DOE/MC/29103 -- 5100
(DE96000629)

# Development of a Long-Term Post-Closure Radiation Monitor -- Phase II

**Topical Report**
**March 1994 - July 1995**

S.E. Reed

July 1995

Work Performed Under Contract No.: DE-AC21-92MC29103

For

U.S. Department of Energy
Office of Environmental Management
Office of Technology Development
Washington, DC

U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Babcock & Wilcox
Alliance, Ohio

DOE/MC/29103 – 5100

# DEVELOPMENT OF A LONG-TERM POST-CLOSURE RADIATION MONITOR – PHASE II

USDOE

DOE/MC/29103 -- 5100
(DE96000629)

# Development of a Long-Term Post-Closure Radiation Monitor -- Phase II

**Topical Report**
**March 1994 - July 1995**

S.E. Reed

Work Performed Under Contract No.: DE-AC21-92MC29103

For

U.S. Department of Energy
Office of Environmental Management
Office of Technology Development
1000 Independence Avenue
Washington, DC 20585

U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880

By
Babcock & Wilcox
1562 Beeson Street
Alliance, Ohio 44601

July 1995

## Executive Summary

The long-term monitoring of a hazardous waste site for migration of radionuclides requires installation of radiation sensors at a large number of subsurface locations. Sensors which can be lowered into boreholes to make radiation measurements are available, but are relatively complex and expensive and generally not suitable for long-term installation underground. This problem is potentially amenable to a solution based on fiber optic technology. The concept under development in the previous and present contract phases employs a passive in-ground measurement probe which contains a scintillator coupled to an optical lightguide. Gamma radiation absorbed by the in-ground scintillator generates optical photons which are coupled into the lightguide, conveyed to the surface and detected as an indication of the instantaneous sub-surface radiation level. The in-ground probes will be configured to geometrically resemble cone penetrometers or penetrometer-based sampling tools and thus can be installed to depths of up to 50 meters using conventional CPT trucks and methods. The use of the penetrometer eliminates the cuttings normally associated with drilled wells, and thus minimizes worker exposure and eliminates the cost of cutting disposal. A large number of the in-ground passive probes can be multiplexed to a single, above-ground opto-electronics unit to provide for detection and readout of any long-term changes in the distribution of the radionuclides in the vadose zone.

The overall goal of the Long-Term Post-Closure Radiation Monitor System (LPRMS) development program is to configure a long-term radiation monitor using commercially available, demonstrated components to the largest extent possible. The development program is planned as a three phase program spanning a total time of 53 months. The problems to be solved during **Phase I** were primarily those associated with selection of the most appropriate components (scintillator, coupling optics, optical fiber, and opto-electronics) to maximize the signal reaching the detectors and thereby minimizing the integration time required to obtain a reliable measure of radiation. Phase I ended with the design of a prototype probe and a non-multiplexed opto-electronics unit which incorporates the test and analysis information developed during the Phase I activities.

**Phase II** (the current Phase) encompassed the fabrication and testing of the prototype LPRMS probe at a contaminated DOE site, the Fernald Environmental Management Project, in southwestern Ohio. Uranium isotopes are the primary contaminants of concern at this site. The single probe and opto-electronic device were used to make measurements in-situ at relatively shallow subsurface depths. The end objective of Phase II was the design of a full-scale prototype system which incorporates all the features expected to be necessary on a commercial system, including 50 meter depth of measurement, multiplexing of multiple probes, and remote transmission of data. This full-scale prototype will be fabricated and field tested for 12 months during **Phase III**, and a commercial design will be developed based upon the data gathered and experience gained during the entire program.

During Phase II, the design developed in Phase I was modified to incorporate additional features anticipated to be needed in the Phase III system, or components with better commercial availability or improved performance. Some design decisions had not been finalized at the end of Phase I; these included selection of the lightguide and the PMT, and the need for features like a shutter and temperature control of the PMT. These decisions were made based on performance, cost and commercial availability; where necessary, lab tests were performed to obtain the needed design data. A prototype probe, capable of gamma measurements at depths up to 4 meters below grade, was then fabricated for field testing. Calibration methods and analysis techniques for field measurements were developed for this probe.

The purposes of the Phase II testing were to benchmark the analysis methods used in Phase I, to quantify the system performance and to provide the field data and experience needed to confidently design the Phase III system. To get the maximum benefit from the testing, the Demonstration Test of this program was coordinated with three other programs: the DOE Uranium in Soils Integrated Demonstration (USID), the DOE Cone Penetrometry Demonstration (CPD) and the B&W funded Survey Tool program. The USID program provided previously characterized soils to be used in fabricating test drums with known activity levels. As part of the CPD program, two locations at the FEMP were sampled and analyzed for uranium contamination vs depth; gamma activities with depth at these locations were also measured with a gamma probe developed by Waterway Experimental Station (WES). The bores at these locations were then cased with 1.5 inch PVC casing for later measurement in our program. The B&W Survey Tool program provided a gamma measuring tool with a butt coupled sodium iodide scintillator which was used to generate comparison data for each of the tests performed. All data from both probes was acquired with B&W's laboratory 2 channel gamma spectrometer.

A total of four weeks of testing were performed at the FEMP, from October 23 to November 17, 1994. The tests included measurements in drums of contaminated soil (at natural moisture and saturated) with known contaminant levels, in-situ tests near grade in an existing monitoring well, in-situ tests in two temporary PVC borings at depths up to 3 meters, and measurements of drums of contaminated water both without and with a sand matrix.

The Phase II tests showed that the methods used in designing and analyzing the probe were adequate for calculating gamma flux, soil and water absorption, window absorption, absorption by the scintillator, scintillation efficiency, optical losses, resolution and count rates. Instrumental and analytical issues, such as the effects of resolution on signal-to-noise ratio and on the performance of spectroscopy analysis software, were not formally considered in the Phase I design. These issues are important to the overall performance of a long-term monitoring system, and will need to be considered in the design of the Phase III system.

Based on the results of the Phase II testing, it was concluded that the LPRMS probe as tested could detect and quantify uranium isotopes at levels of about 100 pCi/g total U, but could not reliably detect and quantify uranium isotopes at levels of 50 pCi/g total U or less. The lower detection limits (LDLs) for the LPRMS with a 90-minute count time were 6.1 pCi/g (U-238) and 0.3 pCi/g (U-235); with 30 minute counts, they were 10.5 pCi/g (U-238) and 0.5 pCi/g (U-235). The precision of the LPRMS (at 5 times the MDA) was about 7.5%.

For comparison, the LDLs for the survey probe for 90-minute counts were 2.5 pCi/g (U-238) and 0.23 pCi/g (U-235); with 30 minute counts, 4.4 pCi/g (U-238) and 0.39 pCi/g (U-235). The precision of the B&W Survey Probe (at 5 times the MDA) was about 5%.

Regulatory limits have not been established for isotopic or total U at this time; for this program, a target value of 35 pCi/g has been used based on discussions with DOE and site personnel. The LPRMS probe designed in Phase I and tested in Phase II was not capable of identifying and quantifying uranium isotopes at activities near concern levels of 35 pCi/g total U (17 pCi/g U-238, 0.85 pCi/g U-235). To detect and monitor these isotopes at such activities, significant improvements in resolution, peak-to-total ratio, or both will be required. With a 90 minute count line, the LDLs for the survey probe were marginally adequate to monitor at these concern levels with 5% precision, although some improvement in performance is desirable. Based on the results obtained with the B&W Survey Probe, it is believed that a resolution of 7.5 to 8.0% (at 662 keV) will be adequate, with some improvement in peak-to-total ratio. We considered the available options to accomplish this, and concluded that a workable approach is readily available, employing a butt-coupled scintillator/PMT probe. This previously rejected approach is now practical because of the recent development of CPT technology to push low cost plastic casing to depths comparable to those attainable with CPT tools. This approach retains the benefits of low installed cost, serviceability, CPT installation and minimal potential for cross-contamination both during installation and in service.

