00	0.28	1.02	0.26
15	10	58	12	1.00	0.17	1.00	0.23
20	16	58	10	1.00	0.14	1.01	0.18
30	38	59	7	0.99	0.11	1.01	0.12
40	61	59	6	0.99	0.09	1.01	0.09

Operating Conditions - 8 sec/0.5 mph							
		Total Uranium (ppm)		Thorium (pCi/g)		Radium (pCi/g)	
Radius (ft)	# Measurements Aggregated	Mean	Std Dev of Mean	Mean	Std Dev of Mean	Mean	Std Dev of Mean
Raw	1	65	18	0.97	0.23	1.03	0.34
10	4	65	11	0.97	0.15	1.03	0.17
15	10	65	8	0.97	0.13	1.03	0.11
20	15	65	7	0.97	0.11	1.03	0.09
30	32	65	4	0.96	0.08	1.03	0.06
40	51	65	3	0.96	0.07	1.03	0.05

TABLE 4-13
***A PRIORI* MDC BASED UPON INDIVIDUAL MEASUREMENTS IN THE USID AREA**

Nuclide	2sec	4 sec	8 sec
Total Uranium (ppm)	76	63[a]	53
Uranium-238 (pCi/g)	25	21	18
Thorium-232 (pCi/g)	0.96	0.91[a]	0.71
Radium-226 (pCi/g)	1.50	1.08[a]	1.02

[a] Estimated from data for 8-second acquisition time.

TABLE 4-14
***A PRIORI* MDC BASED UPON TOTAL SYSTEM UNCERTAINTY FOR AGGREGATED MEASUREMENTS**

Acquisition Time	Nuclide	Number of Aggregated Measurements					
		1[a]	2	5	10	50	100
2 seconds	Total Uranium (ppm)	76[b]	65	53	46	34	31
	Uranium (pCi/g)	25	22	18	15	11	10
	Thorium (pCi/g)	0.96	0.81	0.65	0.55	0.37	0.32
	Radium (pCi/g)	1.49	1.26	1.01	0.87	0.61	0.53
4 seconds	Total Uranium (ppm)	63	54	44	39	30	27
	Uranium (pCi/g)	21	18	15	13	10	9
	Thorium (pCi/g)	0.91	0.77	0.61	0.52	0.35	0.30
	Radium (pCi/g)	1.08	0.92	0.75	0.64	0.47	0.42
8 seconds	Total Uranium (ppm)	53	46	39	34	27	25
	Uranium (pCi/g)	18	15	13	11	9	8
	Thorium (pCi/g)	0.71	0.60	0.48	0.41	0.29	0.25
	Radium (pCi/g)	1.02	0.87	0.71	0.62	0.47	0.42

[a] MDCs for one measurement are taken from Table 4-13.

[b] Numbers are MDCs in ppm for total uranium and pCi/g for thorium-232 and radium-226.

TABLE 4-15
COMPARISON OF RTRAK MDCS WITH MARSSIM CRITERION

	Measurement Aggregation Needed to Meet MARSSIM MDC Criterion[a]								
	2sec			4 sec			8 sec		
	Total U[b]	Th-232	Ra-226	Total U[b]	Th-232	Ra-226	Total U[b]	Th-232	Ra-226
FRL (82 ppm)	18	3	11	8	3	3	4	1	3
Hot Spot (164 ppm)	1	1	1	1	1	1	1	1	1
Hot Spot (246 ppm)	1	1	1	1	1	1	1	1	1
WAC (1030 ppm)	1	na	na	1	na	na	1	na	na

[a] MARSSIM Recommends that MDC be 10 - 50% of Limit
[b] Based on a total uranium FRL of 82 ppm

000097

TABLE 4-16
TOTAL URANIUM RTRAK TRIGGER LEVELS

			2 sec Acquisition Time		4 sec Acquisition Time		8 sec Acquisition Time	
Application	Limit (ppm)	Minimum Acceptable Trigger (ppm)	Single Measurement Trigger (ppm)	No. Aggregated Measurements (Trigger, ppm)	Single Measurement Trigger (ppm)	No. Aggregated Measurements (Trigger, ppm)	Single Measurement Trigger (ppm)	No. Aggregated Measurements (Trigger, ppm)
FRL	10	7	-34 unacceptable	712 (7)	-23 unacceptable	398 (7)	-14 unacceptable	208 (7)
FRL	20	14	-25 unacceptable	182 (14)	-14 unacceptable	102 (14)	-5 unacceptable	53 (14)
FRL	50	35	2 unacceptable	32 (35)	13 unacceptable	18 (35)	22 unacceptable	9 (35)
FRL	82	57	30 unacceptable	12 (57)	41 unacceptable	7 (57)	48 unacceptable	4 (58)
WAC	1030	721	742 acceptable	1 (742)	747 acceptable	1 (747)	750 acceptable	1 (750)

000038

TABLE 4-17
THORIUM-232 RTRAK TRIGGER LEVELS IN pCi/g

			2 sec Acquisition Time		4 sec Acquisition Time		8 sec Acquisition Time	
Application	Limit (pCi/g)	Minimum Acceptable Trigger (pCi/g)	Single Measurement Trigger (pCi/g)	No. Aggregated Measurements (Trigger, pCi/g)	Single Measurement Trigger (pCi/g)	No. Aggregated Measurements (Trigger, pCi/g)	Single Measurement Trigger (pCi/g)	No. Aggregated Measurements (Trigger, pCi/g)
FRL	1.5	1.05	0.90 unacceptable	2 (1.06)	1.00 marginal	2 (1.13)	1.12 acceptable	1 (1.12)
WAC	na	na	na	na	na	na	na	na

TABLE 4-18
RADIUM-226 RTRAK TRIGGER LEVELS IN pCi/g

			2 sec Acquisition Time		4 sec Acquisition Time		8 sec Acquisition Time	
Application	Limit (pCi/g)	Minimum Acceptable Trigger (pCi/g)	Single Measurement Trigger (pCi/g)	No. Aggregated Measurements (Trigger, pCi/g)	Single Measurement Trigger (pCi/g)	No. Aggregated Measurements (Trigger, pCi/g)	Single Measurement Trigger (pCi/g)	No. Aggregated Measurements (Trigger, pCi/g)
FRL	1.7	1.2	0.71 unacceptable	6 (1.20)	0.92 unacceptable	4 (1.21)	1.05 unacceptable	3 (1.23)
WAC	na	na	na	na	na	na	na	na

000099

TABLE 4-19
COMPARISON OF CO-LOCATED STATIC RTRAK AND HPGe MEASUREMENTS

Study Area[1]	Data Point	RTRAK Acquisition Time	Uranium-238 (pCi/g)				Thorium-232 (pCi/g)				Radium-226 (pCi/g)			
			HPGe	HPGe Uncert	RTRAK Mean	RTRAK U_{TOT}	HPGe	HPGe Uncert	RTRAK Mean	RTRAK U_{TOT}	HPGe	HPGe Uncert	RTRAK Mean	RTRAK U_{TOT}
USID	10	2 SEC	22.5	0.6	17.6	5.0	0.70	0.02	0.81	0.22	0.70	0.02	0.85	0.31
USID	10	8 SEC	22.5	0.6	18.2	5.1	0.70	0.02	0.80	0.22	0.70	0.02	0.88	0.31
USID	15	2 SEC	22.4	0.6	17.8	5.0	0.80	0.02	0.86	0.22	0.70	0.02	0.89	0.31
USID	15	8 SEC	22.4	0.6	19.0	5.1	0.80	0.02	0.83	0.22	0.70	0.02	0.97	0.32
USID	35	2 SEC	13.4	0.5	14.4	4.7	0.80	0.02	0.78	0.22	0.70	0.02	0.84	0.31
USID	35	8 SEC	13.4	0.5	14.9	4.7	0.80	0.02	0.80	0.22	0.70	0.02	0.84	0.31
USID	41	2 SEC	13.3	0.5	14.9	4.7	0.70	0.02	0.78	0.22	0.70	0.02	0.89	0.31
USID	41	8 SEC	13.3	0.5	15.9	4.8	0.70	0.02	0.76	0.22	0.70	0.02	0.78	0.31
DBA	RBS 3-1	2 SEC	77.8	0.9	40.9	7.8	4.90	0.70	2.64	0.32	3.04	0.96	2.44	0.46
DBA	RBS 3-1	8 SEC	77.8	0.9	40.7	7.9	4.90	0.70	2.70	0.32	3.04	0.96	2.63	0.48
DBA	RBS 3-2	2 SEC	111	0.7	61.7	10.9	2.05	1.30	1.84	0.27	5.92	0.55	4.69	0.74
DBA	RBS 3-2	8 SEC	111	0.7	61.6	10.9	2.05	1.30	1.84	0.27	5.92	0.55	4.64	0.74

1 - DBA - Drum Baling Area; USID -USID Area

Table 4-20

COMPARISON OF HPGe AND AVERAGE RTRAK MEASUREMENTS WITHIN THE HPGe FIELD OF VIEW - USID AREA

HPGe SAMPLE ID	Uranium-238 (ppm)					Thorium-232 (pCi/g)					Radium-226 (pCi/g)				
	HPGe	2 sec/2 mph		8 sec/0.5 mph		HPGe	2 sec/2 mph		8 sec/0.5 mph		HPGe	2 sec/2 mph		8 sec/0.5 mph	
		Average	StDev	Average	StDev		Average	StDev	Average	StDev		Average	StDev	Average	StDev
500349-6	41.98	44.58	25.64	44.19	11.16	0.66	0.60	0.35	0.76	0.16	0.63	0.87	0.37	0.82	0.19
500349-7	69.48	55.34	28.26	57.41	18.82	0.78	0.75	0.39	0.78	0.15	0.67	0.90	0.44	0.90	0.26
500349-8	59.64	35.53	19.78	48.27	15.38	0.7	0.72	0.32	0.65	0.18	0.67	0.57	0.53	0.66	0.18
500349-9	64.17	49.17	30.31	60.29	16.69	0.68	0.73	0.27	0.75	0.16	0.63	0.78	0.48	0.86	0.30
500349-10	67.46	58.14	33.28	49.17	10.14	0.73	0.71	0.21	0.78	0.13	0.67	0.95	0.52	0.70	0.22
500349-11	45.83	43.45	27.19	41.90	15.96	0.69	0.72	0.34	0.75	0.15	0.67	0.78	0.49	0.69	0.30
500349-12	46.48	39.03	22.34	50.76	15.74	0.75	0.68	0.26	0.62	0.20	0.73	0.81	0.56	0.76	0.12
500349-13	14.47	32.03	24.62	38.91	16.68	0.31	0.59	0.32	0.53	0.20	0.49	0.64	0.52	0.68	0.23
500349-14	53.65	40.77	19.72	48.12	15.84	0.67	0.61	0.28	0.57	0.27	0.61	0.55	0.45	0.71	0.26
500349-15	76.41	52.26	34.85	53.66	12.17	0.84	0.70	0.39	0.81	0.13	0.76	0.69	0.50	0.75	0.27
500349-16	52.16	45.25	22.01	54.73	12.23	0.79	0.89	0.21	0.75	0.14	0.66	0.87	0.61	0.76	0.21
500349-17	41.09	32.30	23.21	42.98	9.73	0.75	0.70	0.29	0.78	0.15	0.66	0.47	0.47	0.74	0.36
500349-18	55.71	48.53	27.17	51.98	13.61	0.8	0.82	0.25	0.80	0.15	0.74	0.52	0.48	0.80	0.30
500349-19	56.66	43.80	24.83	54.99	14.91	0.77	0.78	0.28	0.71	0.16	0.71	0.79	0.53	0.81	0.26
500349-20	59.02	49.73	24.02	45.40	10.21	0.74	0.72	0.27	0.71	0.16	0.75	0.73	0.53	0.77	0.18
500349-21	14.66	35.11	28.02	44.52	9.18	0.31	0.61	0.32	0.56	0.32	0.5	0.50	0.46	0.69	0.30
500349-22	54.55	46.52	27.25	52.57	16.06	0.84	0.75	0.34	0.68	0.17	0.7	0.80	0.52	0.76	0.26
500349-23	47.93	47.80	29.05	53.78	10.73	0.77	0.79	0.27	0.72	0.15	0.68	0.91	0.50	0.73	0.21
500349-24	46.15	49.45	27.10	49.69	12.16	0.75	0.72	0.39	0.75	0.16	0.68	0.77	0.53	0.62	0.29
500349-25	44.64	38.58	30.29	47.74	15.43	0.78	0.87	0.25	0.79	0.08	0.66	0.92	0.56	0.83	0.34
500349-26	52.46	44.19	25.67	50.79	14.50	0.76	0.84	0.34	0.81	0.16	0.74	1.01	0.51	0.83	0.23
500349-27	54.85	51.78	29.53	52.97	11.75	0.77	0.87	0.30	0.75	0.12	0.72	0.86	0.53	0.86	0.24
500349-28	57.24	57.06	20.17	52.21	10.64	0.75	0.79	0.29	0.81	0.10	0.72	0.89	0.32	0.87	0.25
500349-29	50.09	35.63	24.36	49.09	13.84	0.72	0.70	0.22	0.78	0.09	0.75	0.58	0.61	0.84	0.33
500349-30	47.4	45.57	20.45	41.42	14.69	0.67	0.59	0.31	0.56	0.22	0.68	0.78	0.52	0.71	0.29
500349-31	49.46	48.32	26.42	46.46	9.78	0.76	0.75	0.28	0.74	0.13	0.64	0.67	0.50	0.80	0.19
500349-32	52.14	36.97	29.84	47.43	15.45	0.76	0.86	0.26	0.72	0.14	0.7	0.69	0.64	0.79	0.26
500349-33	52.77	34.40	30.91	48.98	10.84	0.7	0.75	0.26	0.79	0.09	0.67	0.69	0.47	0.72	0.24
500349-34	47.96	33.83	20.22	53.29	10.49	0.67	0.86	0.19	0.72	0.16	0.69	0.69	0.34	0.83	0.22
500349-35	40.14	34.29	23.23	43.92	11.16	0.75	0.83	0.30	0.70	0.10	0.73	0.73	0.57	0.73	0.33
500349-36	44.98	40.72	28.73	52.80	12.46	0.71	0.89	0.19	0.77	0.12	0.7	0.92	0.56	0.79	0.30
500349-37	49.44	57.36	32.16	44.53	15.28	0.74	0.70	0.39	0.81	0.14	0.73	0.79	0.71	0.80	0.16
500349-38	47.68	34.22	20.43	46.73	7.52	0.68	0.80	0.37	0.71	0.18	0.72	0.62	0.33	0.68	0.25
500349-39	51.51	50.84	26.07	49.67	10.61	0.76	0.84	0.25	0.55	0.09	0.68	1.09	0.59	0.70	0.26
500349-40	50.65	48.24	29.12	54.32	11.86	0.73	0.66	0.36	0.87	0.14	0.68	0.62	0.57	0.93	0
500349-41	.84	52.60	14.19	50.70	16.17	0.7	0.71		0.72	0.09	0.69	0.87	0.49	0.82	

TABLE 4-21

COMPARISON OF HPGe AND THE AVERAGE RTRAK MEASUREMENTS WITHIN THE HPGe FIELD OF VIEW - DRUM BALING AREA

SAMPLE ID	Uranium-238 (ppm)			Thorium-232 (pCi/g)			Radium-226 (pCi/g)		
	HPGe	2 sec	4 sec	HPGe	2 sec	4 sec	HPGe	2 sec	4 sec
RSS-A3-15G	597	412	370	1.93	2.37	2.27	8.73	9.21	7.52
RSS-A3-17G	50	68	54	0.63	0.72	0.79	1.38	1.23	0.92
RSS-A3-18G	104	499	579	0.88	3.10	2.94	2.64	13.13	15.24
RSS-A3-19G	489	104	132	2.73	1.29	1.40	16.10	3.35	3.96
RSS-A3-22G	251	167	225	2.15	2.07	2.29	5.28	4.34	6.20
RSS-A3-25G	289	177	197	1.90	17.75	15.45	7.12	4.31	5.78
RSS-A3-27G	188	200	242	3.30	3.48	4.34	3.22	4.27	5.09
RSS-A3-30G	303	229	229	10.20	2.86	4.38	7.54	5.20	4.75

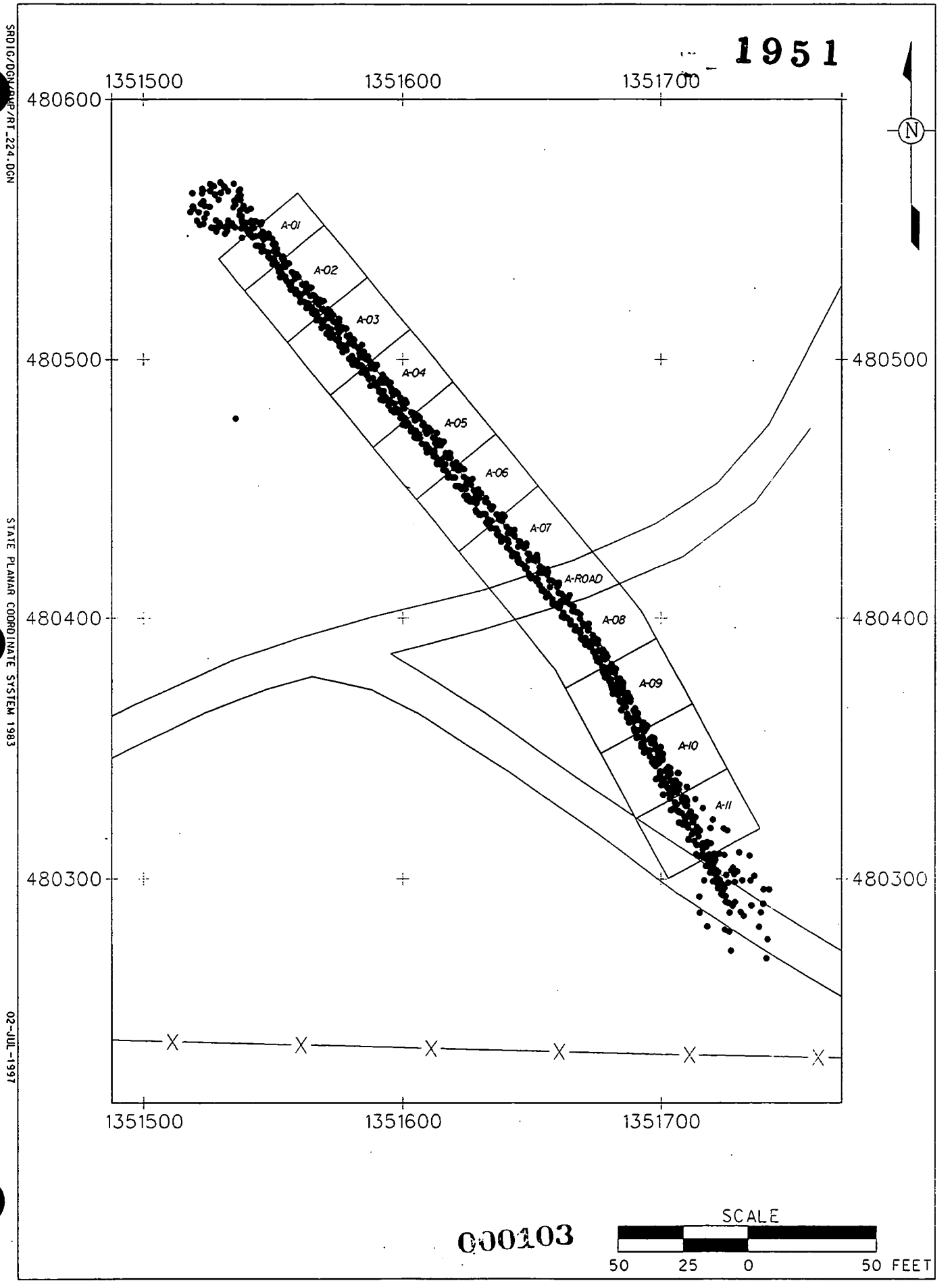
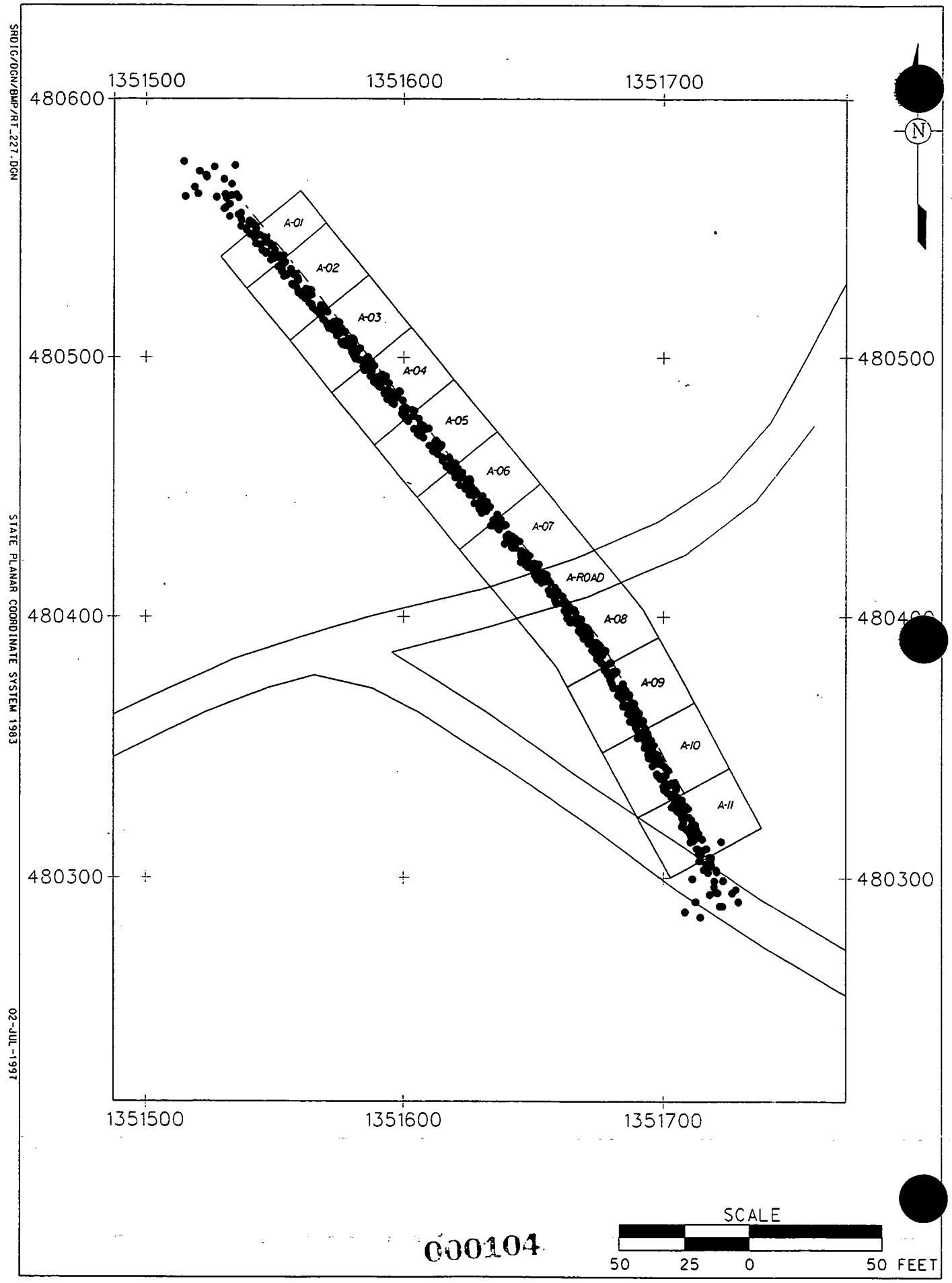


FIGURE 4-1A. CONFIGURATION AND MEASUREMENTS IN PROFILE SEGMENTS FOR U.S.I.D. AREA - 2 M.P.H. / 2 SEC. ACQUISITION



000104

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

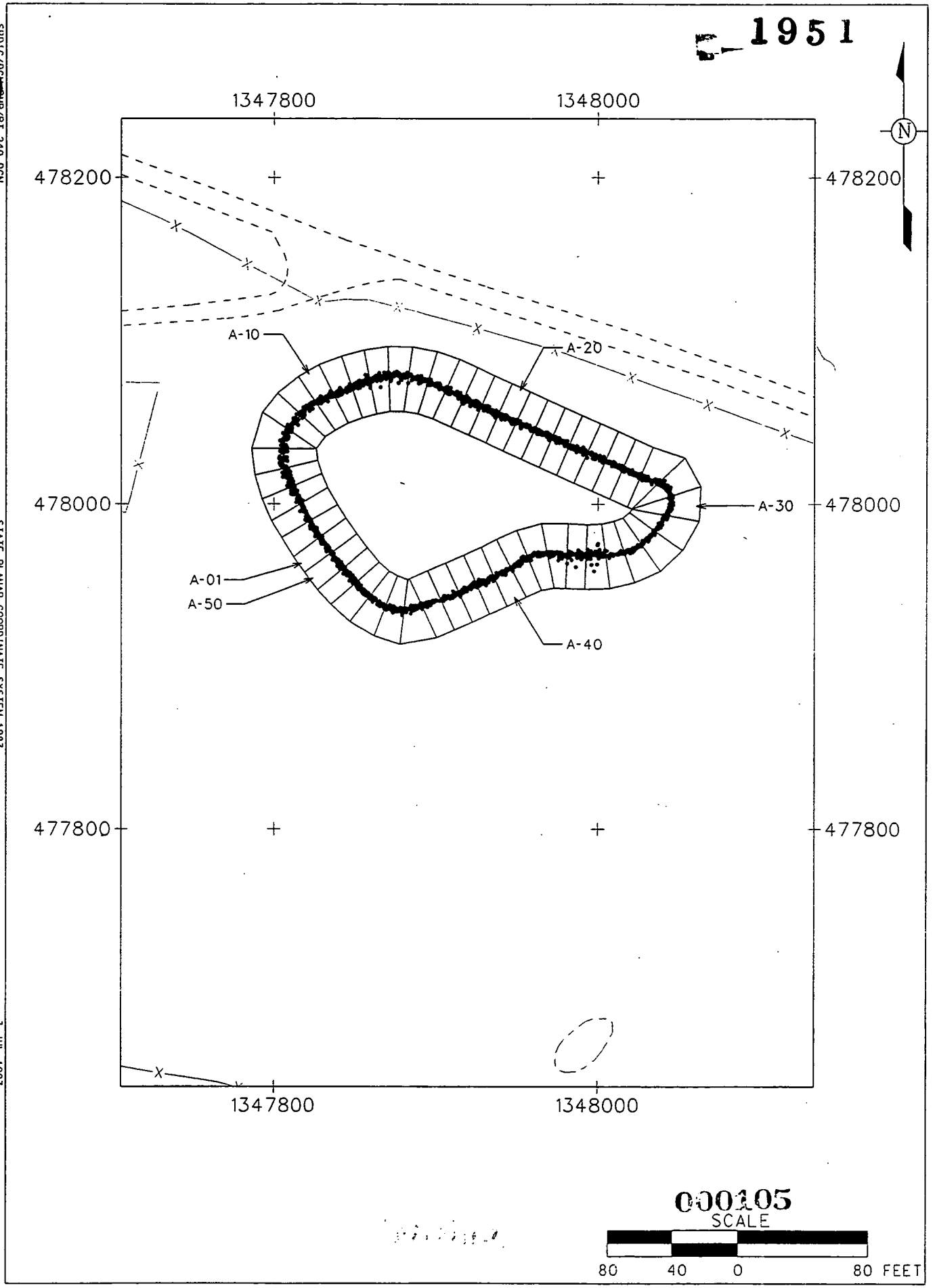
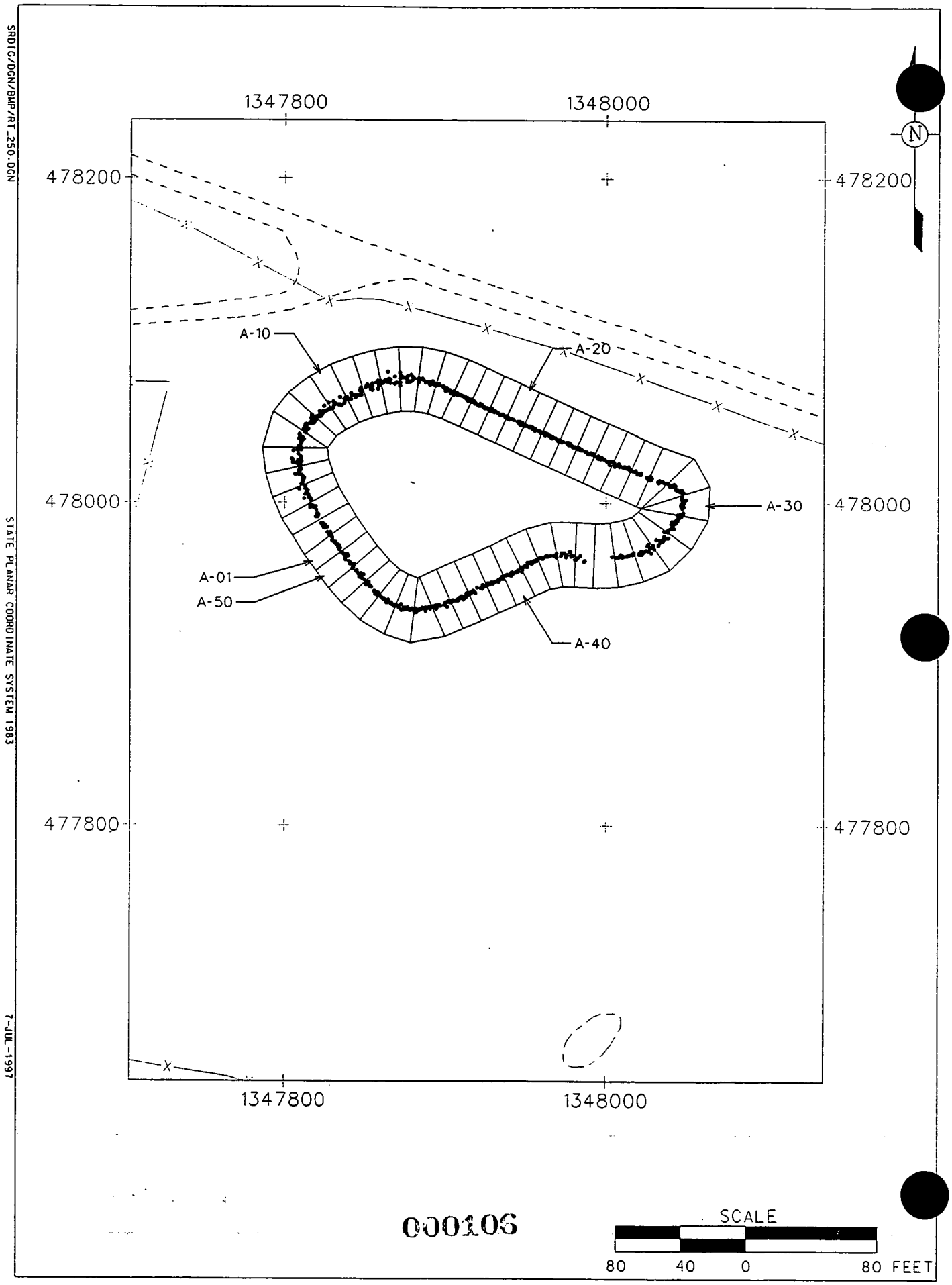


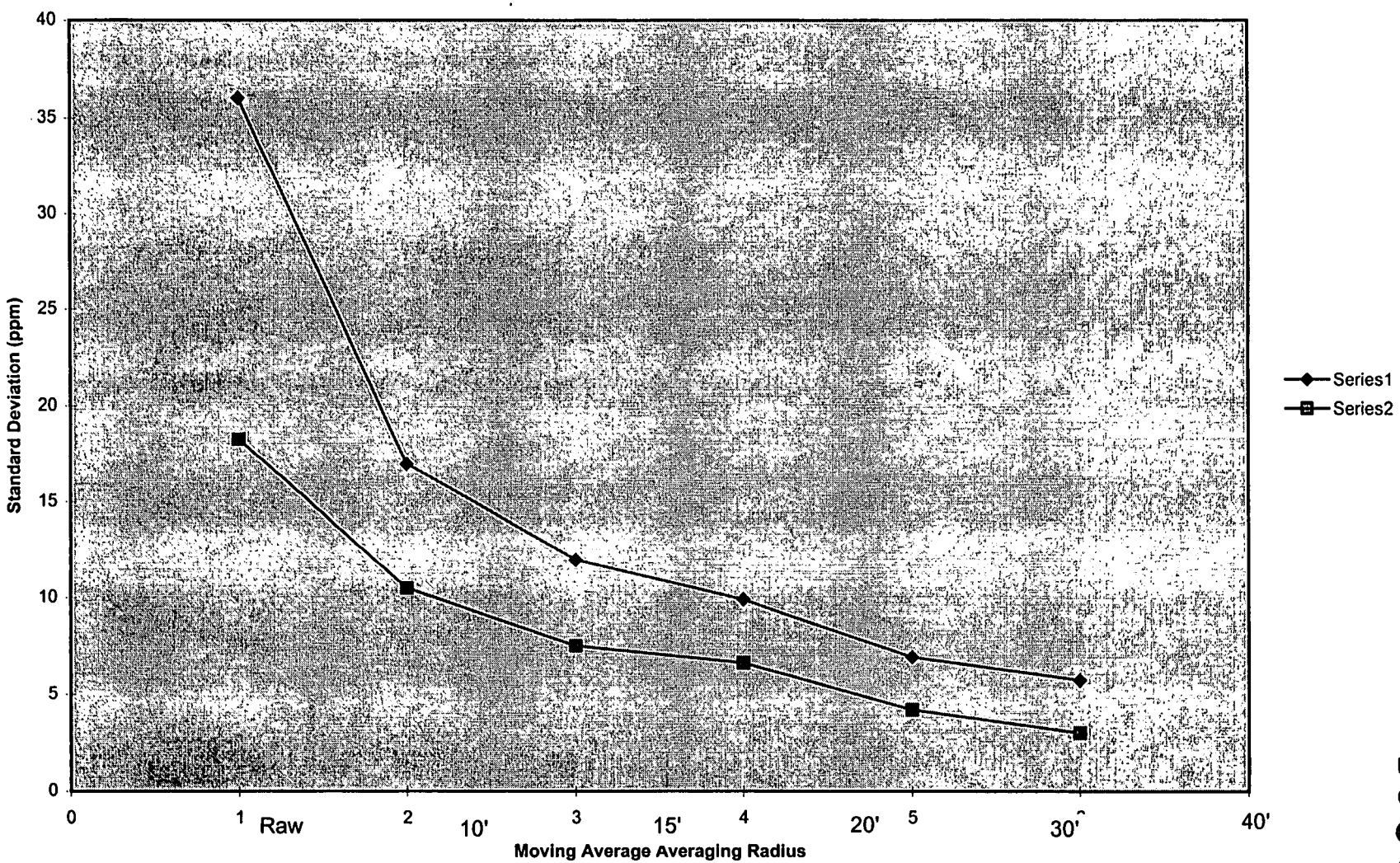
FIGURE 4-2A. CONFIGURATION AND MEASUREMENTS IN PROFILE SEGMENTS FOR SOUTH FIELD AREA - 2 M.P.H./ 2 SEC. ACQUISITION



000106

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

FIGURE 4-3
TOTAL URANIUM VARIABILITY AS A FUNCTION OF AVERAGING RADIUS



C00107

FIGURE 4-4
THORIUM-232 VARIABILITY AS A FUNCTION OF AVERAGING RADIUS

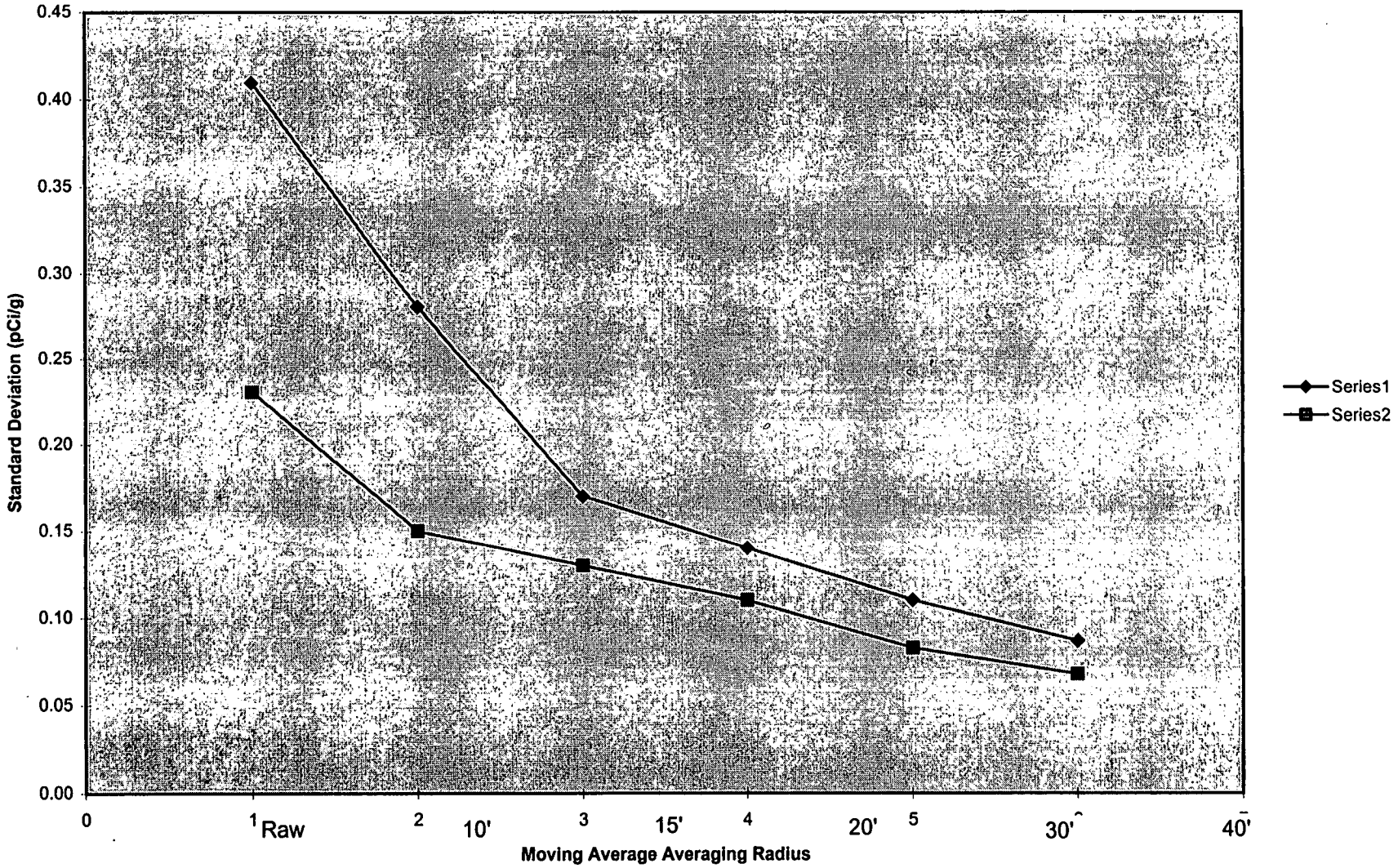
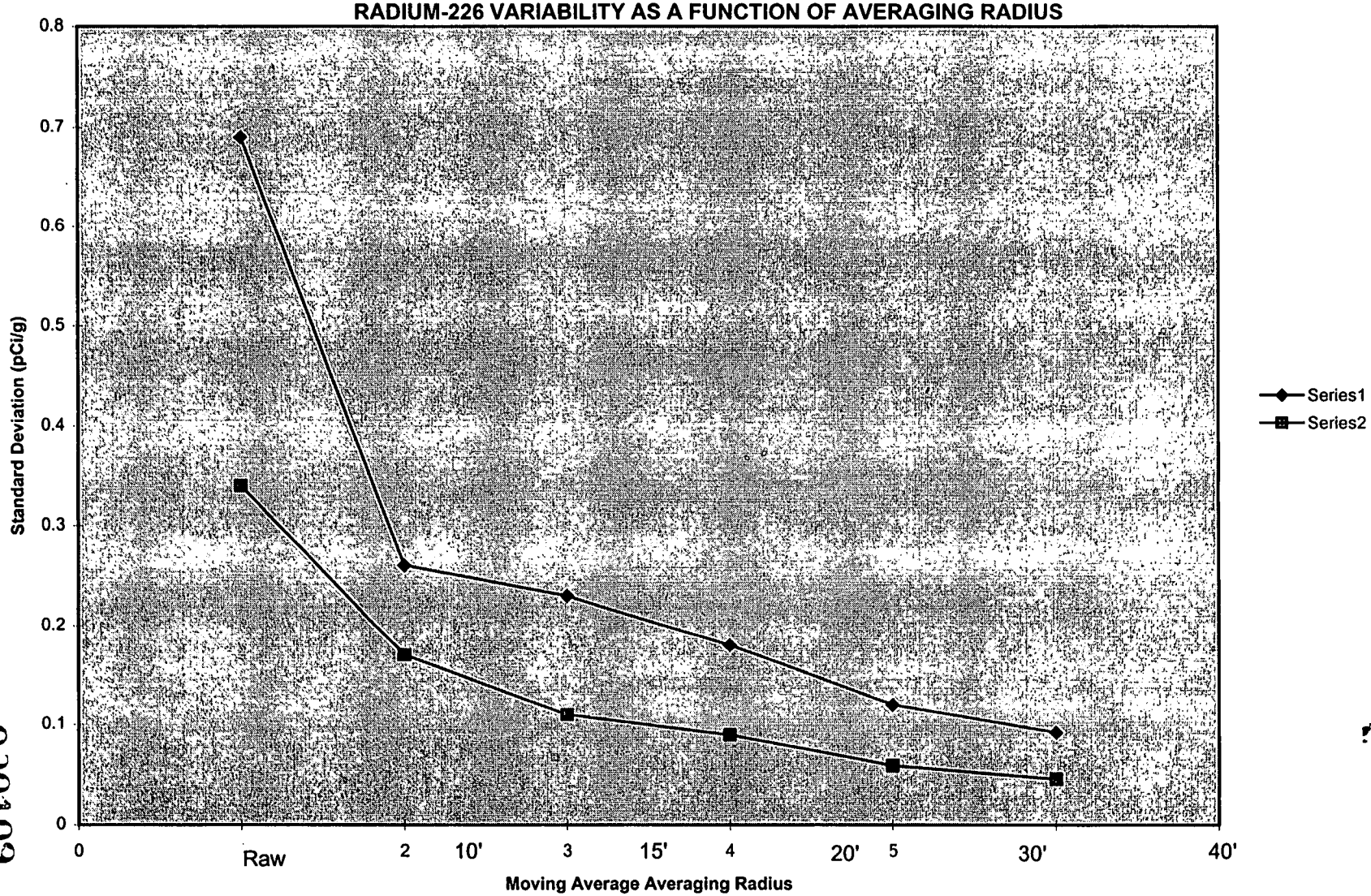