# TABLE OF CONTENTS

Page

## List of Figures

## List of Figures (Continued)

## List of Figures (Continued)

## List of Figures (Continued)

### Appendix A: Reanalysis with User ROIs

Figure | Page

**List of Figures (Continued)**

## List of Tables

# Acronyms

| | |
|---|---|
| ADC | Analog to Digital Convertor |
| ARA | Applied Research Associates |
| ASL | Analytical Standards Level |
| B&W | Babcock and Wilcox |
| Bio-d | Bio-denitrification Facility |
| CAM | Configuration Access Method |
| CERCLA | Comprehensive Environmental Response, Compensation and Liability Act |
| cm | Centimeter |
| CPD | Cone Penetrometer Demonstration |
| CPM | Counts per Minute |
| CPT | Cone Penetrometer Test |
| CRU | CERCLA/RCRA Unit |
| CsI | Cesium Iodide |
| CsI(Tl) | Thallium-doped Cesium Iodide |
| DOE | U.S. Department of Energy |
| dpm, dps | Disintegrations per minute, disintegrations per second |
| EMCR | Environmental Management Contractors Review |
| ES&H | Environmental Safety and Health |
| FEMP | Fernald Environmental Management Project |
| FERMCO | Fernald Environmental Restoration Management Corporation |
| FWHM | Full Width at Half Maximum |
| g | gram or grams |
| GEE | Gamma Energy Equivalent |
| I-129 | Iodine 129 |
| K-40 | Potassium 40 |
| keV | kilo-electron Volts |
| KUTh | Potassium, Uranium, Thorium |
| l | liter or liters |
| LPRMS | Long-term, Post-closure Radiation Monitor System |
| MCA | Multi-channel Analyzer |
| MCNP | Monte Carlo Neutron Photon |
| MDA | Minimum Detectable Activity |
| METC | Morgantown Energy Technology Center |
| MeV | Mega-electron Volts |

**Acronyms (Continued)**

| | |
|---|---|
| NA | Numerical Aperture |
| NaI | Sodium Iodide |
| NaI(Tl) | Thallium-doped Sodium Iodide |
| nCi | nanoCurie ($10^{-9}$ Curie) |
| NEPA | National Environmental Protection Act |
| OD | Outside Diameter |
| OU | Operable Unit |
| PC | Personal Computer |
| pCi | PicoCurie ($10^{-12}$ Curie) |
| PEeq | Photoelectrons Equivalent |
| PH | Pulse Height |
| PHA | Pulse Height Analysis |
| PHR | Pulse Height Resolution |
| PMMA | Poly-methylmethacrylate |
| PMT | Photomultiplier Tube |
| PoC | Point of Contact |
| ppb | Parts per billion |
| ppm | Parts per million |
| PVC | Polyvinyl Chloride |
| QE | Quantum Efficiency |
| RCRA | Resource Conservation and Recovery Act |
| RI/FS | Remedial Investigation/Feasibility Study |
| ROI | Region of Interest |
| RWP | Radiation Work Permit |
| SCAPS | Site Characterization and Analysis Penetrometer System |
| SRB | Stormwater Retention Basin |
| STP | Sewage Treatment Plant |
| TD | Total Depth |
| Th | Thorium |
| TIR | Total Internal Reflection |
| U | Uranium |
| uCi | microCurie ($10^{-6}$ Curie) |
| USID | Uranium in Soils Integrated Demonstration |
| WES | Waterway Experimental Station (US Army Corp of Engineers) |

## References


1 **Reed,** S.E. "Development of a Long-Term Post-Closure Radiation Monitor, Phase I Topical Report". Babcock & Wilcox, January 7, 1994. Contract DE-AC21-92MC29103, DOE/MC/29103-3661.

2 **Reed,** S.E. "Demonstration Test Plan for Technology Development Project Demonstration: Development of a Long-Term Post-Closure Radiation Monitor". Babcock & Wilcox, September 20, 1994. Contract DE-AC21-92MC29103.

3 Genie-PC Version 2.1 Users Manual, volumes 1 and 2. Canberra Nuclear, 1995.

4 **Hayashi,** Tatsuro. Use of Photomultiplier Tubes in Scintillation Applications. Application RES-0790. Hamamatsu TV Co., Ltd.

5 Photomultiplier Handbook. TP-136, Burle Industries, 1980.

6 **Tidd,** J.L., J.R. Dabbs and Norman Levine. Scintillator Handbook with Emphasis on Cesium Iodide. NASA Technical Memorandum TM-X- 64741, 1973.

7 **Gwin,** R and R.B. Murray. Scintillation Process in CsI(Tl), parts I and II. Physical Review, v 131 no 2 (July 1963). pp 501-512.

8 **Wright,** A.G. Sources of Noise in Photomultiplier Tubes. Thorn EMI Electron Tubes, 1988.

9 Photomultipliers and Accessories. Thorn EMI Electron Tubes, 1993.

## 1.0 Introduction

The long-term monitoring of the vadose zone of a hazardous waste site for migration of radionuclides requires installation of radiation sensors at a large number of subsurface locations. Sensors which can be lowered into boreholes to make radiation measurements are available, but are relatively complex and expensive and generally not suitable for long-term installation underground. The existing devices normally incorporate a transduction element (e.g. a scintillator or solid state device) to convert ionizing radiation to an electrical or an electromagnetic (light) emission. In the case of electromagnetic transducers, the emitted light or photons are further converted to an electrical quantity via an attached photoelectronic device (e.g., an electrically powered photomultiplier tube attached directly to a scintillation crystal). Each subsoil point to be monitored must then be equipped with a separate sensor containing the transducer and electronic component. The cost of installing a large number of these radiation sensors in the vadose zone of a waste site can be cost prohibitive and the need for high reliability of the electronic devices underground over a 30 year period would require a significant maintenance budget and costly periodic sensor replacement.

In general the difficulties of maintaining electronic devices underground for extended periods has precluded their use as a continuous monitoring system. Instead, boreholes (sampling wells) are drilled and cased, and then, periodically, sampling probes are dropped into the wells to determine the current radiation level which is then compared to previous measurements. The measurement interval must be short enough to preclude any unacceptable migration between measurement cycles. This approach is viable but is costly in terms of the man-hours required for the periodic monitoring effort and the potential for worker exposure is high.

Upon surveying the radiation monitoring equipment which is available for application to the problem, B&W determined that great leaps in the current technology of radiation detection were not required to develop a system which overcomes the problems of active in-ground detectors. What is required is to configure commercially available components into a low cost, multi-point, reliable system. While only a few specific radionuclides may be of concern at an individual site, ideally, such a system should be able to detect the full range of potential radionuclides at all DOE sites to minimize the need for site-specific engineering. Similarly, the system should be applicable over the full range of soil depths and geologies, and to both perimeter monitoring and monitoring of sub-surface containment structures. Because the system is designated for vadose zone monitoring, it should be applicable in soils which vary from dry to saturated, and thus could potentially be applied to monitoring within a perched or permanent water table, an aquifer, or even in the absence of soil as in a monitoring well. Finally, the system should be capable of monitoring concern levels typical of the post-remediation condition with a reasonable number of individual probes, implying probes which are sensitive to low levels of radionuclides in relatively large soil volumes.

One solution to the problem of measuring low-level radiation at a large number of locations over a long period of time is based on optical waveguide technology. This concept employs an in-ground measurement probe which contains a scintillator coupled to an optical waveguide. Because of the limited range of alpha (<.015 cm) and beta (<1.5 cm) radiation in soil, the scintillator is designed to respond primarily to gamma radiation, with a range of 10's of centimeters to a meter. As shown in **Figure 1-1**, the signals from a large number of in-ground probes are routed to a small building on the surface containing multiplexing equipment and a personal computer for data logging, analysis and transmission. No sub-surface electrical power is required nor is any generated. Gamma radiation absorbed by the in-ground scintillator generates optical photons which are coupled into the optical waveguide, conveyed to the surface and detected as an indication of the instantaneous sub-surface radiation level. The system is to be capable of continuous, unattended monitoring of an array of in-ground detectors to provide an indication of radionuclide migration. The computer is intended to continuously map the distribution of radionuclides by monitoring isotopic activity at each probe location with time, and to be capable of being interrogated from a remote location. Figure 1-2 is a conceptual drawing of the system installed at a waste site for long-term monitoring.

In Phases I and II of this program, a prototype probe based on this concept has been developed; during Phase II, this prototype was extensively field tested and its performance compared to that of a butt-coupled scintillator/PMT probe designed by B&W for in-house survey applications. The results of the field tests performed in Phase II showed that the use of the lightguide results in a significant resolution loss, and an unacceptable increase in the lower detection limits for the probe. No viable means have been identified to significantly improve the resolution of the lightguide coupled probe. For the survey probe, however, at count times of 90 minutes, the lower detection limits were marginally adequate for the detection and monitoring of U-235 and U-238 at post-closure concern levels, with approximately 5% precision.

While this development program has been in progress, several vendors of cone penetrometer tooling have developed and demonstrated the capability to push low cost plastic (PVC) casing to depths comparable to those achievable with conventional CPT tools (up to 50 meters). This opens the possibility for an easily retrievable downhole probe which incorporates both the scintillator and photomultiplier in a single probe package, similar to the survey probe tested.

With this development and the B&W survey probe results from our tests, we have concluded that a workable approach is available for the long-term monitoring of low activity radionuclides, using a butt-coupled scintillator/PMT, installed in a PVC casing pushed with CPT. In this approach, the down-hole probes incorporate the scintillator, PMT and voltage divider; the required signal and power cables run within the water-tight PVC casing and thus are protected. At the surface, a solar-powered remote station at each measurement location incorporates the PMT power supply, pre-amplification, a multi-channel analyzer and an RF transceiver, as shown in **Figure 1-3**. A large number of remote stations can be multiplexed to a single centrally located transceiver, which is connected to a computer which serves as a data concentrator. The data concentrator controls all of the data acquisition by the remote stations, and interfaces to an off-site host computer via a phone line modem. **Figure 1-4** is a conceptual drawing of a system installed at a waste site for long term monitoring. With this system architecture, the components required at each measurement location have the lowest cost, while the more expensive components are required only once per site or per system. The use of CPT provides a proven method for relatively rapid and inexpensive installation of the casing for the probes compared to the cost of drilling and casing a comparable number of wells. The use of penetrometer technology eliminates the cuttings normally associated with drilled wells, and thus minimizes worker exposure and eliminates the cost of cutting disposal. The penetrometer approach also has the advantage of producing minimal cross-contamination, the "smearing" which can result from conventional well drilling which can spread contamination from one stratum to another and invalidate measurements. A large number of the down-hole probes can be multiplexed to a single, above-ground analysis unit, which would provide for detection and readout of any long-term changes in the distribution of the radionuclides in the vadose zone. The in-ground components (the scintillator and PMT) are proven technology and are reliable, and are readily retrievable should maintenance or repair be required.