FIGURE 4-5
RADIUM-226 VARIABILITY AS A FUNCTION OF AVERAGING RADIUS



001009

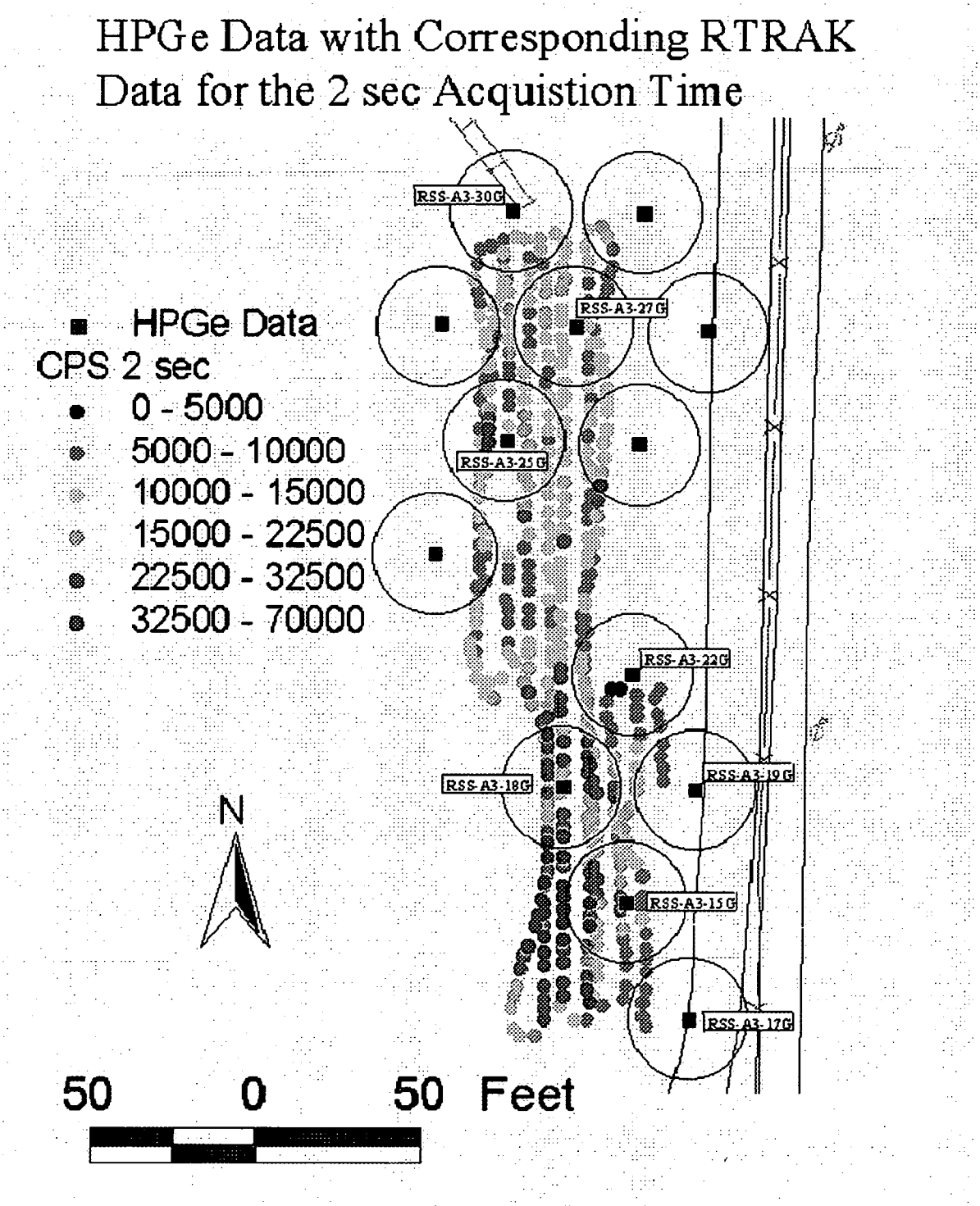


FIGURE 4-6 RTRAK Dynamic Measurements with Locations of Corresponding HPGe Measurements - 2-Second Acquisition Time

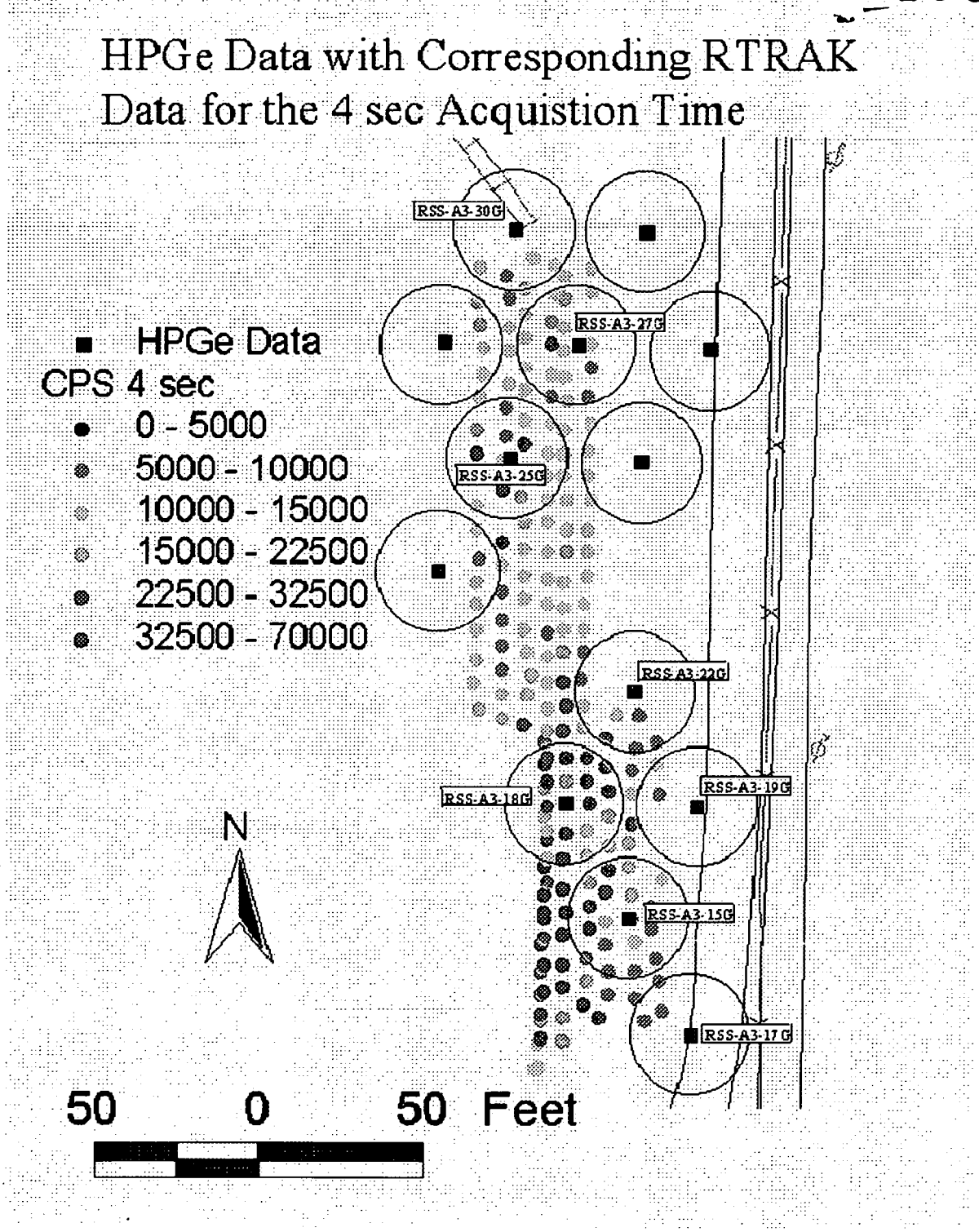


Figure 4-7 RTRAK Dynamic Measurements with Locations of Corresponding HPGe Measurements - 4-Second Acquisition Time

5.0 INTERFERENCES AND DATA REVIEW CRITERIA

5.1 SPECTRUM INTERFERENCES

The RTRAK/RSS system uses a NaI detector which has poor energy resolution in comparison to the germanium detectors typically used for gamma spectrometry. Consequently, it is not possible to readily separate peaks that are close to one another, and gamma photons with energies near those of analytes of interest can result in interferences that affect the accuracy of an RTRAK/RSS result. All three analytes of interest for RTRAK/RSS applications (uranium-238, thorium-232, and radium-226) can be affected by interfering gamma rays. The regions of interest for both the peaks and the backgrounds have been selected to minimize the interferences, and the calibration methodology attempts to take the interferences into account by utilizing multiple linear regression equations. However, when the activity of one or more of these analytes is significantly higher than the others, the interferences can be such that the results for the others will be inaccurate, irrespective of the compensating factors embodied in the calibration equations. The nature of gamma photon interferences are described below for thorium-232, radium-226, and uranium-238, and are summarized in Table 5-1.

5.1.1 Thorium-232

The gamma peak used for quantifying thorium-232 (from thallium-208) occurs at an energy of 2614 keV. There are no radionuclides present at the FEMP that will emit significant numbers of gamma rays at higher energies than either the peak or high-energy-background regions of interest for thorium-232. Consequently, the Compton continuum will contribute few counts in these regions and there are no interfering gammas at the high energy side of the peak or for the high-energy background region of interest. The low energy side of the peak and the low-energy background regions can experience interferences by gammas from the radium-226 decay chain. Bismuth-214, a radium decay product, has small abundance gamma rays at 2204, 2293, and 2448 keV. The 2448 keV peak falls within the thallium-208 peak region of interest, as will a portion of the 2293 keV peak. Some portion of all three bismuth-214 peaks will fall within the low-energy background region. Because these gamma rays have low abundances, they do not have an appreciable impact on the thorium-232 result when the radium-226 concentration is comparable to or lower than the thorium concentration. But when the radium-226 concentrations are much higher than thorium-232 concentrations, the interferences could become significant and would probably lead to the thorium-232 data being biased low.

There are insufficient data available to accurately quantify the impact of these interferences or to accurately determine the radium concentration at which they become significant. Spectra from static RTRAK measurements were visually examined for apparent interferences. On the basis of these examinations, it appears that interferences may become significant when the radium-226 net counts per second exceed the thorium-232 net counts per second by more than 50 percent. However, the available data do not allow the magnitude of the interference to be estimated at this time.

5.1.2 Radium-226

Radium-226 is quantified by the 1764 keV gamma photon emitted by its decay product bismuth-214. A member of the thorium-232 decay chain, actinium-228, emits several gamma photons between 1588 and 1666 keV; the low energy background window for the bismuth peak is 1644.2 - 1693.4. One of the actinium-228 gamma photons falls within the background region, and the others can contribute to the total number of counts within the radium-226 peak region. These gamma photons are low abundance, so they do not have a large affect when radium-226 and thorium-232 are present at comparable concentrations. However, in cases where the thorium-232 concentration is significantly higher than the radium-226 activity concentration, the interfering gamma rays significantly elevate the apparent background for the 1764 keV peak, resulting in an erroneously low value for the radium net counts per second.

There are insufficient data available to quantify the impact of these interferences or accurately determine the thorium concentration at which they become significant. Spectra from static RTRAK measurements were visually examined for apparent interferences. On the basis of these examinations, it appears that interferences may become significant when the thorium-232 net counts per second at 2614 keV exceeds 500; this is equivalent to approximately 30 pCi/g of thorium-232. The thorium-232 concentration at which the interferences become significant will depend upon the radium concentration; the higher the radium concentration, the higher the thorium concentration can be before the interferences become significant. Another indication of thorium decay chain interference is a large negative value for the radium-226 net counts per second. "Large" cannot be accurately quantified at this time, but a rule of thumb of 20 negative net counts per second has been tentatively defined as the interference threshold. There are insufficient data at this time to either better define the interference level or to estimate the magnitude of the interference.

5.1.3 Uranium-238

Uranium-238 is quantified by the 1001 keV gamma peak from its decay product protactinium-234m. This peak is subject to interferences from the decay chains of both thorium-232 and radium-226. The peak region of interest as well as both the high and low energy background regions have interfering gamma photons. Interfering gamma photons from thorium decay products, thallium-208 and actinium-228 occur within all three regions. Gamma photons from a radium-226 decay product, bismuth-214, occur within the peak region and the high energy background region; gamma photons from lead-214 are present within the low-energy background region. The 969 keV gamma photon from actinium-228 has an abundance of approximately 16 percent and so it presents interference problems regardless of the thorium concentration. However, it appears that this interference can be adequately accommodated by the calibration equations. The other gamma photons have low abundances, but at high thorium or radium concentrations, they become significant interferences, primarily by increasing the number of counts in the background regions. A clear indication of interference is a large negative value for the net counts per second for uranium-238. "Large" cannot be accurately quantified at this time, but a rule of thumb of more than 50 negative counts per second has been tentatively established. Thorium-232 activity in excess of 500 net counts per second is an indication of thorium interference with the uranium peak. There are insufficient data to determine the threshold concentration for interferences of uranium by radium.

5.1.4 System Counting Rate Effects

When the RTRAK electronics are processing a signal from a gamma photon that has been detected, the system is insensitive or "dead" to additional signals. When counting rates are low, this does not cause any problems because, in most cases, the processing is finished before another gamma photon is detected. However, as the counting rate increases, the number of counts that can be lost will increase as well. The system analyzer monitors the time that signals are being processed and computes a "live time" when the system can receive incoming counts, and a "dead time" when the system cannot receive incoming counts. The dead time is often stated as a percentage of clock time or "real time." For the RTRAK system, the nominal acquisition time (e.g., 4 sec) is equivalent to the real time, and the RTRAK software outputs a value called the accumulation time which is equivalent to the live time. The percent dead time is then given by the relationship:

$$\%\text{Dead Time} = (T_R - T_L)x100/T_R$$

where:

T_R = real time or nominal acquisition time
T_L = live time or accumulation time as reported by the RTRAK software

The electronics in the RTRAK system provide corrections to the counting rates that are adequate for the intended uses of the RTRAK data. However, high dead times are an indicator of other potential problems, particularly what is known as pulse pile-up. Pulse pile-up occurs when signals from the detector enter the amplifier so rapidly that they cannot be completely separated and portions of one signal may be added to the previous one; that is, the signals may "pile up" on one another. Pulse pile up can lead to degraded spectrum resolution, spectrum shifts, and in extreme cases, a complete absence of peaks in the spectrum. Any of these can lead to incorrect analyte concentrations. The dead time can be used as an indicator of the potential for pulse pile up. A threshold of acceptability of 20 percent dead time has been established on the basis of visual examinations of RTRAK spectra. At dead times in excess of 20 percent, the RTRAK results could be affected by pulse pile up and therefore require close scrutiny prior to use.

High dead time does not necessarily mean that measurement data do not provide useful information. In fact it is an indication that there is a source of high activity nearby. That source could be "shine" from a large quantity of radioactive material near the measurement location, or it could be a result of high concentrations of one or more of the analytes within the measurement location. When high dead times are observed, the locations should be flagged as potentially high activity areas that must be investigated by other techniques for verification or quantification.

5.2 DATA EVALUATION

5.2.1 Raw Isotopic Data

The interferences discussed above must be considered when determining whether RTRAK/RSS data can be used directly or whether they should be considered questionable. A number of criteria have been developed that can be used to identify data requiring further investigation. These are addressed in Section 5.1 and are summarized in Table 5-3. The table identifies the source of each interference, the criterion for flagging the result, and the analytes affected. Exceeding one of the criteria does not indicate that the data should be rejected as having no useful information. In general exceeding one of the criteria is an indication of a source of high activity within or near the measurement location. Such locations should be further investigated using the *in-situ* HPGe or discrete sampling.

5.2.2 Total Activity Data

The total activity data are obtained from the sum of all counts observed in the RTRAK spectrum divided by the data acquisition time. The total activity per second results have a high degree of precision and may be effective in defining general patterns of contamination, but they do not provide radionuclide-specific information. A high gross counts measurement may be a consequence of high activity concentrations of any of the analytes of interest, or some unknown radionuclide. Table 5-3 demonstrates the relationship between the total activity and the general levels of contamination. The values in the table are the averages and standard deviations of all the individual measurements collected in the repeated profile runs. Elevated concentrations of uranium, thorium, and radium are reflected in an increase in the number of gross counts per second.

Because both thorium-232 and radium-226 have relatively high gamma ray intensities, the total activity is affected more by their presence at elevated levels in the soil as compared to comparable levels of uranium which has much lower gamma intensities. A doubling of the thorium-232 or radium-226 above background will have a marked effect on the total activity whereas doubling background uranium would produce a negligible effect. Only with changes in the total uranium concentrations in the range of hundreds of ppm will the change be reflected in the total activity.

The data in Table 5-3 illustrate one risk inherent in the interpretation of the total activity data. The total activity in the South Field is about 3% lower than that in the USID area. However, the uranium-238 concentration in the South Field is about 7% lower than the concentration in the USID area, the radium-226 concentration in the South Field is approximately 1.5 times higher than in the USID area and the thorium-232 concentration is about 11% higher in the South Field. Thus although the total activity in the South Field in nearly equal to that in the USID area, the concentrations of the individual radionuclides differ, particularly for the radium-226, and these differences do not correlate with the relative total activities.

Additional perspective in interpreting total activity data can be garnered by examination of Figure 5-1. Based upon RTRAK data collected in the DBA (where total uranium concentrations cover a wide range), Figure 5-1 displays a general trend of increasing RTRAK total activity with increasing RTRAK total uranium concentrations. By bounding the data by upper and lower 95% confidence intervals from

a regression analysis, a level of 18,000 cps can be assigned as an indication of potential WAC exceedances.

The following general guidance has been developed for the interpretation of total activity data:

1. Total activity below 3000 cps indicates that total uranium, thorium-232, and radium-226 do not likely exceed the FRL. This applies for a total uranium FRL of 82 ppm, but does not hold for uranium FRLs of 10 or 20 ppm.

2. Total activity between 5000 and 15,000 cps likely indicates that one or more of the analytes - total uranium, thorium-232, or radium-226 - exceeds the FRL or may indicate a hot spot exceedance. Total activity above 18,000 cps may indicate a WAC exceedance. Areas with total activity in excess of 18,000 cps should be confirmed by *in-situ* HPGe.

3. In a given area, a range of concentration differences of 50% (high total activity relative to low total activity) may indicate a significant increase in concentration of one or more analytes.

4. Total activity measurements are intended for field use, to provide guidance on the need for additional RTRAK or HPGe measurements. The analyte-specific results should be used for final interpretation of contamination patterns.

TABLE 5-1
SUMMARY OF GAMMA PHOTON INTERFERENCES

Radionuclide of Interest	Radionuclide of Emission	Energy of Gamma Photon Used for Quantification (keV)	Radionuclide Emitting Interfering Gamma Photon	Energy of Interfering Gamma Photon (keV)	Effect of Interference
Thorium-232	Thallium-208	2614	Bismuth-214 (from Ra-226 decay)	2204 2293 2448	Bias Th-232 low
Radium-226	Bismuth-214	1764	Actinium-228	1644-1666 (4 gammas) 1887	Bias Ra-226 low
Uranium-238	Protactinium-234m	1001	Thallium-208 (from Th-232 decay)	982	Bias U-238 high
				860 1093	Bias U-238 low
			Actinium-228 (from Th-232 decay)	969	Bias U-238 high
				944-1033 (7 gammas)	Bias U-238 high
				835 840 1065 1095	Bias U-238 low
			Bisumth-214 (from Ra-226 decay)	964	Bias U-238 high
				1069 1120	Bias U-238 low
			Lead-214 (from Ra-226 decay)	839	Bias U-238 low

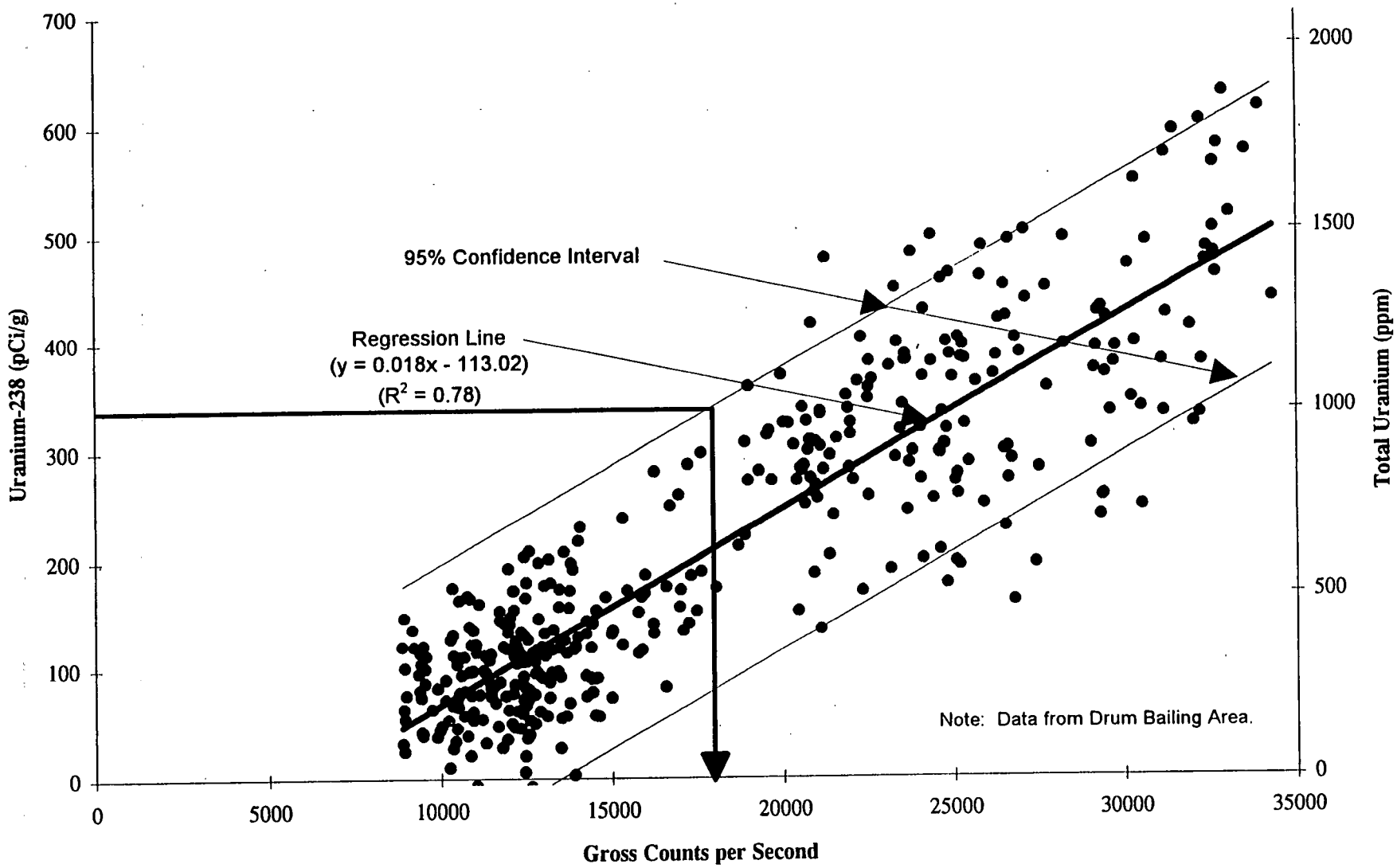
TABLE 5-2
INDICATORS OF POTENTIAL RTRAK/RSS INSTRUMENTAL PROBLEMS OR SPECTRAL INTERFERENCES DURING DATA ACQUISITION

Flagging Criterion	Interference Source	Analytes Affected	Comments
Dead Time > 20 %.	Counting Rate	Thorium Radium Uranium	May indicate high activity concentration of one or more analytes or nearby source of activity resulting in "shine"
More than 20 negative net thorium counts per second..	Spectrum shifts; Electronics failure	Thorium Radium Uranium	May indicate that spectrum shifts have caused peaks to fall outside of analyte regions of interest
Thorium net counts per second >500.	Thorium	Radium Uranium	May indicate that sources of high thorium activity are causing interferences.
More than 20 negative net radium counts per second.	Thorium	Radium Uranium	May indicate that sources of high thorium activity are causing interferences.
More than 50 negative net uranium counts per second.	Thorium Radium	Uranium	May indicate that sources of high thorium or radium activity are causing interferences.

TABLE 5-3
COMPARISON OF RTRAK GROSS ACTIVITY DATA TO RTRAK ISOTOPIC DATA AT 0.5 MPH WITH AN EIGHT SECOND DATA ACQUISITION TIME

Area	Uranium-238 (pCi/g)		Thorium-232 (pCi/g)		Radium-226 (pCi/g)		Total Activity (gross cps)	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
USID	16	5	0.75	0.17	0.79	0.27	2990	293
South Field	15	6	0.80	0.41	1.20	0.82	2907	916
Drum Baling	94	56	3.16	1.41	6.36	3.91	15,643	5523

FIGURE 5-1
URANIUM CONCENTRATIONS VS GROSS COUNTS



6.0 SUMMARY AND CONCLUSIONS

The RTRAK was calibrated against HPGe by making measurements at the same location using both systems. For these measurements, the RTRAK was operated in a static mode. The calibration equations were derived by performing a multiple linear regression on the HPGe and RTRAK measurement data. The forms of the equations are designed to compensate for interferences from gamma rays other than the primary one in each region of interest. In general, the equations are more effective at compensating for the interferences than previous equations, although there is a high positive intercept for uranium. This may be an indication that the equations overcompensate at low concentrations. This presumably occurs because several of the calibration measurements had high concentrations of thorium-232 and radium-226, both of which interfere with the uranium region of interest. The strong interferences in the data set may have resulted in excess weighting of the interference compensation. The consequence of the high intercept is that RTRAK measurements with low uranium concentrations may be biased high, particularly in areas with very low thorium and radium concentrations. Because of the potentially high bias, uranium-238 concentrations below approximately 50 ppm or 17 pCi/g should be considered questionable.

There is very good agreement between HPGe measurements and the RTRAK operating both statically and dynamically, for measurements made in the USID area. Differences can be attributed to differences in the fields of view of the HPGe and RTRAK systems. Poorer agreement was observed for both static and dynamic RTRAK measurements in the DBA. Comparisons for the dynamic RTRAK data in the DBA are not meaningful because obstructions and the terrain did not allow complete coverage of the fields of view of the corresponding HPGe measurements. In addition, for the HPGe measurements that did have reasonable coverage, there activity distribution was very heterogeneous. The consequence of these problems is that no conclusions could be drawn from the DBA data. These data was intended to provide a comparison of RTRAK with HPGe in a location of elevated analyte concentrations. Unfortunately, measurements of this sort are most practical in areas with relatively homogeneous analyte distributions. As a general rule, at the FEMP, areas that have elevated analyte concentrations tend to have very heterogeneous distributions. However, on the basis of the excellent agreement for measurements in the USID area, it can be concluded that RTRAK results agree well with HPGe.

The counting uncertainties are major contributors to the total uncertainty of the measurements, particularly at low concentrations. The uncertainty can be reduced by increasing the acquisition time. The counting uncertainty will decrease by the square root of the factor by which the acquisition time is increased. This will decrease the total uncertainty, but not proportionately because the other contributors to the total uncertainty are not acquisition-time dependent. At high concentrations, the systematic uncertainties associated with the RTRAK calibration tend to dominate the total uncertainty. This is to be expected because the magnitudes of these contributions are calculated as a fixed percentage of the measured activity. The relative uncertainty associated with each of these parameters remains constant while those of the counting and instrument/operational uncertainties decrease with increasing analyte concentration.

Tables 4-5 through 4-11 summarize the contributions of various sources of uncertainty to the overall standard deviation of the measurements and provide estimates of the total uncertainty for individual RTRAK measurements at various analyte concentrations. The concentrations include the FRLs, hot spot criteria, and the total uranium WAC. These estimates are based on the minimum expected standard deviations, counting uncertainties, and systematic uncertainties discussed in Section 4. Actual measurements are likely to have different total uncertainties primarily because of variations in the relative concentrations of the radionuclides. However, these estimates are appropriate to characterize the RTRAK quality parameters and are useful for planning purposes.

The high standard deviations for the individual RTRAK measurements limit their usefulness at analyte concentrations near background. However, at higher concentrations, the fractional standard deviation (standard deviation as a fraction of the concentration) becomes relatively small even for uranium. In addition, a number of measurements can be combined, or aggregated, to obtain a measurement with a lower standard deviation. The disadvantage to the use of aggregated measurements is that spatial resolution is lost. However, when the goal is to determine the concentration of an analyte averaged over a large area, the aggregation of a large number of measurements can provide data with a high degree of precision. The standard deviations of aggregated measurements were calculated and incorporated in the calculation of trigger levels (Tables 4-16 through 4-18).

Total activity results have high precision for the individual measurements because of the large number of counts and consequent low relative counting uncertainty. This would allow these data to be used

even at concentrations near background. Because these data provide no radionuclide-specific information, they are of only limited usefulness in cases where knowledge of concentrations of individual analytes is needed. However, general trends have been identified that allow the data to be of use in field evaluations of data. Evaluation criteria based on these trends are discussed in Section 5.2. In addition, because a single measurement covers an area of only 8.8 square meters, the total activity data can provide excellent spatial resolution when determining general patterns of contamination (total activity measurements do not have to be aggregated).

The MDCs for individual measurements are near or greater than the the FRLs for all three radionuclides of interest for the three acquisition times evaluated. The guideline provided in MARSSIM for the MDC for radiological scanning measurements is 10% - 50% of the applicable limit. Single-measurement MDCs exceed the MARSSIM criteria for the FRLs for the three analytes of concern for all three acquisition times evaluated. Single-measaurement MDCs satisfy MARSSIM criteria for hot spots (both 2xFRL and 3xFRL) thorium-232 and radium-226 and uranium-238 at the 82 ppm FRL, at all three acquisition times. The single-measurement MDCs are also adequate for the uranium WAC.

The relatively poor energy resolution of the detector in the RTRAK system results in a number of gamma photon interferences that must be considered in evaluating the data. Interferences are of particular concern in areas with high concentrations of thorium-232 or radium-226, which can lead to erroneous results. Effects and consequences of interferences and related phenomena are summarized in Tables 5-1 and 5-2.

The results and evaluations in this report lead to the following general conclusions:

1. **The preferred operating conditions are 4 second acquisition time with a travel speed of 1 mph.** The precision studies demonstrate that increasing the acquisition time improves the precision of the measurements. For the studies, the 8-second acquisition time provided the best precision. However, it is necessary to balance the precision against spatial resolution and logistical considerations. To maintain a constant field of view for the RTRAK in a dynamic mode, it is necessary to reduce the travel speed by a factor equivalent to any factor increase in the acquisition time. Field experience has shown that with the current engine speed and transmission, it is difficult for the RTRAK operator to maintain a travel speed of below 1 mph while also adequately controlling the direction of travel. In addition, as the travel speed is reduced, the amount of time required to scan an area increases. If the required scanning time is too

large, the utility of the RTRAK is reduced. The combination of 4 sec/1 mph was selected because it presented the best balance between precision and logistical consideration.

2. **The current calibration equations provide good agreement with HPGe at high except at low uranium concentrations.** The agreement is good over the full range of concentrations evaluated for thorium-232 and radium-226. For uranium-238 at low concentrations, the calibration equation may yield results with a high bias, particularly when the thorium and radium concentrations are near background levels.

3. **Spectrum interferences increase as the concentrations of thorium-232 and radium-226 increase.** All three analytes of interest (uranium-238, thorium-232, and radium-226) are subject to interferences from one or more of the other analytes. Uranium-238 is the most severely affected. In areas where thorium-232 or radium-226 are of the order of tens of pCi/g, the uranium-238 results are questionable, and spectra need to be carefully examined to determine whether the interferences preclude their use. Radium-226 results may also be affected when thorium-232 is in the range of 30 pCi/g or higher, and again, spectra must be examined to determine the impact of the interferences. At high radium-226 concentrations, thorium-232 may be biased low; data are not yet available to quantify the level at which the interferences become significant. Tables 5-1 and 5-2 summarize the interferences and criteria to be used to identify spectra requiring careful examination.

4. **High total uncertainties limit the usefulness of individual measurements at low concentrations.** For total uranium, the total uncertainty for a single measurement (4 sec/1 mph) at the FRL of 82 ppm is 25 ppm (30% of the FRL). At WAC levels, the total uncertainty for total uranium is 172 ppm, or 17% of the WAC. The percent uncertainties for thorium-232 and radium-226 are smaller than for uranium-238, but they are still significant for concentrations near the FRLs. At the FRL, the total uncertainty (at 4 sec/1 mph) is 0.37 (25% of the FRL) for thorium-232 and 0.51 (30% of the FRL) for radium-226. Total uncertainties are presented in Tables 4-9 through 4-11.

5. **Spatial averaging or aggregation of measurements can be used to improve precision, but at a loss of spatial resolution.** Individual measurements can be aggregated or spatially averaged to obtain a result with improved precision. When such averaging is performed, the appropriate precision parameter is the standard deviation of the mean which decreases with the square root of the number of measurements. However, aggregating measurements increases the size of the area for which the calculated value applies, thus degrading the spatial resolution.

6. **Single-measurement MDCs meet MARSSIM criteria for scanning measurements for hot spots or WAC.** The MARSSIM guideline for MDCs for scanning measurements is that the MDC should be between 10% and 50% of the applicable limit such as FRL, hot spot, or WAC. The MDCs for single RTRAK measurements meet the criteria for WAC, uranium hot spots for the 82 ppm FRL, and for thorium and radium hot spots. Measurements must be aggregated to meet the criteria for FRLs,

except for thorium-232 with an acquisition time of 8 seconds, and uranium hot spots where FRLs are 10 or 20 ppm.

7. **Trigger levels can be used to facilitate the use of the RTRAK .** A trigger level is defined as a value, that if exceeded by a measurement, would require further action. The total uncertainties were used to calculate trigger levels that can be used during field activities. To achieve acceptable trigger levels, measurements must generally be aggregated. In general, aggregation of two consecutive measurements is sufficient for WAC and hot spot determinations. Tables 4-16 through 4-18 provide trigger levels for the FRLs and WAC.

8. **Total activity data (gross count rates) can be used for preliminary field screening and determining overall patterns of contamination.** Total activity data, or gross count rates, do not provide any information on specific radionuclide concentrations, and so are of limited value. However, these measurements exhibit high precision and provide excellent spatial resolution for determining overall patterns of contamination. An increase in gross counts means that one or more of the analytes of interest has increased in concentration, but it cannot be determined which analytes are responsible for the increase without further information. Despite that difficulty, an evaluation of the trends seen in the total activity has allowed the establishment of some general guidelines for its use in the field. These guidelines are detailed in Section 5.2.2.

9. **The studies described in this report provide estimates of key quality parameters, uncertainty and MDC.** The repeated profile measurements provided the field measurement data to form the basis for calculating total uncertainties and analyte-specific MDCs. These are discussed in detail in Sections 4.3 and 4.5 respectively. Table 6-1 summarizes these parameters for the preferred set of operating conditions, 4 sec/1 mph.

TABLE 6-1
SUMMARY OF RTRAK QUALITY PARAMETERS
(4 seconds/1 mph Operating Conditions)

Quality Parameters 4 sec/1 mph	Uranium-238	Thorium-232	Radium-226	Gross Counts
Total Uncertainty (at the FRL[a])	8 pCi/g 25 ppm[b]	0.37 pCi/g	0.51 pCi/g	194 cps[c]
MDC[d]	31 pCi/g 63 ppm[b]	0.91 pCi/g	1.08 pCi/g	NA
Spectrum Interference	thorium radium	radium	thorium	NA

[a] For total uranium FRL of 82 ppm (equivalent to 27 pCi/g uranium-238)

[b] ppm refers to total uranium

[c] there is no applicable FRL for gross counts, this is the average standard deviation for South Field repeated profile measurements with an average mean of 2893 cps)

d MDC with a 4 second acquisition time is estimated from measurements with an 8 second acquisition time

REFERENCES

Currie, L.A., 1968, "Limits for Qualitative Detection and Quantitative Determination." Analytical Chemistry, Vol. 40, No. 3, pp. 586-593.

U.S. Department of Energy, 1997a, "Comparability of In-Situ Gamma Spectrometry and Laboratory Data," 20701-RP-0001, Revision 0, DOE, Fernald Environmental Management Project, Cincinnati, OH.

U.S. Department of Energy, 1997b, "RTRAK Applicability Study," 20701-RP-0003, Revision 0, DOE, Fernald Environmental Management Project, Cincinnati, OH.

U.S. Department of Energy, 1997c, "Comparability of Total Uranium Data as Measured by *In-Situ* Gamma Spectrometry and Four Laboratory Methods," Addendum to 20701-RP-0001, DOE, Fernald Environmental Management Project, Cincinnati, OH.

U.S. Department of Energy, 1997d, "Comparability of *In-Situ* Gamma Spectrometry and Laboratory Measurements of Radium-226," Second Addendum to 20701-RP-0001, DOE, Fernald Environmental Management Project, Cincinnati, OH.

U.S. Department of Energy, 1997e, "Effect of Environmental Variables upon *In-Situ* Gamma Spectrometry Data," Third Addendum to 20701-RP-0001, DOE, Fernald Environmental Management Project, Cincinnati, OH.

U.S. Department of Energy, 1997f, "RTRAK Applicability Measurements in Locations of Elevated Radionuclide Concentrations," Addendum to 20701-RP-0003, Revision 0, DOE, Fernald Environmental Management Project, Cincinnati, OH.

U.S. Department of Energy, 1998a, "User Guidelines, Measurement Strategies, and Operational Factors for Deployment of In-Situ Gamma Spectrometry at the Fernald Site," 20701-RP-0008, DOE, Fernald Environmental Management Project, Cincinnati, OH.

U.S. Department of Energy, 1998b, "Sitewide Excavation Plan," 2500-WP-0028, Revision 0, DOE, Fernald Area Office, Fernald, OH.

U.S. Department of Energy, 1998c, "Real-Time Instrumentation Measurement Program Quality Assurance Plan," 20300-PL-0002, Revision 0, DOE Fernald Environmental Management Project, Cincinnati, OH.

U.S. Department of Energy, 1998d, "In-Situ Gamma Spectrometry Quality Control Measurements," ADM-16, Revision 0, DOE, Fernald Environmental Management Project, Cincinnati, OH.

U.S. Department of Energy, 1998e, "Comparability of In-Situ Gamma Spectrometry and Laboratory Data," 20701-RP-0001, Revision 1, DOE, Fernald Environmental Management Project, Cincinnati, OH.

U.S. Nuclear Regulatory Commission, U.S. Environmental Protection Agency, U.S. Department of Energy, and U.S. Department of Defense, 1997, "Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM), Nureg-1575, EPA 402-R-97-016, Washington DC.

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APPENDIX A

THE RTRAK SYSTEM

APPENDIX A
THE RTRAK SYSTEM

A.1 GENERAL DESCRIPTION

The RTRAK is a gamma-ray spectrometry system mounted on a four-wheel drive John Deere tractor which serves as a mobile counting platform. This platform carries a low resolution 4x4x16-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-inch diameter 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 gamma ray detector consists of a large single crystal of sodium iodide which is optically coupled to a photomultiplier tube (PMT). When radiation particles or rays strike the NaI crystal it emits light or scintillates. Detectors which work on this principle are referred to as scintillation detectors. It is crucial to the accuracy of devices which use this principle that the amount of light emitted when radiation strikes the detector be proportional to the energy absorbed by the crystal, which, in turn, is proportional to the energy of the radiation that caused the scintillation. The principle of scintillation is briefly discussed below.

When gamma rays emitted from radioactive nuclei strike the NaI detector, some or all of the energy of the gamma rays causes the atomic electrons to make transitions to higher energy states, thereby resulting in the absorption of the gamma rays. When these excited atoms return to their more stable ground state, the energy that was absorbed is re-emitted in the form of visible light. This process in which nuclear radiation impinging on a detector results in the production of light flashes or pulses is called "scintillation" and the detector is said to be a scintillation detector.

To be measured, the light emission must be converted to an electronic signal. This process occurs in the photomultiplier tube. Sodium iodide (NaI) detectors emit light that has too high a frequency to be seen in most PMTs. To shift the light frequency to a region visible by the PMT, an additive called an

activator is added to the 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).

When the PMT is optically coupled to the NaI(Tl) detector, light photons emitted by the crystal strike a photosensitive surface in the PMT where the light energy causes one or more electrons to be ejected from the "photocathode." These liberated 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 (PHA). The height of the resultant voltage pulse is proportional to the energy of the radiation that caused it.

In the NaI(Tl) detector the minimum energy required to record a radiation event is quite high compared to that required by a high purity germanium (HPGe) detector. In order for a signal to be generated, an electron in the crystal must be excited from the valence band to the conduction band. When the excited electron returns to a lower energy state, light photons are emitted. For NaI(Tl) crystals, this process requires approximately 30 eV of energy. By comparison, the corresponding process in a HPGe detector requires only about 0.6 eV. Because the NaI(Tl) requires so much more energy to produce a detection signal, its energy resolution is much poorer than a HPGe detector. In practical terms, this means that the peaks in a NaI spectrum are much broader than those in a HPGe spectrum. If one used both detectors to look at a radioactive standard containing cesium-137 (Cs-137), the NaI detector would result in a peak full width at half the maximum peak height (FWHM) of about 55 Kev, whereas the HPGe peak width would be approximately 2 Kev. This means that two gamma rays which differ in energy by 30 to 40 Kev would appear as one broad peak in a sodium iodide spectrum, but they would appear as two well-separated peaks in a HPGe spectrum. The lower resolution of sodium iodide detectors does present some limitations on their use, but these are not serious limitations in most situations encountered at the FEMP.

A.3 MULTI-CHANNEL PULSE HEIGHT ANALYSIS SYSTEM

The technique of gamma ray spectrometry makes use of the fact that for many nuclides, the energies of the gamma photons constitute a pattern unique to the particular isotope which emitted them. Much like a human fingerprint can be used to identify an individual, when gamma photons are detected they indicate the presence of specific isotopes. For example, all potassium-40 (K-40) nuclei emit photons with an energy of 1460.8 Kev, while Cs-137 nuclei emit gamma rays with an energy of 661.6 Kev. As

stated above, the NaI detector is a useful tool for the measurement of gamma ray energies because the height of the output voltage pulse from the PMT is directly proportional to the energy of the photon which initiated it. Thus we can determine the number of gamma rays of a specific energy which are detected in a fixed period of time by counting the number of voltage pulses which are generated in the PMT with a certain height. This number is related to the amount of a specific radioactive isotope which is emitting the detected gamma rays.

The function of determining pulse heights and counting them is performed electronically by an instrument called a multichannel pulse height analyzer (MCA). This instrument measures the height of each voltage pulse coming from the photomultiplier tube and counts the number of pulses that occur in each one of a set of predefined voltage ranges. A separate count of the number of pulses that occurs in each range is performed simultaneously and stored in unique memory registers called channels, with one channel for each voltage. Since the pulse heights are proportional to the energies of the gamma rays that were responsible for the generation of the pulses, the MCA system allows the collection of a gamma ray energy spectrum, which can be analyzed to identify and quantify radioactive isotopes that are present within the detector's field of view. The MCA instrument permits the simultaneous identification of many nuclide decay energies during a single analysis. The RTRAK PHA counting system is coupled to a computer containing commercially available gamma spectral analysis software. Gamma peaks displayed in the spectrum are identified by comparing the peak energies to known characteristic isotopic photon decay 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 each identified nuclide. The RTRAK counting system may also be used as a gross survey instrument by summing the total counts in the spectrum. This feature is useful in discriminating between areas of high and low activity.

A.3.1 RTRAK Energy Calibration

Since the pulse height is proportional to the energy of the gamma ray that was responsible for the generation of t he pulse, the MCA system allows the collection of a gamma ray energy spectrum. The output of the MCA is a gamma ray spectrum which consists of a count of the number of gamma photons detected as a function of the photon energy. Peaks in these spectra occur at energies which are characteristic of the radionuclides present in the soil and other surroundings. But, in order to make use of this information, the energy at which the spectral peaks occur must be identified. The process of

energy calibration is accomplished by exposing the NaI detector to a radioactive source which contains radioisotopes of known identity. By knowing the energy of the photons emitted by the isotopes in the radioactive source and identifying from the accumulated spectrum the channel number where the maximum count in each peak occurs, one can develop an equation which describes the relationship between the channel number at which a spectral photopeak occurs and the energy of that photopeak.

This process is described in FEMP procedure EQT-30, "Operation of Radiation Tracking Vehicle Sodium Iodide Detection System." Lantern mantles containing radioactive thorium-232 (Th-232) and its decay progeny are used as an energy calibration source for the RTRAK. This is a particularly convenient source to use for calibration because it emits both low energy and high energy gamma rays which span the energy region of interest for the remediation projects at the FEMP. The RTRAK detector system is energy calibrated before each use by placing the thorium mantle in the center of the detector housing and acquiring a spectrum. If necessary, the pulse amplifier is adjusted so that the centroid of the photopeak at energy 238.6 Kev falls in MCA channel 40, while at the same time, the centroid of the photopeak at energy 2615 Kev falls in channel 447. Lead-212 (Pb-212) is the source of the 238.6 keV gamma ray, while the 2615 Kev gamma ray originates from thallium-208 (Tl-208). Both of these isotopes are radioactive daughters of Th-232. When the system is adjusted as described above, the slope of the energy versus channel number graph is equal to 5.85 Kev per channel. Thus a peak which appeared in channel 171 would correspond to an energy of 1000 Kev (171 times 5.85). Peaks do appear in RTRAK spectra near this channel and they may be attributed to the 1001 Kev peak from Pa-234m, a radioactive daughter of U-238. The presence of a peak at this energy is used by the FEMP in-situ measurements staff to infer the presence of U-238 in the soil scanned by the RTRAK.

As noted earlier, sodium iodide is a low resolution detector which results in fairly broad peaks in the accumulated gamma spectra. Regions of interest (ROIs) which span the full width of each photopeak must be defined and the counts in all the MCA channels within the ROI must be summed to ensure counting all the events associated with a particular gamma emission. The regions of interest or energy windows for the primary radiological contaminants of concern at the FEMP are given in Table A-1. The boundaries of the windows are chosen so that they are wide enough to accept as many counts as possible from the nuclide of interest without allowing undue interference from other peaks in the spectrum. Also shown in Table A-1 are the windows used to subtract the background from the signal windows. These also represent a compromise between windows wide enough to accurately

characterize the background near the peak of interest and windows narrow enough to exclude interferences from other photopeaks. As described elsewhere in this report, steps must be taken when developing the calibration equations to compensate for interferences in both the signal and background windows.

A.3.2 RTRAK Efficiency Calibration

After properly completing an energy calibration, the NaI detector can be used to determine the identity of the radioisotopes in the soil scanned by the RTRAK provided that the photon energies are at least 70 Kev apart. However, in order to use the RTRAK to also determine how much of each radionuclide is present, one must relate the number of gamma ray counts of a particular energy registered by the counter to the amount of the corresponding radionuclide present in the in the soil. In a laboratory setting, this would be accomplished by reproducibly positioning and counting a container filled with an accurately known quantity of a radioactive standard for a fixed period of time. Such radioactive standards may be purchased along with certificates documenting their activity from the National Institute of Standards and Technology (NIST) or other vendors who maintain measurements programs which are traceable to NIST. The detection efficiency would be computed simply as the ratio of the number of gamma photons of a specified energy detected in a fixed period of time divided by the number of photons of that energy emitted by the standard in the same time interval. Since some of the photons emitted from the standard don't travel toward the detector, while others travel through the detector material without interacting at all, the computed efficiency will be a number between zero and one. The efficiency will vary with photon energy. If all the measurement conditions that prevailed during efficiency calibration are the same when samples are counted (e.g., distribution of radionuclides in the material being counted, the size, shape and composition of the counting container, and the relative position of container and detector) the measurement process will be accurate.

Since the RTRAK was designed as an in-situ measurement system, it is not practical to purchase and use certified standard materials to reproduce the calibration process described above. However, if one has multiple field locations which have been accurately characterized, these may be used to experimentally determine the relationship between the concentration of a particular radionuclide in the soil and the count rate detected by RTRAK for that isotope. This process was described in the July 1997 RTRAK Applicability Study (DOE 1997b). That study made use of a separate study conducted at the FEMP in which the comparability of laboratory analyses with in-situ gamma

spectrometry measurements using hyper-pure germanium detectors (HPGe) was demonstrated. The present RTRAK study makes use of the same calibration technique, but the calibration range is extended to higher analyte concentrations.

As in the previous RTRAK report, the efficiency of the RTRAK detector was determined by comparing static RTRAK measurements to HPGe readings at the same locations. HPGe measurements taken with a detector height of 31 cm were used as the basis for "known" concentrations of U-238, Th-232, and Ra-226. This height was used because it gave the best match between the fields of view of the two detectors. Multiple linear regression analyses of the net RTRAK counts per second versus the soil radionuclide concentrations were performed to derive a calibration equation which can be used to compute isotopic concentrations in the soil from the net count rate from each isotope. When the calibration was extended to higher concentrations, interferences not evident in the earlier study became apparent, and it became necessary to use multiple linear regressions to derive the calibration equations.

The data set which was used to develop RTRAK calibration equations is shown in Table A-2. It consists of data collected at the ten field locations used in the Part B Comparability Study plus an additional eight locations in the Drum Baling area, the USID area, and the South Field area of the FEMP. At each location, 31 cm HPGe measurements and 300 second static RTRAK measurements were performed. Multiple linear regression analyses were performed to determine the relationship between the net RTRAK count rates for each contaminant isotope and the HPGe measurements. The method for obtaining the net count rate for each peak of interest is discussed in section A.5.1 of this appendix. The regression analyses resulted in the following equations for quantifying RTRAK net count rates. In the equations below, the subscripted quantities are the Net Counts Per Second for the particular analyte.

<u>Thorium-232 Calibration Equation</u>

The extended range calibration for Th-232, derived from a multiple linear regression, is represented by:

$$\text{RTRAK Th-232 pCi/g} = 0.05725481*Th_{NCPS} - 0.0044179*Ra_{NCPS} + 0.09624421$$

Note: The Ra-226 count rate effects the RTRAK thorium result because of contributions to the thorium signal window which arise from low abundance radium daughters. This interference becomes important at high radium concentrations.

Radium-226 Calibration Equation

The extended range Ra-226 calibration, derived by multiple linear regression, is expressed by the equation:

$$\text{RTRAK Ra-226 pCi/g} = 0.12145634*Ra_{NCPS} + 0.01735413*Th_{NCPS} + 0.13277316$$

Note: Low abundance gamma rays from Th-232 daughters contribute counts to the background windows for Ra-226. If this interference were not considered, the normal mode of background correction would overcompensate, thus yielding Ra-226 results with a low bias. The thorium term in the Ra-226 equation above compensates for this.

Uranium Calibration Equation

The extended range U-238 calibration equations, as derived from multiple linear regression, are shown below in units of U-238 pCi/g and total uranium ppm:

$$\text{RTRAK U-238 pCi/g} = 0.95562898*U_{NCPS} - 0.4031465*Th_{NCPS} + 1.01951125*Ra_{NCPS} + 9.408$$

$$\text{RTRAK Total U ppm} = 2.86307076*U_{NCPS} - 1.20782959*Th_{NCPS} + 3.05446247*Ra_{NCPS} + 28.186$$

Note: Two equations are provided for uranium so that either set of units will be readily available to a user. The second equation is derived from the first by making use of known constants and weight to activity conversion factors, and further assuming that the uranium encountered in the soil will be of normal enrichment. Uranium experiences interferences in both the signal window and the background windows. Th-232 daughter gamma rays at 969 Kev contribute to the signal window, while Ra-226 daughter gamma rays at 1120 Kev contribute to the background window. Thus a term proportional to the Th-232 activity must be subtracted from the counts in the signal window, while a term proportional to the Ra-226 activity must be added back in to compensate for the overcorrection due to the elevated background counts.

A.4 GLOBAL POSITIONING SYSTEM

The physical location at which each spectrum was acquired 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 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. 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 by the RTRAK driver to control the travel speed.

An investigation has revealed that when the GPS system does not receive "clean" satellite signals, erroneous location coordinates or other erroneous file parameters are associated with the measurement. Because the actual location of these measurements cannot be determined, the data must be discarded. The problem arises when measurements are being made in locations having obstructions that may interfere with the receipt of the satellite transmission, such as trees or buildings. Such obstructions are, in part, a consequence of the position of the satellite at the time the measurement is made. In locations where obstructions are not severe, clear signals can be received during certain periods of the day.

Measurements with GPS problems can be identified by an examination of the RTRAK data files. This examination has been included as one of the routine data quality checks for the RTRAK measurements.

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 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; the standard acquisition time is four seconds.

Standard mobile operation of the RTRAK consists of driving the tractor at approximately one mile per hour (~ 1.5 ft/sec) over an area to be measured and collecting, GPS tagging and storing a spectrum every four seconds. Each four second measurement integrates the concentration over approximately 8.8 square meters. Alternatively, the tractor may be operated at a other speeds with different acquisition times. Slowing the RTRAK travel speed and increasing the acquisition time, adding detectors, or averaging measurements over a large area reduces the relative error of the data collected by roughly the square root of the change in acquisition time, number of detectors, or number of aggregated measurements.

Windows or regions of interest for those nuclides of concern 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.

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 why the uncertainty in RTRAK measurements tends to be large. The "counting background" is substantially larger than the measured net peak counts; but both background and net counts contribute to the uncertainty. These large uncertainties occur as a result of short spectrum acquisition count time (typically 4 seconds) and because we are often measuring activity that is at or just above background concentrations.

The resulting net counts are divided by the count time (4 seconds) to compute a net count rate for the signal window with units of counts per second (cps or ncps). The signal net counts per second are then inserted into appropriate "calibration equation" to yield a quantified activity concentration in pCi/g. These data are also saved to electronic media for later data reduction and contour mapping.

A.6 PLANNED RTRAK SYSTEM UPGRADES

In December 1997, DOE was awarded funding for a proposal to deploy an integrated suite of technologies to be used in delineating contamination in soils in support of soil remedial actions at the FEMP. Fluor Daniel Fernald, the Environmental Assessment Division of Argonne National Laboratory, the DOE Environmental Measurements Laboratory, and the Idaho Environmental and Engineering Laboratory were partners in the proposal with DOE. The technologies to be deployed were the RTRAK mobile NaI detection system, which is the subject of this report, and multiple HPGe gamma spectrometry systems along with technologies to make the processes of data acquisition and reduction, data transfer and storage, and mapping of results more reliable and more automated. Important objectives of this Accelerated Site Technology Deployment (ASTD) project are:

1. To automate the process by which data are transferred from the field to the Sitewide Environmental Database (SED),

2. To expedite the uploading of in-situ soil remediation measurements to make them available on the world wide web to regulators and other interested stakeholders within 24 hours of data acquisition,

3. To facilitate production of maps in real time as an aid to the remediation decision making process during excavation work,

4. To provide RTRAK operators in the field with a reliable means of determining areas that have been scanned, and

5. To provide RTRAK operators real time readouts of the results of their measurements and of equipment status.

With the funding provided by DOE for the RTRAK/RSS development through its technology deployment initiative, improvements will be made to the RTRAK system hardware and software. New gamma spectrometry software will be purchased. New GPS hardware will be purchased to make GPS positional data acquisition more reliable and to facilitate the production of maps which display radionuclide contamination levels. Wireless data transmission equipment will be purchased to permit automated downloads of field data from the RTRAK and multiple HPGe detectors. Mapping software will be purchased. A smaller version of the RTRAK will be developed for use in wooded areas or trenches that are inaccessible to the RTRAK. Obviously, some of the manufacturers' names and model numbers and some of the software packages mentioned in the ASTD will change. Despite the numerous changes that are being planned, all the important capabilities of the current RTRAK system will be maintained or improved.

TABLE A-1
ENERGY WINDOWS USED FOR RTRAK SPECTRA

Measured Nuclide	Measured Nuclide Energy, keV	Gamma Photon Abundance (%)	Nuclide of Interest	Low Background Window keV	Signal Window keV	High Background 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	0.3586*	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

* Includes a 0.359 branching ratio of decay of Bismuth-212.

TABLE A-2
RTRAK CALIBRATION DATA USED TO PERFORM MULTIPLE LINEAR REGRESSIONS TO OBTAIN CALIBRATION EQUATIONS

MEASUREMENT LOCATION	RTRAK NET CPS			0.31 m. HPGe pCi/g		
	U-238	Th-232	Ra-226	U-238	Th-232	Ra-226
A3-11	68.7	67.7	137.1	200.0	3.49	20.5
A11-3	12.6	13.6	4.3	25.2	0.93	0.887
A13-3	43.6	79.1	1.3	9.5	4.14	1.15
A15-2	7.8	13.4	5.3	5.2	0.82	1.21
A9-1	2.9	10.8	4.7	2.9	0.67	0.744
A11-4-1	9.1	13.5	4.9	15.35	0.90	0.871
A11-5-2	8.8	13.8	4.3	21.1	0.91	0.93
A3-12-4	69.5	43.4	137.6	180	1.76	14.7
PBC-01	3.3	8.4	3	3	0.52	0.64
PBC-02	4.1	14.8	2.9	10.4	0.64	0.665
PBC-03	16.6	24.9	28.6	75.8	1.80	6.0
PBC-04	8.7	12.3	4.1	18.9	0.80	0.825
PBC-05	5.8	12.2	3.6	14.1	0.80	0.715
PBC-06	11.7	12.4	4.4	25.6	0.81	0.802
PBC-07	19.5	14.8	5.4	47.1	0.99	0.8
PBC-08	2.2	9.3	3.6	2	0.56	0.65
PBC-09	3	10.1	3.6	2.2	0.63	0.73
PBC-10	52.1	94.7	4.9	27	5.82	1.875

In Situ NaI Spectrum

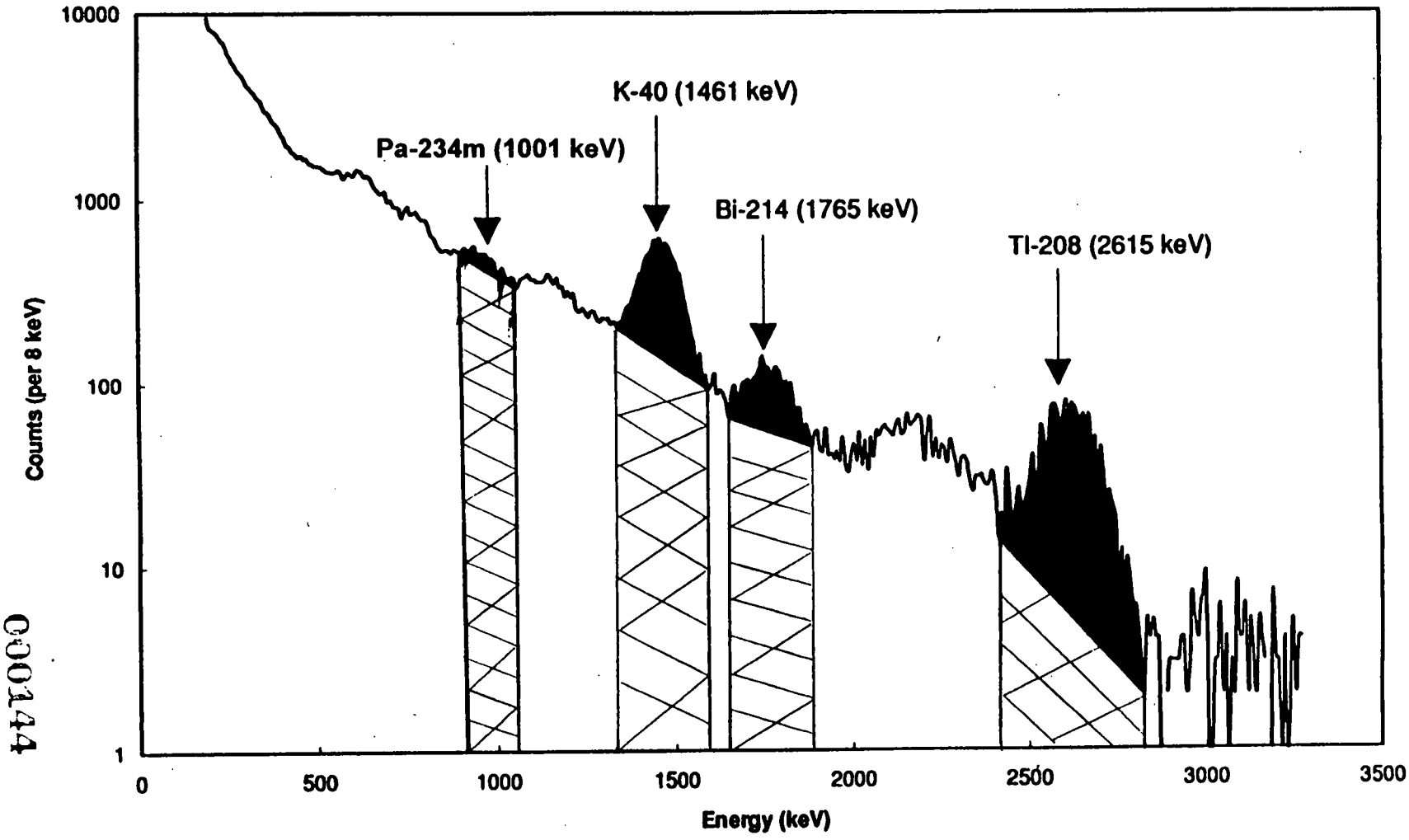

Figure A-1

APPENDIX B

PROFILE RUNS FOR USID, SOUTH FIELD, AND DRUM BALING AREAS

TABLE B-1

URANIUM-238 (pCI/g) - REPEATED PROFILE RUNS IN USID AREA

AREA	2 sec - 2 mph				2 sec - 0.5 mph				8 sec - 0.5 mph			
	No. Measurements	MEAN	STD DEV	% STD DEV	No. Measurements	MEAN	STD DEV	% STD DEV	No. Measurements	MEAN	STD DEV	% STD DEV
A-01	41	14.4	8.5	59	129	12.4	9.3	75	27	15.9	4.2	26
A-02	71	13.3	8.8	66	217	14.1	9.1	65	52	14.6	4.3	29
A-03	73	15.5	9.0	58	206	15.6	9.0	58	44	16.2	4.3	27
A-04	72	16.0	8.7	54	205	15.2	8.3	55	50	17.3	5.2	30
A-05	76	15.8	9.0	57	216	16.8	8.7	52	47	16.4	4.9	30
A-06	73	16.3	8.7	54	225	14.5	9.4	65	43	16.5	5.1	31
A-07	69	15.4	7.7	50	200	16.5	9.6	58	46	17.4	4.4	25
A-ROAD	52	14.4	7.4	51	120	12.2	7.3	60	28	13.3	4.9	37
A-08	75	18.8	9.5	51	231	17.0	9.2	54	49	17.5	5.7	32
A-09	84	20.4	9.3	45	232	18.0	9.3	51	53	18.0	5.1	28
A-10	80	18.6	8.2	44	240	17.2	9.8	57	55	17.8	4.7	26
A-11	73	14.7	9.7	66	193	15.2	8.6	56	44	15.1	5.1	33
AVERAGES		16.3	8.8	55		15.7	9.1	59		16.6	4.8	29
MINIMA		13.3	7.7	44		12.4	8.3	51		14.6	4.2	25
MAXIMA		20.4	9.7	66		18.0	9.8	75		18.0	5.7	33

TABLE B-2

URANIUM-238 (pCi/g) - REPEATED PROFILE RUNS IN SOUTH FIELD

AREA	2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph			
	No. Measurements	MEAN	STD DEV	% STD DEV	No. Measurements	MEAN	STD DEV	% STD DEV	No. Measurements	MEAN	STD DEV	% STD DEV
A-01	42	11.7	8.9	76	15	17.4	6.3	36	16	9.6	5.0	52
A-02	38	15.0	10.2	68	15	15.2	5.8	38	14	14.3	4.3	30
A-03	43	18.6	9.1	49	16	14.8	6.2	42	17	14.9	4.5	30
A-04	44	13.5	11.3	84	17	17.9	9.0	50	15	17.3	5.8	34
A-05	42	17.6	12.7	72	17	16.4	7.0	42	16	17.8	7.0	39
A-06	43	18.3	10.2	56	19	17.7	5.3	30	16	15.2	3.9	25
A-07	44	15.0	9.5	63	10	15.6	7.4	47	17	14.1	6.1	43
A-08	37	17.4	11.8	68	17	21.9	9.8	45	17	21.2	5.1	24
A-09	42	21.5	14.7	69	14	25.2	9.0	36	15	20.8	8.6	42
A-10	40	15.6	8.2	53	16	13.3	6.6	49	15	14.1	5.3	38
A-11	42	14.4	8.3	58	13	15.7	4.3	27	14	13.5	4.6	34
A-12	43	12.7	9.2	72	13	13.1	7.2	55	15	12.8	5.4	42
A-13	35	15.1	8.9	59	15	10.9	6.5	59	10	15.1	5.2	34
A-14	41	14.8	11.3	77	16	14.3	7.3	51	15	15.5	6.7	43
A-15	42	14.8	8.2	56	17	15.6	5.3	34	19	14.3	4.1	29
A-16	41	15.1	10.5	70	14	13.4	8.5	64	15	11.1	5.5	50
A-17	39	16.4	7.9	48	16	13.7	7.1	52	13	14.5	4.3	30
A-18	51	15.1	7.7	51	13	16.7	7.3	44	19	13.2	4.8	37
A-19	53	14.1	8.6	61	17	15.6	5.6	35	14	15.2	4.3	28
A-20	42	12.5	10.0	80	15	14.5	4.8	33	17	12.6	4.8	38
A-21	35	12.1	9.6	80	17	13.2	6.2	47	14	14.1	1.7	12
A-22	45	13.2	9.7	73	13	13.0	7.3	56	15	13.3	5.0	38
A-23	43	14.7	9.4	64	13	12.5	6.9	55	15	13.8	2.8	20
A-24	43	12.3	8.4	68	17	12.3	6.1	50	17	12.6	2.2	18
A-25	38	12.7	7.0	55	15	12.5	4.2	34	15	13.7	4.2	30
A-26	45	10.9	9.9	91	16	7.4	10.1	137	16	9.0	6.9	76
A-27	42	12.5	9.7	78	14	9.8	6.3	64	15	15.2	4.5	29
A-28	36	14.2	9.0	63	16	13.7	6.5	48	17	15.4	5.0	32
A-29	45	19.6	12.2	62	18	21.2	10.3	49	19	20.2	6.4	32
A-30	47	26.4	11.9	45	17	22.8	8.2	36	19	27.3	5.6	20
A-31	43	28.1	13.8	49	20	31.2	11.2	36	17	29.7	7.3	24
A-32	42	23.3	12.8	55	19	24.6	9.9	40	18	23.9	7.2	30
A-33	34	19.4	9.6	49	17	18.4	6.9	38	16	18.0	4.4	24
A-34	32	14.2	8.2	58	14	14.2	6.7	47	20	13.3	4.8	36
A-37	48	10.9	7.6	69	15	11.6	6.8	59	14	14.7	4.3	30

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A-38	37	13.7	6.3	46	15	12.1	5.6	46	14	12.8	3.4	27
A-39	42	12.3	7.2	58	18	16.1	5.5	34	16	12.8	4.1	32
A-40	38	12.1	6.9	57	15	13.3	4.4	33	15	14.4	3.3	23
A-41	48	14.7	8.8	60	21	13.0	5.2	40	16	13.1	4.1	32
A-42	46	12.3	7.3	59	17	14.6	5.5	38	20	13.8	3.5	25
A-43	45	12.4	8.6	70	16	15.3	5.9	38	14	12.7	6.2	49
A-44	33	11.6	8.8	76	16	13.4	7.5	56	18	13.2	4.1	31
A-45	43	15.7	7.4	48	18	14.8	7.8	53	17	13.3	4.7	35
A-46	45	12.2	8.7	72	14	17.0	4.4	26	14	13.6	3.6	26
A-47	45	13.8	7.8	57	18	13.3	6.9	52	16	14.8	3.6	25
A-48	41	12.6	7.6	60	17	13.3	6.2	46	16	13.3	4.3	32
A-49	52	14.2	7.5	53	14	14.5	8.7	60	16	12.4	5.0	41
A-50	38	11.8	7.8	66	18	10.1	5.4	53	13	11.5	5.0	43
AVERAGES		15.1	9.3	63		15.4	6.8	47		15.1	4.8	33
MINIMA		10.9	6.3	45		7.4	4.2	26		9.0	1.7	12
MAXIMA		28.1	14.7	91		31.2	11.2	137		29.7	8.6	76

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TABLE B-3

URANIUM-238 (pCi/g) - REPEATED PROFILE RUNS IN DRUM BALING AREA

AREA	2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph			
	No. Measurements	MEAN	STD DEV	% STD DEV	No. Measurements	MEAN	STD DEV	% STD DEV	No. Measurements	MEAN	STD DEV	% STD DEV
DB-A01	40	161.7	37.1	23	45	162.8	38.9	24	27	177.4	29.5	17
DB-A02	42	140.3	75.9	54	43	125.8	64.9	52	27	133.4	66.6	50
DB-A03	40	77.6	33.5	43	35	83.4	29.9	36	29	85.2	24.5	29
DB-A04	40	145.1	28.8	20	43	139.7	27.4	20	27	148.5	14.6	10
DB-A05	41	150.6	35.4	23	38	139.0	35.1	25	29	140.8	38.3	27
DB-A06	41	58.1	24.2	42	45	69.6	32.4	47	28	60.3	23.4	39
DB-A07	42	39.7	17.0	43	38	40.8	12.4	30	28	44.9	9.2	20
DB-A08	40	44.3	19.7	44	44	50.4	15.5	31	28	50.3	12.7	25
DB-A09	48	61.9	32.6	53	39	72.9	42.5	58	28	55.0	19.0	34
DB-A10	32	49.8	20.1	40	39	49.6	17.1	34	29	48.3	18.4	38
AVERAGES		92.9	32.4	39		93.4	31.6	36		94.4	25.6	29
MINIMA		39.7	17.0	20		40.8	12.4	20		44.9	9.2	10
MAXIMA		161.7	75.9	54		162.8	64.9	58		177.4	66.6	50

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TABLE B-4

THORIUM-232 (pCi/g) - REPEATED PROFILE RUNS IN USID AREA

AREA	2 sec - 2 mph				2 sec - 0.5 mph				8 sec - 0.5 mph			
	No. Measurements	MEAN	STD DEV	% STD DEV	No. Measurements	MEAN	STD DEV	% STD DEV	No. Measurements	MEAN	STD DEV	% STD DEV
A-01	41	0.75	0.28	37	129	0.75	0.26	35	27	0.73	0.13	18
A-02	71	0.82	0.30	37	217	0.77	0.32	42	52	0.77	0.15	19
A-03	73	0.74	0.29	39	206	0.75	0.27	36	44	0.80	0.14	18
A-04	72	0.75	0.28	37	205	0.80	0.31	39	50	0.75	0.16	21
A-05	76	0.77	0.28	36	216	0.73	0.29	40	47	0.78	0.15	19
A-06	73	0.75	0.35	47	225	0.76	0.29	38	43	0.77	0.15	19
A-07	69	0.84	0.30	36	200	0.78	0.31	40	46	0.77	0.15	19
A-ROAD	52	0.41	0.29	71	120	0.48	0.29	60	28	0.55	0.21	38
A-08	75	0.84	0.32	38	231	0.75	0.34	45	49	0.76	0.18	24
A-09	84	0.77	0.28	36	232	0.75	0.32	43	53	0.78	0.17	22
A-10	80	0.75	0.28	37	240	0.73	0.31	42	55	0.75	0.14	19
A-11	73	0.72	0.27	38	193	0.75	0.28	37	44	0.68	0.17	25
AVERAGES		0.77	0.29	38		0.76	0.30	40		0.76	0.15364	20
MINIMA		0.41	0.28	36		0.48	0.26	35		0.55	0.13	18
MAXIMA		0.84	0.35	71		0.80	0.34	60		0.80	0.21	38

TABLE B-5

THORIUM-232 (pCi/g) - REPEATED PROFILE RUNS IN SOUTH FIELD

AREA	2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph			
	No. Measurements	MEAN	STD DEV	% STD DEV	No. Measurements	MEAN	STD DEV	% STD DEV	No. Measurements	MEAN	STD DEV	% STD DEV
A-01	42	0.77	0.25	32	15	0.92	0.18	20	16	0.89	0.17	19
A-02	38	0.92	0.26	28	15	0.84	0.20	24	14	0.86	0.13	15
A-03	43	0.77	0.30	39	16	0.86	0.29	34	17	1.02	0.29	28
A-04	44	1.57	0.64	41	17	1.98	0.65	33	15	1.73	0.47	27
A-05	42	1.53	0.74	48	17	1.39	0.65	47	16	1.20	0.44	37
A-06	43	0.96	0.35	36	19	0.89	0.19	21	16	0.91	0.19	21
A-07	44	0.95	0.30	32	10	0.91	0.30	33	17	1.09	0.28	26
A-08	37	1.37	0.46	34	17	1.94	0.39	20	17	1.77	0.43	24
A-09	42	2.24	0.71	32	14	3.07	0.41	13	15	2.40	0.51	21
A-10	40	1.32	0.59	45	16	0.95	0.33	35	15	0.97	0.39	40
A-11	42	0.73	0.25	34	13	0.72	0.22	31	14	0.71	0.11	15
A-12	43	0.69	0.30	43	13	0.74	0.28	38	15	0.76	0.09	12
A-13	35	0.83	0.31	37	15	0.82	0.32	39	10	0.72	0.15	21
A-14	41	0.92	0.42	46	16	0.73	0.32	44	15	0.75	0.17	23
A-15	42	0.69	0.27	39	17	0.68	0.19	28	19	0.71	0.17	24
A-16	41	0.65	0.28	43	14	0.63	0.15	24	15	0.68	0.14	21
A-17	39	0.65	0.28	43	16	0.68	0.20	29	13	0.64	0.13	20
A-18	51	0.64	0.24	38	13	0.62	0.23	37	19	0.66	0.13	20
A-19	53	0.60	0.29	48	17	0.69	0.20	29	14	0.63	0.12	19
A-20	42	0.69	0.29	42	15	0.67	0.19	28	17	0.63	0.13	21
A-21	35	0.73	0.30	41	17	0.73	0.17	23	14	0.68	0.13	19
A-22	45	0.62	0.24	39	13	0.55	0.16	29	15	0.54	0.10	19
A-23	43	0.60	0.24	40	13	0.61	0.16	26	15	0.66	0.14	21
A-24	43	0.58	0.22	38	17	0.61	0.15	25	17	0.55	0.14	25
A-25	38	0.53	0.25	47	15	0.55	0.21	38	15	0.54	0.16	30
A-26	45	0.91	0.49	54	16	1.03	0.52	50	16	1.33	0.39	29
A-27	42	0.75	0.36	48	14	0.83	0.36	43	15	0.69	0.16	23
A-28	36	0.64	0.21	33	16	0.60	0.23	38	17	0.64	0.13	20
A-29	45	0.63	0.30	48	18	0.63	0.23	37	19	0.64	0.14	22
A-30	47	0.66	0.36	55	17	0.63	0.32	51	19	0.82	0.17	21
A-31	43	0.92	0.50	54	20	1.00	0.29	29	17	0.92	0.21	23
A-32	42	0.90	0.35	39	19	0.88	0.35	40	18	0.84	0.20	24
A-33	34	0.80	0.34	43	17	0.76	0.21	28	16	0.72	0.20	28
A-34	32	0.72	0.23	32	14	0.67	0.23	34	20	0.61	0.13	21
A-37	48	0.63	0.25	40	15	0.56	0.27	48	14	0.56	0.10	18

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A-38	37	0.58	0.25	43	15	0.65	0.15	23	14	0.56	0.10	18
A-39	42	0.55	0.27	49	18	0.62	0.14	23	16	0.56	0.09	16
A-40	38	0.64	0.22	34	15	0.62	0.18	29	15	0.53	0.15	28
A-41	48	0.55	0.24	44	21	0.53	0.20	38	16	0.60	0.13	22
A-42	46	0.50	0.30	60	17	0.47	0.17	36	20	0.50	0.14	28
A-43	45	0.63	0.33	52	16	0.66	0.10	15	14	0.65	0.17	26
A-44	33	0.69	0.29	42	16	0.76	0.27	36	18	0.73	0.16	22
A-45	43	0.71	0.28	39	18	0.65	0.22	34	17	0.68	0.09	13
A-46	45	0.64	0.27	42	14	0.65	0.19	29	14	0.60	0.14	23
A-47	45	0.61	0.23	38	18	0.68	0.18	26	16	0.60	0.11	18
A-48	41	0.49	0.28	57	17	0.53	0.13	25	16	0.61	0.13	21
A-49	52	0.56	0.29	52	14	0.45	0.22	49	16	0.57	0.10	18
A-50	38	0.58	0.26	45	18	0.71	0.23	32	13	0.72	0.18	25
AVERAGES		0.79	0.33	42		0.82	0.25	32		0.80	0.18	22
MINIMA		0.49	0.21	28		0.45	0.10	13		0.50	0.09	12
MAXIMA		2.24	0.74	60		3.07	0.65	51		2.40	0.51	40

TABLE B-6

THORIUM-232 (pCi/g) - REPEATED PROFILE RUNS IN DRUM BALING AREA

AREA	2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph			
	No. Measurements	MEAN	STD DEV	% STD DEV	No. Measurements	MEAN	STD DEV	% STD DEV	No. Measurements	MEAN	STD DEV	% STD DEV
DB-A01	40	2.44	0.84	34	45	2.29	0.94	41	27	2.63	0.47	18
DB-A02	42	2.34	0.82	35	43	2.38	0.84	35	27	2.34	0.42	18
DB-A03	40	2.29	0.66	29	35	2.24	0.57	25	29	2.33	0.46	20
DB-A04	40	3.09	0.71	23	43	2.86	0.59	21	27	2.87	0.33	11
DB-A05	41	2.98	0.86	29	38	3.04	0.61	20	29	3.05	0.48	16
DB-A06	41	1.96	0.59	30	45	1.97	0.47	24	28	1.92	0.48	25
DB-A07	42	1.82	0.51	28	38	1.91	0.45	24	28	1.94	0.41	21
DB-A08	40	3.29	1.03	31	44	3.55	1.00	28	28	3.69	1.06	29
DB-A09	48	5.82	2.22	38	39	6.78	2.73	40	28	5.42	1.34	25
DB-A10	32	4.90	0.90	18	39	4.98	1.21	24	29	5.33	0.87	16
AVERAGES		3.09	0.91	30		3.20	0.94	28		3.15	0.63	20
MINIMA		1.82	0.51	18		1.91	0.45	20		1.92	0.33	11
MAXIMA		5.82	2.22	38		6.78	2.73	41		5.42	1.34	29

000153

TABLE B-7

RADIUM-226 (pCi/g) - REPEATED PROFILE RUNS IN USID AREA

AREA	2 sec - 2 mph				2 sec - 0.5 mph				8 sec - 0.5 mph			
	No. Measurements	MEAN	STD DEV	% STD DEV	No. Measurements	MEAN	STD DEV	% STD DEV	No. Measurements	MEAN	STD DEV	% STD DEV
A-01	41	0.76	0.52	68	129	0.72	0.50	70	27	0.74	0.23	31
A-02	71	0.68	0.48	70	217	0.79	0.51	64	52	0.75	0.26	35
A-03	73	0.78	0.47	60	206	0.82	0.47	57	44	0.77	0.27	35
A-04	72	0.76	0.53	69	205	0.76	0.53	70	50	0.79	0.26	33
A-05	76	0.78	0.55	71	216	0.82	0.54	66	47	0.81	0.24	30
A-06	73	0.78	0.56	71	225	0.76	0.52	68	43	0.87	0.24	28
A-07	69	0.80	0.45	56	200	0.80	0.54	68	46	0.87	0.22	25
A-ROAD	52	0.61	0.44	73	120	0.59	0.45	76	28	0.72	0.29	40
A-08	75	0.80	0.56	69	231	0.82	0.59	72	49	0.83	0.33	40
A-09	84	0.89	0.41	46	232	0.87	0.51	58	53	0.82	0.24	29
A-10	80	0.84	0.49	59	240	0.77	0.48	63	55	0.87	0.28	32
A-11	73	0.70	0.45	64	193	0.76	0.50	65	44	0.66	0.26	39
AVERAGES		0.78	0.50	64		0.79	0.52	66		0.80	0.26	32
MINIMA		0.68	0.41	46		0.72	0.45	57		0.66	0.23	28
MAXIMA		0.89	0.56	73		0.87	0.59	76		0.87	0.33	40

TABLE B-8

RADIUM-226 (pCi/g) - REPEATED PROFILE RUNS IN SOUTH FIELD

AREA	2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph			
	No. Measurements	MEAN	STD DEV	% STD DEV	No. Measurements	MEAN	STD DEV	% STD DEV	No. Measurements	MEAN	STD DEV	% STD DEV
A-01	42	0.95	0.52	55	15	1.11	0.32	29	16	0.96	0.24	25
A-02	38	0.89	0.57	64	15	1.02	0.33	32	14	1.01	0.26	26
A-03	43	1.02	0.65	64	16	1.06	0.25	24	17	1.07	0.27	25
A-04	44	1.04	0.80	77	17	1.22	0.58	48	15	0.98	0.30	31
A-05	42	1.11	0.57	51	17	1.11	0.41	37	16	1.22	0.39	32
A-06	43	1.03	0.55	53	19	1.20	0.45	38	16	1.11	0.24	22
A-07	44	0.98	0.53	54	10	1.24	0.27	22	17	0.90	0.19	21
A-08	37	0.92	0.68	74	17	1.15	0.48	42	17	0.90	0.35	39
A-09	42	1.14	0.83	73	14	1.23	0.68	55	15	1.07	0.49	46
A-10	40	0.75	0.61	81	16	0.95	0.47	49	15	0.92	0.25	27
A-11	42	0.93	0.41	44	13	0.81	0.25	31	14	0.88	0.26	30
A-12	43	0.86	0.46	53	13	0.96	0.44	46	15	0.89	0.27	30
A-13	35	1.15	0.45	39	15	0.91	0.41	45	10	0.84	0.19	23
A-14	41	1.21	0.59	49	16	1.08	0.44	41	15	1.31	0.31	24
A-15	42	1.14	0.48	42	17	1.25	0.32	26	19	1.14	0.22	19
A-16	41	1.03	0.58	56	14	1.01	0.39	39	15	0.91	0.24	26
A-17	39	1.02	0.43	42	16	1.07	0.29	27	13	1.02	0.23	23
A-18	51	0.93	0.49	53	13	0.94	0.36	38	19	0.93	0.35	38
A-19	53	0.85	0.57	67	17	0.92	0.35	38	14	1.03	0.30	29
A-20	42	0.89	0.55	62	15	0.94	0.31	33	17	0.82	0.24	29
A-21	35	0.95	0.50	53	17	1.05	0.29	28	14	0.85	0.26	31
A-22	45	0.84	0.52	62	13	1.01	0.53	52	15	0.90	0.25	28
A-23	43	0.98	0.50	51	13	0.89	0.27	30	15	0.96	0.25	26
A-24	43	0.88	0.54	61	17	0.92	0.49	53	17	0.83	0.16	19
A-25	38	0.81	0.48	59	15	0.78	0.35	45	15	0.90	0.27	30
A-26	45	1.09	0.54	50	16	0.84	0.56	67	16	1.41	0.40	28
A-27	42	1.22	0.60	49	14	1.22	0.28	23	15	1.21	0.23	19
A-28	36	1.33	0.66	50	16	1.30	0.41	32	17	1.29	0.23	18
A-29	45	2.12	1.00	47	18	2.08	1.11	53	19	2.17	0.70	32
A-30	47	2.99	0.98	33	17	2.61	0.70	27	19	3.65	1.08	30
A-31	43	3.99	1.13	28	20	4.37	0.90	21	17	4.46	0.45	10
A-32	42	3.21	0.90	28	19	2.99	1.26	42	18	2.98	0.56	19
A-33	34	2.17	0.84	39	17	2.12	0.55	26	16	1.87	0.50	27
A-34	32	1.35	0.69	51	14	1.19	0.38	32	20	1.12	0.26	23
A-37	48	0.69	0.46	67	15	0.70	0.41	59	14	0.80	0.29	36

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A-38	37	0.61	0.48	79	15	0.85	0.28	33	14	0.71	0.25	35
A-39	42	0.64	0.53	83	18	0.85	0.41	48	16	0.82	0.23	28
A-40	38	0.79	0.47	59	15	0.88	0.32	36	15	0.90	0.16	18
A-41	48	1.04	0.49	47	21	0.79	0.39	49	16	0.81	0.23	28
A-42	46	0.88	0.41	47	17	0.92	0.40	43	20	0.90	0.19	21
A-43	45	0.86	0.48	56	16	0.85	0.36	42	14	0.87	0.19	22
A-44	33	0.77	0.58	75	16	0.84	0.31	37	18	0.83	0.27	33
A-45	43	1.06	0.45	42	18	0.87	0.40	46	17	0.78	0.22	28
A-46	45	0.91	0.45	49	14	1.05	0.33	31	14	0.86	0.25	29
A-47	45	0.87	0.63	72	18	0.89	0.28	31	16	0.96	0.21	22
A-48	41	0.88	0.46	52	17	0.96	0.33	34	16	0.96	0.20	21
A-49	52	0.96	0.51	53	14	0.84	0.26	31	16	0.78	0.33	42
A-50	38	0.74	0.48	65	18	0.85	0.31	36	13	0.78	0.29	37
AVERAGES		1.16	0.59	55		1.18	0.43	38		1.17	0.30	27
MINIMA		0.61	0.41	28		0.70	0.25	21		0.71	0.16	10
MAXIMA		3.99	1.13	83		4.37	1.26	67		4.46	1.08	46

TABLE B-9

RADIUM-226 (pCi/g) - REPEATED PROFILE RUNS IN DRUM BALING AREA

AREA	2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph			
	No. Measurements	MEAN	STD DEV	% STD DEV	No. Measurements	MEAN	STD DEV	% STD DEV	No. Measurements	MEAN	STD DEV	% STD DEV
DB-A01	40	11.73	2.55	22	45	11.10	2.19	20	27	11.80	1.56	13
DB-A02	42	9.33	4.66	50	43	8.07	3.36	42	27	8.45	3.41	40
DB-A03	40	6.29	2.32	37	35	6.59	2.25	34	29	6.84	2.29	33
DB-A04	40	11.65	2.39	21	43	11.06	2.06	19	27	11.00	1.67	15
DB-A05	41	10.25	2.63	26	38	9.95	2.71	27	29	10.06	2.79	28
DB-A06	41	3.86	1.52	39	45	4.26	1.79	42	28	3.84	1.56	41
DB-A07	42	2.58	0.99	38	38	2.66	0.69	26	28	2.98	0.52	17
DB-A08	40	2.60	1.10	42	44	2.89	0.81	28	28	2.79	0.64	23
DB-A09	48	3.13	1.44	46	39	3.57	1.12	31	28	2.92	0.58	20
DB-A10	32	3.81	1.27	33	39	3.47	0.91	26	29	3.32	0.79	24
AVERAGES		6.52	2.09	35		6.36	1.79	29		6.40	1.58	25
MINIMA		2.58	0.99	21		2.66	0.69	19		2.79	0.52	13
MAXIMA		11.73	4.66	50		11.10	3.36	42		11.80	3.41	41