This approach utilizes the proven superior resolution performance of a butt-coupled scintillator/PMT combination while maintaining the advantages of low installed cost, serviceability, CPT installation and minimal potential for cross-contamination both during installation and in service. It has the advantage that the major hardware components of the system are already demonstrated and commercially available. What is still required is to configure these commercial components into a low-cost, multi-point, reliable system with a straightforward user interface, and to demonstrate a multi-point prototype system in a monitoring application at a DOE site. This is our recommended approach for Phase III of this program. This approach should result in a sensitive and reliable long-term post-closure monitoring system which significantly reduces the costs of long term radiation monitoring compared to conventional sampling and analysis, with superior results due to more frequent monitoring and by eliminating the errors associated with sampling.

**Figure 1-1. Original System Concept.**

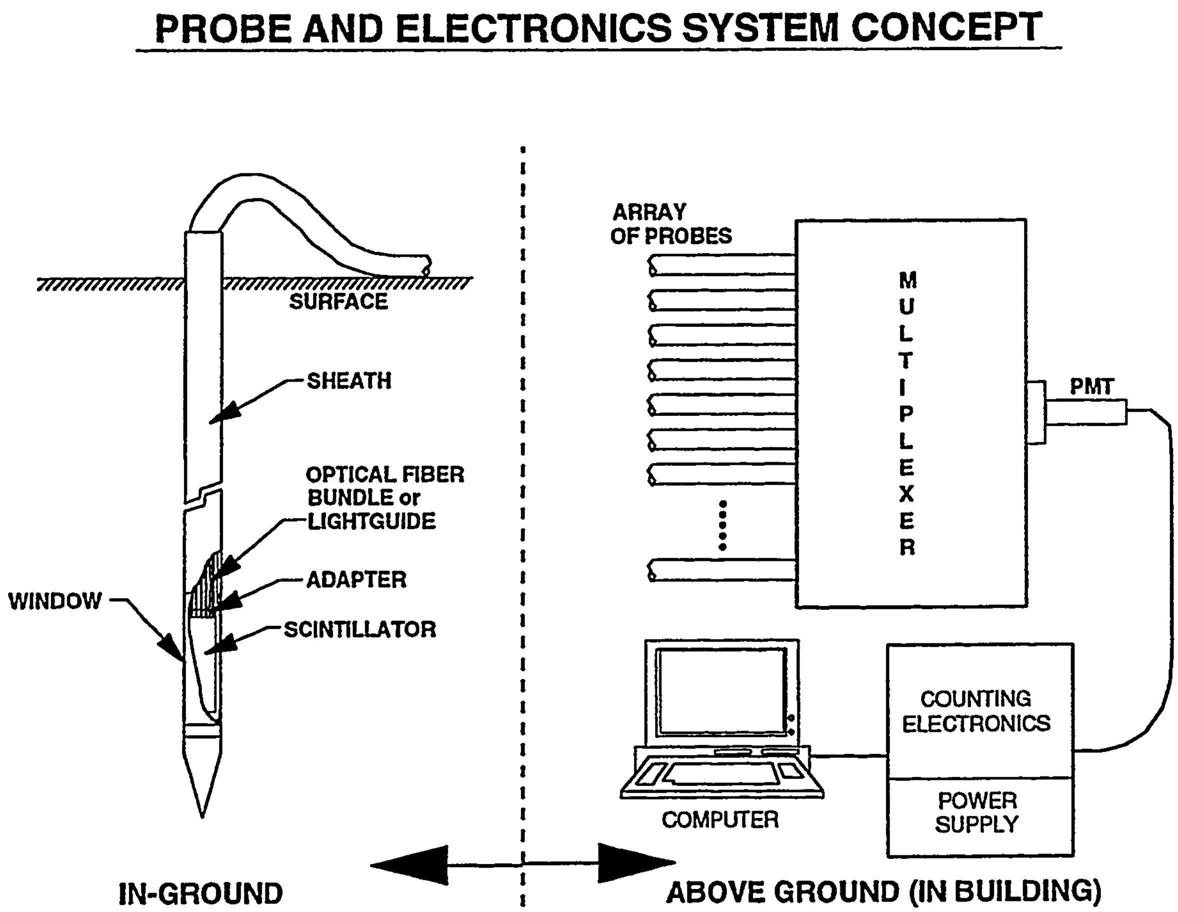


**Figure 1-2. Installed System (Original Concept).**

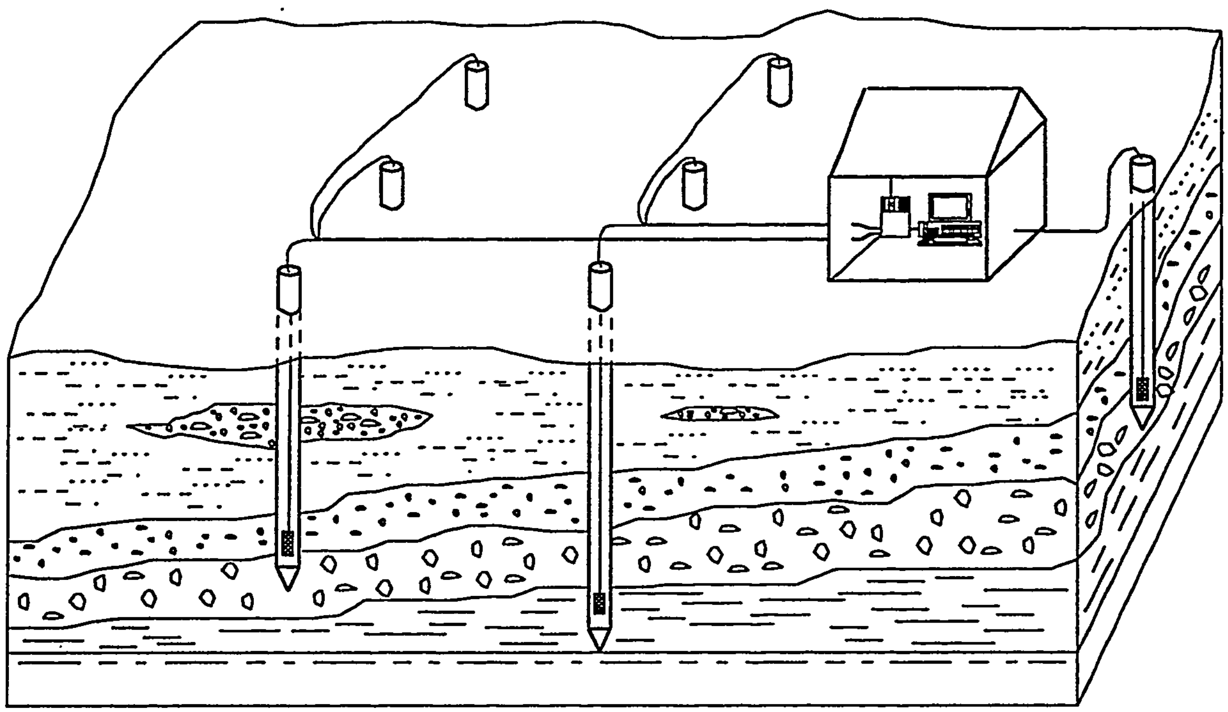


**Figure 1-3. System Architecture (Phase III).**

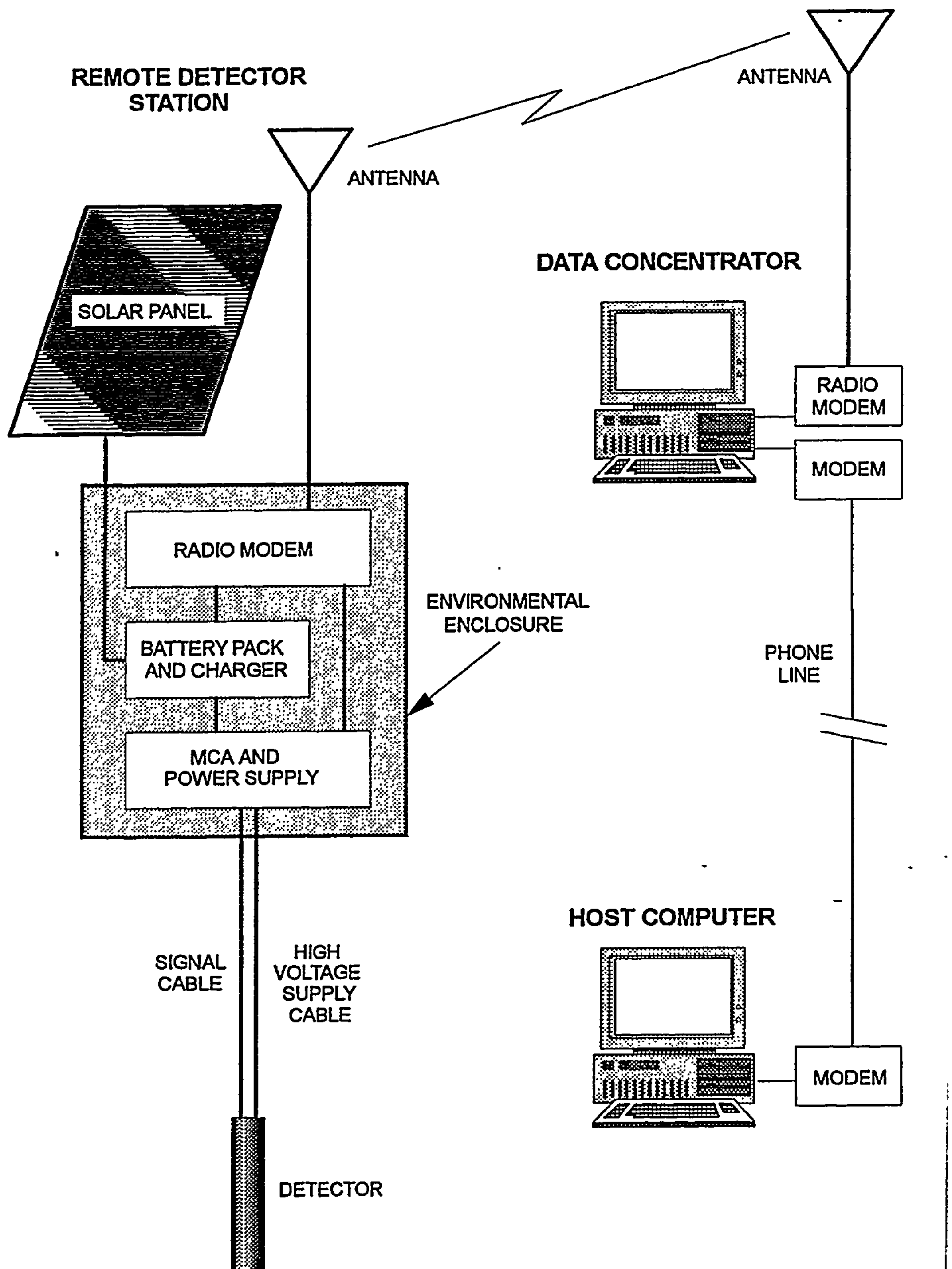
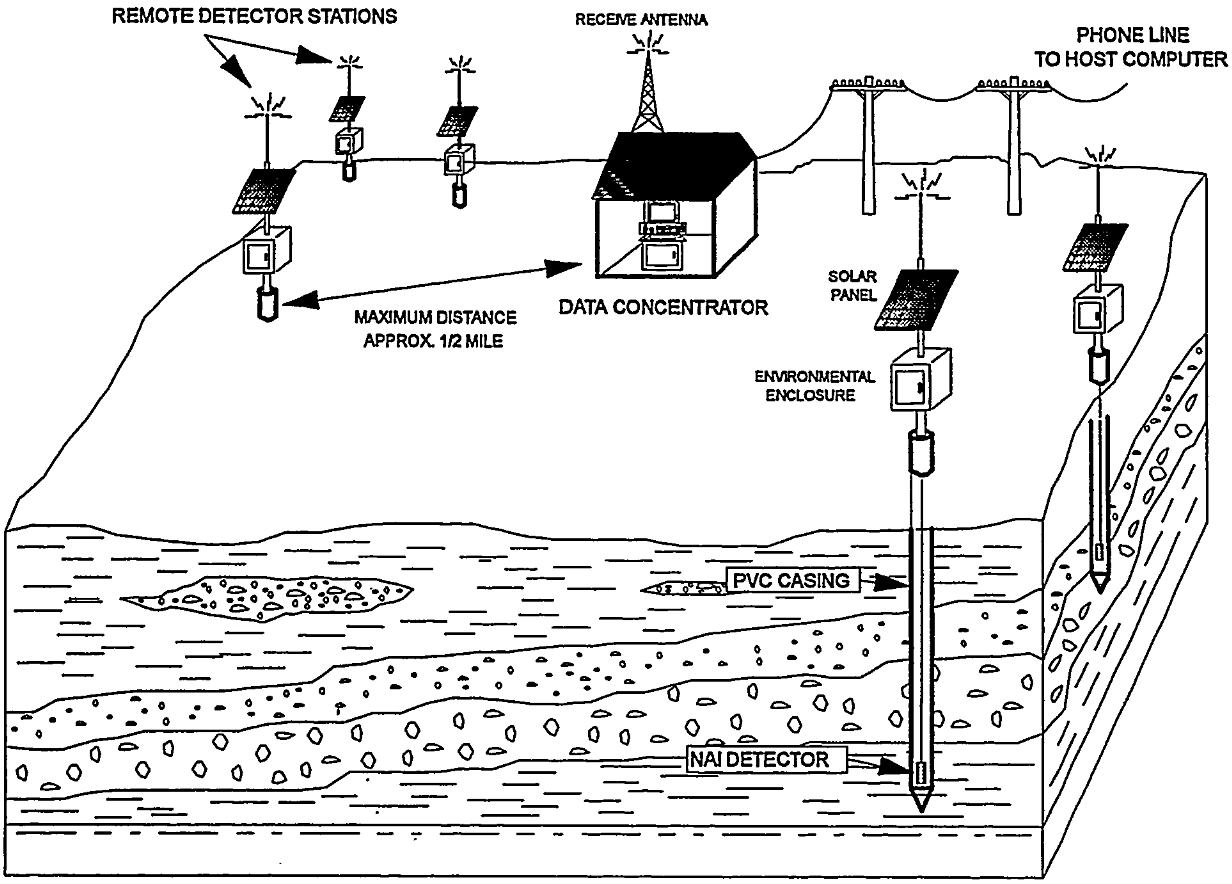


**Figure 1-4. Installed System (Phase III).**



## 2.0 Program Approach

The overall goal of the development program is to configure a long-term radiation monitor using commercially available, demonstrated components to the largest extent possible. This has the benefits of minimizing development and application costs, and minimizing technological risk associated with new technology development. In developing the radiation monitoring system, two general approaches were available. In the first, the desired system performance parameters in all relevant areas would first be quantified and then used to specify the required performance characteristics of each system component; this approach begins at the system output and the performance requirements flow upstream to the primary detectors. In the second approach, the system requirements are qualitative and the achievable performance of individual commercially available components is optimized and evaluated; this approach begins at the detector and the achievable performance flows downstream along the signal path. Because many of the system performance parameters cannot be readily quantified at this time and because of the desirability of applying currently available technology and components to the largest possible extent, the second approach was selected for the first two phases of this program.

The program is structured so that the technology areas addressed first are those areas where applicable products are not yet commercially available, but components are; these are the areas of greatest technical risk in achieving a workable system at reasonable cost, and the areas requiring the greatest amount of configuration work. The technology areas addressed first are those which relate to the gamma detectors, the in-ground probes; the performance of these probes ultimately limits the system performance. In addition, the probes must be highly reliable because they cannot be readily serviced, and because of the multiplexed system architecture, the probe costs have a significant impact on the overall system cost.

Program needs in more mature technology areas which provide a number of viable commercial alternatives are deferred until later phases, unless they impact directly on the current phase. For example, cone penetrometry (CPT) was chosen as the probe installation method in Phase I because it is the only field-proven installation method for depths up 50 meters in a wide variety of soils which does not require drilling, and because the envelope of CPT tools constrains the design of both the scintillator and the light guide. The choice of a specific geometry could be deferred until Phase II, because a range of acceptable options exist.

## 2.1 Description of Program Phases

The Long-Term Post-Closure Radiation Monitor development program was planned as a three phase program spanning a total time of 53 months. The problems addressed in **Phase I** were primarily those associated with selection of the most appropriate components (scintillator, coupling optics, optical fiber, and opto-electronics) to maximize the signal reaching the detectors and thereby minimizing the integration time required to obtain a reliable measure of radiation. Phase I resulted in the design of an integrated unit consisting of a single probe and a non-multiplexed opto-electronics unit which incorporates the test and analysis information developed during the Phase I activities.

**Phase II** (the current phase) included the fabrication and testing of the integrated probe at a contaminated site. The probe was used to make measurements in-situ at relatively shallow subsurface depths. Phase II activities included configuring the probe and detection electronics capable of field measurements in contaminated soil. Phase II resulted in the design of a full-scale prototype system. This full-scale prototype system incorporates the features expected to be necessary on a fully commercial system, including 50 meter depth of measurement, multiplexing of multiple probes, and remote transmission of data.

The full-scale prototype system will be fabricated and field tested during **Phase III**. The engineering of the multiplexing interface, the remote data acquisition, and the installation of permanent probe sheaths will be undertaken. The field test will have a nominal duration of 12 months. A full commercial design will be developed based upon the data gathered and experience gained during the entire program.

## 2.2 Phase II Technical Approach

Phase II was planned as a build and test phase. The workscope of Phase II thus focussed on component selection and fabrication of the in-ground probe and on testing of this probe over a broad range of conditions. The LPRMS probe was built based on the design developed in Phase I, but with modifications to use proven commercially available components to the largest extent possible, and to incorporate additional features which are anticipated to be needed in the Phase III system. Limited laboratory testing was performed to evaluate alternative components for application in the Phase II probe, and to develop the calibration information needed for quantitative field testing.