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TABLE B-10

TOTAL ACTIVITY (CPS) - REPEATED PROFILE RUNS IN USID AREA

AREA	2 sec - 2 mph				2 sec - 0.5 mph				8 sec - 0.5 mph			
	No. Measurements	MEAN (cps)	STD DEV	% STD DEV	No. Measurements	MEAN (cps)	STD DEV	% STD DEV	No. Measurements	MEAN (cps)	STD DEV	% STD DEV
A-01	41	2781	113	4	129	2772	142	5	27	2814	118	4
A-02	71	2927	62	2	217	2932	66	2	52	2954	65	2
A-03	73	2964	65	2	206	2946	64	2	44	2969	53	2
A-04	72	3034	66	2	205	3027	69	2	50	3043	56	2
A-05	76	3089	71	2	216	3076	73	2	47	3102	63	2
A-06	73	3036	77	3	225	3028	72	2	43	3061	62	2
A-07	69	3097	187	6	200	3101	120	4	46	3025	259	9
A-ROAD	52	2075	480	23	120	2008	524	26	28	2307	568	25
A-08	75	3141	302	10	231	3050	430	14	49	3029	471	16
A-09	84	3184	79	2	232	3192	76	2	53	3210	65	2
A-10	80	3066	122	4	240	3084	111	4	55	3118	137	4
A-11	73	2850	84	3	193	2868	79	3	44	2838	199	7
AVERAGES		3015	112	4		3007	118	4		3015	141	5
MINIMA		2781	62	2		2772	64	2		2814	53	2
MAXIMA		3184	480	23		3192	524	26		3210	568	25

TABLE B-11

TOTAL ACTIVITY (CPS) - REPEATED PROFILE RUNS IN SOUTH FIELD

AREA	2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph			
	No. Measurements	MEAN (CPS)	STD DEV	% STD DEV	No. Measurements	MEAN (CPS)	STD DEV	% STD DEV	No. Measurements	MEAN (CPS)	STD DEV	% STD DEV
A-01	42	2628	137	5	15	2768	163	6	16	2751	115	4
A-02	38	2886	85	3	15	2935	64	2	14	2943	49	2
A-03	43	3017	129	4	16	3193	127	4	17	3218	170	5
A-04	44	3711	544	15	17	4106	517	13	15	3959	623	16
A-05	42	3726	639	17	17	3492	622	18	16	3298	542	16
A-06	43	3159	137	4	19	3065	128	4	16	2979	127	4
A-07	44	2827	137	5	10	2829	79	3	17	2958	203	7
A-08	37	3178	201	6	17	3763	446	12	17	3746	402	11
A-09	42	4108	654	16	14	5078	307	6	15	4587	480	10
A-10	40	3169	756	24	16	2900	379	13	15	2871	436	15
A-11	42	2541	59	2	13	2554	41	2	14	2562	35	1
A-12	43	2534	100	4	13	2558	49	2	15	2561	33	1
A-13	35	2757	207	8	15	2696	119	4	10	2636	130	5
A-14	41	2988	146	5	16	2976	105	4	15	2884	120	4
A-15	42	2665	121	5	17	2675	89	3	19	2640	114	4
A-16	41	2546	42	2	14	2586	25	1	15	2566	21	1
A-17	39	2521	49	2	16	2539	44	2	13	2540	36	1
A-18	51	2526	76	3	13	2539	75	3	19	2539	81	3
A-19	53	2412	62	3	17	2399	42	2	14	2449	36	1
A-20	42	2487	61	2	15	2502	66	3	17	2543	86	3
A-21	35	2664	60	2	17	2658	72	3	14	2638	71	3
A-22	45	2360	143	6	13	2334	76	3	15	2318	44	2
A-23	43	2402	76	3	13	2420	65	3	15	2424	40	2
A-24	43	2277	114	5	17	2316	105	5	17	2226	100	4
A-25	38	2163	152	7	15	2203	161	7	15	2324	165	7
A-26	45	2922	490	17	16	3135	611	19	16	3444	412	12
A-27	42	2803	357	13	14	2926	394	13	15	2768	208	8
A-28	36	2731	171	6	16	2784	133	5	17	2874	122	4
A-29	45	3622	588	16	18	3497	639	18	19	3684	509	14
A-30	47	4882	632	13	17	4604	584	13	19	5292	945	18
A-31	43	6076	251	4	20	6365	277	4	17	6330	405	6
A-32	42	5027	331	7	19	4721	1046	22	18	4665	525	11
A-33	34	3814	522	14	17	3631	489	13	16	3353	351	10
A-34	32	2928	182	6	14	2931	174	6	20	2811	206	7
A-37	48	2244	75	3	15	2280	79	3	14	2206	57	3

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A-38	37	2119	32	2	15	2160	29	1	14	2158	26	1
A-39	42	2172	40	2	18	2200	37	2	16	2218	24	1
A-40	38	2237	143	6	15	2229	24	1	15	2217	22	1
A-41	48	2160	50	2	21	2218	114	5	16	2167	43	2
A-42	46	2060	73	4	17	2071	120	6	20	2060	58	3
A-43	45	2239	228	10	16	2295	182	8	14	2360	140	6
A-44	33	2517	52	2	16	2554	28	1	18	2557	35	1
A-45	43	2555	44	2	18	2575	42	2	17	2550	42	2
A-46	45	2461	59	2	14	2461	51	2	14	2433	47	2
A-47	45	2335	46	2	18	2332	35	1	16	2316	35	2
A-48	41	2196	97	4	17	2206	70	3	16	2200	42	2
A-49	52	2153	40	2	14	2202	29	1	16	2187	32	1
A-50	38	2254	111	5	18	2407	135	6	13	2398	98	4
AVERAGES		2849	198	6		2893	193	6		2883.5	180.0	5
MINIMA		2060	32	2		2071	24	1		2060.3	21.0	1
MAXIMA		6076	756	24		6365	1046	22		6329.9	945.5	18

TABLE B-12

GROSS ACTIVITY (CPS) - REPEATED PROFILE RUNS IN DRUM BALING AREA

AREA	2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph			
	No. Measurements	MEAN (CPS)	STD DEV	% STD DEV	No. Measurements	MEAN (CPS)	STD DEV	% STD DEV	No. Measurements	MEAN (CPS)	STD DEV	% STD DEV
DB-A01	40	24548	2550	10	45	24495	2953	12	27	24433	2020	8
DB-A02	42	19841	5893	30	43	19011	5825	31	27	19477	6423	33
DB-A03	40	14611	2729	19	35	14962	2312	15	29	15485	2364	15
DB-A04	40	20708	1533	7	43	20913	1497	7	27	20820	1259	6
DB-A05	41	20532	2337	11	38	20360	3152	15	29	19905	3356	17
DB-A06	41	11892	2153	18	45	12502	3060	24	28	11741	3036	26
DB-A07	42	9443	801	8	38	9458	815	9	28	9901	1061	11
DB-A08	40	10485	626	6	44	10663	656	6	28	10652	543	5
DB-A09	48	12573	1936	15	39	13374	2897	22	28	12287	1491	12
DB-A10	32	12029	908	8	39	12223	1038	8	29	12335	1430	12
AVERAGES		15666	2147	13		15796.1	2420.5	15		15704	2298	14
MINIMA		9443	626	6		9458.1	656.3	6		9901	543	5
MAXIMA		24548	5893	30		24495.2	5825.2	31		24433	6423	33

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

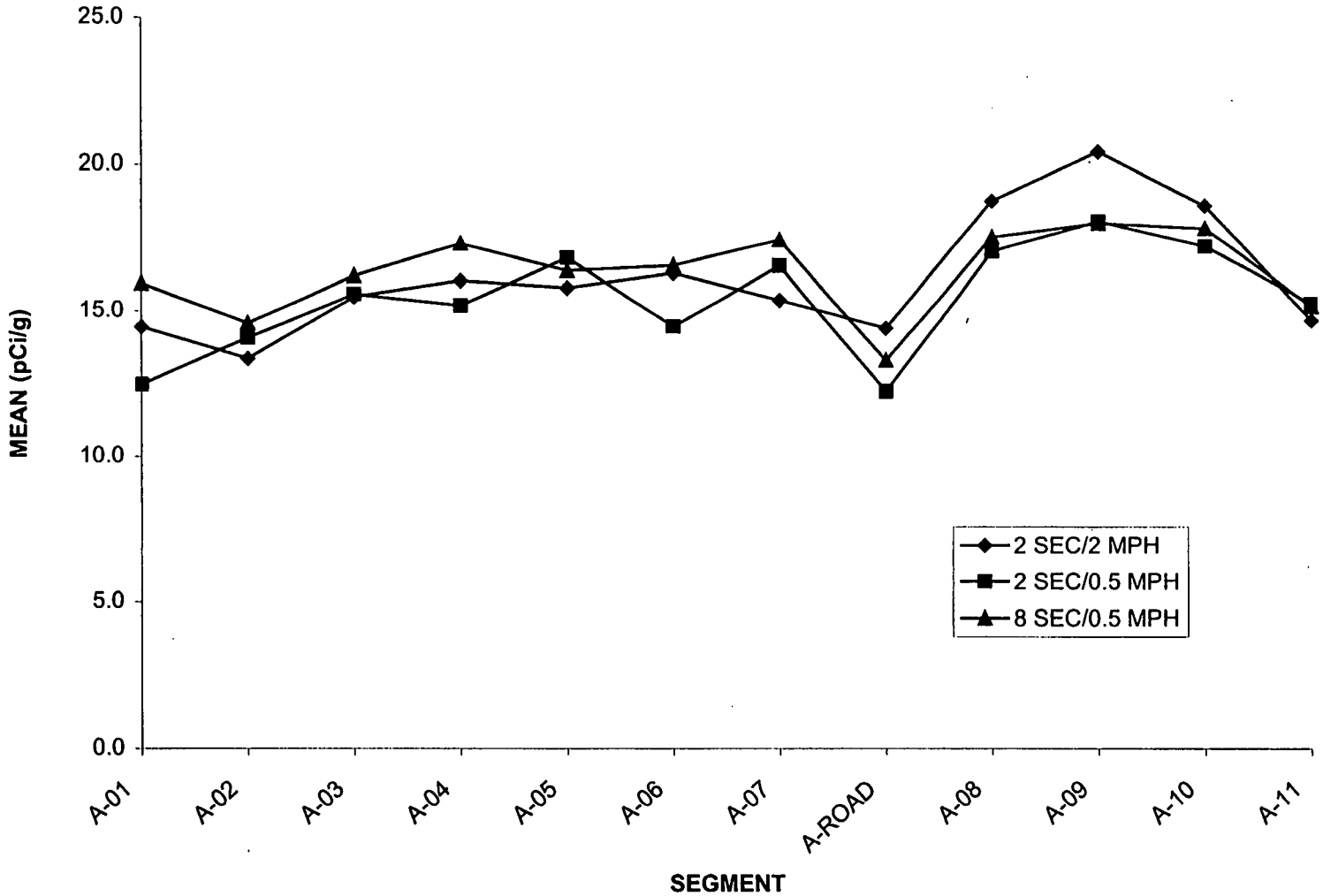

FIGURE B-2
URANIUM-238 - USID AREA - STANDARD DEVIATION

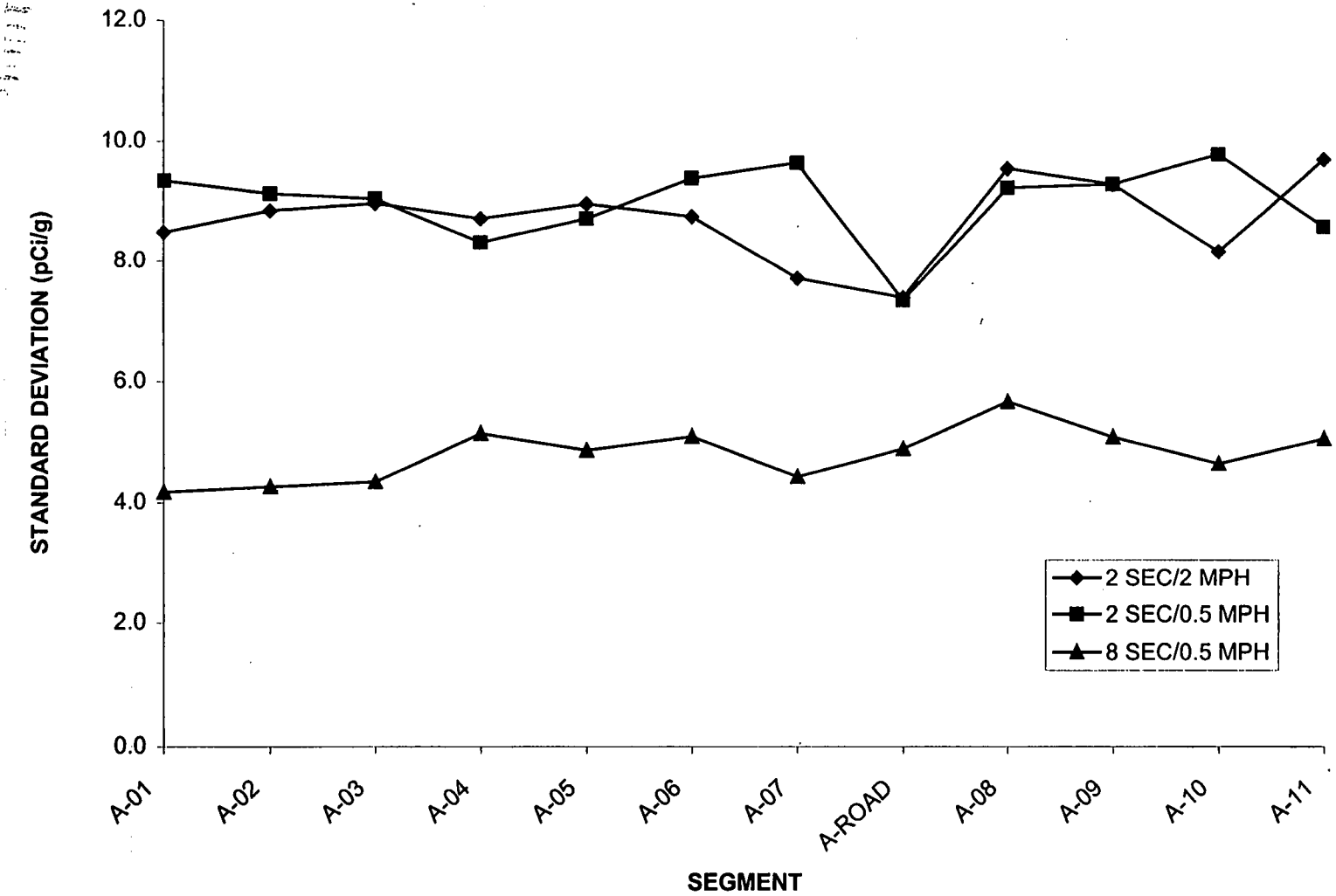

FIGURE B-3
URANIUM-238 - USID AREA - % STANDARD DEVIATION

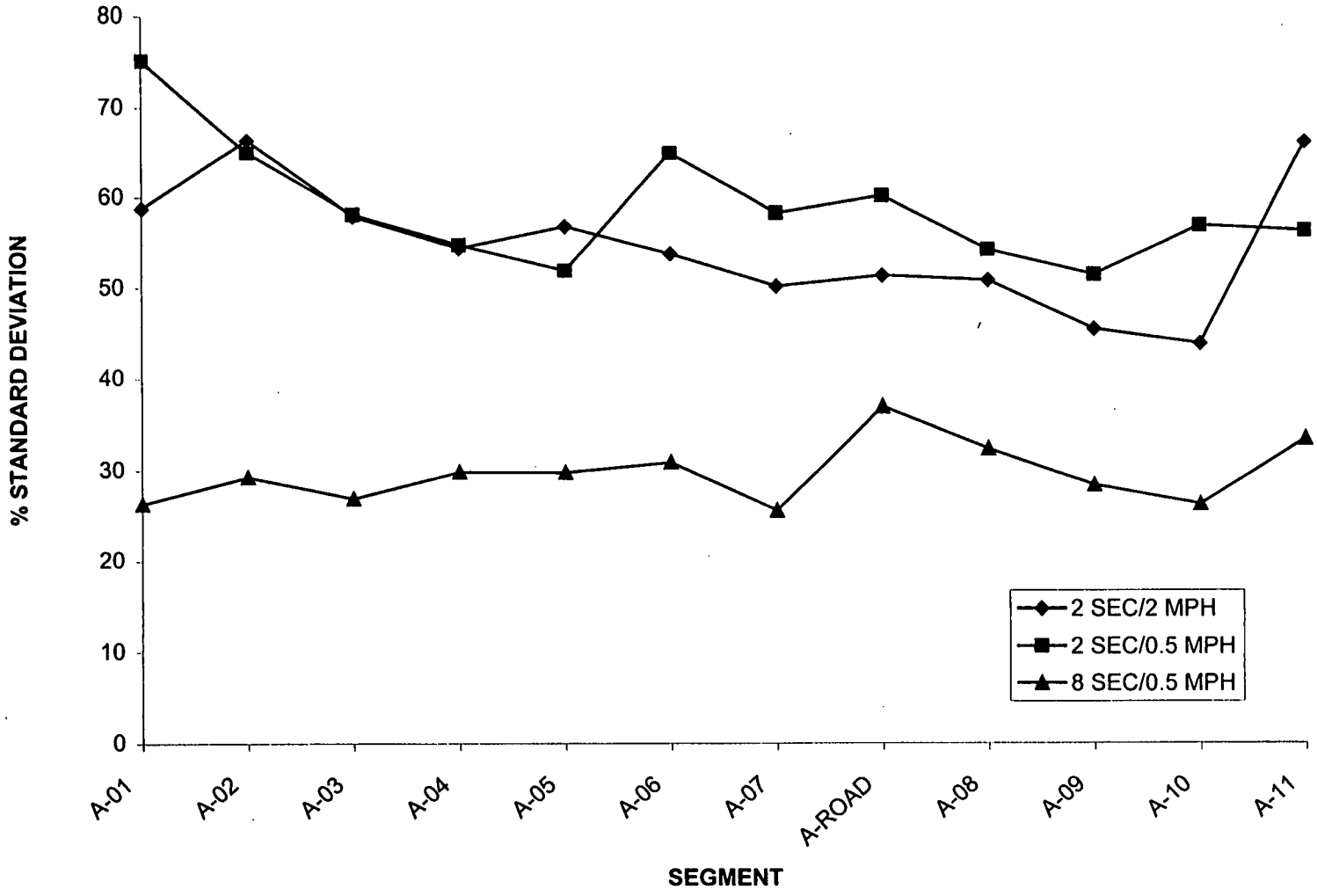

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FIGURE B-4
URANIUM-238 - SOUTH FIELD - MEAN

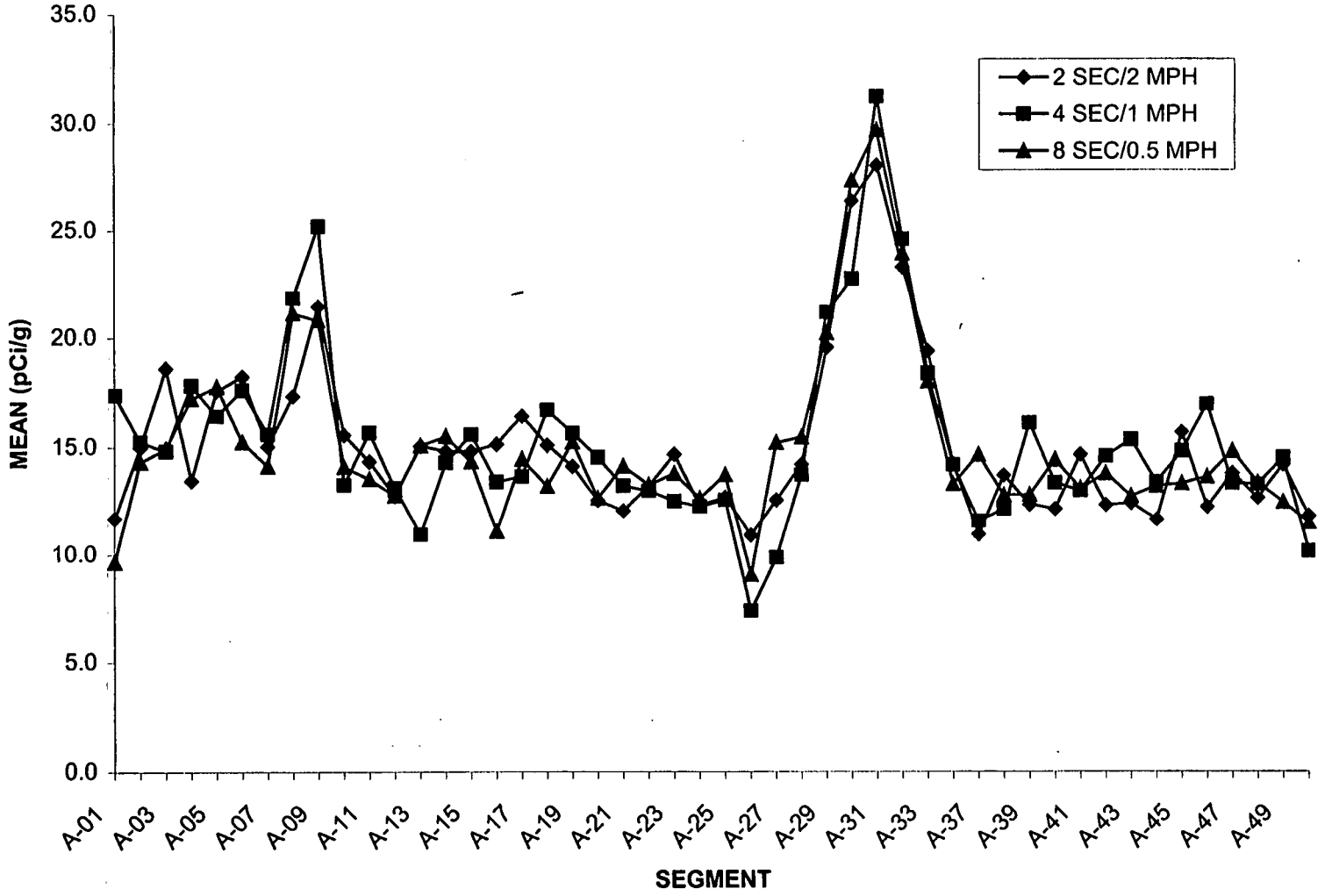

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FIGURE B-5
URANIUM-238 - SOUTH FIELD - STANDARD DEVIATION

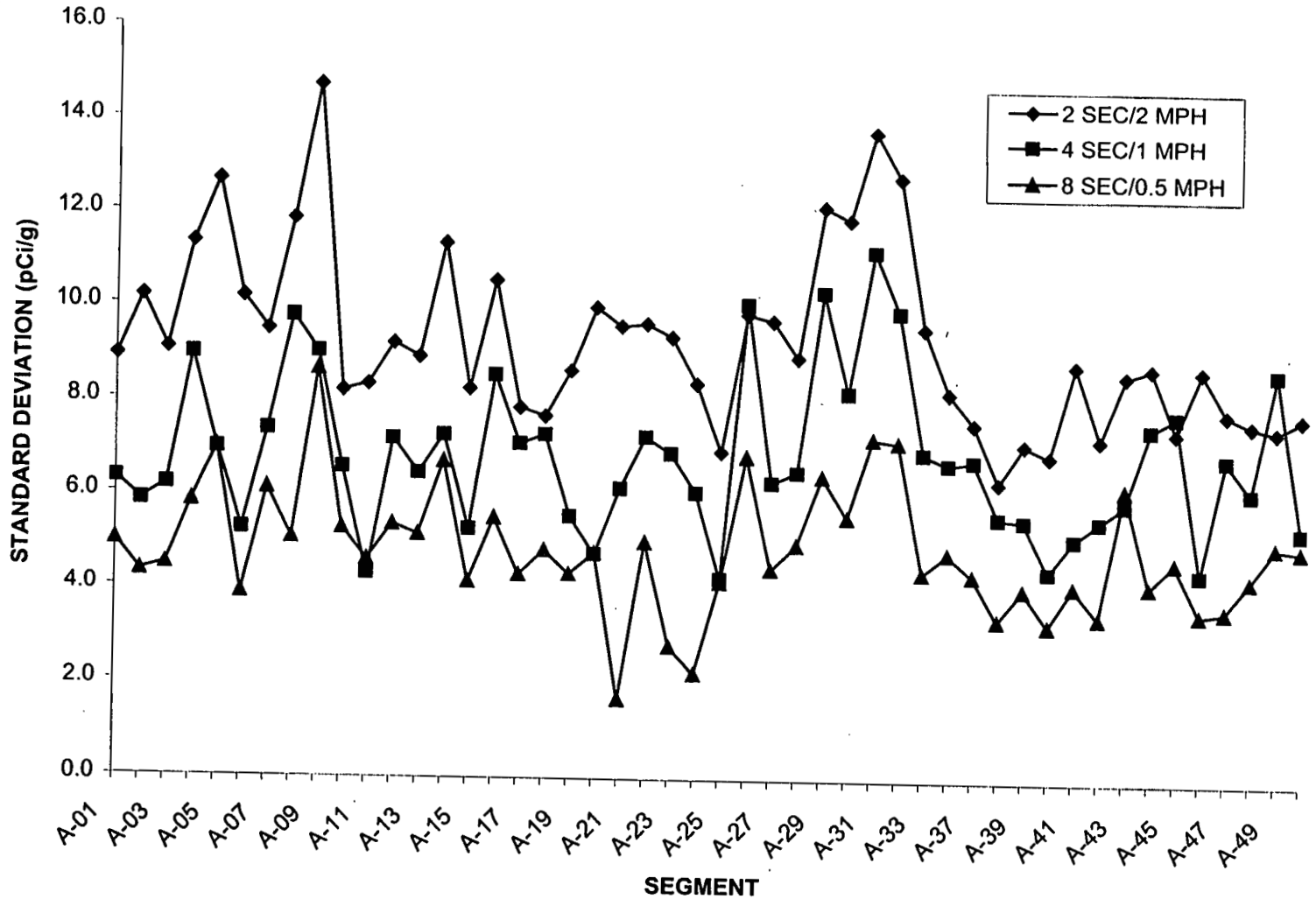

FIGURE B-6
URANIUM-238 - SOUTH FIELD - % STANDARD DEVIATION

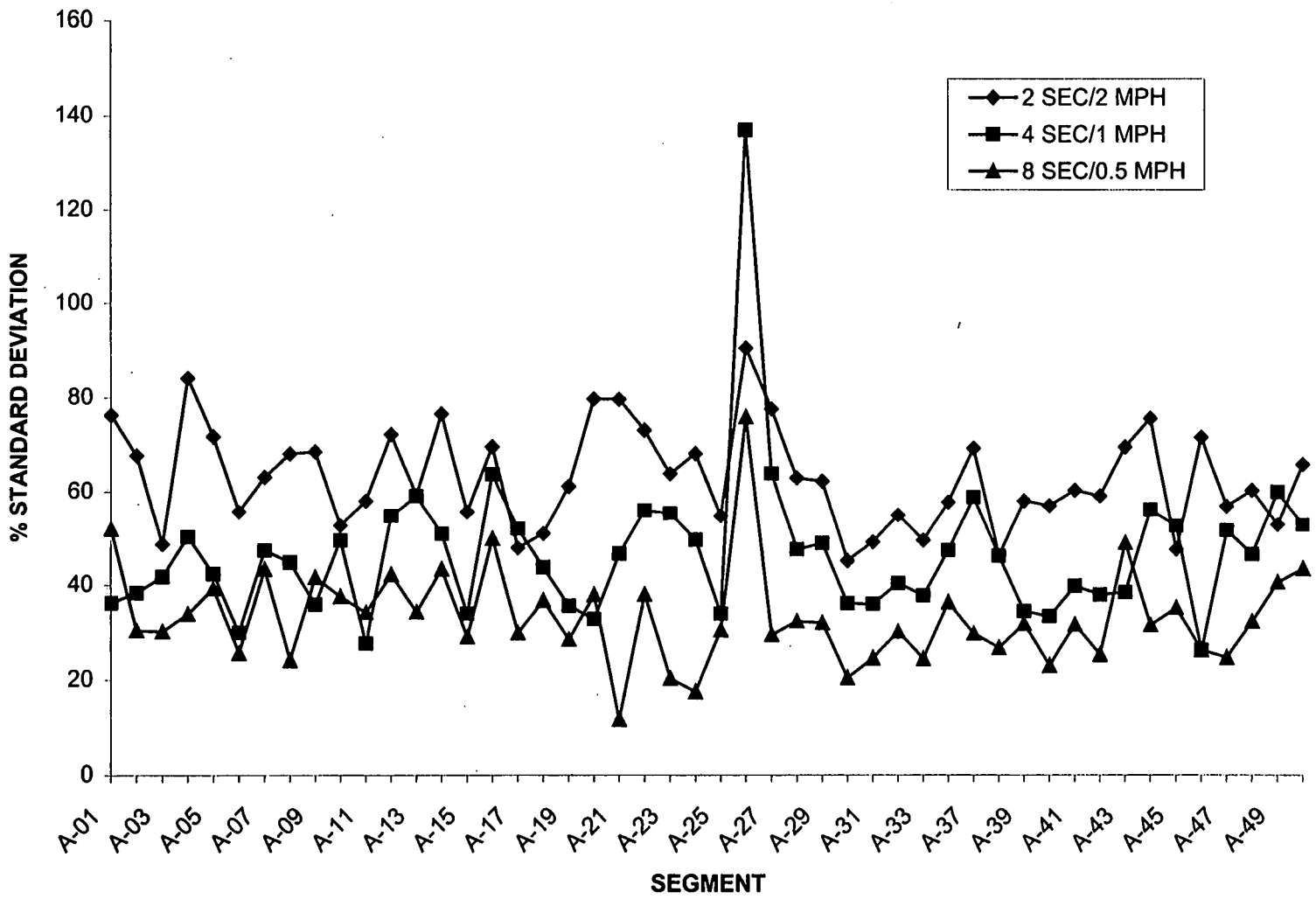

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FIGURE B-7
URANIUM-238 - DRUM BALING AREA - MEAN