The purpose of the Phase II testing was to obtain field data to validate the design methods used, to quantify the system performance and to provide the field experience needed to confidently design the Phase III system for broad applicability. The site selected for these tests was the DOE Fernald Environmental Management Project (FEMP) at Fernald, Ohio. The tests were designed to evaluate the probe primarily in soils, and to incorporate a broad range of activity levels. The tests included soils with both known and unknown contaminant levels, as well as water samples. The tests were performed using barrels of soil and in-situ in an existing monitoring well and in cased temporary borings. Sample contamination levels were chosen which were well below, near and well above the expected measurement threshold of the probe. All data were acquired and analyzed with a commercially available two channel gamma spectrometer, typical of what might be used in Phase III.

To get the maximum amount of data, these tests were coordinated with three other test programs: the DOE Uranium in Soils Integrated Demonstration (USID), the DOE Cone Penetrometer Demonstration (CPD) and the B&W funded Survey Tool program. The USID program provided previously characterized soils to be used in fabricating test drums with known activity levels. As part of the CPD program, two locations at FEMP were sampled and analyzed for contamination vs depth; these locations were also measured for gamma activity using a gamma probe developed by Waterways Experimental Station (WES) and with a commercially available probe supplied by Applied Research Associates (ARA). These bores were then temporarily cased with 1.5 inch schedule 80 PVC for later measurements in our test program. The B&W Survey Tool program provided a gamma tool with a butt-coupled sodium iodide scintillator which was used to generate comparison data.

### 2.3 Phase II Task Breakdown

The major Phase II activities consisted of the following five tasks.

#### Task 7 - Project Planning

The purpose of this task was to develop and provide to DOE all required project planning (management, cost and technical) documents and to provide DOE-METC and FEMP the information required for the preparation of the National Environmental Protection Act (NEPA) documentation for this project. DOE-METC obtained and granted to B&W a categorical exclusion for the NEPA documentation for Phase II. This task also included support of and attendance at the annual EMCR meeting or equivalent, as directed by DOE.

#### Task 8 - Fabricate Sub-scale System

The purpose of this task was to perform all the work necessary to build the probe system designed in Phase I and to prepare it for the field tests. The workscope included design modifications, selection and procurement of components, fabrication and assembly, and laboratory testing of components. This task also included the development of methods for energy and efficiency calibration.

#### Task 9 - Field Testing

The purpose of this task was to obtain field data needed to benchmark the design methods used in Phase I and to be able to quantify the system performance. The workscope included all work necessary to plan and execute the field demonstration test at the FEMP. This task included interfacing activities with Fernald, DOE and subcontractor personnel to plan the tests and coordinate the test program with other demonstration tests, the preparation of the draft and final Demonstration Test Plan, performance of four weeks of testing at the FEMP and post test data analysis.

**Task 10 - Prototype System Design**

The purpose of this task was to design the prototype multi-probe system for Phase III testing, based on the analyses of Phase I, the tests of Phase II and input from suppliers who will provide components and sub-systems for the Phase III system. The intent of this task was to design a system which, to the greatest extent possible, could be readily fabricated by the commercial vendors who would ultimately supply a commercial system.

This task also included identification of the U.S. Environmental Protection Agency (EPA) Data Quality Objectives (DQOs) for the Phase III testing, and development of a preliminary plan and test matrix to meet these DQOs.

**Task 11 - Reporting**

The purpose of this task was to prepare comprehensive draft and final reports on the development work and testing performed in this Phase and to present these results at an End-of-Phase meeting at DOE-METC.

This task also included the activities to prepare and issue to DOE a separate proposed workscope and the associated costs for Phase III.

## 3.0 Phase I Summary

The activities, analyses, and results of Phase I of this program are described in detail in Ref. 1, "Development of a Long-Term Post-Closure Radiation Monitor - Phase I Final Report" (12/93).

The workscope in Phase I was to configure a probe with the highest sensitivity to gamma radiation and the lowest optical losses, within the available CPT envelope, using commercially available components, at the lowest possible cost. In addition, it was judged highly desirable that the resultant design maintain the potential for energy discrimination which might be needed for nuclide identification or background compensation. The approach taken in this phase was to identify the nuclides of concern at DOE sites (to determine the required detection range of gamma energies and to permit quantitative estimates of performance), to optimize each component of the probe in signal path sequence between the soil and the opto-electronics, (consistent with the criteria listed above), and to assess their individual loss characteristics and their combined behavior in a probe. The overall performance of the probe could then be estimated to determine the volume of soil which could be monitored by the probe and the expected output optical pulse heights and rates for each of the nuclides of concern.

A total of 23 radionuclides were identified as occurring with significant frequency and activity on DOE lands, including natural decay products and fission fragments (see Tables 3-1 and 3-2). Decay chain relationships were examined for each of these. Three of the nuclides, H-3, Sr-90/Y-90 and Tc-99, decay by $beta^-$ with little or no associated gamma emission. Detection of these nuclides with the present gamma scintillation approach will be difficult or impossible; this may reduce the application of this technology at some DOE sites. For the other 20 nuclides, viable gamma monitoring approaches are available based on direct monitoring, short-lived daughters or known isotopic ratios.

Four classes of commercially available scintillators were evaluated for overall efficiency based on density, mass absorption characteristics, scintillation efficiency and emission wavelength. Three alternative geometries were evaluated for collection efficiency and uniformity. Based on these evaluations, the preferred scintillator for the long-term post-closure radiation monitor is a large aspect ratio cylindrical scintillator of thallium-doped cesium iodide, CsI(Tl). Thallium-doped sodium iodide, NaI(Tl), would be a potential alternative, although its shorter emission wavelength would result in increased spectral losses in the transmission fiber and its hygroscopic nature would require greater attention in the probe design and fabrication. The higher cost of a CsI(Tl) scintillator compared to one of NaI(Tl) (about $900 vs $600 for a 2.5 cm by 25 cm geometry) would be more than offset by this additional design and fabrication effort. Both conic and CPC geometries for the scintillator have greater collection efficiencies than the cylinder, but are highly non-uniform in response, precluding energy discrimination.

Conventional optical elements and several alternative methods of coupling a scintillator to a transmission fiber were evaluated to determine if it was possible to couple more light into the transmission fiber than would be coupled in by directly butt-coupling the fiber to the scintillator. It was found that none of the means evaluated could improve on the butt-coupled geometry. Because of its simplicity and efficiency, the butt-coupled geometry is the preferred approach for the long-term post-closure radiation monitor.

Six commercially available candidate fiber types were evaluated for suitability as transmission fiber. Based on all of the parameters investigated (cost, NA, spectral loss characteristics and stem effect) the preferred transmission fiber for the long-term post-closure radiation monitor is a poly-methylmethacrylate (PMMA)/fluorinated polymer fiber. This fiber is readily commercially available in relatively large fiber core sizes. A pure fused silica fiber would also provide acceptable technical performance if it could be obtained at reasonable cost. The costs per meter of the required large area fiber bundle are high even with PMMA; an alternative was identified for reducing the lightguide cost by using PMMA rods clad with Teflon AF. This alternative is not yet commercially available, but was evaluated in Phase II of this program.

A soil model was developed and used to examine the effects of soil density and degree of saturation on the gamma flux through the scintillator volume. While variations in soil density can produce changes in gamma flux of 30% or more, changes in soil density large enough to cause concern are not judged likely barring major disturbances in the sub-surface soils or major changes in surface conditions. Periodic or seasonal variations in the degree of saturation of the soil within the monitored volume are more likely. A variation of 50% in soil water content (likely in some soils) will produce a 10% variation in the gamma flux and thus a 10% change in the output of the monitor. The effective radius over which soil radionuclides contribute to the probe output was also calculated, and found to vary over a factor of three with energy within a given soil type, and also to have significant variations with soil density and degree of saturation. This may influence the system design but should not be an operational concern.

A probe was designed for in-situ testing in Phase II, based on a 10 $cm^2$ cone penetrometer tool, incorporating a CsI(Tl) scintillator, butt-coupled PMMA lightguide and detection electronics. The performance of this probe was estimated using the soil model described above for each of the radionuclides identified. At activity levels of 5 pCi/gram it is estimated that all of the radionuclides of concern can be monitored with count times of 3 minutes or less, except U-234, Th-230, Pb-210, Po-210 and Tc-99. At 30 pCi/gram, Pb-210 can be monitored with a count time less than 3 minutes and Th-230 with a count time of less than 10 minutes. It is possible to infer Po-210 from secular equilibrium with its Pb-210 parent in some cases. Monitoring of U-234 (rather than inferring it from isotopic ratios) will require long count times or relatively high activity levels. Monitoring of Tc-99 and the pure $beta^-$ emitters H-3 and Sr-90/Y-90 are not practical using the present gamma scintillation approach.

**Table 3-1. Natural Decay Products**

| Radionuclide | Daughters† | Gamma Energy, KeV (yield, %) |
|---|---|---|
| U-234 | None | 53(.12) 121(.04) |
| U-235 | | 143.8(10.5) 185.7(54) |
| | Th-231 | 25.6(14.8) 84.2(6.5) |
| U-238 | | 49.6(.07) |
| | Th-234 | 63.3(3.8) 92.4(2.7) |
| | Pa-234m | 765(.36) 1001(.59) |
| Ra-224 | | 241(3.9) |
| | Rn-220 | 55(.07) |
| | Po-216 | 128(.002) |
| | Pb-212 | 239(44.6) 300(3.4) |
| Ra-226 | | 185.7(4.0) |
| | Rn-222 | 510(.07) |
| | Po-218 | 837(.0011) |
| | Pb-214 | 242(3.7) 295(19.2) 352(36) |
| | +others | |
| Ra-228 | | 6.7(6x10$^{-5}$) |
| | Ac-228 | 338(11.4) 911(27.7) 969(16.6) |
| | Th-228 | 84(1.19) 132-166(.19) 216(.27) |
| | Ra-224 | see Ra-224 above |
| | +others | |
| Th-228 | | 84(1.19) 132-166 (.19) 216(.27) |
| | Ra-224 | See Ra-224 above |
| Th-230 | | 67.8(.59) 142(.070) 184(.014) 253(.017) |
| | None | |
| Th-232 | | 59(.19) 126(.04) |
| | Ra-228 | See Ra-228 above |
| Am-241 | | 59.4(35.7) 99(.02) |
| | None | |
| Pa-233 | | 300(6.2) 312(36) 340(4.2) |
| | None | |
| Pa-237 | | 149(1.9x10$^{-4}$ |
| | U-237 | 60(33.5) 208(21.7) |
| Np-237 | | 86.5(12.6) 143(0.4) |
| | Pa-233 | See Pa-233 above |
| Pb-210 | | 46.5(4) |
| | Bi-210 | None |
| | Po-210 | See below |
| Po-210 | | 802(.0011) |
| | None | |
| Ac-227 | | 70(.017) 100(.032) 160(.019) |
| | Th-227 | 50(8.5) 236(11.2) 300-330(5.8) |
| | Ra-223 | 144-154(8.9) 269(13.6) 324-338(6.7) |
| | Rn-219 | 271(9.9) 402(6.6) |

† daughters in secular equilibrium with parent species

## Table 3-2. Fission Fragments and Others

| Radionuclide | Daughters† | Gamma Energy, KeV (yield, %) |
|---|---|---|
| H-3 | | None |
| Co-60 | | 1173(100) 1333(100) |
| Sr-90 | | Bremsstrahlung |
| | Y90 | Bremsstrahlung |
| Tc-99 | | 89.4(6x$10^{-4}$) |
| Ru-105 | | 316(11.7) 469(17.5) 724.5(49) |
| Cs-137 | | |
| | Ba-137m | 661.6(90) |
| Ce-144 | | 133.5(10.8) |

† daughters in secular equilibrium with parent species

# 4.0 Prototype Probe Design

Based on the radionuclides identified and the analyses and tests performed in Phase I, a prototype LPRMS probe was designed during Phase I for Phase II testing. The purpose of the testing of this probe in Phase II was to validate the calculational methods used to design and predict its performance, and to provide a demonstration of a single channel system in a short-term field test at a DOE site in actual contaminated soil. The probe design developed in Phase I embodied most of the key features anticipated for the long-term post-closure radiation monitor system, but the design was not optimized for cost or manufacturing. The probe design was modified slightly from the Phase I design to incorporate additional features anticipated in Phase III or components with better commercial availability or improved performance.

## 4.1 Design Base from Phase I

The mechanical design of the probe was based on the dimensional envelope of a 10 $cm^2$ cone penetrometer with a 1-7/16 inch (3.65 cm) outside diameter and a conventional 60 degree cone tip angle. The probe consisted of a scintillation head housing the scintillator, a detection head housing the PMT and detection electronics, and several threaded extension sections for the push rods and lightguide. The scintillation head incorporated a 2.5 cm diameter by 25 cm long CsI(Tl) scintillator inside a 0.25 cm thick aluminum window section which extended slightly past the scintillator on both ends. Both the cone tip and the window were to be fabricated from 6061-T6 aluminum alloy and subsequently "Tuff-coated" (a proprietary hard anodizing impregnated with teflon) to reduce friction and increase abrasion resistance. In this design, the window material carried the push forces applied to the tool; this limited the maximum push force for this tool to about 4 tons. Because of the relatively short length of this probe (about 2 meters), although it would be made in 1 meter sections, it would be fully assembled above ground prior to installation and testing. This would permit the tool to be readily moved between test locations, much like a survey tool. Probes intended for full-depth installations using a CPT truck would be assembled 1 meter at a time during the push similar to CPT strings.

The optical photons from the scintillator would be transmitted by a 2.5 cm optical fiber bundle made up of 7500 PMMA/fluor optical fibers each 0.025 cm diameter, or alternatively a single clad PMMA rod 2.5 cm OD. The transmission bundle would be directly butt-coupled to the scintillator. To accommodate this bundle, the bore of the extension sections would be increased to 2.7 cm from the normal CPT rod bore of 1.6 cm. The extension sections would be approximately 1 meter in length and extend to the surface. At the surface end of the probe, the extension sections would be coupled to a detection head containing a 1-1/8" head-on PMT, a voltage divider base, a pre-amp and pulse shaping electronics. The transmission fibers would be directly butt-coupled to a shutter assembly coupled to the PMT face.

The PMT would be operated in the pulse mode with a cathode ground (positive high voltage). This mode of operation is consistent with either photon counting or spectroscopic analysis techniques. The PMT would be magnetically shielded, and shielded from background radiation (terrestrial and cosmogenic) using low radioactivity materials; this shielding was judged likely to employ layers of materials with different atomic numbers, such as lead/copper or lead/stainless steel, to minimize the effects of secondary radiation on the PMT and detection electronics. The need for cooling or temperature control of the PMT in the Phase II probe and approaches to accomplish this were still under consideration. It was planned to use spectroscopy (energy discrimination by pulse height analysis) in Phase II to permit nuclide identification and background subtraction.

### 4.2 Design Modifications

The basic design concept developed in Phase I was used for the Phase II probe. The probe used a CsI(Tl) scintillator, lightguide coupled to a PMT at the surface, housed in a CPT type tool. The probe design was modified from the Phase I design to incorporate additional features anticipated in Phase III and components with better commercial availability or improved performance, or to modify or eliminate components to reduce cost while maintaining satisfactory performance. These are described below.

### 4.2.1 Shutter

During Phase I, incorporation of an optical shutter between the lightguide and the PMT was considered. Closing this shutter would permit the PMT and electronic background noise spectra to be counted and subsequently subtracted from measured spectra. However, introduction of a shutter introduces an optical loss ranging from less than 1 dB to over 3 dB, (depending on the particular implementation), and introduces additional mechanical complexity.

The major sources of the PMT noise are thermal noise, naturally occurring trace radioactives (primarily K-40) in the PMT window and cosmic radiation. At room temperature, the PMT thermal noise occurs at between 0.5 and 2 photoelectrons equivalent (PEeq). K-40 in the PMT window contributes noise in the PMT due to Cerenkov radiation and direct interaction with the photocathode. In a butt-coupled configuration, the K-40 gamma radiation may also directly excite the scintillator. The window Cerenkov K-40 contribution occurs between 2 and 15 PEeq, the contribution from direct scintillator excitation occurs at 1460 keV, and the cosmic radiation contribution occurs above 15 PEeq. With the expected scintillator yield and PMT quantum efficiency, the thermal noise will occur at a gamma energy equivalent (GEE) of 1 to 7 keV, the window Cerenkov K-40 at a GEE of 7 to about 50 keV and the cosmic radiation above 50 keV. [See Ref. 8.]

The thermal noise has by far the largest contribution to background count rate, but occurs at a GEE well below gamma energy levels of interest, where a lower level discriminator (LLD) would normally be used anyway to reduce electronic noise. The majority of the Cerenkov K-40 contribution would also be eliminated by the LLD, because most of the counts are at the low energy end (below 10 PEeq, 35 keV GEE). The Cerenkov K-40 contribution of a standard borosilicate PMT could be expected to contribute up to 90 counts per minute if an LLD were not used, less than 20 CPM with the LLD. This could be reduced to 5 CPM total or less by specifying a low-background envelope for the PMT, if the K-40 were a significant problem. The contribution of the K-40 through direct excitation of the scintillator (at 1460 keV) is not a factor with a lightguide coupled scintillator. The contribution of the cosmic radiation cannot be removed using the discriminator, and because the cosmic radiation involved is comprised mainly of relativistic muons and electrons, shielding is difficult. Fortunately, for a 25 mm diameter photocathode, the expected rate for cosmic radiation interactions is only about 4 CPM at sea level [Ref. 9, p 16]. At this frequency, the potential background from this source is small, and even with count times of 30 minutes or more, cannot be adequately characterized by background counting.

In summary, the types of background which can be compensated by use of a shutter are either readily controlled by other means or will be relatively unimportant in this application. Based on these factors, it was decided not to incorporate a shutter in the Phase II probe.

### 4.2.2 Lightguide Selection

The probe design done in Phase I assumed that the lightguide would consist of a bundle of 7500 polymethyl methacrylate optical fibers clad with fluorinated polymer (PMMA/fluor). This fiber bundle is commercially available; it has a nominal numerical aperture (NA) of 0.5, good stem effect performance, and adequate loss characteristics when coupled with a CsI(Tl) scintillator. The disadvantages of this approach are that it introduces optical losses because of bundle efficiency (core area/total bundle area) and a cost of approximately $400/meter or more.