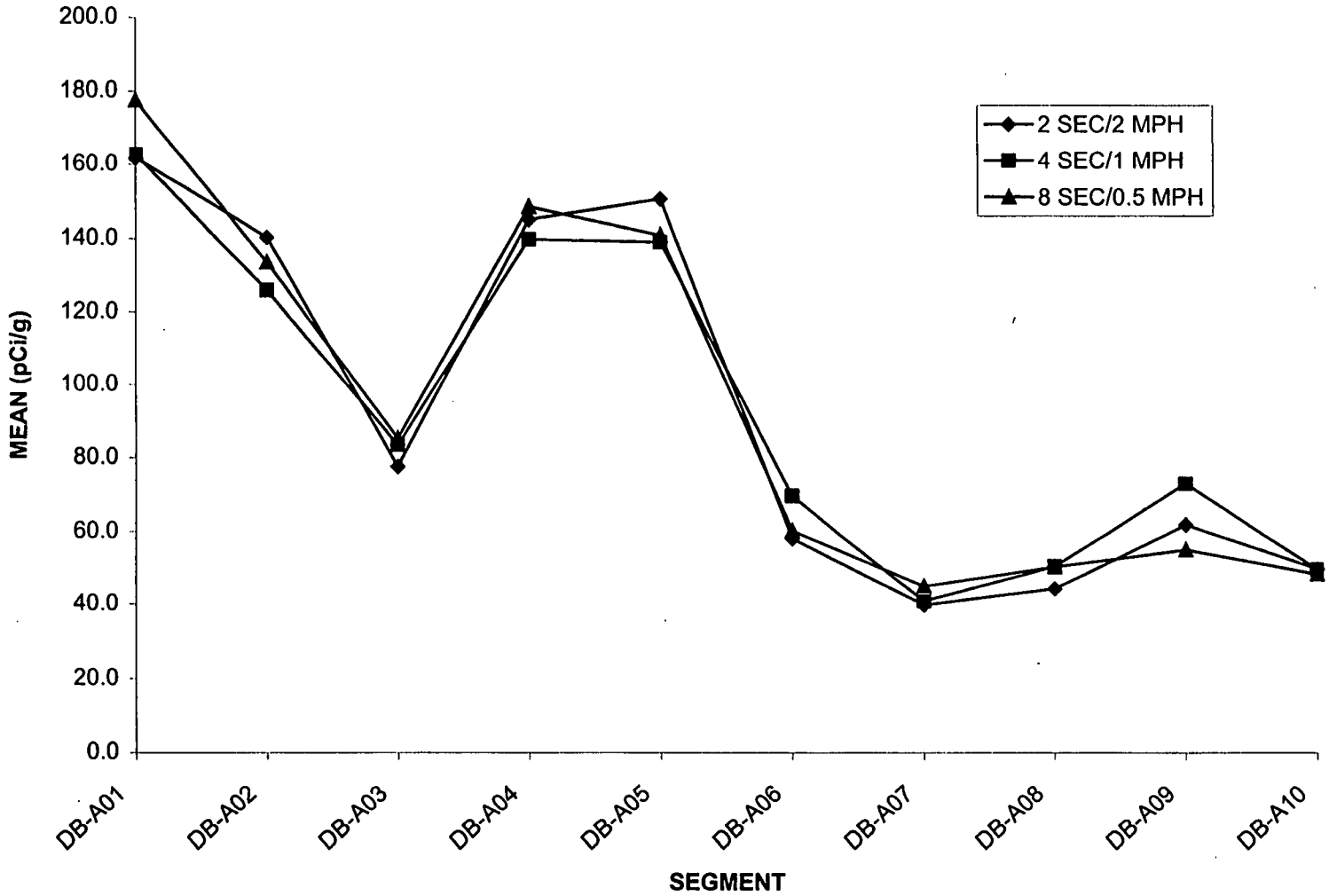

FIGURE B-8
URANIUM-238 - DRUM BALING AREA - STANDARD DEVIATION

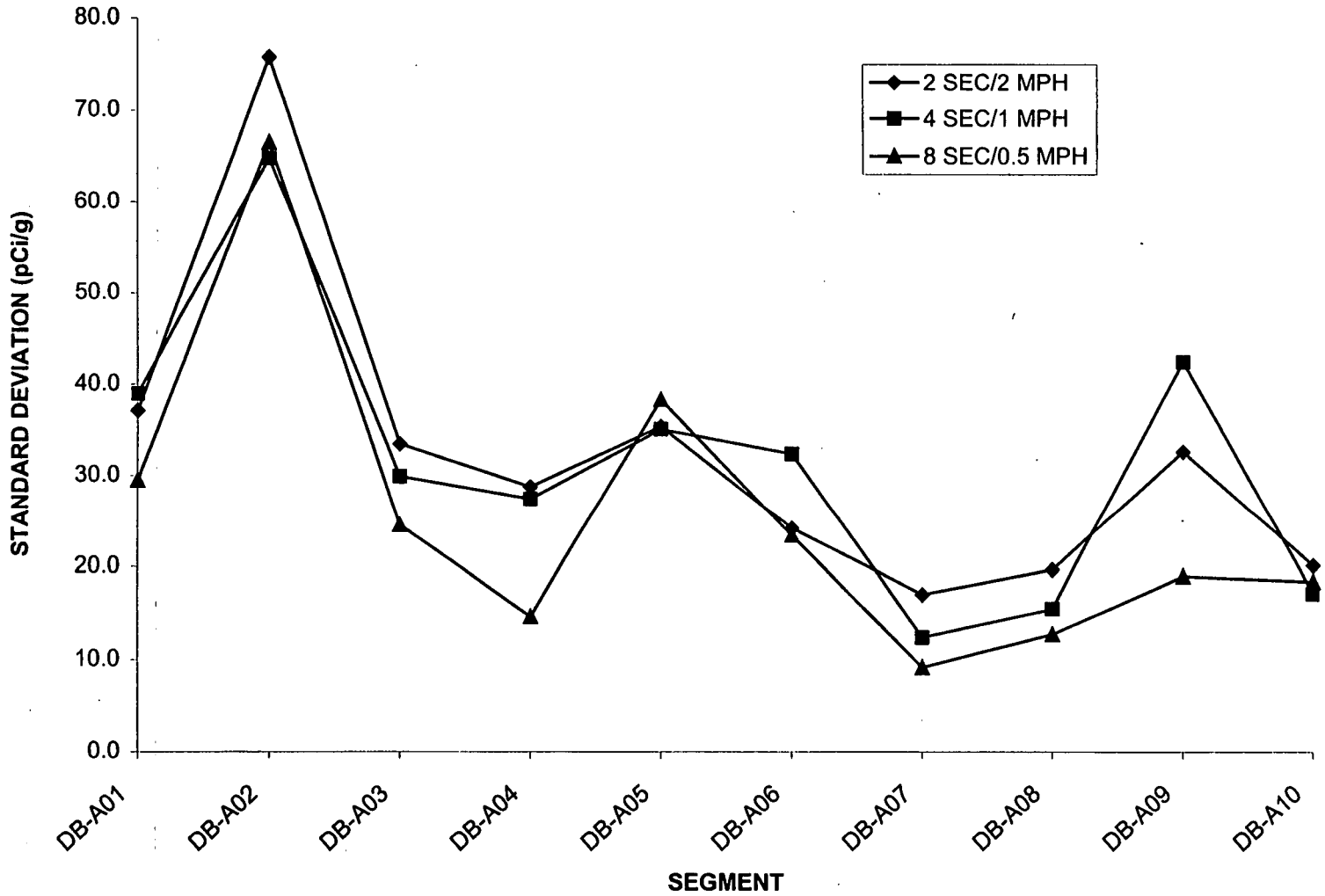

FIGURE B-9
URANIUM-238 - DRUM BALING AREA - % STANDARD DEVIATION

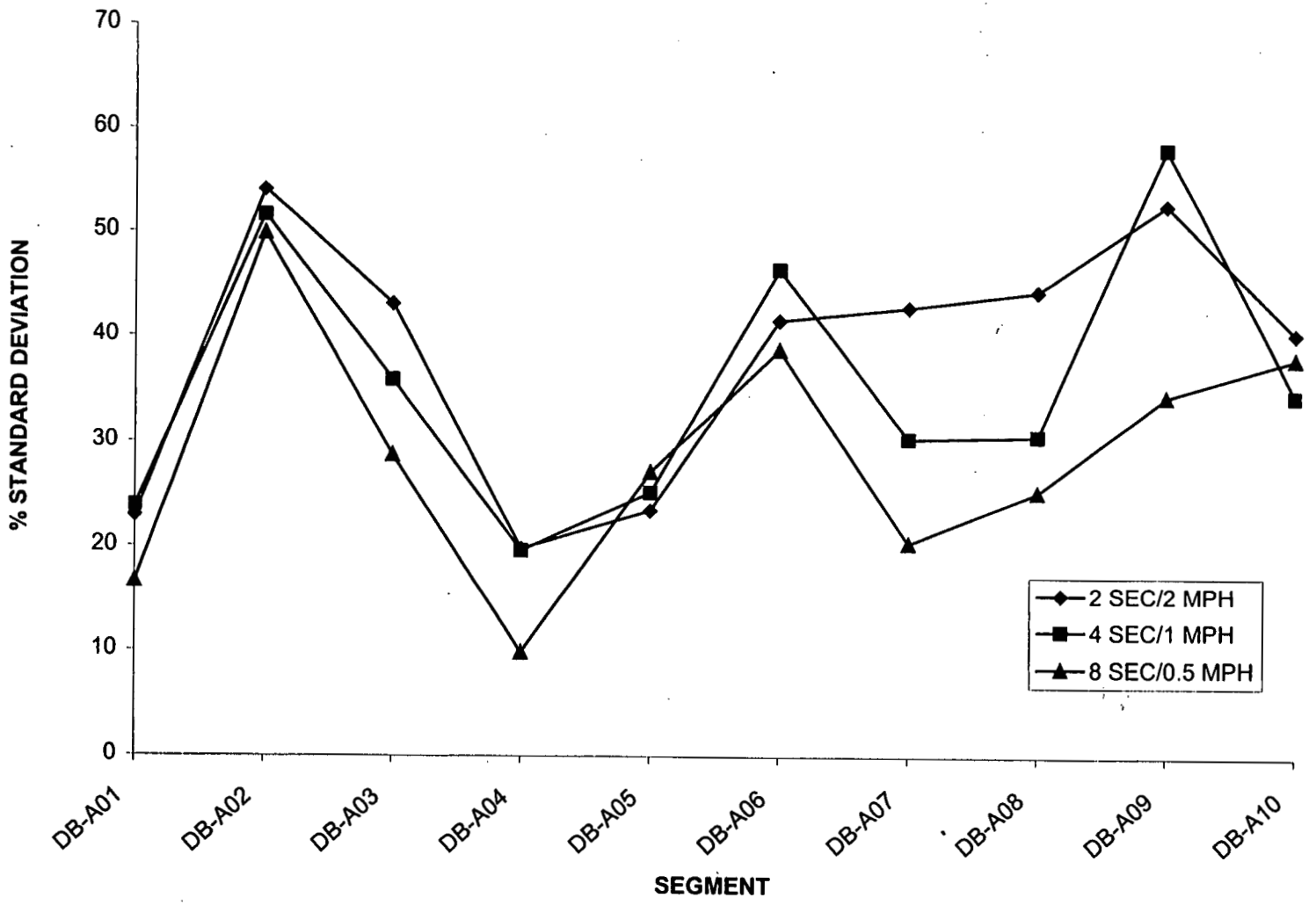

FIGURE B-10
THORIUM-232 - USID AREA - MEAN

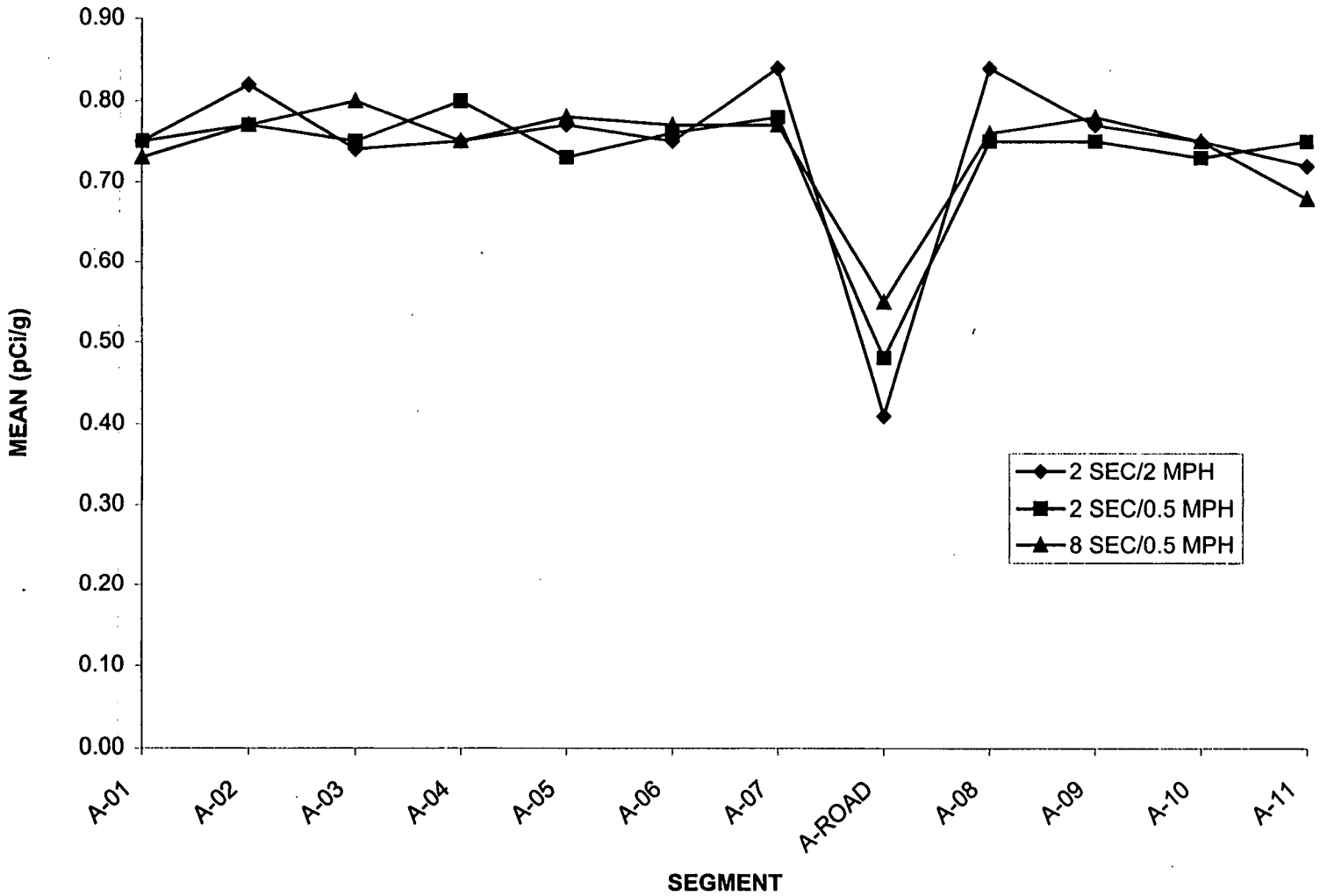

FIGURE B-11
THORIUM-232 - USID AREA - STANDARD DEVIATION

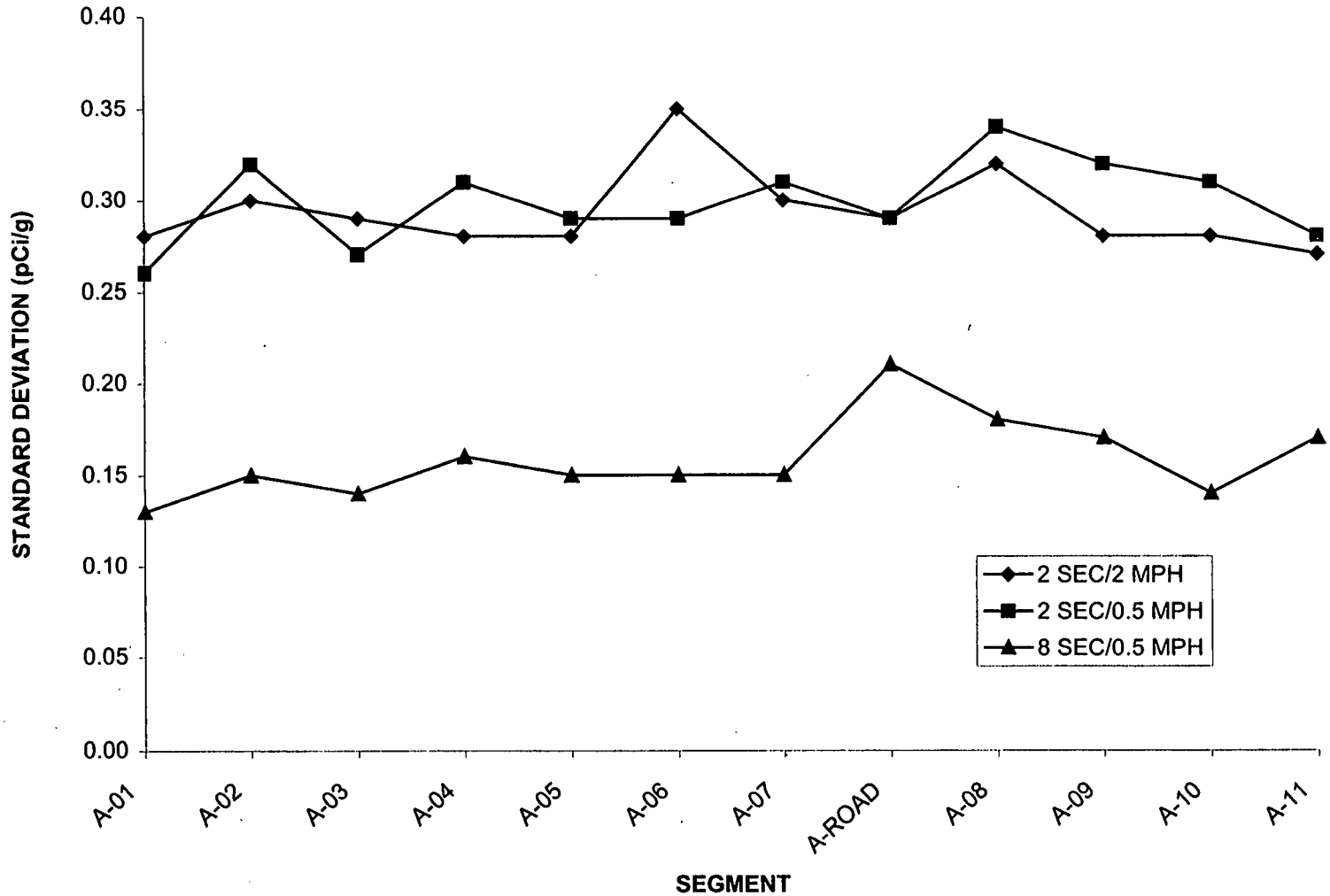

FIGURE B-12
THORIUM-232 - USID AREA - % STANDARD DEVIATION

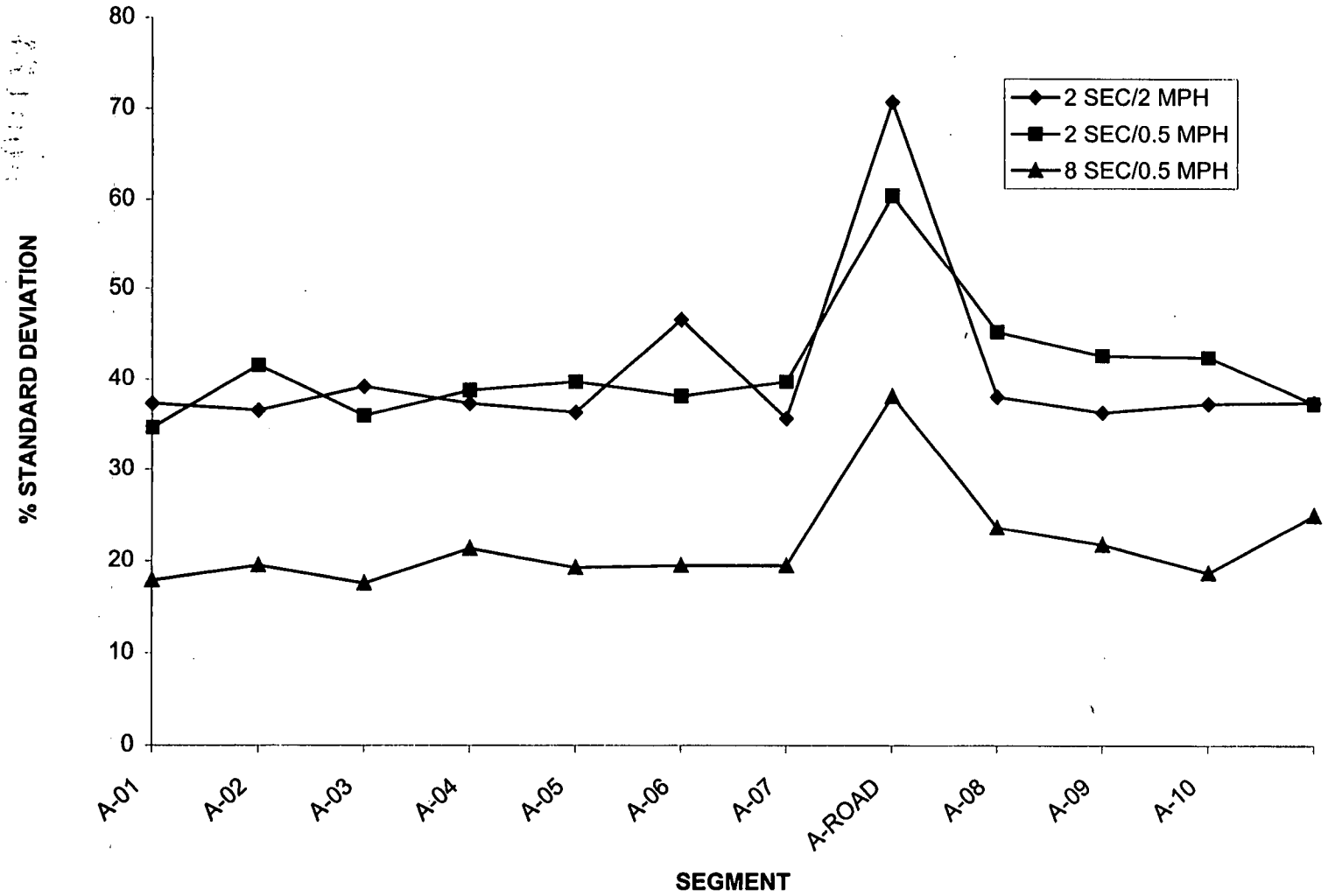

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FIGURE B-13
THORIUM-232 - SOUTH FIELD - MEAN

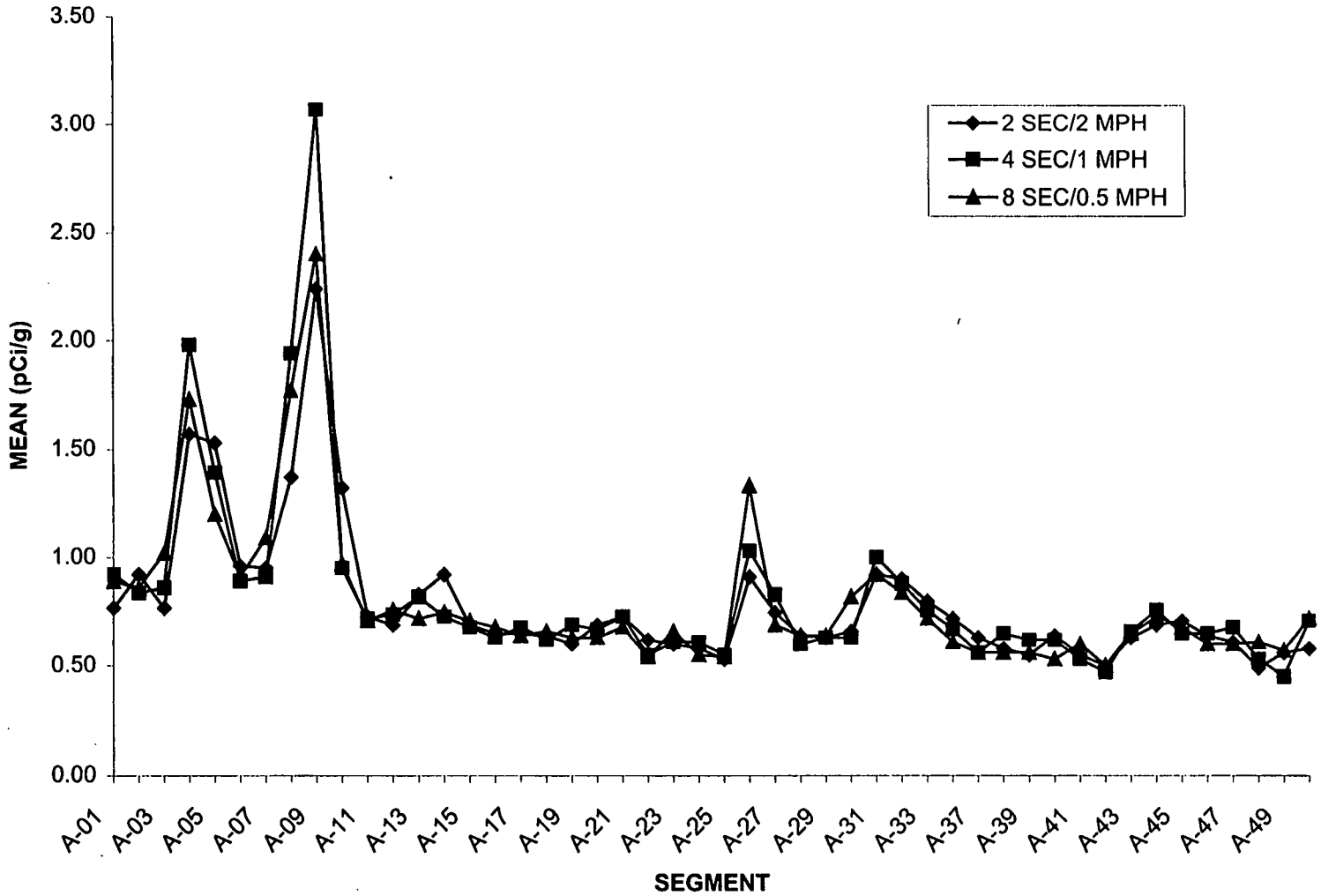

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FIGURE B-14
THORIUM-232 - SOUTH FIELD - STANDARD DEVIATION

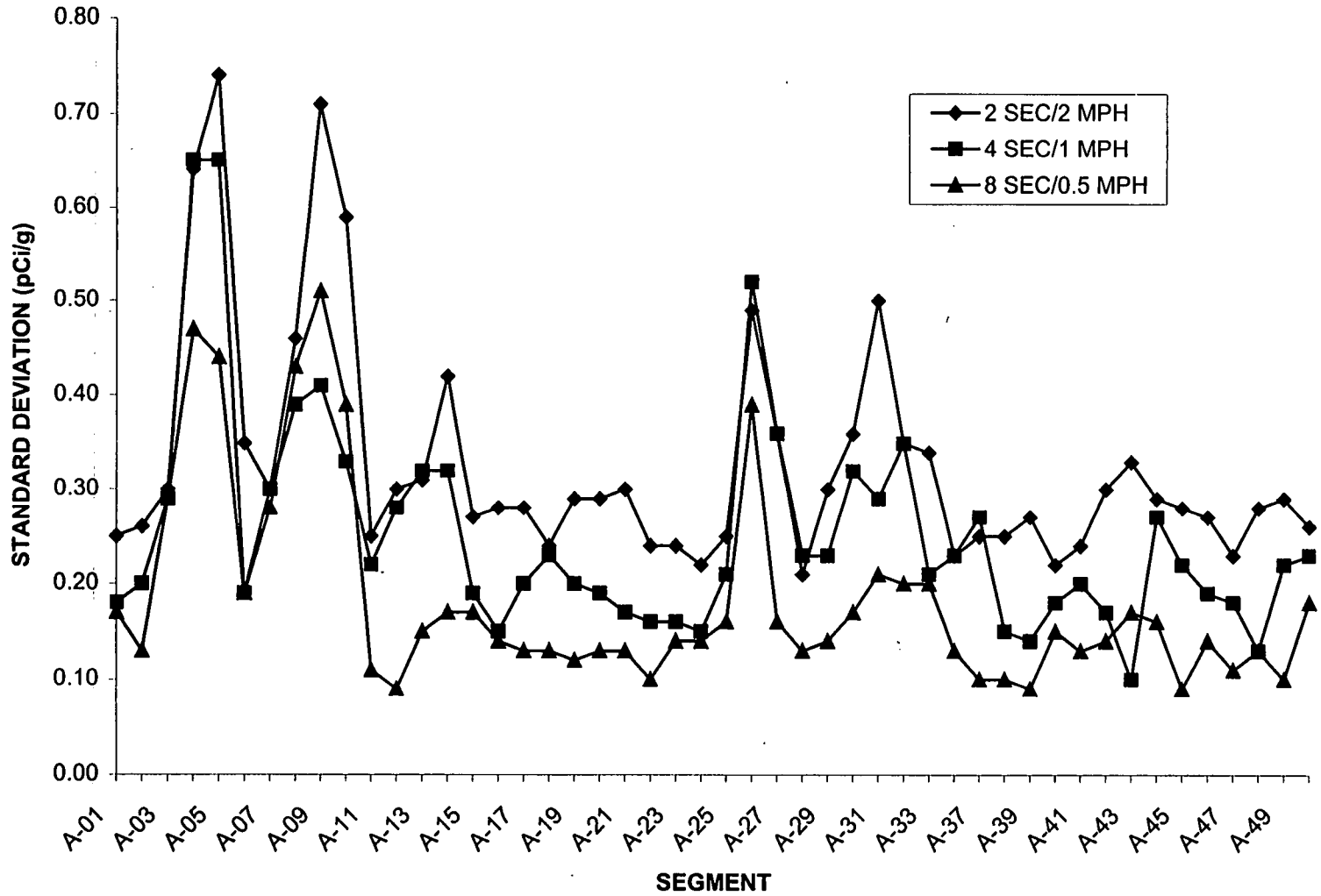

FIGURE B-15
THORIUM-232 - SOUTH FIELD - % STANDARD DEVIATION

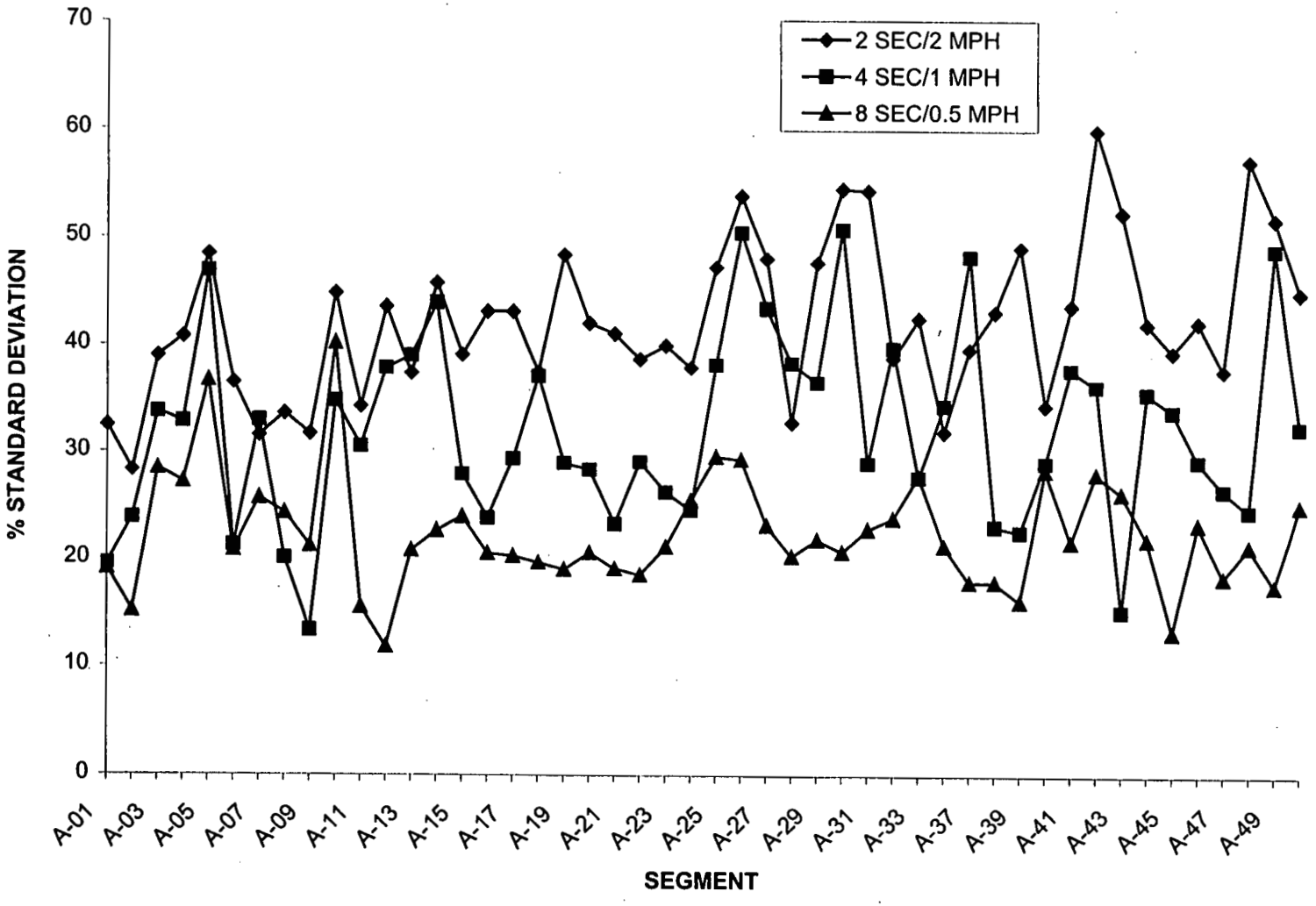

FIGURE B- 16
THORIUM-232 - DRUM BALING AREA - MEAN

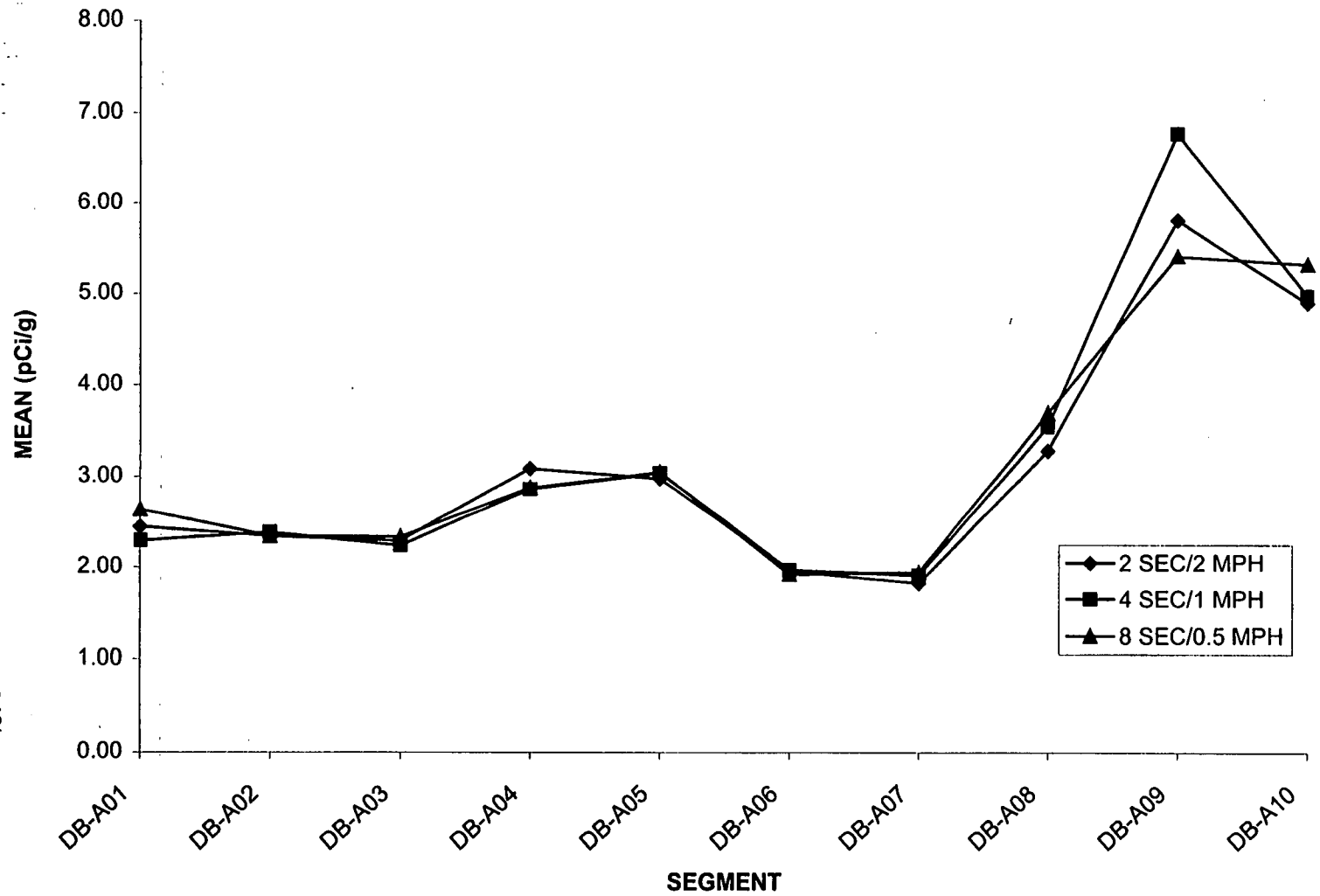

FIGURE B-17
THORIUM-232 - DRUM BALING AREA - STANDARD DEVIATION

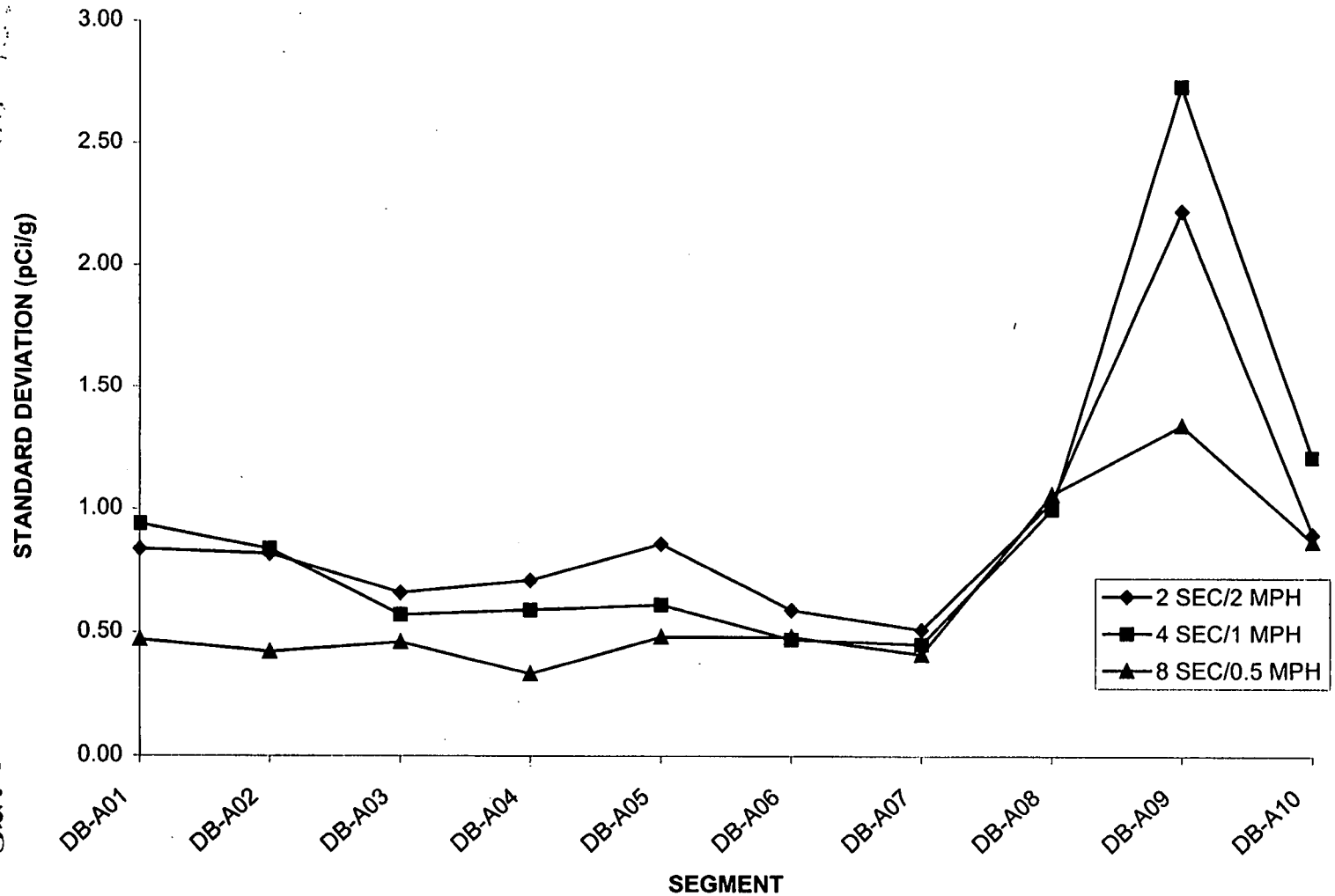

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FIGURE B-18
THORIUM-232 - DRUM BALING AREA - % STANDARD DEVIATION

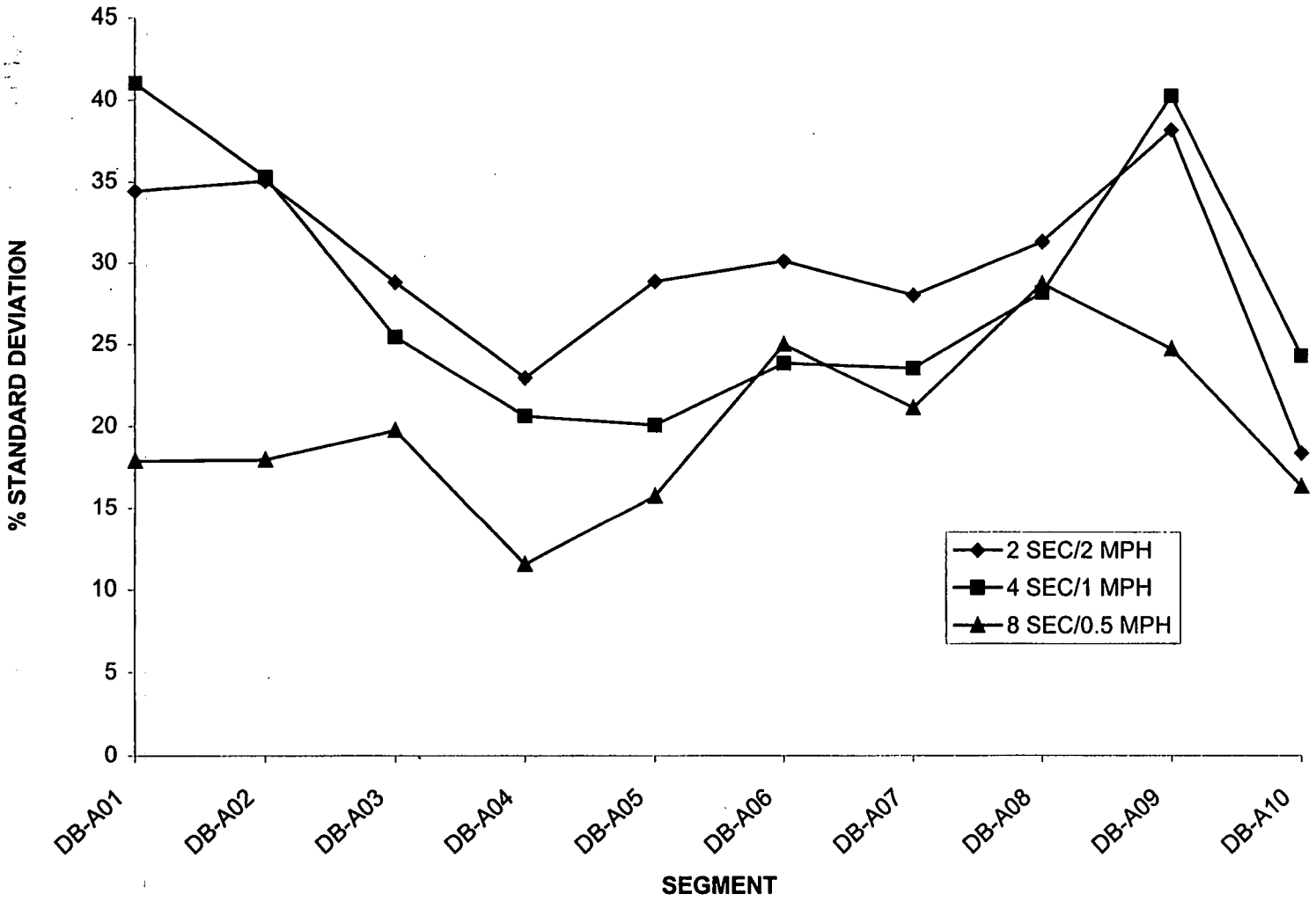

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FIGURE B-19
RADIUM-226 - USID AREA - MEAN