An alternative identified in Phase I was to use a rod of optical grade PMMA or fused silica (SiO) as a lightguide. This approach would reduce optical losses by eliminating the bundle efficiency, and would potentially be significantly cheaper than a conventional fiber bundle. Vendors for unclad rods were identified for both PMMA and SiO. The quoted costs for these rods were $16/meter for PMMA and $75/meter for SiO. Several PMMA rods were procured and tested to determine their loss characteristics and NA in unclad and clad configurations.

#### 4.2.2.1 Throughput Losses

The optical loss was measured using a halogen light source filtered with 450 nm long pass and 650 nm short pass filters to produce spectral characteristics similar to those of a CsI(Tl) scintillator. The output light was coupled into an optical fiber collimator, which was then passed through two apertures to reduce the beam size and angular dispersion. The loss for a 1 meter section of lightguide was determined by measuring the photocurrent of a bialkali PMT with the lightguide in the optical path and removed from the optical path, correcting for the Fresnel losses at the lightguide end faces. The measured loss value was 0.16 dB/meter, compared to a published value of 0.12 dB/meter for PMMA/fluor fiber with monochromatic light at 550 nm. Since the measured result is not corrected for the spectral response characteristics of either the light source or the PMT (both slanted toward the blue where losses are higher) this was judged to be good agreement. On the basis of loss characteristics, a rod type lightguide will function as well as a fiber bundle.

#### 4.2.2.2 Numerical Aperture

A bare rod will function as a lightguide with air acting as the cladding; such a configuration results in the highest possible NA for a given core material, because the index of refraction of air is essentially 1.0, while other cladding materials have higher indices. The disadvantage of an air-clad lightguide is that it susceptible to losses resulting from contaminants such as dust or fingerprints on the OD of the lightguide, from contact with supporting structures or from damage or deterioration of the surface. The presence of a cladding material on the outside of the lightguide reduces the NA, but provides stable optical confinement and some immunity from environmental factors. A sample quantity of Teflon AF (6% solids, index of refraction = 1.3) was procured, and fixturing and techniques were developed to coat 1 meter long PMMA rod sections with this material. PMMA rods were then tested for NA in the bare configuration, clad with Teflon AF and wrapped with teflon, kapton or mylar tapes.

The NAs of the rods were measured using the collimated light source used for the loss tests. The lightguide under test was butt-coupled to the PMT with silicon grease; the throughput vs input angle was measured and corrected for one-surface Fresnel loss to determine the NA. All of the taped rods showed an acceptance half-angle (-1 dB) of about 25 degrees, for an NA of about 0.42. Both the bare rods and Teflon AF clad rods showed an acceptance half-angle (-1 dB) of nearly 45 degrees for an NA of over 0.65. The Teflon AF clad rod showed greater losses than the bare rod at larger angles of incidence. On the basis of NA, either a bare rod or a Teflon AF clad rod will offer better performance than a PMMA/fluor fiber bundle; the performance of taped rods is similar or slightly worse than the fiber bundle.

#### 4.2.2.3 Rod Support Effects

When installed in a probe, the lightguides will require alignment between the end faces of the 1 meter sections and lateral support to keep the lightguides centered and the end faces parallel. The throughput vs angle characteristics were measured for the bare and Teflon AF clad rods with tape wraps or O-rings installed at three positions along a 1 meter length. As expected, the tape and O-rings had virtually no effect on the throughput characteristics of the clad rod, but degraded the performance of the bare rod; the O-rings produced less degradation than tape wraps. A test was performed on the bare rod using three specular reflectors (polished aluminum rings) at the support locations under the O-rings. With this support configuration, the presence of the supports produced no measurable change in the throughput vs angle.

#### 4.2.2.4 Lightguide Selection

Based on the evaluations described above, either the Teflon AF clad or the bare PMMA rod lightguide can provide comparable or better performance than the fiber bundle of the base design, while reducing optical losses by about 20%, at substantially lower cost. The cost of the material and application of the Teflon AF is not trivial: a 100 mL sample cost $280. With a uniform coating only 0.010" thick (.025 cm), each rod would require roughly

20 mL of coating material ($56 worth), plus the cost of the processing, significantly increasing the lightguide costs. Once installed in the probe housing, the lightguides are in a relatively benign and protected environment; it was reasoned that an initially clean air-clad lightguide should remain adequately clean. An air-clad lightguide was thus chosen for use in the Phase II probe. This lightguide would be centered and laterally supported using short aluminum specular reflectors under O-rings, and polished aluminum guides at the joints between lightguide sections.

### 4.2.3 PMT Selection

In any scintillator/PMT system, both the scintillator and the PMT contribute to the energy resolution limits attainable with the system. For practical systems, the resolution is most often described by the pulse height resolution (PHR), which is defined as the ratio of the width of a peak in the energy spectrum at half the maximum peak height (full width at half maximum = FWHM) to the mean energy of the peak, usually defined by the centroid. For gamma spectroscopy, this is most commonly specified at a single energy (the 662 keV line of Cs-137), and is expressed as a percentage. This single value is sufficient because the resolution can be assumed to vary as the inverse square root of the gamma photon energy. For conventional NaI(Tl) scintillators, the PHR at 662 keV is typically in the range of 6.5% to 7.5%.

The single most important contributor to resolution is statistical broadening. Because scintillation is a quantum mechanical process, the broadening generally follows Poisson statistics. The statistical variations have the greatest effect at the point in the signal chain where the number of "information carriers" is the lowest. For a scintillator/PMT combination, this point occurs at the photocathode of the PMT. The attainable energy resolution is ultimately limited by the statistical variation in the number of photoelectrons leaving the photocathode; assuming Poisson statistics, the standard deviation is the square root of the mean number of photoelectrons. Two factors control the number of photoelectrons: the number of optical photons per gamma event which arrive at the photocathode, and the number of photoelectrons which are generated for each optical photon arriving (the quantum efficiency, QE, of the PMT). The scintillator and lightguides for the probe have been optimized within the design constraints to result in the largest possible number of optical photons per keV-gamma arriving at the PMT photocathode. In selecting the PMT, the objective is to obtain the highest possible QE to maximize the number of photoelectrons, without significantly degrading other performance parameters of the PMT, such as dark noise.

PMT photocathodes may be either opaque or semi-transparent. Opaque photocathodes receive optical photons and emit photoelectrons from the same side of the photocathode; they are typically used in side-on type PMTs, generally with fairly small area photocathodes. To use a side-on PMT in this application, additional optical elements would be required to focus the light from the lightguide onto the photocathode with a resulting increase in the optical losses (about 0.5 dB/element). Because of the size and large NA of the lightguide, even with additional optics, the minimum cathode size would be about 0.5 inch diameter, and would require careful control of the focus of the optical elements. Semi-transparent photocathodes receive optical photons on one side of the photocathode and emit photoelectrons from the other; they are generally used in end-on type PMTs, and are directly deposited on the inside of the tube end window. They are available with larger photosensitive areas than opaque photocathodes and typically have better spatial uniformity. With a PMT of this type, the lightguide can be directly butt-coupled to the PMT face minimizing interface losses, and the photocathode area can be closely matched to the lightguide size. A semi-transparent photocathode in an end-on configuration was chosen for use in the probe application.

The spectral emission characteristics of CsI(Tl) are shown in **Figure 4-1**, based on published data for spectral intensity vs wavelength [Ref. 7, p 509]. This data shows that the spectral peak is at about 565 nm, and that the spectral distribution is approximately Gaussian with a FWHM of 172.5 nm. Because there is almost no light emitted below 300 nm, a borosilicate PMT envelope was selected. This is the lowest cost and most widely available envelope, and it also has relatively low sensitivity to high energy cosmic radiation. Because the PMMA lightguide will be directly coupled to the PMT face and has a refractive index close to that of borosilicate glass (1.492 vs 1.485), the use of a prismatic end window would not provide an increase in quantum efficiency. Since photocathode spatial uniformity is more important in this application than electron time-of-flight, a flat photocathode was chosen as the preferred geometry.

To select the optimum photocathode material, spectral response characteristics of a wide variety of photocathode materials from five different vendors were reviewed. Materials with predominantly UV response, such as Cs-I and Cs-Te, were eliminated because they have virtually no response in the spectral range of interest. Likewise, those with very broad response characteristics, but relatively low quantum efficiencies, such as Ag-O-Cs, were also eliminated. This left four basic types of photocathode materials: bialkali, Sb-Cs (S-11), multialkali (S-20), and extended-red multialkali (ERMA). The S-11 response characteristic of Sb-Cs has the same spectral shape as bialkali, but has a lower quantum efficiency at every wavelength so it could be eliminated as well.

To compare the response characteristics of the remaining photocathode materials, quantum efficiency vs wavelength data from three different vendors was first curve fit. This curve fit was multiplied by a normalized Gaussian (area under the curve = 1) with a mean of 565 nm and a FWHM of 172.5 nm to give a spectral response function for CsI(Tl) with each of the three photocathode materials. This response function was integrated over a range of 300 to 800 nm to determine the spectrally averaged quantum efficiency for the scintillator/PMT combination. This analysis showed that bialkali, multialkali and ERMA PMTs will all have a spectrally averaged QE of about 10% when coupled to a CsI(Tl) scintillator. QE values ranged from a low of 9.3% to a high of 11.5%; this is within the range of variation from vendor to vendor for the same photocathode material, and close to the expected tube-to-tube variation for any one vendor, assuming tubes that are not specially selected for uniformity of QE. Because of the additional expense and more limited availability of ERMA photocathodes, they were dropped from further consideration. A bialkali photocathode was tentatively selected because of its superior thermionic noise characteristics, pending consideration of thermal sensitivity.