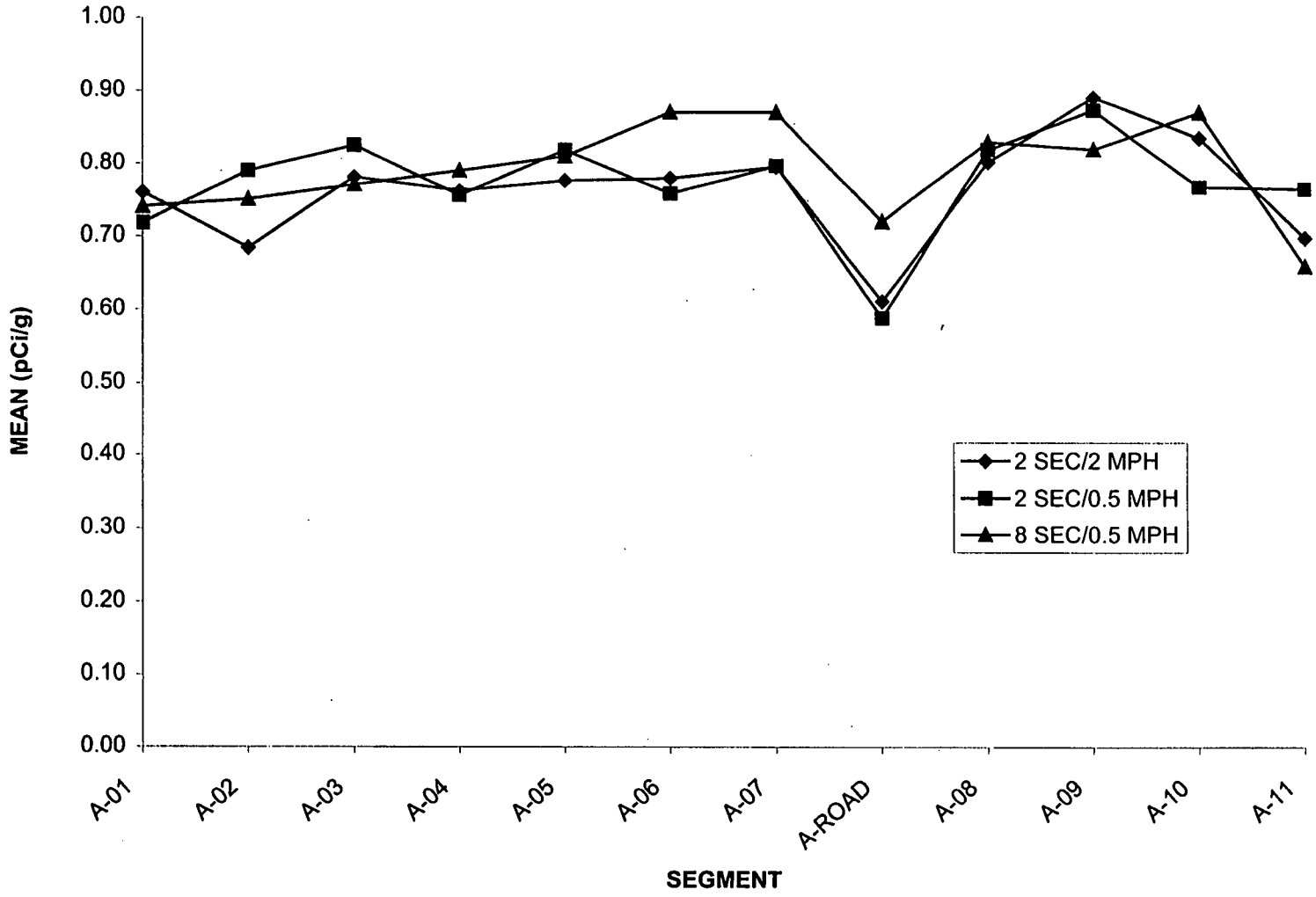

FIGURE B-20
RADIUM-226 - USID AREA - STANDARD DEVIATION

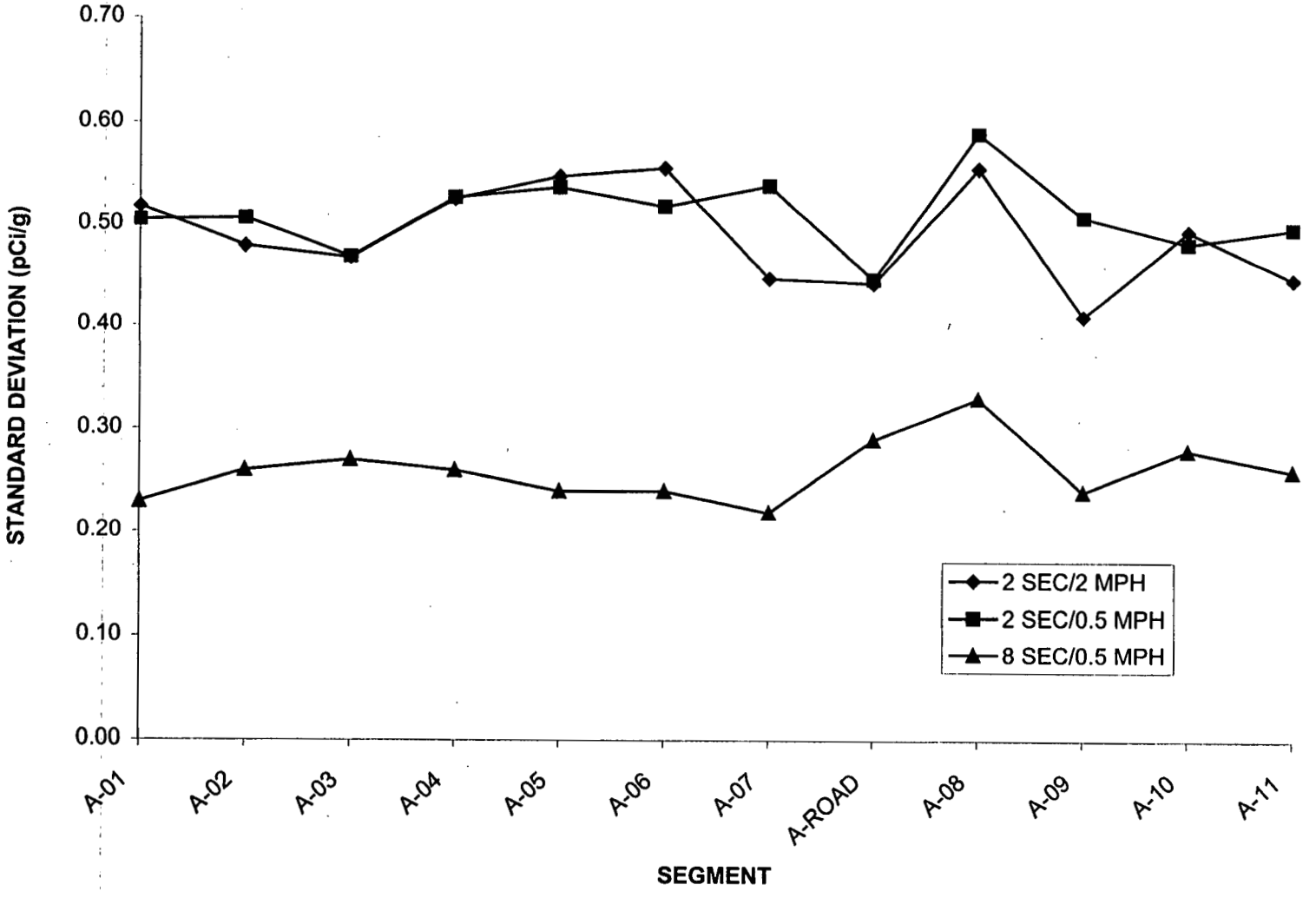

FIGURE B-21
RADIUM-226 - USID AREA - % STANDARD DEVIATION

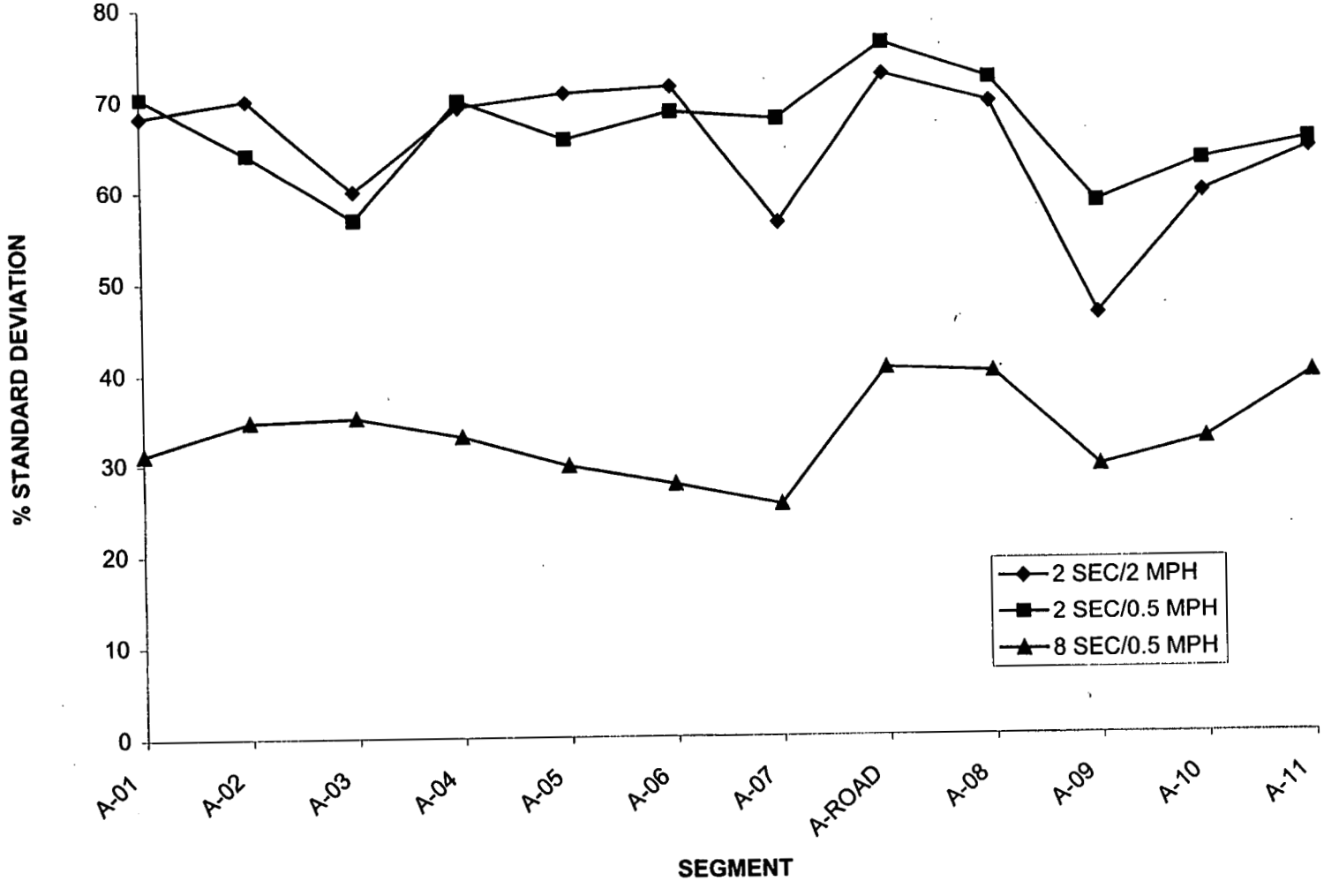

FIGURE B-22
RADIUM-226 - SOUTH FIELD - MEAN

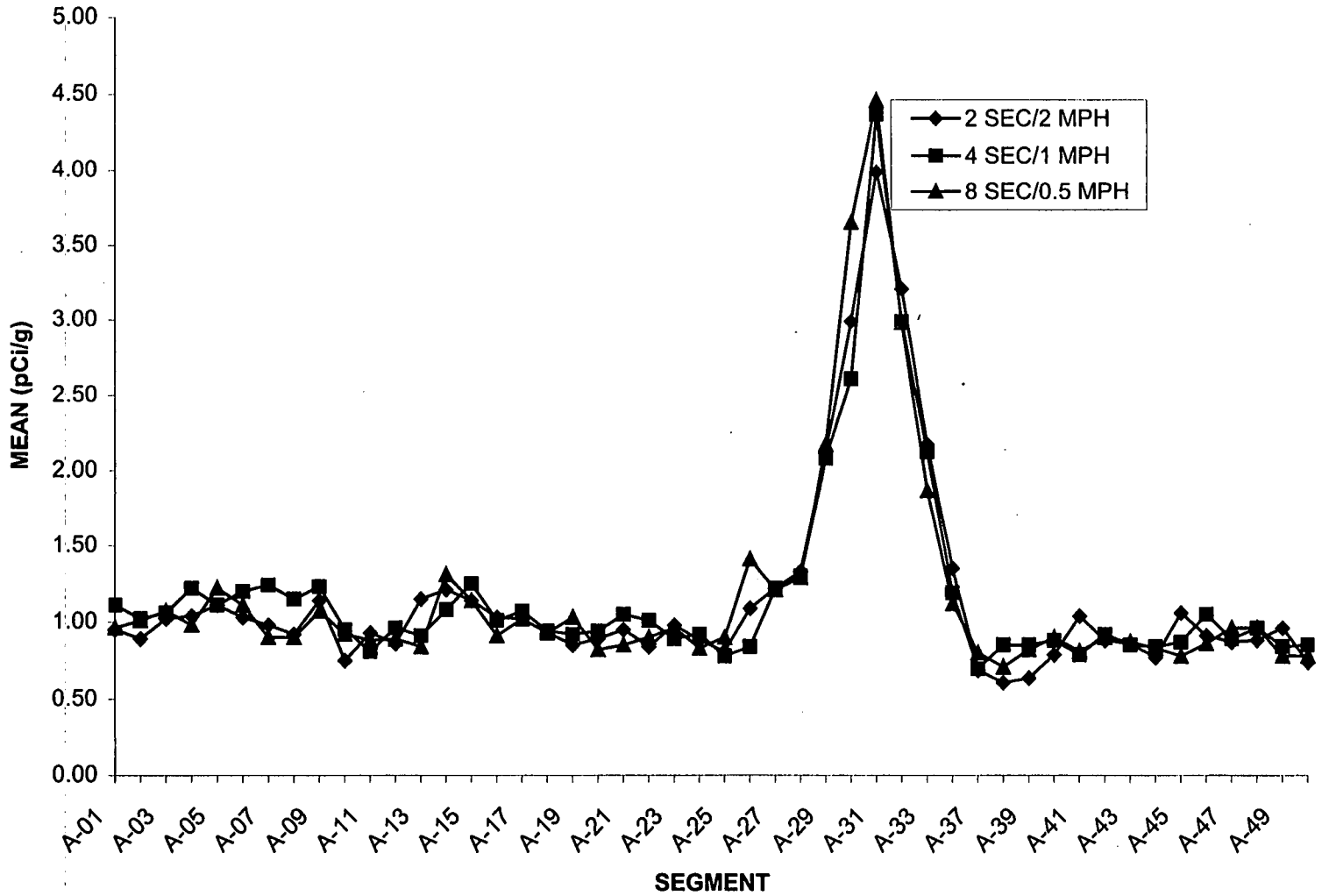

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FIGURE B-23
RADIUM-226 - SOUTH FIELD - STANDARD DEVIATION

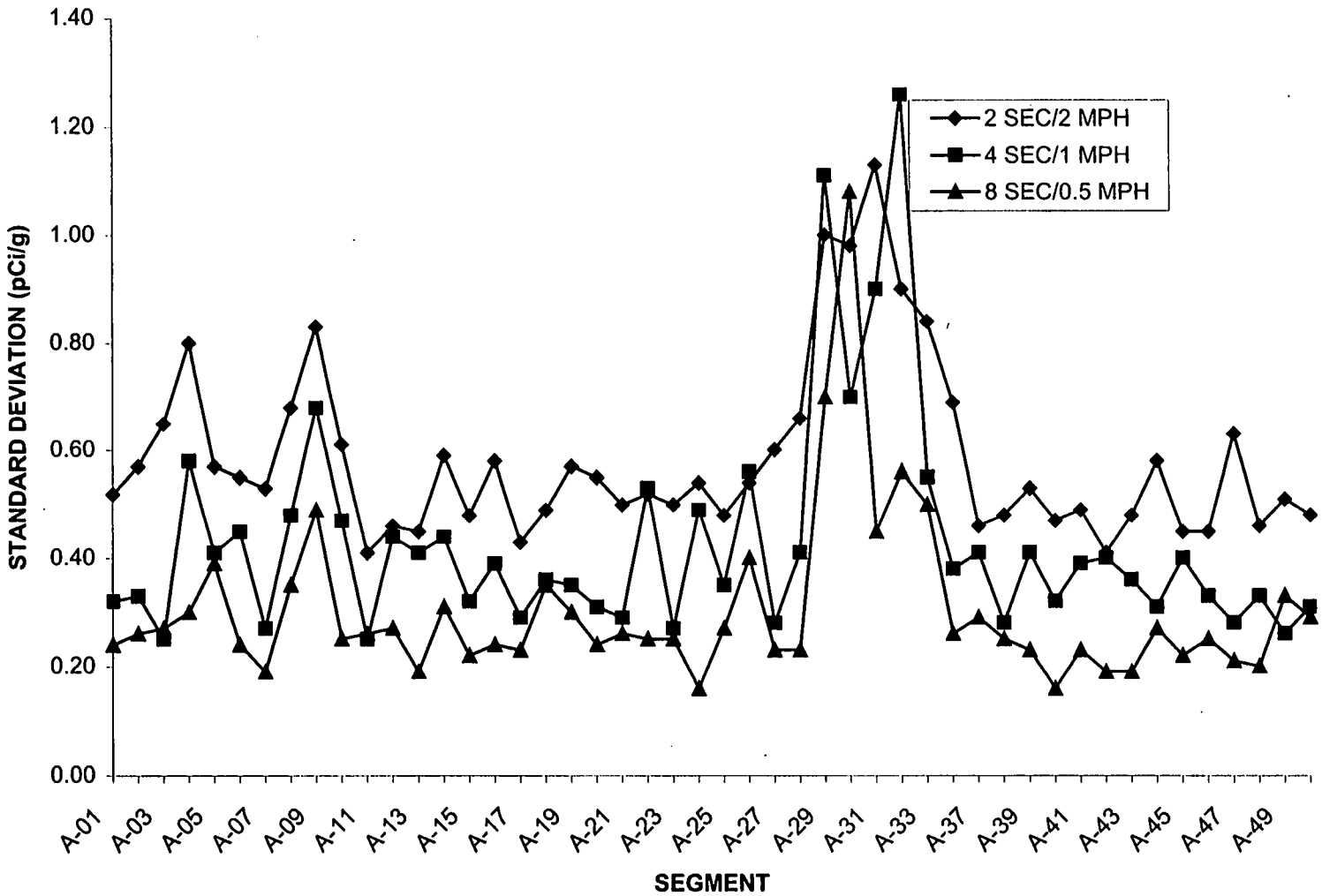

FIGURE B-24
RADIUM-226 - SOUTH FIELD - % STANDARD DEVIATION

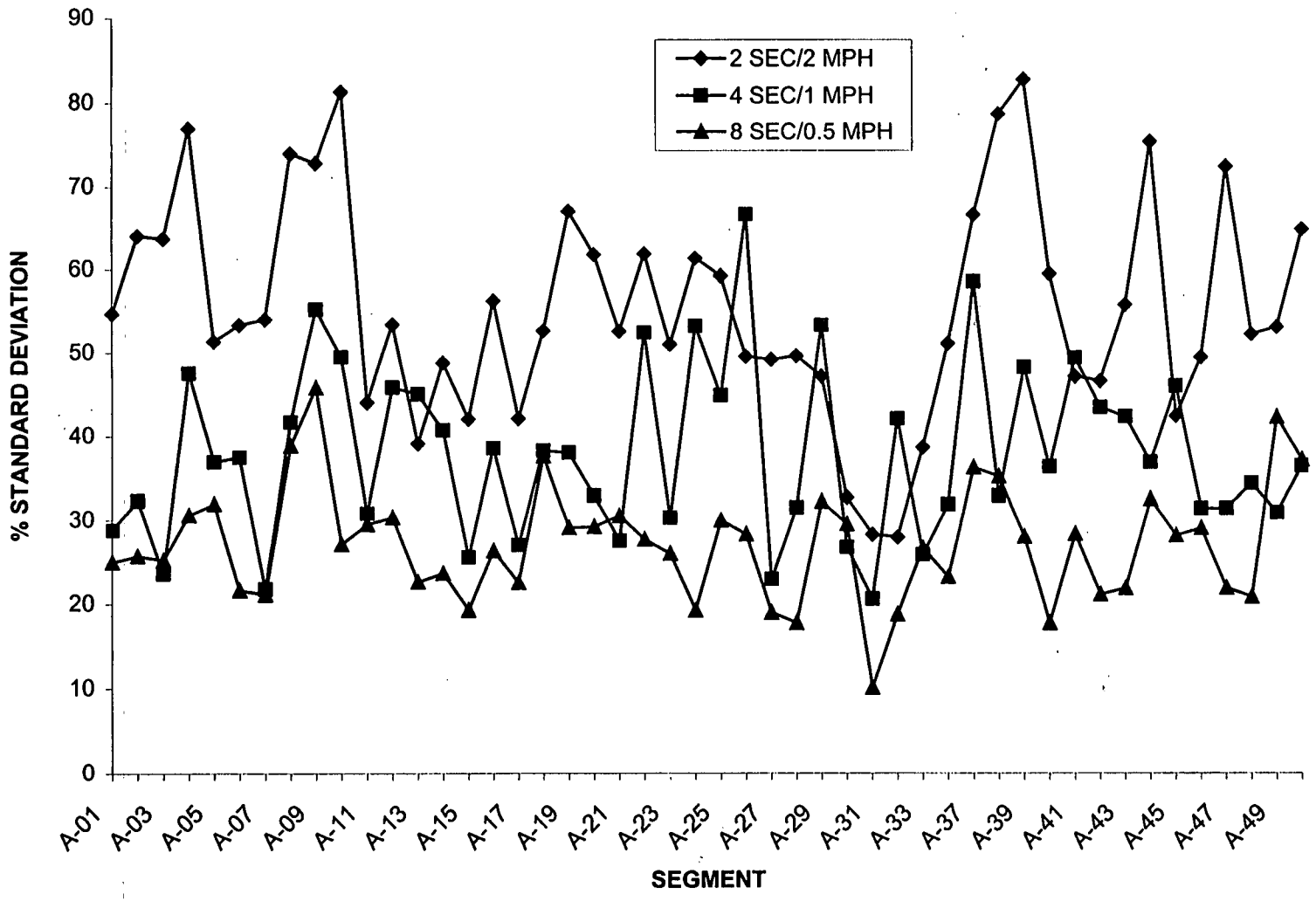

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FIGURE B- 25
RADIUM-226 - DRUM BALING AREA - MEAN

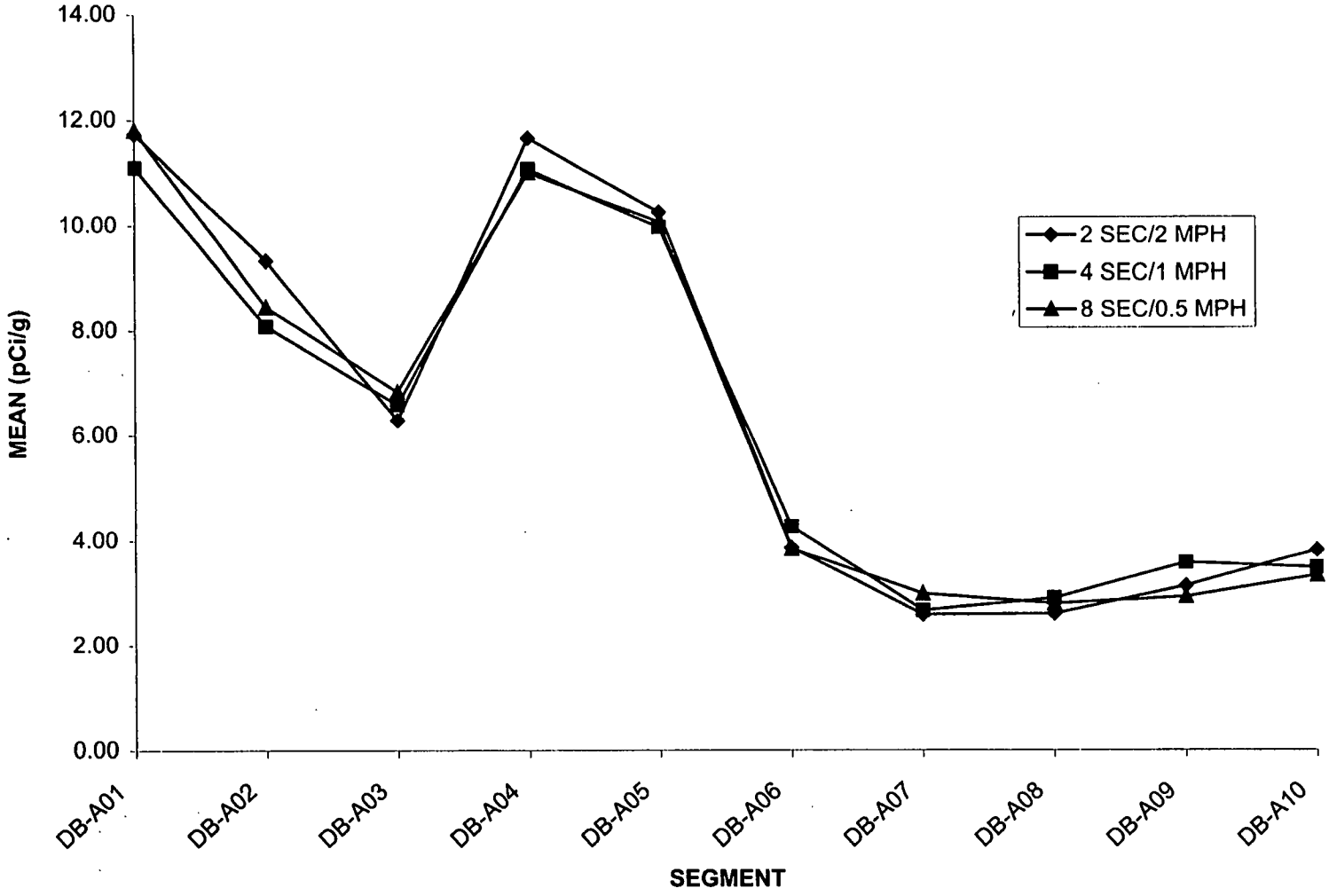

FIGURE B-26
RADIUM-226 - DRUM BALING AREA - STANDARD DEVIATION

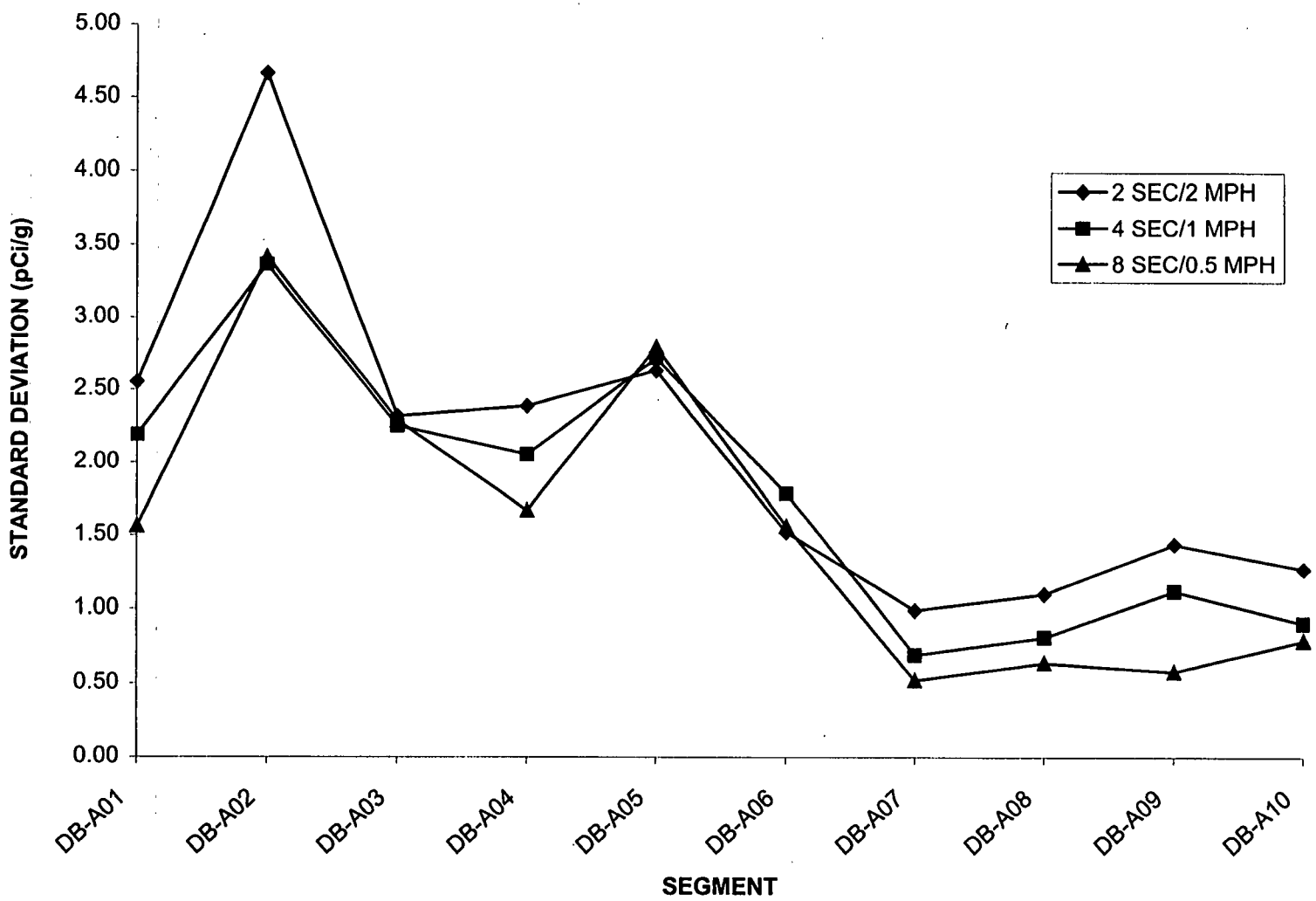

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FIGURE B-27
RADIUM-226 - DRUM BALING AREA - % STANDARD DEVIATION

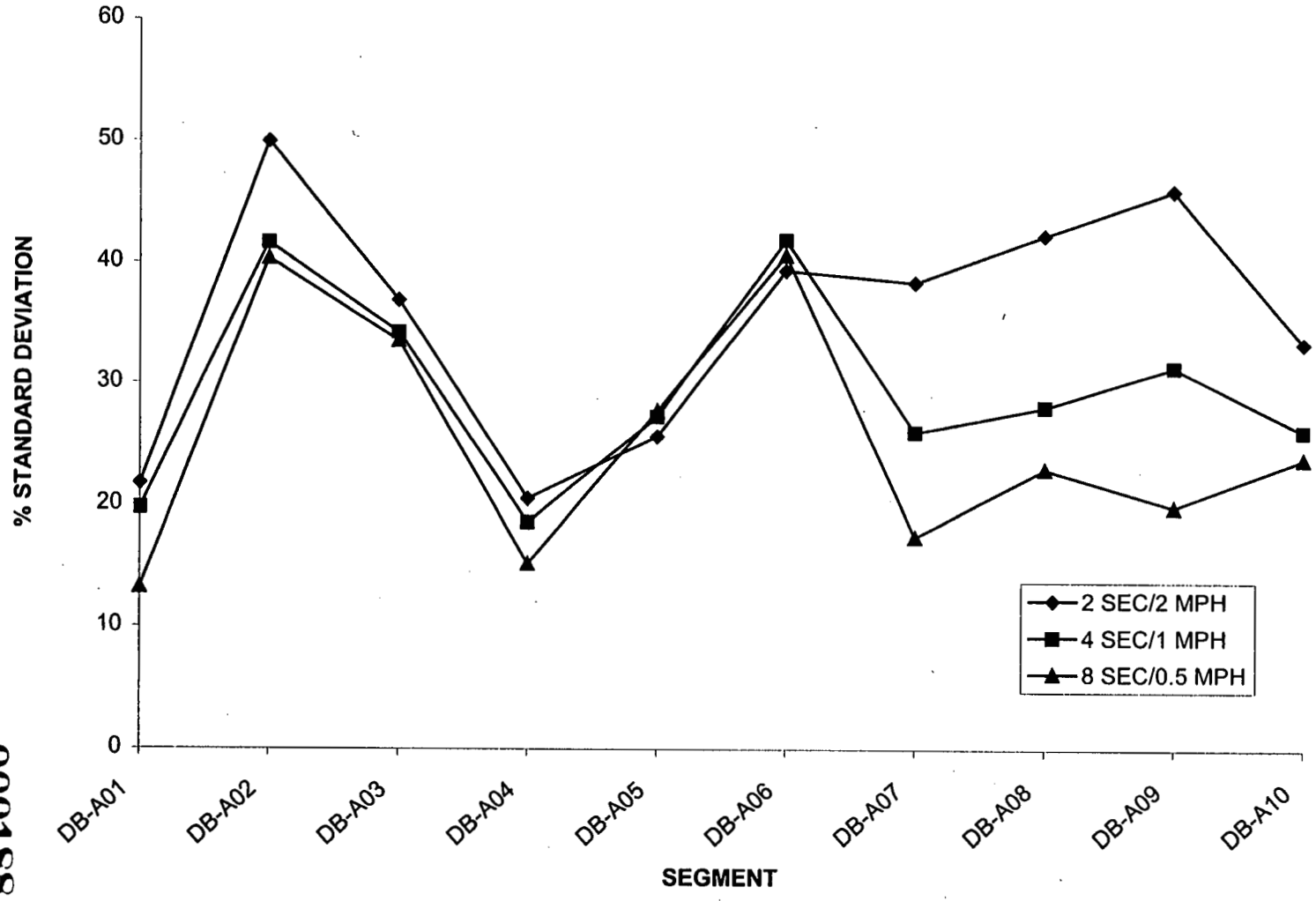

FIGURE B-28
TOTAL ACTIVITY (CPS) - USID AREA - MEAN

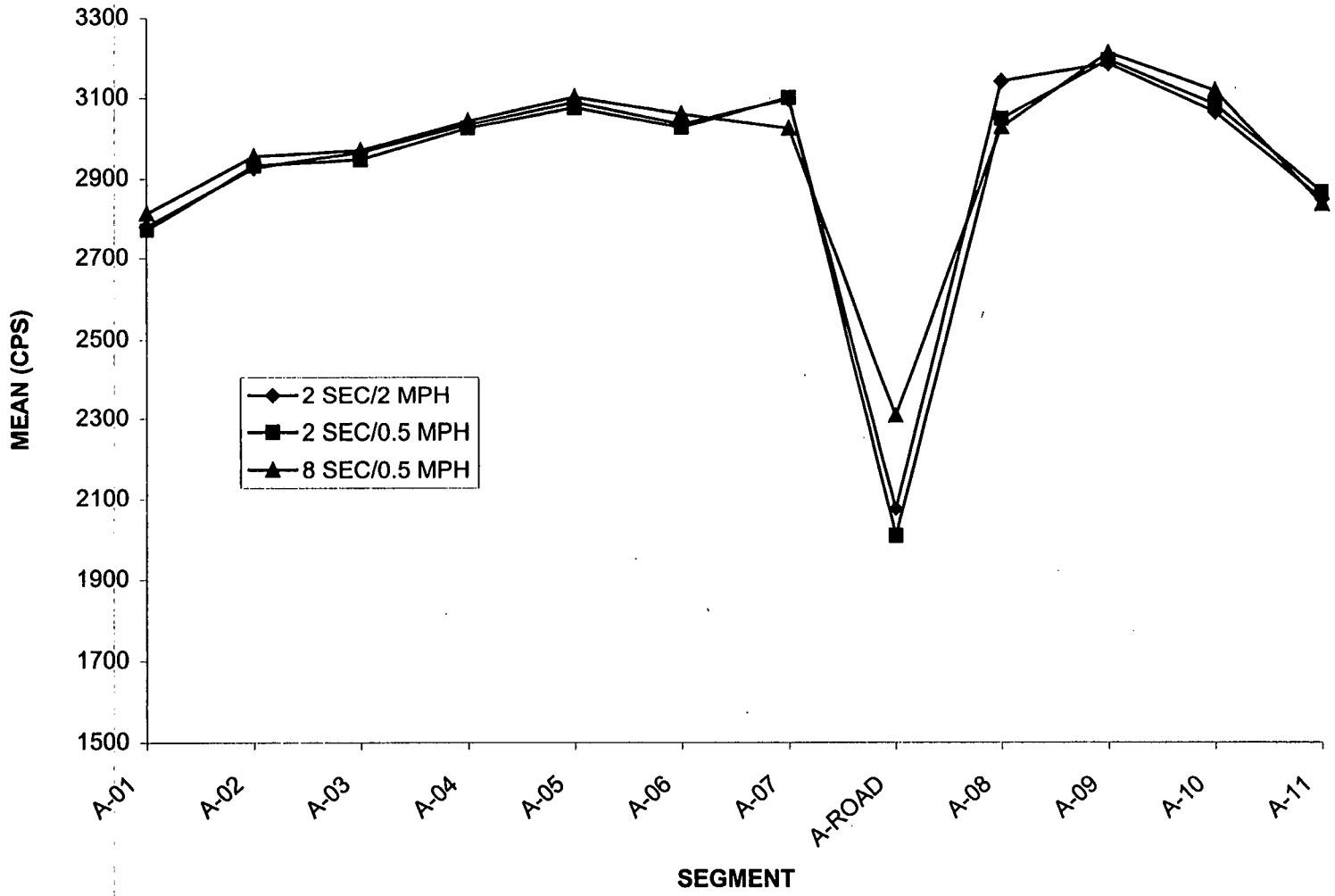

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FIGURE B-29
TOTAL ACTIVITY (CPS) - USID AREA - STANDARD DEVIATION

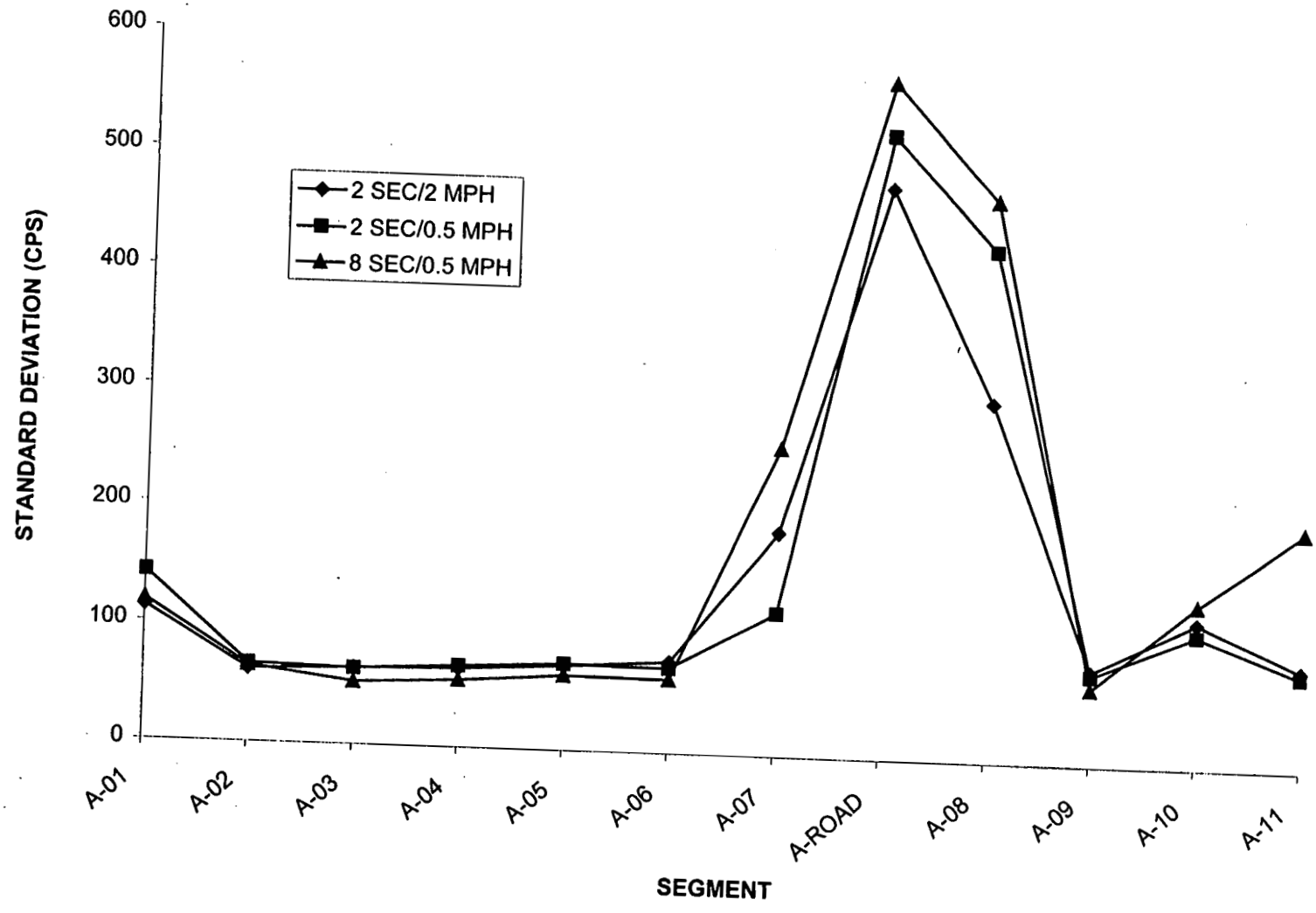

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FIGURE B-30
TOTAL ACTIVITY (CPS) - USID AREA - % STANDARD DEVIATION

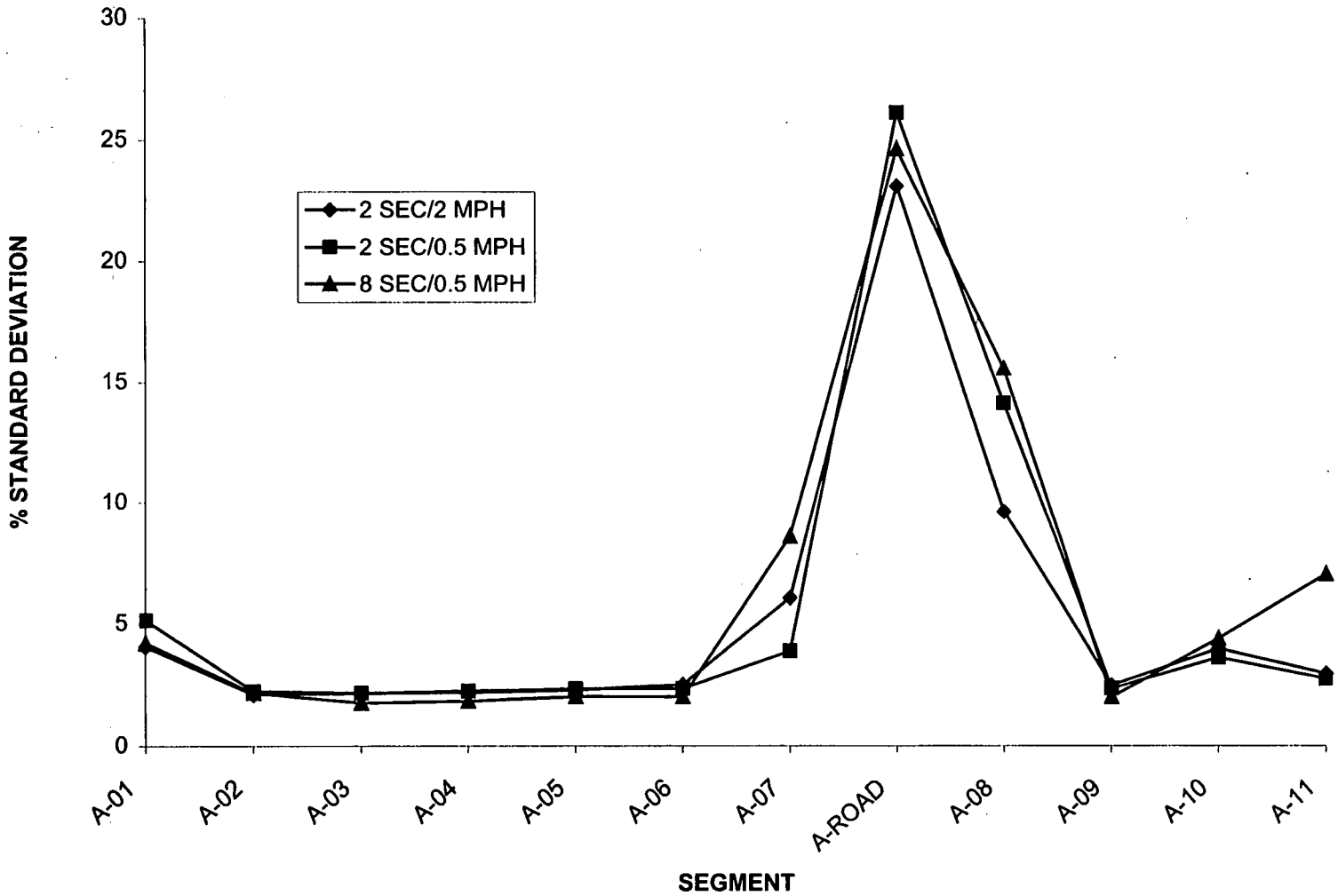

FIGURE B-31
TOTAL ACTIVITY (CPS) - SOUTH FIELD - MEAN

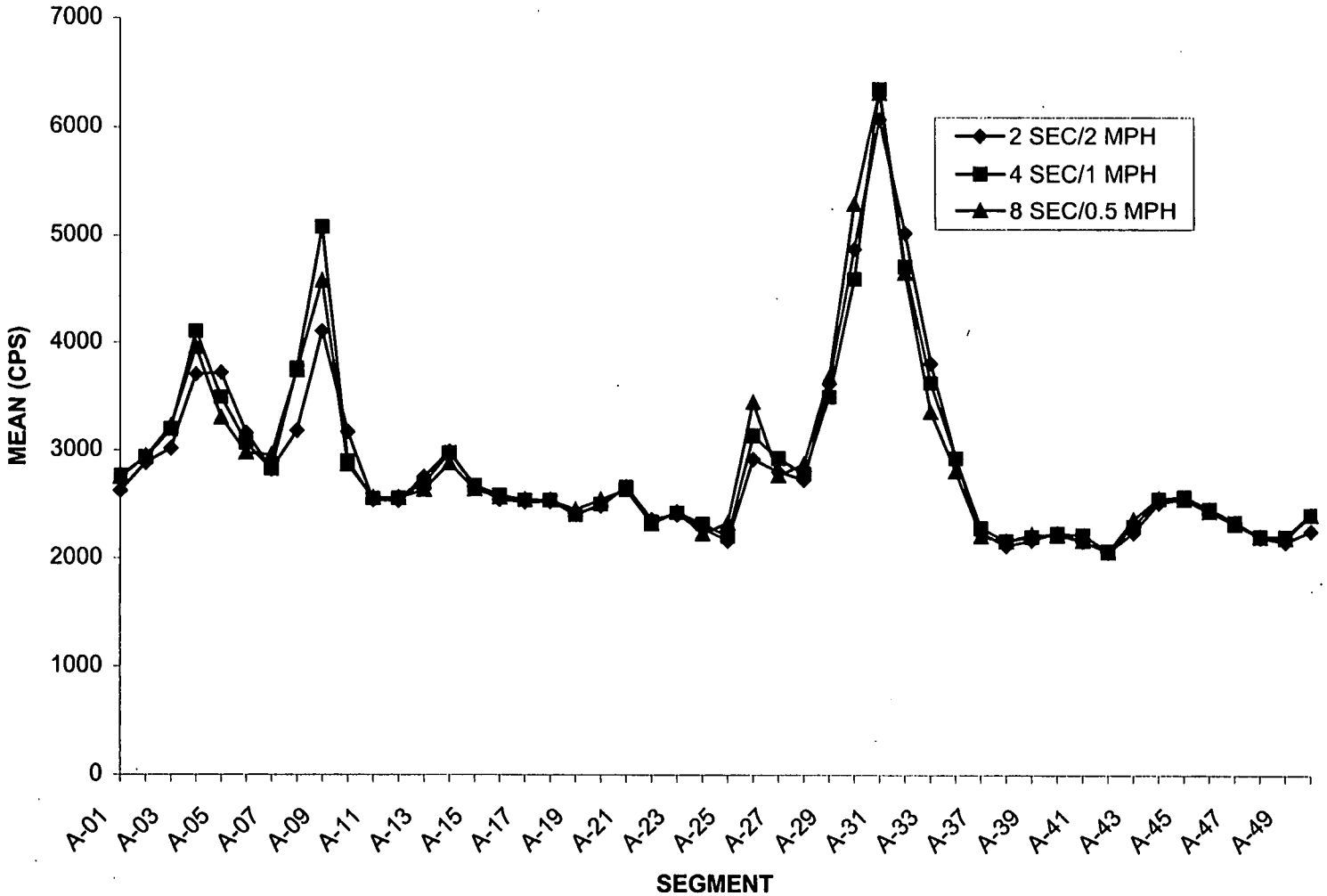

FIGURE B-32
TOTAL ACTIVITY (CPS) - SOUTH FIELD - STANDARD DEVIATION

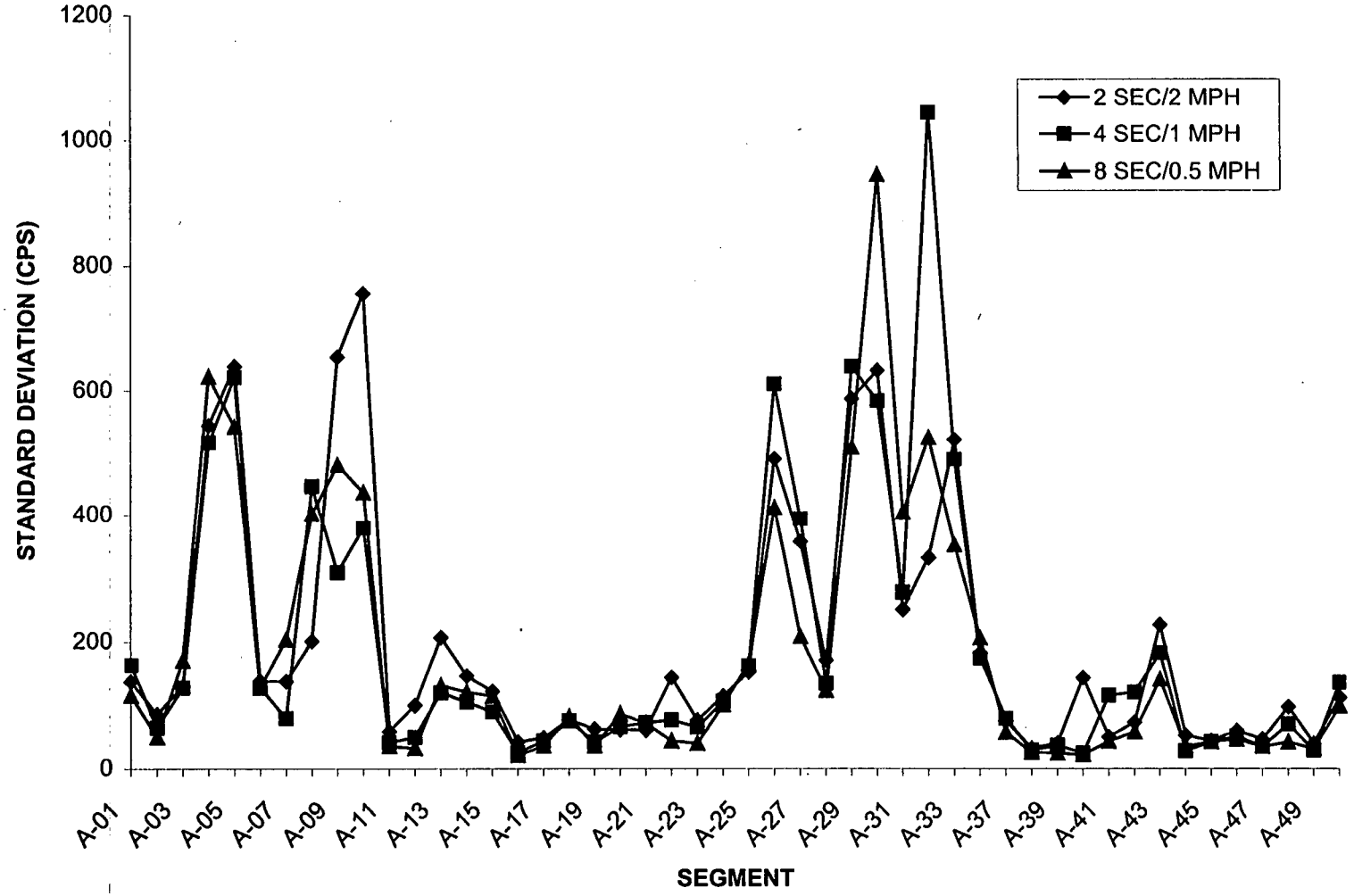

FIGURE B-33
TOTAL ACTIVITY (CPS) - SOUTH FIELD - % STANDARD DEVIATION

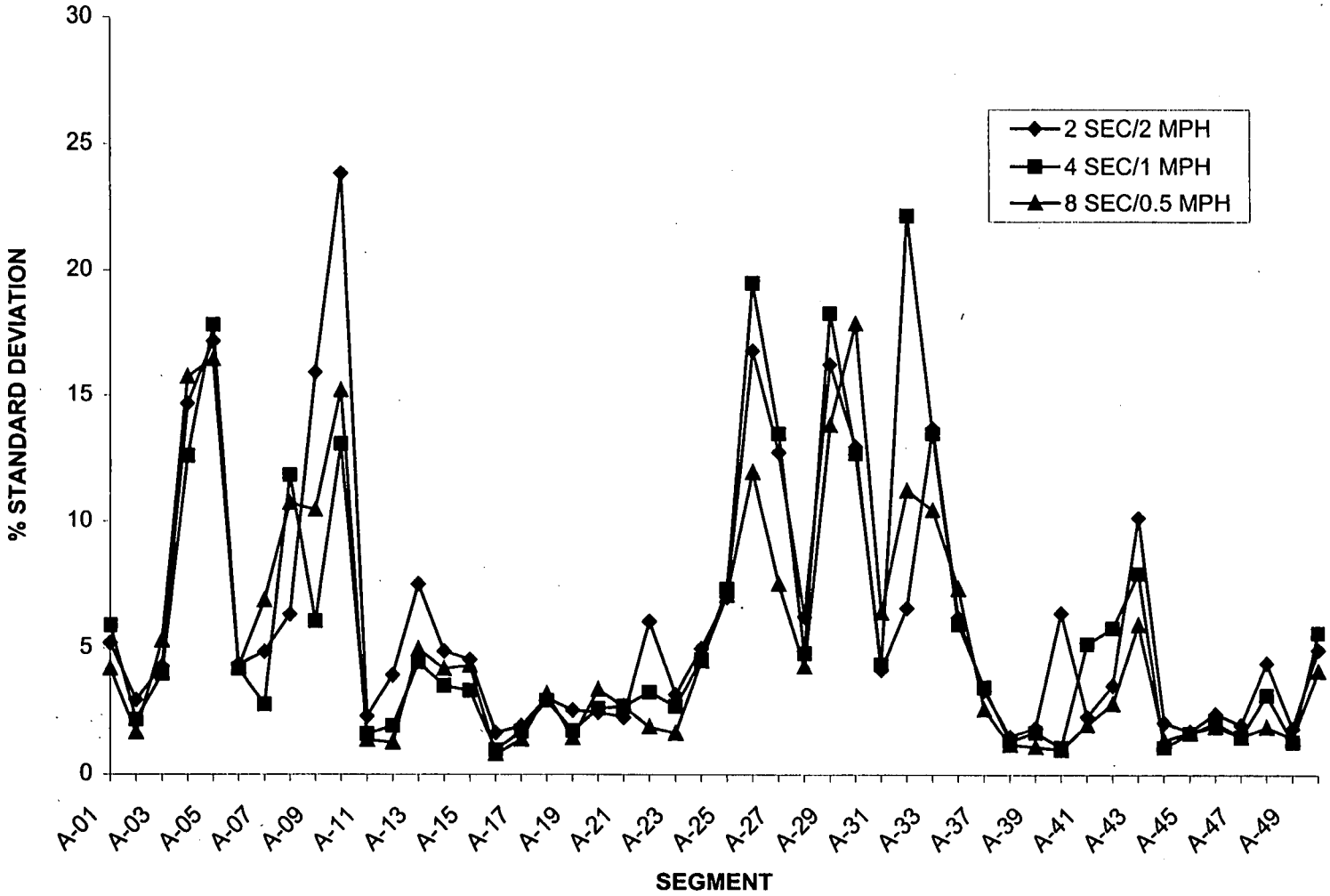

FIGURE B-34
GROSS ACTIVITY (CPS) - DRUM BALING AREA - MEAN

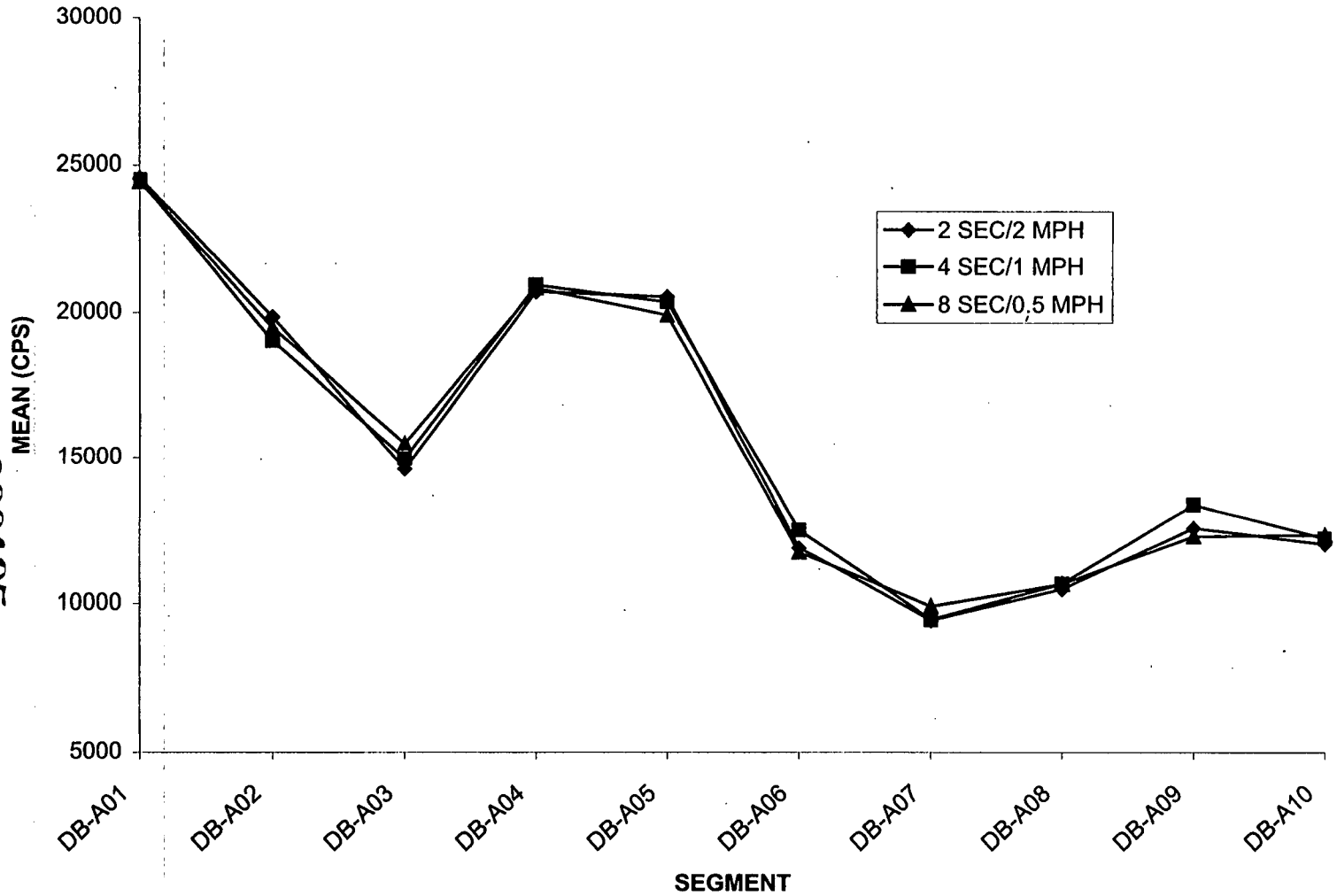

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FIGURE B-35
GROSS ACTIVITY (CPS) - DRUM BALING AREA - STANDARD DEVIATION

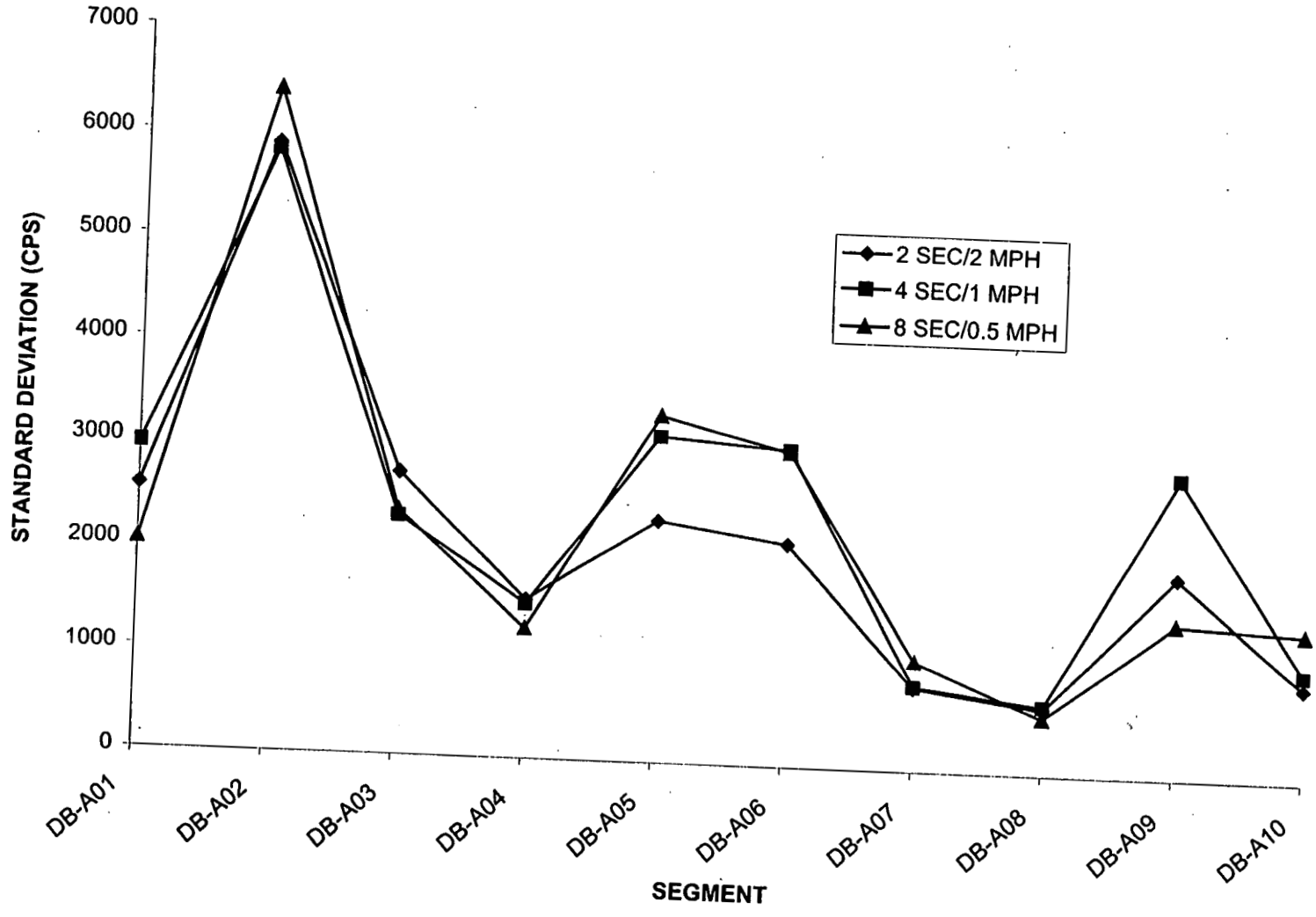
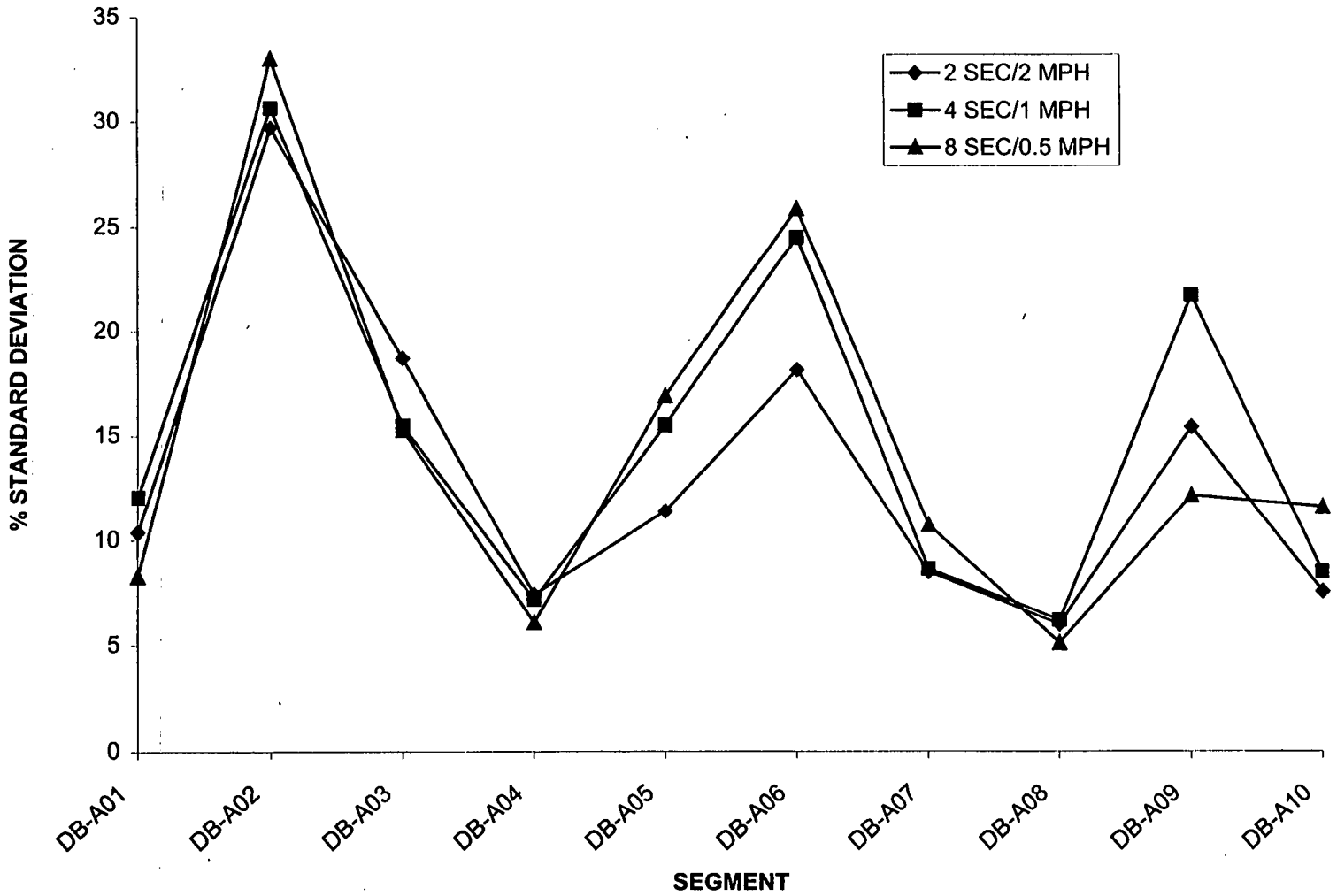


FIGURE B-36
GROSS ACTIVITY (CPS) - DRUM BALING AREA - % STANDARD DEVIATION



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APPENDIX C

THE RADIATION SCANNING SYSTEM (RSS)

APPENDIX C
THE RADIATION SCANNING SYSTEM (RSS)

C.1 RSS SYSTEM DESCRIPTION: SIMILARITIES AND DIFFERENCES FROM RTRAK

Like the RTRAK system, the Radiation Scanning System (RSS) is a gamma ray spectrometry system. However, it is mounted on a mobile platform which is much smaller and consequently more maneuverable than the RTRAK. The RSS vehicle is a three-wheeled jogging stroller. But the gamma spectrometry equipment and software, including sodium iodide detector, signal processing electronic modules, computer-based multichannel pulse height analysis system, and gamma spectrometry software are identical to those used on the RTRAK. The 4x4x16-inch NaI detector is mounted to the frame of the jogging stroller such that the detector is 31 centimeters above the ground. To scan an area, the RSS is pushed by hand by the operator. As with the RTRAK, the preferred mode of operation is to move at a speed of one mile per hour while acquiring a series of 4-second gamma spectra. The RSS and RTRAK make use of the same satellite Global Positioning System (GPS) to mark the location at which each gamma spectrum was acquired.

As nearly as possible, the operation of the RSS system is identical to that of the RTRAK. Like the RTRAK, the RSS sodium iodide detector must undergo an energy calibration and an efficiency calibration before it can be used to quantify the radionuclide concentrations in the soil. The same radioactive source is used to energy calibrate the RSS and the equipment is adjusted so that the peaks from this source appear in exactly the same MCA memory channels as in the RTRAK. That is for both the RTRAK and RSS, the 238.6 Kev peak from Pb-212 is positioned in channel 40 $\pm$ 2 and the 2615 Kev peak from Tl-208 is positioned in channel 447 $\pm$ 2. This results in a "gain" of 5.84 Kev per channel for both systems. Since the NaI detectors on the two systems are the same size and the signal processing electronics are the same, the resolution of the two systems (i.e., peak full width at half maximum) will be nearly identical. The detector enclosures and the surrounding insulating materials are not identical; but this will not result in significant differences in the sensitivity of the two systems. Both systems undergo the same quality control instrument performance checks before they are used for data acquisition, and the acceptance criteria are the same. The RSS field data review criteria are the same as for RTRAK and the data are processed and used in exactly the same manner.

Apart from the size of the mobile platform of the Radiation Scanning System, the intent was to construct a system as nearly identical to the RTRAK as possible. By using the same data analysis

software, detector and signal processing electronics, this objective was accomplished. However, the RSS does differ in two respects from the RTRAK. First, the RSS computer and electronics are not enclosed in an air-conditioned cab like they are in the RTRAK. Second, the long axis of the RSS NaI detector is mounted parallel to the direction of travel, whereas in the RTRAK, the long axis is perpendicular to the direction of motion.

C.2 DESCRIPTION OF RSS CALIBRATION STUDY

Energy calibration of the RSS detector was described above. The process was identical to the process of energy calibrating the RTRAK. The process of efficiency calibrating the NaI detectors, as descried in detail in Section 3 of this report, was also the same for both the RSS and RTRAK. Recall that as a result of the efficiency calibration process, one derives the relationship between the number of counts recorded in each spectral region of interest and the concentration of the corresponding radionuclide in the soil. HPGe measurements were performed to determine the concentrations of the radionuclides of interest.

Ten measurement points were chosen in five different areas of the FEMP site to conduct the RSS calibration study. These areas were chosen because they contained uranium levels ranging from background to high contamination. Multiple measurement locations were chosen in the Drum Baling Area where the contamination was known to be heterogeneous to extend the range of concentrations over which the instrument was calibrated and to provide information on the effects of heterogeneity. At each of the study locations, fifteen minute HPGe readings were collected at detector heights of one meter, 1 foot and 6 inches. Two 5-minute RSS spectra were also collected at each of these locations with the RSS remaining stationary during data collection. One spectrum was acquired with the RSS in its normal orientation, that is with the long axis of the NaI crystal parallel to the intended direction of travel. The second spectrum was acquired with the stationary RSS rotated 90 degrees so that the long axis of the NaI crystal was perpendicular to the intended path. In this latter orientation, the RSS crystal alignment would be the same as that of the RTRAK crystal. But the RSS could not be used for mobile scanning while oriented in this manner.

The measurements were performed to see if the different crystal orientations effected the readings in a significant manner. (RTRAK measurements were also performed at these locations. These are described elsewhere in this report.)

Following the static calibration measurements, the newly developed calibration equations were tested by operating the RSS system in a mobile mode. The verification consisted of comparing RSS results to RTRAK results in two separate areas. In the USID Area, just west of the original RTRAK profile path, both the RTRAK and the RSS were repeatedly driven over the same straight line path. The RTRAK was driven back and forth twenty times along a straight line path at a speed of 1 mile per hour while acquiring 4 second spectra. The RSS was pushed directly behind the RTRAK at the same speed and with the same spectral acquisition time to permit a direct comparison of RSS and RTRAK moving measurements in a relatively homogeneous area. The resulting data were also used to derive information about the precision of the RSS compared to that of the RTRAK. A full area scan was also performed in the Drum Bailing Area with both the RSS and the RTRAK to serve as additional verification of the calibration and to develop data on system quality parameters. The data from the Drum Baling Area would also permit a direct comparison of RSS and RTRAK moving measurements in a heterogeneous area to aid in assessing the effects of heterogeneity.

C.3 RSS EFFICIENCY CALIBRATION

As explained in other sections of this report, before any gamma spectrometry system can be used to quantify individual isotopes in the soil, the response of the detector to gamma photons from radionuclides distributed in the soil must be determined. This process is analogous to the laboratory process of efficiency calibration of a gamma spectrometry system for a given sample and detector relative arrangement (i.e, geometry). The process used to efficiency calibrate the RSS is exactly the same as that used for the RTRAK. The RSS net counts per second for specified spectral regions of interest are correlated to HPGe readings obtained at the same location. The spectral regions of interest were chosen because each is characteristic of different gamma ray energies emitted by the specific isotopes of interest. However, when multiple isotopes are present, as is often the case, the gamma emissions from one isotope may cause spectral interferences that effect regions of interest used to quantify other isotopes. As explained in the discussion of the RTRAK efficiency calibration (Section 3.3 and Appendix A), to properly account for these effects multiple linear regression analyses were performed. These analyses related soil radionuclide concentrations of a single isotope to the net counts per second in the Th-232, Ra-226 and U-238 spectral regions of interest.

HPGe measurements were performed with detector heights set at 1 meter, 0.31 meters and 0.15 meters. The correlations between the RSS and HPGe results were investigated for all three HPGe

detector heights. Better correlations were observed with the 0.31 meter data than with the 0.15 or 1 meter data. This was also true of the RTRAK calibration data, which is not surprising in light of the fact that the field of view of the RSS detector is a closer match to the 0.31 m HPGe field of view. The regression analyses for each of the isotopes of concern are discussed in greater detail below. Only the correlations with the 0.31 m HPGe results will be presented since these are the ones that will be used to convert RSS net counts per second to radionuclide concentrations in pCi/g or ppm of total uranium.

C.3.1 Orientation of the RSS Detector

Because of the configuration of the frame of the RSS jogging stroller, it was easier to mount the NaI crystal with its long dimension parallel to the direction of travel. However, the RTRAK NaI crystal is mounted so that its long axis is perpendicular to the direction of travel. Roughly speaking, the field of view of both detectors is somewhat elliptical, but each is reasonably well approximated by a circle. On this basis, it was postulated that the 90 degree difference in orientation of the RSS and RTRAK detectors would not significantly effect the measurement results. To test this hypothesis, stationary RSS measurements were performed at ten calibration locations with the long detector axis oriented first at 0 degrees to the direction of travel and then at 90 degrees to the direction of travel. The results of these measurements are displayed in Tables C-1 through C-3 for Th-232, Ra-226 and U-238 respectively. By examining the data in these tables, it can be seen that the 0 degree and 90 degree results generally agree with one another. There were distinct differences between the 0 degree and 90 degree results at only two locations. The locations where marked differences occurred were the same for all three isotopes. These were locations A3-8 in the Drum Baling Area and A13-3 in the South Field. The data associated with these two locations is shaded in the tables for ease of identification. As discussed further below, there were also anomalies associated with the HPGe readings at these locations

C.3.2 RSS Calibration Equations

HPGe readings at three detector heights were also collected at each calibration location. These data are also displayed in Tables C-1 through C-3. There was generally good agreement between the HPGe results at the three detector heights. However, once again, locations A3-8 and A13-3 did not fit the normal pattern in that the Th-232 and the U-238 HPGe results for these locations exhibited poorer agreement. Taken together, the HPGe data and the RSS data indicate that there is something unusual about these two locations. It is likely that there are Th-232 and, to a lesser extent, U-238 hot spots at

these locations. The hot spots may or may not be colocated. Based on the variation of the data, it appears that the hot spots were located on the edge of the field of view of the HPGe detector when it was at a height of 15 cm. This could place the hot spot directly under one end of the RSS NaI detector when it was in one orientation, and with the 90 degree rotation of the RSS system, the hot spot would no longer be directly under the NaI detector. In the case of the measurements at location A3-8, the zero degree orientation of the RSS detector yielded a higher result than the 90 degree orientation; but, at location A13-3 the opposite was true. The explanation given above applies equally well to both cases, except that in the first case we must postulate that the hot spot was directly under one end of the detector when it was in its zero degree orientation, and in the second case the hot spot was directly under one end of the detector in its 90 degree orientation.

To avoid the ambiguities associated with these locations, it was decided to delete these locations from the calibration data set. So eight locations were used to derive calibration equations for all of the isotopes of concern. It turns out that the regression technique used to derive the calibration equations showed that the Th-232 correlation was significantly poorer when the data from locations A3-8 and A13-3 were included in the regression analyses..

Th-232 Calibration Equation

The measurement results on which the Th-232 calibration equation is based are presented in Table C-4. The table displays the Th-232 HPGe results for a detector height of one foot (0.31 meters) as well as the RSS net counts per second for both the Th-232 and the Ra-226 regions of interest. Although these measurement results were previously displayed in Tables C-1 through C-3, they were gathered in one table for the convenience of the reader. The data were collected with the RSS detector in its normal traveling orientation, but they represent stationary spectra with five minute acquisition times. The regression analysis was preformed with the 31 cm HPGe data because the field of view at this detector height approximates that of the RSS detector and because better fits resulted. Also displayed in Table C-4 are the predicted Th-232 results based on the "best fit" multiple linear regression equation given below:

$$\text{RSS Th-232 pCi/g} = 0.04183917 * Th_{NCPS} - 0.0008506 * Ra_{NCPS} + 0.31023$$

where the subscript NCPS stands for Net Counts Per Second in a given spectral region of interest.

This is the equation that will be used to convert counts registered by the RSS NaI defector to Th-232 concentrations in the soil. The form of this equation is identical to that of the RTRAK Th-232 calibration equation. Like the RTRAK Th-232 equation, the negative radium term in the RSS equation compensates for the fact that Ra-226 contributes some extra counts to the thorium signal window. The radium contribution must be subtracted to arrive at an accurate Th-232 activity. If both thorium and radium counts are zero, the calculated Th-232 activity will be 0.3 pCi/g, which is acceptably close to zero. Both the form of the RSS equation for Th-232 and the magnitude of the coefficients are similar to RTRAK. This lends credence to the assertion that the differences between the RTRAK and RSS systems are not significant and the measurement results produced by the two systems are comparable.

Ra-226 Calibration Equation

The measurement results on which the Ra-226 calibration equation is based are presented in Table C-5. The table displays the 31 cm. Ra-226 HPGe results as well as the RSS net counts per second in the Ra-226, and Th-232 regions of interest. Also displayed in Table C-5 are the predicted Ra-226 results based on the "best fit" multiple linear regression equation given below:

$$\text{RSS Ra-226 pCi/g} = 0.14083561*Ra_{NCPS} + 0.02261263*Th_{NCPS} + 0.0090192$$

Low abundance gamma rays from daughters of Th-232 contribute counts to the Ra-226 background windows. If this interference was ignored, the usual process of background subtraction would overcompensate for the background. In order to compensate for this background over-subtraction, a term which is proportional to the thorium net count rate must be added back into the Ra-226 equation. This explains the positive sign on the thorium term in the Ra-226 equation. The Ra-226 equation has the desirable feature that its intercept is near zero. These same features appear in the RTRAK Ra-226 calibration equation.

U-238 Calibration Equation

The measurement results on which the uranium calibration equation is based are presented in Table C-6. The table displays the 31 cm. U-238 HPGe results as well as the RSS net counts per second in the U-238, Th-232 and Ra-226 regions of interest. Table C-6 also displays the predicted U-238 results based on the "best fit" multiple linear regression equations given below. Two equations are provided for uranium so the reader can readily work in units of picocuries per gram of U-238 or

total uranium in parts per million. The second equation is derived from the first by making use of known constants and weight to activity conversion factors, and further assuming that the uranium encountered in the soil is of normal enrichment.

$$\text{RSS U-238 pCi/g} = 1.21208317*U_{NCPS} - 0.1650803*Th_{NCPS} + 1.4384184*Ra_{NCPS} - 2.266268$$

$$\text{RSS Total U ppm} = 3.6314092*U_{NCPS} - 0.4945817*Th_{NCPS} + 4.3095111*Ra_{NCPS} - 6.789784$$

Uranium experiences interferences both in the signal and the background windows. A Th-232 daughter emits 969 Kev gamma rays which contribute extra counts to the U-238 signal window, while a Ra-226 daughter emits 1120 Kev gamma rays which add excess counts to the background window. In the first instance you compensate by subtracting a quantity which is proportional to the Th-232 activity, while in the second instance you must add a term to the equation which is proportional to the Ra-226 activity to compensate for background over-subtraction.

C.3.3 Assessment of the RSS Calibrations

Several things can be assessed to indicate the quality of the calibration equations presented above. Figures C-1 through C-3 display in graphical form the results of the multiple linear regression analyses for Th-232, Ra-226 and U-238 respectively. In each figure, HPGe results are plotted on the x-axis and the predicted RSS results based on the multiple linear regression analyses are plotted on the y-axis. Tabular data from the two right hand columns in Tables C-4 through C-6 were used to construct these graphs. The graphs also display the calibration equation and the square of the correlation coefficient derived from the regression analyses. Values of R^2 near one are an indication that the derived equation accounts well for the variability seen in the data.

If there were perfect agreement between the HPGe and predicted RSS results, all the data points would lie on a straight line with a slope of one. Such a line was added to each graph to help the reader judge qualitatively the goodness of the calibration. The solid line in each figure is NOT the "best fit" regression line. Most of the data points fall near the "slope of one" line despite the fact that the data spans a fairly wide range.

One can quantitatively assess the degree of agreement between the HPGe measurement results and the predictions made with the RSS calibration equation by computing the percent difference between HPGe and calculated RSS results. For purposes of this analysis, the difference between the two results was expressed as a percentage of the HPGe result. In the case of Th-232, the absolute value of the percent differences ranged from 1.44% to 23.33% with an average value of 11.43%. Ra-226 differences ranged from 1.55% to 20.67%, with an average value of 10.09%. U-238 percent differences varied from 0.18% to 91.91%, with an average value of 29.67%. It is not surprising that the U-238 results show the poorest agreement between RSS and HPGe results, since the U-238 region of RSS spectra is subject to more interferences than are the Th-232 or Ra-226 spectral regions. The largest percentage difference occurred where the U-238 concentration was the lowest, at location A9-1. Large percent differences when the net count rates are low is not surprising. If location A9-1 is excluded, the average percent difference between HPGe and RSS U-238 results becomes 20.78%. As discussed elsewhere in this report, the magnitudes of the percent differences between HPGe and RTRAK (for the RTRAK calibration data set) are similar in magnitude to the RSS values for all three isotopes of concern. On a percentage basis, the differences between RSS and HPGe results are no larger at high analyte concentrations than they are at low concentrations.

In addition to the square of the correlation coefficient, R^2, the sum of the residuals, where residual is as defined below is another means of quantitatively assessing the goodness of the regression analysis.

$$\text{Residual} = \text{HPGe Result} - \text{RSS Result}$$

The sum of residuals will be near zero when the regression analysis yields a good fit to the data. Of the three isotopes, U-238 has the largest sum of residuals with a value of 1.36E-13. The sum of residuals for Ra-226 and Th-232 are ten and one hundred times lower than the U-238 sum of residuals respectively.

In summary, the following quantitative parameters all indicate that the three RSS calibration equations are excellent representations of the data over a wide range of analyte concentrations: values of R^2 greater than or equal to 0.95, sum of residuals less than or equal to 1.36E-13, and average absolute percent differences less than or equal to 29.67% (20.78% if one U-238 data point is excluded).

C.3.4 Comparison to RTRAK Calibration Equations

Measurements at eighteen locations were used to calibrate the RTRAK, while the RSS calibration data were collected at only eight locations. Ongoing remediation work had removed the contamination at some of the RTRAK calibration locations. Only four locations were common to both data sets. Despite this fact, the resultant RTRAK and RSS calibration equations are quite similar. The algebraic signs of corresponding terms in the two sets of equations are the same. For example, both the RTRAK and RSS U-238 equations have negative signs on the terms which are proportional to the Th-232 net counts per second, while the Ra-226 net counts per second terms have positive signs. By understanding how the radium and thorium interfered with the uranium region of the gamma ray spectrum, we were able to provide a rationale for the signs of each term. This rationale is independent of which system was used to acquire the data. All the corresponding coefficients also, roughly speaking, have comparable values. For example, the uranium, thorium and radium coefficients in the RSS U-238 equation are 1.21, -0.165 and 1.438, respectively, while in the RTRAK equation they have values of 0.956, -0.403 and 1.02, respectively. The thorium and radium intercepts in corresponding RSS and RTRAK equations are also roughly the same. The RSS and RTRAK uranium intercepts do not agree as well as those for the other isotopes. This may be attributed to the difference in the data sets used in the regression analyses to derive the two equations. Spectral interferences play an important role when computing the net uranium count rate, and thus they strongly influence the outcome of the regression analysis. Presumably, if the number of data points used to derive both RSS and RTRAK calibration equations was much larger, differences in the data sets would have less influence on the outcome of the regression analyses. Overall, the similarities in the two sets of calibration equations support the contention that the two systems are not significantly different in spite of the different vehicles conveying them and the difference in orientation of the RSS and RTRAK detectors.

C.4 CALIBRATION VERIFICATION

The calibration measurements discussed above were all stationary measurements. Since the RSS would normally be operated in a mobile mode, it was deemed prudent to test the newly developed RSS calibration equations by performing mobile measurements in well characterized areas. The RSS measurements were compared to RTRAK measurements in two separate areas. One area was known from previous work to have a relatively homogeneous distribution of contaminants, while contamination in the other area was rather heterogeneous.

In the first area, the USID Area, just west of the original RTRAK profile path, the RTRAK was driven back and forth twenty times over the same straight line path at a speed of 1 mile per hour while acquiring 4 second spectra. The RSS was pushed directly behind the RTRAK at the same speed and with the same spectral acquisition time to permit a direct comparison of RSS and RTRAK moving measurements in a relatively homogeneous area. The profile path was divided into segments and RSS and RTRAK results within each segment were compared. Figures C-4 and C-5 show the segments into which the USID profile path was divided and the locations of individual RSS and RTRAK measurements. A total of 868 RSS spectra and 760 RTRAK spectra were collected. The data from the mobile calibration verification testing in the USID Area are summarized in Tables C-7 through C-9 for Th-232, Ra-226 and U-238 respectively. For these isotopes, the tables show the minimum, maximum and average isotopic concentration in the soil as well as the number of readings (4 second spectra) collected in each segment. The standard deviation of the measured values is also presented in units of pCi/g and as a percentage of the segment mean. Segment by segment, the RTRAK data are presented right below the corresponding RSS data so that comparisons can be readily made. The degree of similarity between RSS and RTRAK measurements can be assessed by comparing RSS and RTRAK minima, maxima and means for individual segments. In many cases these segment quantities are quite similar. With some exceptions, the standard deviations, which are indicative of the dispersion in the data also tend to be similar. In the overall summary at the bottom of each table, the differences between RSS and RTRAK segment means have been averaged. These average differences have been presented in three ways: as an average difference (with units of pCi/g), as an average percent difference, and as an average of absolute percent difference values disregarding the algebraic signs of the average differences. Comparing the last two figures will reveal if the averages are being diminished when positive and negative differences cancel one another. This is not a problem with these two sets of data. Reviewing the overall comparisons between RSS and RTRAK in the USID Area, it can be seen that there is good agreement between the measurements performed with the two systems. The degree of agreement is quite good for thorium and radium, but is less so for uranium. On average the differences between RSS and RTRAK measurements in the USID Area are less than 10% for thorium and radium, but they are on the order of 44% for uranium. The poorer agreement is not surprising. The uranium concentrations in the USID Area are rather low. Thus we are in a domain - below 16.7 pCi/g U-238 (50 ppm total uranium) - where the uranium calibration equations are not very reliable. There are a variety of reasons for this. The minimum detectable concentration (MDC) for the RTRAK/RSS system is estimated elsewhere in this report to be 21 pCi/g U-238 (63 ppm total U).

All of the measurements in the USID Area are lower than this MDC. The uranium region of the spectrum is subject to more interferences than the other isotopic regions, and the emission probability for the gamma ray used to quantify U-238 (i.e., the gamma abundance of the 1001 Kev emission) is extremely low. These factors combine to make U-238 counts relatively low and the background in the uranium window rather high, which results in an elevated MDC. The regression analysis used to derive the uranium calibration equation yields a rather large intercept. For the RTRAK system the intercept is 9.4 pCi/g U-238 (28 ppm total U), while the intercept in the RSS equation is -2.3 pCi/g U-238 (-6.8 ppm U). This also contributes to the reduced reliability of the calibration equations bellow 17 pCi/g (51 ppm). It gives rise to a systematic bias in the RTRAK measurements compared to RSS results. The RTRAK segment means in Table C-9 are typically 6 to 10 pCi/g higher than RSS means. In large measure, this accounts for the poorer agreement of the uranium data gathered in the USID Area segments. It is also the reason for the difference in the segment standard deviations in this area. The magnitudes of the RSS and RTRAK segment standard deviations are generally comparable. However, the percent standard deviations for the RTRAK data are smaller because of the bias introduced by the large intercept in the RTRAK calibration equation. Because the RTRAK results have a high bias when compared to RSS results, the RTRAK standard deviations, as a percentage of the result, will be lower than RSS standard deviations. Both of these trends are evident in Table C-9.

To test the equivalence of the RTRAK and RSS segment means in the USID Area, student's t tests were performed for each segment. These tests were accomplished by comparing the <u>difference</u> between RTRAK and RSS segment means to the <u>uncertainty of the difference</u> at the 95% confidence level. The following equations were used:

$$\Delta = | RT_{AVG} - RS_{AVG} |$$

$$U_D = t_{f,\,0.05} * \left\{ S_{RT}^2 + S_{RS}^2 \right\}^{1/2}$$

where RT_{AVG} and RS_{AVG} are RTRAK and RSS segment means

Δ = the difference between segment means

S_{RT} and S_{RS} = the RTRAK and RSS segment standard deviations

$t_{f,\,0.05}$ = the student's t parameter for f degrees of freedom and 95% confidence

U_D = the uncertainty if the difference between means at the 95 % confidence level

In these statistical tests the RTRAK and RSS segment standard deviations were assumed to be unequal. This the most conservative assumption and it is supported by the data in Tables C-7 through C-9. After calculating the quantities above, the following decisions could be made:

$$\text{IF } \Delta > U_D \text{ the means differ}$$

$$\text{IF } \Delta < U_D \text{ the means do not differ.}$$

The t tests showed that 8 of 10 Th-232 segment means were equivalent and all 10 Ra-226 segment means were equivalent, but none of the U-238 means were equivalent in the USID Area. As noted above, the poor agreement for the uranium means can be explained by the low U-238 concentration in the USID Area and the large difference in the intercepts of the RTRAK and RSS calibration equations.

The second area where mobile RSS and RTRAK measurements were compared to test the validity of the RSS calibration was the Drum Baling Area, which was known to be relatively heterogeneous. Both the RSS and the RTRAK were used to perform a full scan of a designated portion of the Drum Baling Area (DBA). In this test, no attempt was made to have the RSS follow exactly the same back and forth path as the RTRAK. Furthermore, a full area scan was performed, rather than driving back and forth along the same path. Figures C-6 and C-7 show the locations within the Drum Baling Area where RSS and RTRAK measurements were collected for this test. These figures also show the coordinates of the area which was scanned and the segments into which the area was divided. The data from this test were compared as described as above. Within each segment the minimum, maximum and average result was determined for the three isotopes of concern for both systems . The standard deviation of the results within each segment was also computed on an absolute scale and as a percentage of the mean. A compilation of these data are presented in Tables C-10 through C-12 for Th-232, Ra-226 and U-238 respectively. Despite the fact that the Drum Baling Area is heterogeneous, there is generally good agreement between the RSS segment means and the RTRAK segment means. The RSS and RTRAK percent standard deviations of the data within a segment are also generally similar to one another. The data from the Drum Baling Area are summarized at the bottom of each table by presenting the average value of the differences between RTRAK and RSS segment means. These are expressed in absolute units, i.e. in pCi/g, and as a percentage of the RTRAK segment mean.

The RTRAK and RSS differences averaged over the DBA segments were 19%, 10% and 18% for Th-232,
Ra-226 and U-238 respectively. These values are somewhat different from those seen in the USID Area. The Th-232 average absolute percent difference for the DBA was slightly higher and the U-238 value dropped to half the value seen in the USID Area. The average absolute percent difference for Ra-226 was the same in both areas. The larger Th-232 percent difference in the Drum Baling Area can be explained by the heterogeneous distribution of the Th-232 contamination in the DBA. The U-238 average percent difference is smaller because the levels of uranium contamination in the DBA are greater than in the USID Area. Although the radioactivity is not uniformly distributed in the Drum Baling Area, the higher levels of U-238 can be measured with greater accuracy and better precision, thus reducing the average difference between RSS and RTRAK measurements in the Drum Baling Area. The systematic bias between RTRAK and RSS U-238 segment means that was noted in the USID Area data is no longer present in the DBA, again because of the higher uranium concentrations. In summary, RTRAK and RSS measurement results proved to be comparable for all three isotopes during the mobile calibration verification testing in the DBA.

Statistical comparisons of RTRAK and RSS segment means in the DBA were conducted in the same manner as described above. By the acceptance criteria stated above for the t-test, seven Th-232 segment means, ten Ra-226 segment means and nine U-238 segment means were judged to be equivalent at the 95% confidence level. This provides strong statistical evidence that RTRAK and RSS mobile measurements are equivalent.

C.5 RSS SYSTEM QUALITY PARAMETERS

As stated earlier in this Appendix, the sodium iodide detector, the signal processing electronics, the computer-based multichannel analyzer and the gamma spectrometry software on the RTRAK and RSS systems are identical. In addition, the mobile calibration verification results discussed in the previous section demonstrate that even in situations where the distribution of radioactive contaminants in the soil is nonuniform, the RTRAK and RSS systems yield equivalent results when each system's calibration equations are applied to spectral data accumulated during mobile scans of the same area. Under these circumstances, it is entirely reasonable to expect that the quality parameters for the two systems will be the same. These quality parameters include accuracy, precision, and minimum detectable concentration. All of the parameters relevant to the derivation of these quantities are the same for the

RSS system as for RTRAK. If all the measurements from which the RTRAK quality parameters were derived were repeated for the RSS, the results would be equivalent, and thus, the value of the quality parameters would be the same, for all practical purposes. The values quoted for these parameters quoted in Section 4 of this report will also be applied to the RSS system.

Potential interferences and data review criteria for the RTRAK system have been described in Section 5 of this report. All of these potential interferences and data review criteria apply equally well to RSS data. In developing these criteria, RSS data as well as RTRAK data were considered. Having the same data review criteria and acceptance limits for both RTRAK and RSS data reduces the likelihood of errors during the data review process. It will simplify personnel training and data review issues and thus contribute to the overall quality and consistency of the real time measurements program.

C.6 SUMMARY AND CONCLUSIONS

In this appendix, the process of calibrating the RSS system was described and the resulting calibration equations were presented. The mathematical form of the RSS calibration equations were the same as the RTRAK equations, and the magnitudes of the corresponding coefficients were similar. All of the RSS calibration equations had intercepts near zero, with correlation coefficients greater than 0.95 and residual sums of 1.36E-13 or less. All of these numerical factors indicate that the RSS equations are good representations of the calibration data. After the calibration equations were developed based on stationary RSS measurements, they were tested in two separate areas by comparing RTRAK and RSS mobile measurement results. In the USID Area, RSS and RTRAK measurements were performed by having each vehicle travel back and forth twenty times along the same straight line path. When all the RSS measurements in each path segment were compared to all the RTRAK measurements within the same segment, there was good agreement between the results from the two systems with the exception of uranium. The reasons for the poorer agreement of the U-238 measurements were related to the low U-238 concentration in the USID Area. When the U-238 concentrations are higher, the two systems exhibit better agreement. The second calibration verification was performed by doing full area scans of a portion of the Drum Baling Area , which is known to be more heterogeneous and to have higer contaminant concentrations. In this test, no effort was made to ensure that the two vehicles followed the same paths. Once again, the area scanned by the two systems was divided into segments and the isotopic data from the two systems were compared. With the exception of the U-238 segment means in

the USID Area, the segment means in both areas agreed with one another to within twenty percent. For both areas, t-tests were performed to evaluate the statistical equivalence of the segment means. The t-tests showed that, in the overwhelming majority of cases, the RSS and RTRAK segment means were equivalent at the 95% confidence level. Segment standard deviations were also compared as a means of assessing RSS measurement precision compared to RTRAK precision. Based on this comparison, RSS and RTRAK system precisions were found to be comparable.

Except for the vehicle on which it is mounted, the various hardware and software components of the RSS system are identical to those of the RTRAK system. On the smaller RSS vehicle, the sodium iodide crystal is mounted in a different orientation relative to the direction of travel than the RTRAK crystal, and the RSS signal processing electronics and on-board computer are not operated in an air conditioned environment like the RTRAK equipment. Despite these differences, the data generated by the two systems were found to be comparable.

TABLE C-1
COMPARISON OF 0 and 90 DEGREE RSS CALIBRATION DATA
AND CORRESPONDING HPGe READINGS
THORIUM-232

SAMPLE LOCATION	RSS NET CPS			HPGe READINGS in pCi/g		
	0 Deg.	90 Deg.	Ratio	1 m.	0.31 m.	0.15 m.
A3-10	38.3	41.4	0.9239	2.46	2.00	1.85
A3-7	47.5	45.1	1.0532	2.3	1.93	1.68
A3-9	74.9	62.7	1.1946	2.59	2.72	2.97
A3-11	62.3	57.8	1.0779	3.27	3.49	3.92
A3-8	238.4	146.0	1.6329	13.2	32.2	88.8
A3-6	140.3	111.8	1.2549	12.7	6.26	4.63
A9-1	11.0	10.6	1.0377	0.645	0.67	0.963
A11-3	13.9	13.6	1.0221	0.906	0.93	0.963
A13-3	13.0	90.8	0.1433	2.47	4.14	4.9
A15-2	11.4	11.2	1.0224	0.678	0.82	1.05

TABLE C-2
COMPARISON OF 0 and 90 DEGREE RSS CALIBRATION DATA
AND CORRESPONDING HPGe READINGS
RADIUM-226

SAMPLE LOCATION	RSS NET CPS			HPGe READINGS in pCi/g		
	0 Deg.	90 Deg.	Ratio	1 m.	0.31 m.	0.15 m.
A3-10	104.5	106.6	0.9803	15.9	16.5	16.0
A3-7	97.7	97.6	1.0010	14.0	12.3	11.7
A3-9	105.0	109.3	0.9807	14.2	14.4	15.0
A3-11	111.7	110.7	1.0090	16.4	20.5	25.5
A3-8	-2.5	5.1	-0.4902	3.36	3.35	3.36
A3-6	12.2	15.6	0.7821	4.25	5.14	6.08
A9-1	3.25	3.7	0.8784	0.731	0.74	0.75
A11-3	4.1	3.8	1.0789	0.654	0.89	0.87
A13-3	3.3	-1.0	-3.3000	1.18	1.15	1.21
A15-2	5.5	5.5	1.0092	1.19	1.21	1.21

TABLE C-3
COMPARISON OF 0 and 90 DEGREE RSS CALIBRATION DATA
AND CORRESPONDING HPGe READINGS
URANIUM-238

SAMPLE LOCATION	RSS NET CPS			HPGe READINGS in pCi/g		
	0 Deg.	90 Deg.	Ratio	1 m.	0.31 m.	0.15 m.
A3-10	44.65	49.7	0.8984	219	196	183
A3-7	29.1	21.9	1.3288	170	146	145
A3-9	48.7	36.1	1.3490	176	202	222
A3-11	33.3	43.1	0.7726	176	200	230
A3-8	203.5	105.5	1.9289	97.5	157	241
A3-6	83.9	68.1	1.2320	98.5	91.4	93.5
A9-1	4.15	3.2	1.2969	2.95	2.93	3.37
A11-3	10.6	9.2	1.1522	22.8	25.2	25.4
A13-3	8.9	39.5	0.2253	8.91	9.52	10.4
A15-2	4.4	3.7	1.1892	4.67	5.16	6.51

TABLE C-4
RSS CALIBRATION DATA
THORIUM-232

Sample Location	0 Degree RSS Net CPS		0.31 m. HPGe Th-232 pCi/g	Predicted Result Th-232 pCi/g
	Th-232	Ra-226		
A3-10	38.3	104.5	2.00	1.82
A3-7	47.5	97.7	1.93	2.21
A3-9	74.9	105.0	2.72	3.35
A3-11	62.3	111.7	3.49	2.82
A3-6	140.3	12.2	6.26	6.17
A9-1	11.0	3.25	0.67	0.77
A11-3	13.9	4.1	0.93	0.89
A15-2	11.4	5.5	0.82	0.78

TABLE C-5
RSS CALIBRATION DATA
RADIUM-226

Sample Location	0 Degree RSS Net CPS		0.31 m. HPGe Ra-226 pCi/g	Predicted Result Ra-226 pCi/g
	Ra-226	Th-232		
A3-10	104.5	38.3	16.5	15.6
A3-7	97.7	47.5	12.3	14.8
A3-9	105.0	74.9	14.4	15.5
A3-11	111.7	62.3	20.5	17.2
A3-6	12.2	140.3	5.1	4.9
A9-1	3.25	11.0	0.74	0.72
A11-3	4.1	13.9	0.89	0.90
A15-2	5.5	11.4	1.21	1.04

TABLE C-6
RSS CALIBRATION DATA
URANIUM-238

Sample Location	0 Degree RSS Net CPS			0.31 m. HPGe U-238 pCi/g	Predicted Result U-238 pCi/g
	U-238	Th-232	Ra-226		
A3-10	44.65	38.3	104.5	195.5	195.9
A3-7	29.1	47.5	97.7	146.0	165.7
A3-9	48.7	74.9	105.0	202.0	195.4
A3-11	33.3	62.3	111.7	200.0	188.5
A3-6	83.9	140.3	12.2	91.4	93.8
A9-1	4.15	11.0	3.25	2.93	5.6
A11-3	10.6	13.9	4.1	25.2	14.2
A15-2	4.4	11.4	5.5	5.2	9.1

TABLE C-7
RSS CALIBRATION VERIFICATION MEASUREMENTS IN THE USID AREA
THORIUM-232

SEGMENT ID	MEASUREMENT SYSTEM	No. of READINGS	MIN pCi/g	MAX pCi/g	MEAN pCi/g	STD DEV pCi/g	% STD DEV
US-RS-1	RSS	75	0.27	1.12	0.91	0.17	20.7%
	RTRAK	73	0.26	1.27	0.76	0.20	27.0%
US-RS-2	RSS	75	0.31	1.11	0.82	0.16	20.1%
	RTRAK	73	0.30	1.38	0.78	0.20	26.1%
US-RS-3	RSS	78	0.46	1.24	0.82	0.15	18.2%
	RTRAK	72	0.18	1.28	0.76	0.23	29.8%
US-RS-4	RSS	78	0.42	1.07	0.81	0.14	17.9%
	RTRAK	72	0.33	1.36	0.82	0.21	25.7%
US-RS-5	RSS	75	0.25	1.09	0.81	0.16	19.4%
	RTRAK	73	0.09	1.28	0.78	0.24	31.2%
US-RS-6	RSS	76	0.36	1.23	0.83	0.16	18.8%
	RTRAK	71	0.21	1.26	0.72	0.24	32.9%
US-RS-7	RSS	153	-0.03	1.17	0.74	0.22	29.9%
	RTRAK	76	0.15	1.14	0.60	0.23	38.9%
US-RS-8	RSS	97	0.54	1.19	0.84	0.16	19.0%
	RTRAK	70	0.37	1.23	0.85	0.20	23.2%
US-RS-9	RSS	75	0.46	1.15	0.83	0.13	16.0%
	RTRAK	101	0.23	1.25	0.80	0.19	24.3%
US-RS-10	RSS	86	0.36	1.16	0.76	0.16	21.7%
	RTRAK	79	0.27	1.21	0.73	0.24	33.4%

OVERALL COMPARISON

	AVE DIFF pCi/g	AVE % DIFF	AVE ABSOLUTE % DIFF
DIFF = RTRAK MEAN - RSS MEAN	-0.05	-6.9%	7.6%

TABLE C-8
RSS CALIBRATION VERIFICATION MEASUREMENTS IN THE USID AREA
RADIUM-226

SEGMENT ID	MEASUREMENT SYSTEM	No. of READINGS	MIN pCi/g	MAX pCi/g	MEAN pCi/g	STD DEV pCi/g	% STD DEV
US-RS-1	RSS	75	-0.42	1.62	0.72	0.42	58.7%
	RTRAK	73	0.04	1.71	0.84	0.36	43.1%
US-RS-2	RSS	75	-0.56	1.52	0.81	0.44	54.2%
	RTRAK	73	-0.11	1.66	0.84	0.33	38.7%
US-RS-3	RSS	78	-0.08	1.52	0.73	0.39	54.3%
	RTRAK	72	-0.10	1.80	0.79	0.34	43.0%
US-RS-4	RSS	78	-0.62	1.80	0.73	0.44	59.7%
	RTRAK	72	0.15	1.44	0.77	0.32	42.0%
US-RS-5	RSS	75	-0.38	2.13	0.79	0.47	59.8%
	RTRAK	73	0.03	1.44	0.84	0.31	37.6%
US-RS-6	RSS	76	-0.14	1.70	0.87	0.43	48.7%
	RTRAK	71	-0.18	1.75	0.82	0.33	40.5%
US-RS-7	RSS	153	-0.42	1.78	0.71	0.41	57.6%
	RTRAK	76	-0.08	1.75	0.69	0.39	56.5%
US-RS-8	RSS	97	-0.28	1.69	0. 75	0.45	59.2%
	RTRAK	70	0.09	1.77	0.83	0.41	49.6%
US-RS-9	RSS	75	-0.58	1.93	0.78	0.47	60.1%
	RTRAK	101	0.01	1.69	0.85	0.39	46.2%
US-RS-10	RSS	86	-0.50	1.60	0.72	0.41	57.4%
	RTRAK	79	-0.37	1.77	0.70	0.40	57.3%

OVERALL COMPARISON

	AVE DIFF pCi/g	AVE % DIFF	AVE ABSOLUTE % DIFF
DIFF = RTRAK MEAN - RSS MEAN	0.04	4.3%	6.8%

TABLE C-9
RSS CALIBRATION VERIFICATION MEASUREMENTS IN THE USID AREA
Uranium-238

SEGMENT ID	MEASUREMENT SYSTEM	No. of READINGS	MIN pCi/g	MAX pCi/g	MEAN pCi/g	STD DEV pCi/g	% STD DEV
US-RS-1	RSS	75	-7.17	26.21	7.40	7.84	106.0%
	RTRAK	73	1.39	28.68	17.08	6.16	36.1%
US-RS-2	RSS	75	-12.26	30.34	10.07	8.76	87.0%
	RTRAK	73	-1.09	29.34	16.36	6.76	41.3%
US-RS-3	RSS	78	-16.41	30.53	8.70	8.02	92.2%
	RTRAK	72	-0.92	30.94	16.28	6.60	40.6%
US-RS-4	RSS	78	-12.39	30.93	8.49	9.28	109.4%
	RTRAK	72	3.84	33.24	15.28	6.46	42.3%
US-RS-5	RSS	75	-7.05	29.48	9.64	8.10	84.1%
	RTRAK	73	4.63	31.28	16.83	6.00	35.7%
US-RS-6	RSS	76	-12.90	29.17	8.52	8.54	100.3%
	RTRAK	71	-4.35	31.67	17.09	7.58	44.4%
US-RS-7	RSS	153	-9.33	38.55	8.92	9.48	106.2%
	RTRAK	76	0.25	31.07	14.48	5.53	38.2%
US-RS-8	RSS	97	-12.33	33.60	11.46	9.77	85.3%
	RTRAK	70	4.28	38.71	19.60	7.46	38.0%
US-RS-9	RSS	75	-0.74	32.02	13.31	7.68	57.7%
	RTRAK	101	-0.18	34.88	19.44	6.90	35.5%
US-RS-10	RSS	86	-12.80	33.26	9.54	8.73	91.5%
	RTRAK	79	0.57	36.43	17.89	7.53	42.1%

OVERALL COMPARISON

	AVE DIFF pCi/g	AVE % DIFF	AVE ABSOLUTE % DIFF
DIFF = RTRAK MEAN - RSS MEAN	7.43	43.7%	43.7%

TABLE C-10
RSS CALIBRATION VERIFICATION MEASUREMENTS
IN THE DRUM BALING AREA
Thorium-232

SEGMENT ID	MEASUREMENT SYSTEM	No. of READINGS	MIN pCi/g	MAX pCi/g	MEAN pCi/g	STD DEV pCi/g	% STD DEV
DB-RS-1	RSS	23	1.49	10.13	2.63	1.72	65.1%
	RTRAK	14	2.04	7.29	3.24	1.33	41.0%
DB-RS-2	RSS	32	1.12	5.97	2.15	1.05	48.9%
	RTRAK	22	1.29	11.20	3.15	2.07	65.6%
DB-RS-3	RSS	21	1.46	14.59	4.44	3.30	74.5%
	RTRAK	15	2.01	20.37	6.54	6.13	93.8%
DB-RS-4	RSS	26	1.54	12.46	5.02	2.80	55.8%
	RTRAK	17	1.76	13.06	4.59	2.70	58.8%
DB-RS-5	RSS	32	0.79	3.63	1.58	0.56	35.4%
	RTRAK	23	0.87	5.64	2.12	1.09	51.1%
DB-RS-6	RSS	47	0.38	3.16	1.70	0.68	39.9%
	RTRAK	23	0.78	4.08	2.10	0.76	36.1%
DB-RS-7	RSS	40	0.48	3.92	2.05	0.93	45.2%
	RTRAK	28	0.41	3.63	1.90	0.88	46.5%
DB-RS-8	RSS	45	0.39	3.73	1.77	0.79	44.7%
	RTRAK	27	0.61	7.27	2.09	1.37	65.4%
DB-RS-9	RSS	44	0.56	5.22	1.58	0.94	59.6%
	RTRAK	17	0.26	5.71	1.86	1.30	70.0%
DB-RS-10	RSS	47	0.22	3.25	1.23	0.70	57.0%
	RTRAK	20	0.38	3.71	1.48	0.88	59.3%

OVERALL COMPARISON

	AVE DIFF pCi/g	AVE % DIFF	AVE ABSOLUTE % DIFF
DIFF = RTRAK MEAN - RSS	0.49	15.6%	19.1%

TABLE C-11
RSS CALIBRATION VERIFICATION MEASUREMENTS
IN THE DRUM BALING AREA
Radium-226

SEGMENT ID	MEASUREMENT SYSTEM	No. of READINGS	MIN pCi/g	MAX pCi/g	MEAN pCi/g	STD DEV pCi/g	% STD DEV
DB-RS-1	RSS	23	1.95	8.26	4.14	1.36	32.9%
	RTRAK	14	2.09	5.58	3.79	0.90	23.8%
DB-RS-2	RSS	32	0.95	6.55	3.37	1.58	47.0%
	RTRAK	22	1.24	6.18	3.63	1.34	36.9%
DB-RS-3	RSS	21	0.26	7.49	3.99	1.50	37.6%
	RTRAK	15	2.58	6.97	4.15	1.34	32.4%
DB-RS-4	RSS	26	1.73	7.07	3.88	1.46	37.5%
	RTRAK	17	1.17	6.80	3.74	1.48	39.7%
DB-RS-5	RSS	32	0.70	6.32	3.08	1.29	41.8%
	RTRAK	23	0.50	8.06	3.42	1.57	45.8%
DB-RS-6	RSS	47	0.42	18.84	5.90	4.54	77.0%
	RTRAK	23	1.70	21.55	7.77	5.56	71.6%
DB-RS-7	RSS	40	0.67	21.93	9.02	5.47	60.7%
	RTRAK	28	0.35	18.77	8.92	4.82	54.0%
DB-RS-8	RSS	45	0.46	18.07	8.00	4.72	59.0%
	RTRAK	27	0.76	22.67	8.93	6.52	73.0%
DB-RS-9	RSS	44	0.56	24.43	7.27	6.46	88.8%
	RTRAK	17	-0.18	32.04	10.09	9.53	94.4%
DB-RS-10	RSS	47	-0.16	24.05	5.13	5.49	106.9%
	RTRAK	20	0.22	17.73	5.27	4.95	94.3%

OVERALL COMPARISON

	AVE DIFF pCi/g	AVE % DIFF	AVE ABSOLUTE % DIFF
DIFF = RTRAK MEAN - RSS MEAN	0.59	7.1%	10.0%

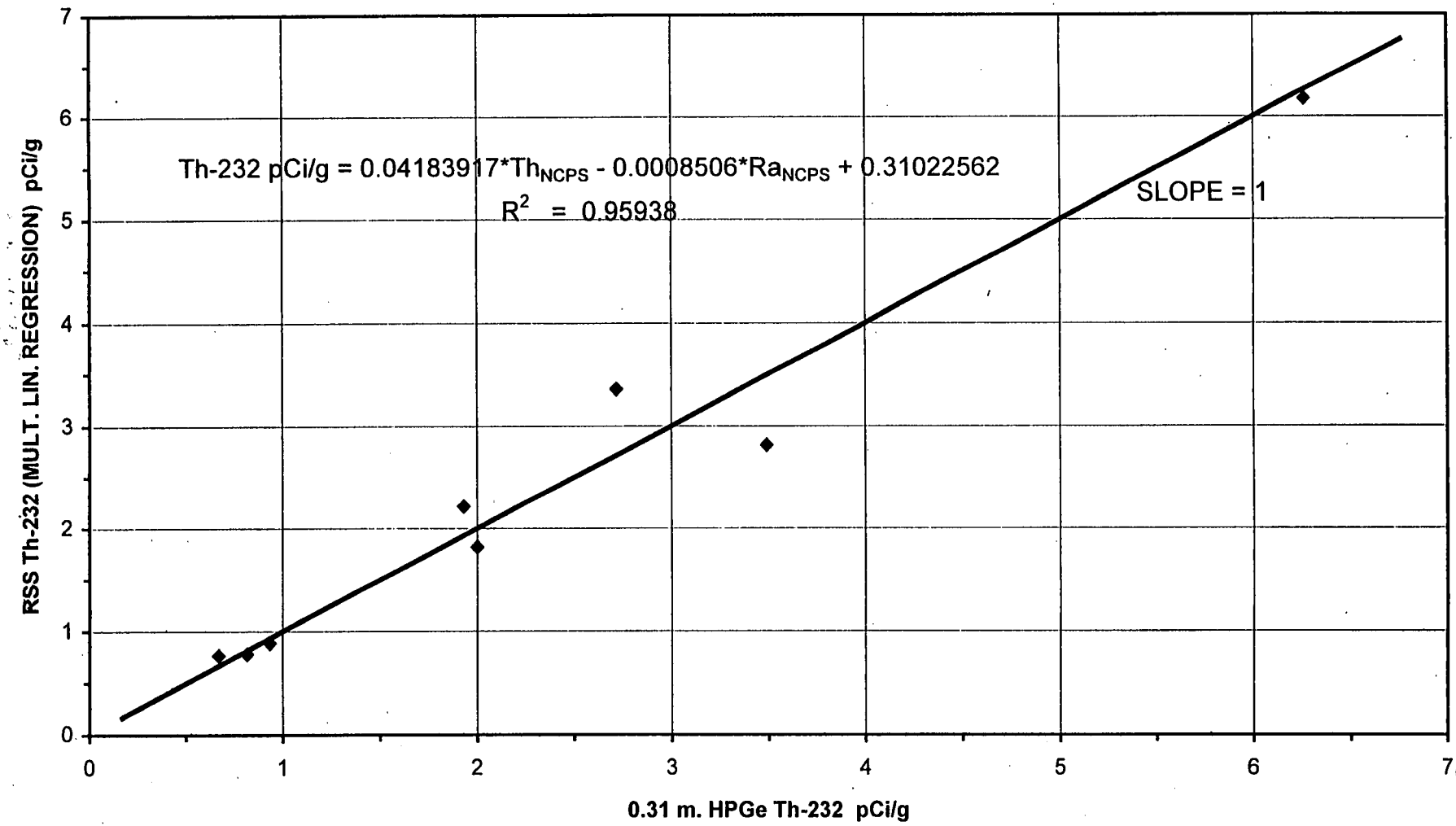
TABLE C-12
RSS CALIBRATION VERIFICATION MEASUREMENTS
IN THE DRUM BALING AREA
Uranium-238

SEGMENT ID	MEASUREMENT SYSTEM	No. of READINGS	MIN pCi/g	MAX pCi/g	MEAN pCi/g	STD DEV pCi/g	% STD DEV
DB-RS-1	RSS	23	30.07	139.61	80.01	29.03	36.3
	RTRAK	14	24.84	91.96	64.15	21.23	33.1
DB-RS-2	RSS	32	15.41	122.28	64.12	28.24	44.0
	RTRAK	22	23.79	174.16	60.16	32.99	54.8
DB-RS-3	RSS	21	17.52	115.51	65.17	27.61	42.4
	RTRAK	15	20.67	90.57	53.38	17.62	33.0
DB-RS-4	RSS	26	5.29	214.91	84.56	49.91	59.0
	RTRAK	17	23.01	140.16	59.96	28.52	47.6
DB-RS-5	RSS	32	-3.73	85.26	42.95	19.42	45.2
	RTRAK	23	13.96	94.97	47.21	18.47	39.1
DB-RS-6	RSS	47	-10.92	184.28	63.88	53.40	83.6
	RTRAK	23	9.13	222.73	93.58	62.41	66.7
DB-RS-7	RSS	40	-10.80	239.25	109.41	71.60	65.4
	RTRAK	28	17.05	191.11	106.17	60.10	56.6
DB-RS-8	RSS	45	-15.45	286.73	116.52	82.71	71.0
	RTRAK	27	6.79	273.72	123.30	89.71	72.8
DB-RS-9	RSS	44	-12.21	285.86	84.29	81.37	96.5
	RTRAK	17	-0.52	281.37	119.37	100.05	83.8
DB-RS-10	RSS	47	-11.58	337.75	53.66	66.84	124.6
	RTRAK	20	-8.10	188.08	59.97	54.29	90.5

OVERALL COMPARISON

	AVE DIFF pCi/g	AVE % DIFF	AVE ABSOLUTE % DIFF
DIFF = RTRAK MEAN - RSS MEAN	2.27	-1.1%	18.4%

Figure C-1
COMPARISON OF RSS & HPGe Th-232 RESULTS



000226

Figure C-2
COMPARISON OF RSS & HPGe Ra-226 RESULTS

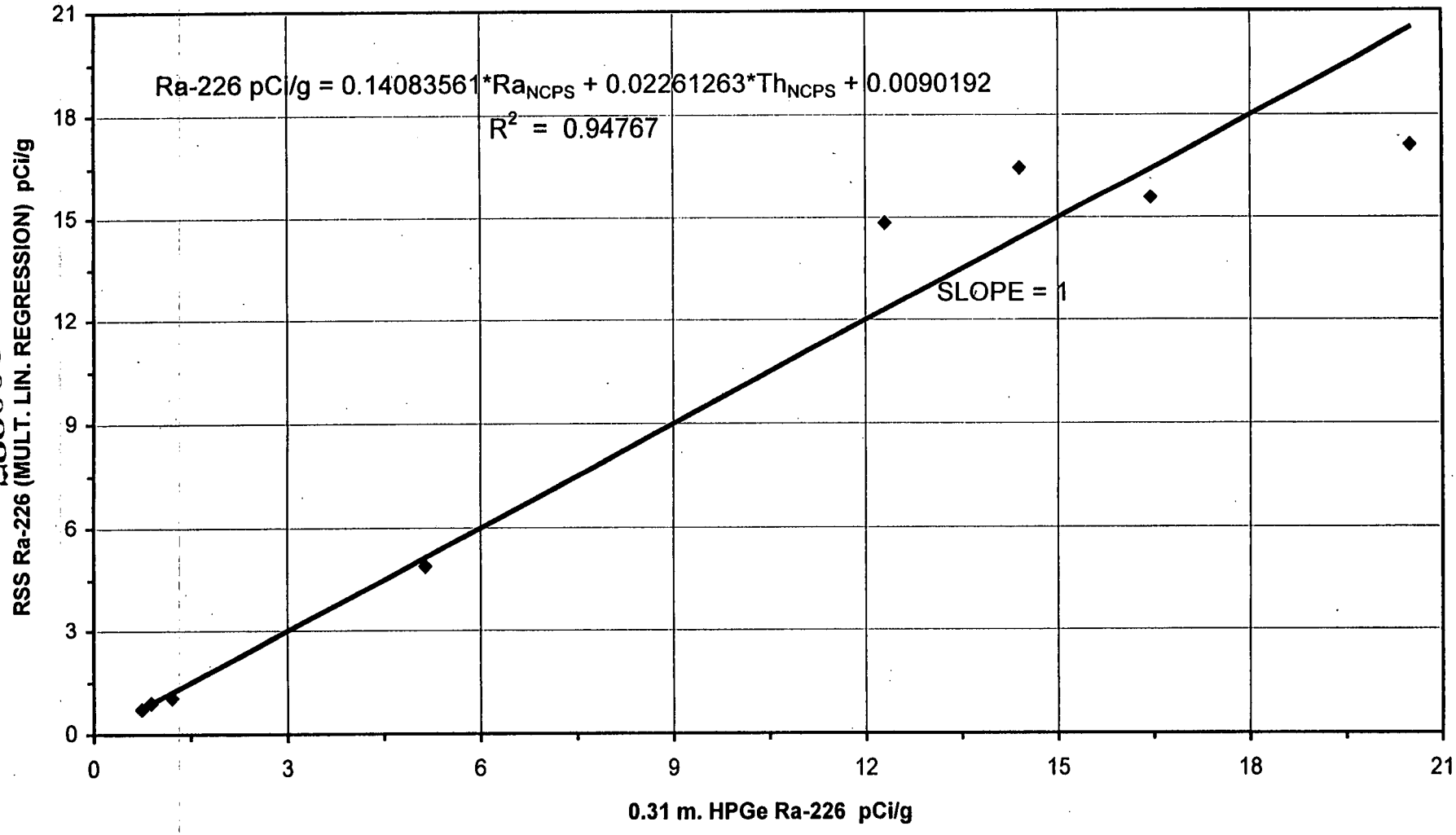


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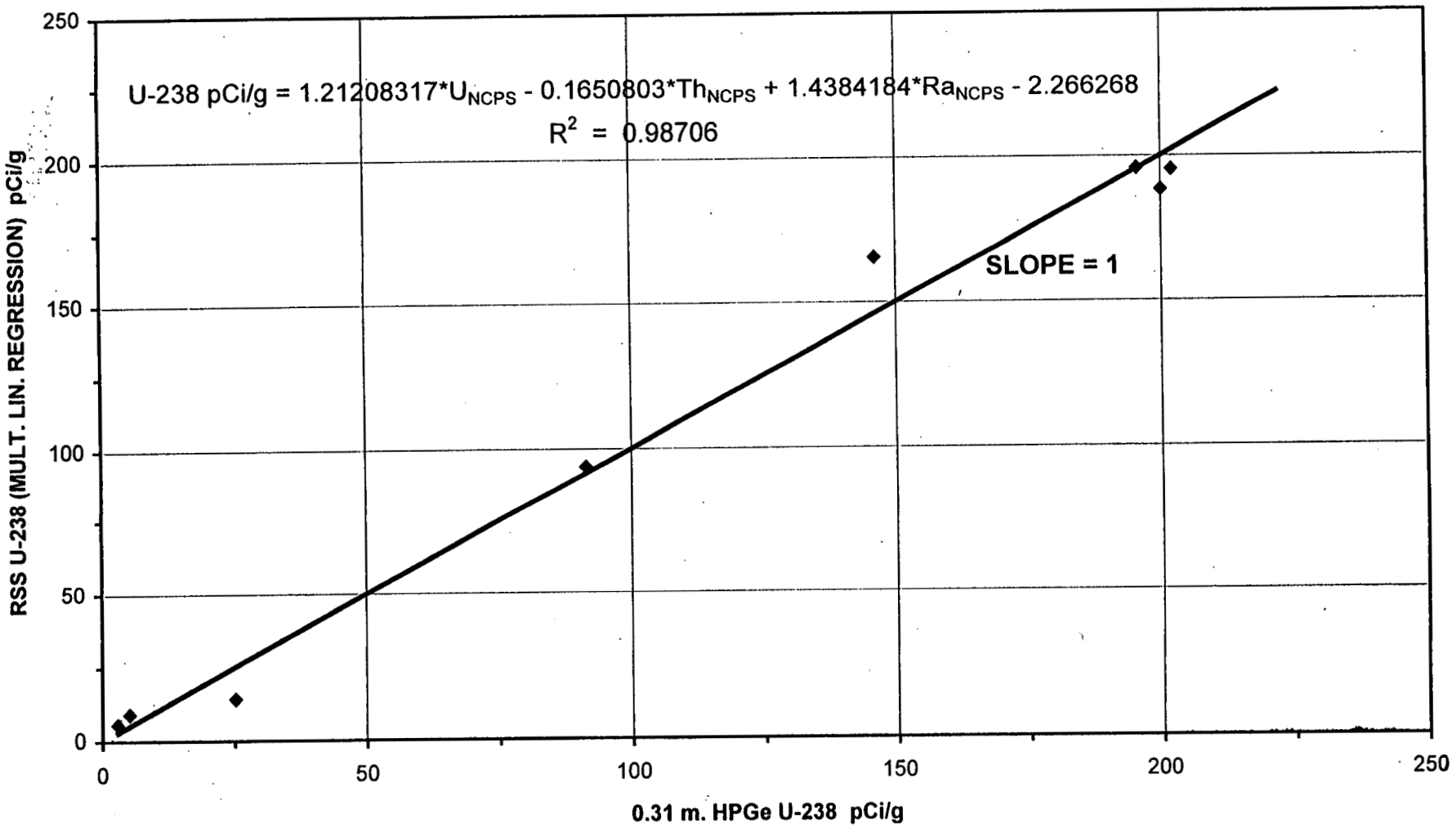
Figure C-3
COMPARISON OF RSS & HPGe U-238 RESULTS



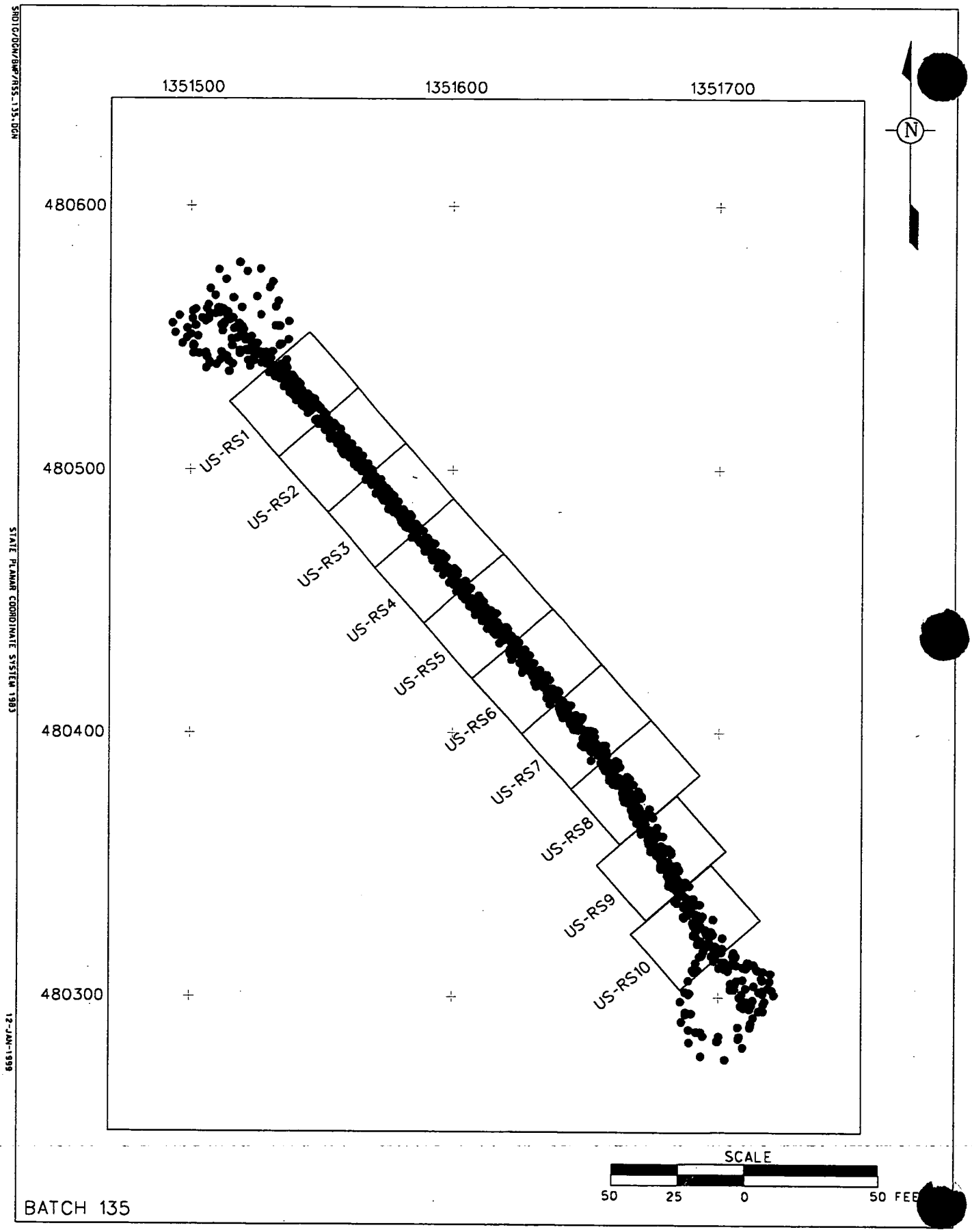


FIGURE C-4. RSS PROFILE RUN IN USID AREA - 1 mph/4 sec ACQUISITION

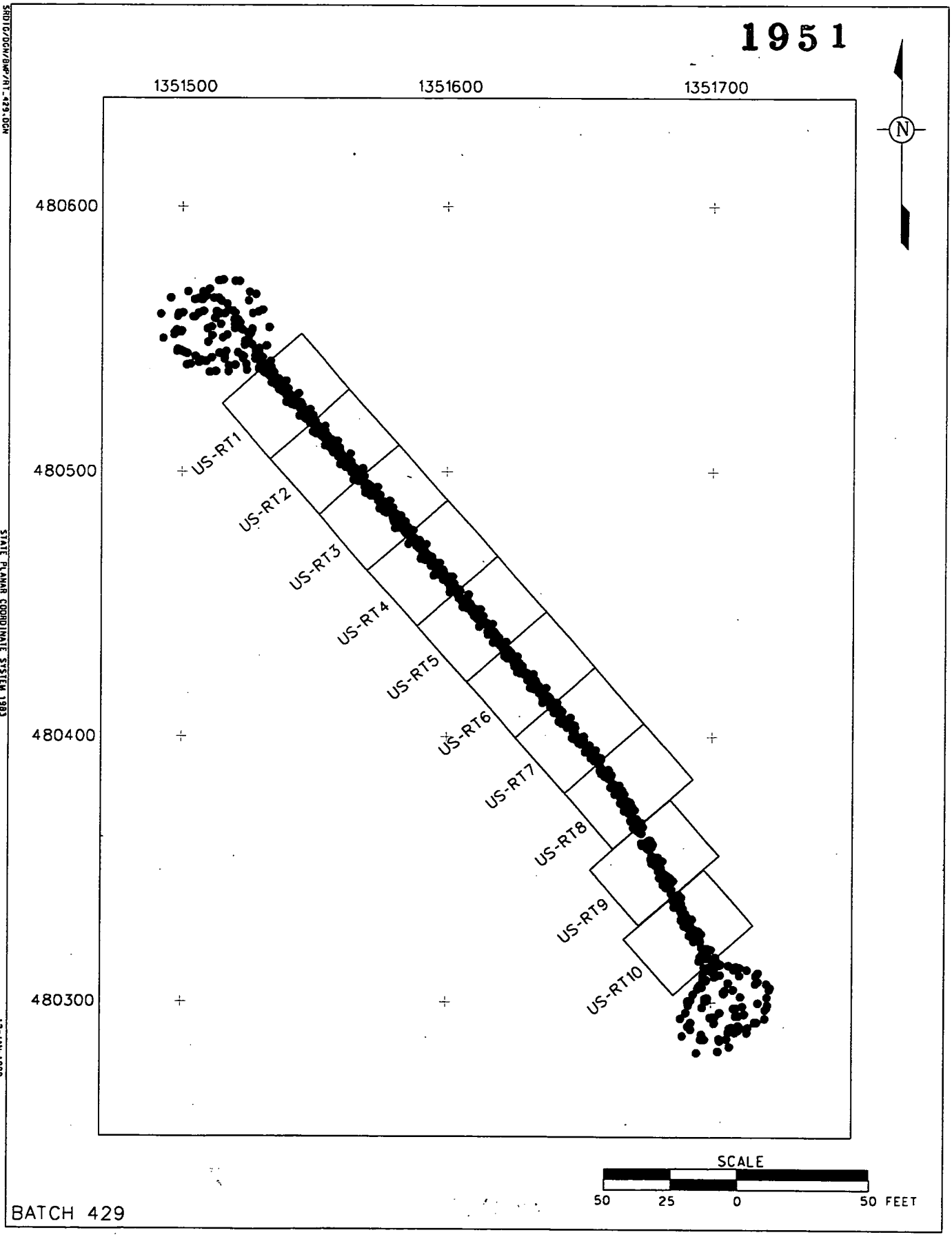


FIGURE C-5. RTRAK PROFILE RUN IN USID
AREA - 1 mph/4 sec ACQUISITION

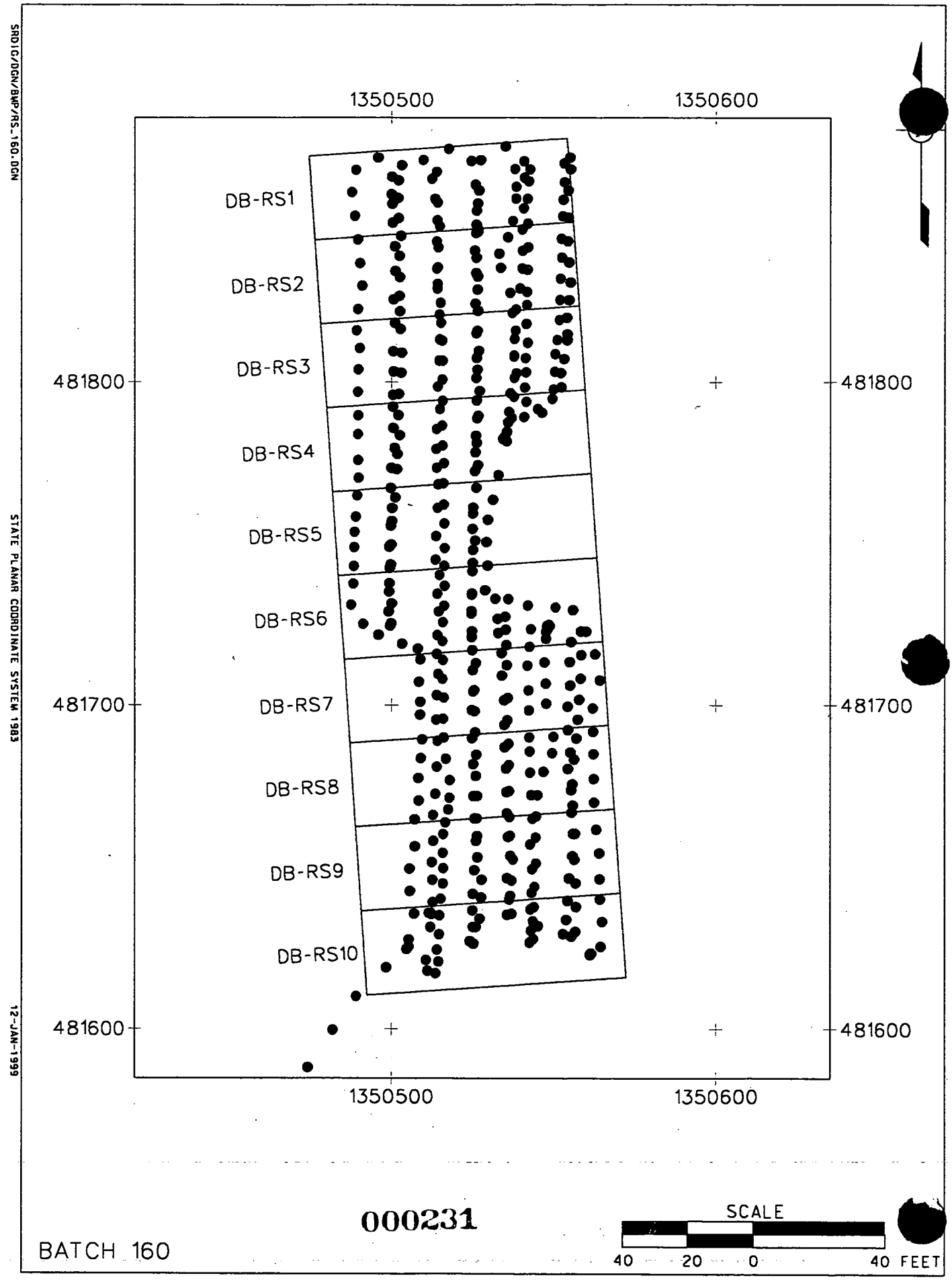


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FIGURE C-6. RSS MOBILE FULL AREA SCAN IN DRUM BALING AREA - 1 mph/4 sec ACQUISITION

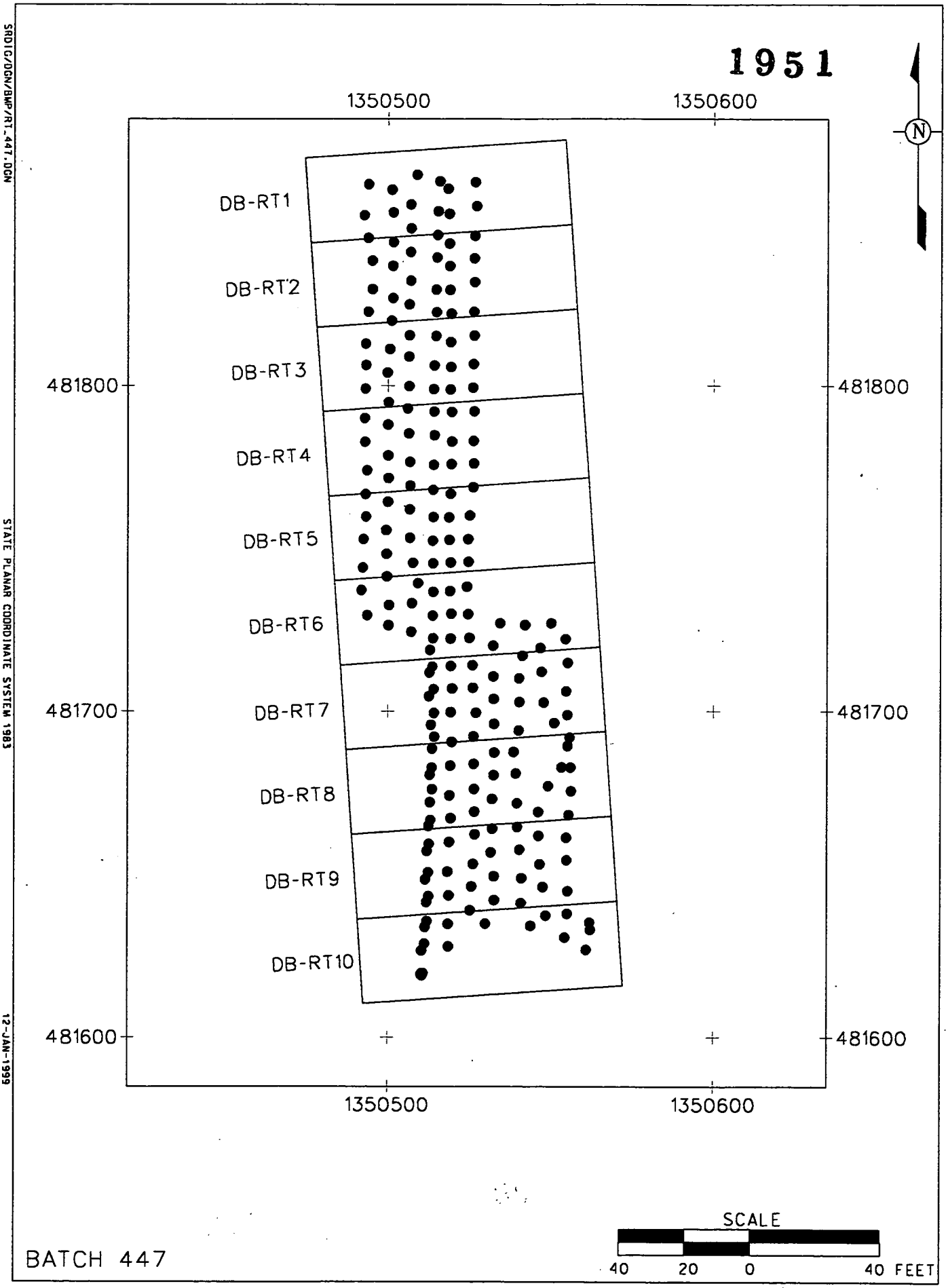

FIGURE C-7. RTRAK MOBILE FULL AREA SCAN IN DRUM BALING AREA - 1 mph/4 sec ACQUISITION