A bialkali PMT (Hamamatsu R-268) and a multialkali PMT (Hamamatsu R-1104) were tested butt-coupled to the probe's CsI(Tl) scintillator just prior to the field tests to verify their spectral resolution characteristics. The PMTs tested were selected to be interchangeable in the test setup and the probe; they were nearly identical except for their photocathode material: they had the same envelope dimensions, photocathode area, operating voltage, dynode stages, pinout and voltage divider network, and similar dynode structure and gain characteristics. These tests showed that the resolution (@ 662 keV) of the bialkali PMT (9.2%) was slightly better than that of the multialkali PMT (9.6%), confirming that the spectrally averaged QE of the two types was nearly identical.

#### 4.2.4 PMT Cooling/Temperature Control

Temperature has two detrimental effects on PMTs: increased temperature increases the background count rate, and temperature affects the photocathode and dynodes producing changes in gain and spectral response. The major sources of background count rate were discussed in section 4.2.1 above. Of the sources discussed, only the thermal noise is significantly affected by temperature or temperature change. Since this noise occurs at low GEE, it will largely be removed by the lower level discriminator and will not be a factor. Cooling of the PMT for background noise reduction is thus not required in this application.

When the temperature of a PMT is decreased, the response of the photocathode at the short wavelength (blue) end is usually improved, while the response at the long wavelength (red) end is degraded [Ref. 5 p 38]. The response of the dynodes is also improved with decreasing temperature, resulting in an increase in gain independent of wavelength. At temperatures near 20 C, the overall behavior of the PMT is dominated by the dynode response at shorter wavelengths and by the photocathode loss of red sensitivity at longer wavelengths. The wavelength crossover point for a bialkali PMT where the temperature effect is nil is around 550 nm, very close to the center wavelength of CsI(Tl). At 500 nm, below the crossover, the temperature effect on PMT response can be expected to be about -0.2%/C; at 600 nm, above the crossover, the response change can be expected to be +0.3%/C [Ref. 5, p 38]. For a 30 C temperature range (-5 to +25 C) for the PMT, the total monitoring change in any of the system components. Using the known energy lines of such a source (or of such a source plus the K-40 background), corrections can be made for both gain and offset changes in the energy calibration. The known activity of the reference source can be used to correct for changes in detection efficiency, and the K-40 background peak can be used to correct for changes in environmental changes such as soil moisture content.

To be useful for monitoring calibration, a gamma source cannot be a nuclide which is to be monitored, cannot have an interference with a nuclide of interest, and cannot be an expected background nuclide or have an interference with an expected background nuclide. The nuclide should be long lived compared to the expected time of monitoring so that replacement is not required, and decay corrections are minimized. The decay scheme should be simple so that the radioactive decay products are not present or are unimportant. The gamma lines of the nuclides of interest and short-lived descendants identified in Phase I were examined to determine whether there were any available "windows" in the energy spectrum where a calibration line would not have an interference with a nuclide of interest. No window of any significant width was available below approximately 400 keV. Between 400 and 1000 keV, the maximum window width was about 100 keV (between 510 and 609 keV). Above 1000 keV, windows were available between 1001 and 1173 keV and above the 1460 keV K-40 line.

A review of gamma emitting nuclides which might be suitable for calibration sources showed that only Bi-207 had a sufficiently long half-life (30 years) and gamma lines which fell within the available spectral windows: 570 (98%), 1064 (77%) and 1771 keV (9%), including emissions from a Pb-207m daughter. Use of this nuclide as a built in calibration source has two drawbacks. First, the high energies of the gamma lines will result in a significant contribution to the Compton continuum, making analysis of unknowns at lower energies more difficult. Second, no commercial supplier of this isotope or its parent (At-211) could be located in the US.

The possibility of using an isotope with a low energy gamma line (below 100 keV) was then evaluated, since several commercially available calibration materials are available in this energy range. Among the nuclides of interest, the lowest energy for a critical gamma line was at 59.5 keV (Am-241); all other isotopes have adequate lines for identification at energies higher than 60 keV. I-129 was identified as potentially suitable; it decays by beta emission to stable Xe-129 and emits a single gamma at 39.6 keV (7.5%) and three closely spaced X-rays at about 30 keV (combined yield 70.1%). It has a half-life of 1.6 x $10^7$ years, and is readily commercially available. The use of I-129 for a calibration source required a redesign of the gamma window to minimize the contribution of both nuclides of interest and background isotopes in this energy range (see Section 4.2.6).

Potential difficulties remain with the choice of I-129. The gamma line and three X-ray lines are closely spaced and will not be resolved by the CsI(Tl) scintillator; this will result in a non-Gaussian peak shape with a high tail. The I-129 peaks will be close to the LLD, further distorting the peak shape. While the low energy of the source photons will not produce significant Compton, the peaks in the energy spectrum will be on top of the Compton continuum resulting from the unknowns and the background, reducing signal-to-noise ratio. The gamma and X-ray energies are near the iodine edge for CsI(Tl) where the behavior of the scintillator is most non-linear, making the energy calibration more difficult. All of these factors will make it more difficult for the analysis software to accurately identify and quantify the I-129 peaks. The importance of these factors was difficult or impossible to quantify; it was decided to install an I-129 source in the probe and evaluate the performance in the field testing. The source would be installed in the end-on location relative to the scintillator. Based on the gamma and X-ray yields, source and scintillator geometries, self-absorption, end window absorption and peak-to-total ratio, an 11 nCi I-129 sealed source was selected. This source should produce a peak count rate of about 65 CPS, or about 12000 counts in a three minute count time.

### 4.2.6 Window Design and Material

The gamma window designed in Phase I was 0.27 cm (0.107 in) thick aluminum. This window needed to be redesigned to incorporate additional shielding to substantially eliminate low energy gammas and X-rays. This could be accomplished by increasing the thickness of the aluminum window, adding an additional shield layer inside the aluminum window or by a change in the window material. To minimize the energy of secondary X-rays, it was desirable for the window to be composed predominantly of light elements. The design goal was to provide sufficient attenuation so that at soil activity levels of 50 pCi/gram, the 25.6 keV gamma of Th-231 (U-235 decay) and the 50 keV gamma of Th-227 (Ac-227 decay) would not produce a count rate of more than 1% of the I-129 source count rate.

To accomplish this attenuation by increasing the thickness of the aluminum window would require a thickness of 0.95 centimeter (about 0.375"). Since the probe is 3.65 cm (1.4375 inch) OD and the scintillator is approximately 2.6 cm (1.024 inch) OD, only 1 cm (0.4 inch) is available on the diameter, 0.5 cm (0.2 inch) on the radius. Thus increasing the thickness of the aluminum window is not practical. If an additional shield layer of copper is added inside the aluminum window, the thickness required to produce the desired attenuation is about 0.23 cm (0.090 inch). The available space is marginally adequate for this approach, although tolerances would be very tight; an alternative would be to replace the aluminum window with a beryllium copper or aluminum bronze window 0.24 cm (0.093 inch) thick. These materials would provide the desired attenuation and have approximately the same mechanical strength as the original aluminum window, but would increase the cost of the probe.

Substituting an iron or steel window for the aluminum was therefore considered. The thickness required to obtain the desired attenuation was 0.36 cm (.142 in.), leaving an adequate 0.16 cm (0.065 in.) radial clearance between the window ID and the scintillator OD. If the window were fabricated from the steel normally used for CPT push rods (4130), the mechanical strength of the window would be adequate to sustain a push force of 20 tons. Type 4130 steel is predominantly iron, alloyed with chrome (Cr, Z=24), and molybdenum (Mo, Z=42). The Mo X-ray emission lines are at 17.4 keV (K-alpha) and 19.6 keV (K-beta), potentially a problem for secondary emission. However, Mo represents only about 0.2% of the alloy; the iron matrix can thus be expected to absorb more than 99% of all Mo X-rays produced, except those generated in the innermost layer 0.00003 cm (0.000013 in.) thick. All other secondary X-rays would be at energies of 7 keV or less. This was judged to be acceptable. The presence of the window will cause attenuation of the incident gamma at all energies; this attenuation amounts to 70% at 100 keV, 30% at 200 keV and about 20% at energies over 500 keV. This will have the effect of reducing the detector efficiency; this was judged to be acceptable because this reduction will be allowed for in the efficiency calibration. Some degradation of the signal-to-noise ratio can also be expected, as well as some increase in the backscatter.

Steel is likely to contain some radioactive contaminants, including K-40, U-238, Th-232, Co-60 and Cs-137. Specific data for 4130 steel could not be located, but typical values for other construction materials were reviewed. Using worst case activity levels and a window weight of 0.68 kg, the total activity of the contaminants might be as high as 108 pCi (4 DPS). For simplicity, it was assumed that every disintegration had a 100% yield, 50% passed through the detector volume, and 75% of these were absorbed. The resulting count rate would be approximately 1.5 CPS (90 CPM) divided between a minimum of three gamma lines. This was judged to be extremely conservative, and acceptable, so special low radioactivity materials were not required for the gamma window. A 4130 steel window, 0.36 cm (.142 in.) thick, was selected.

### 4.2.7 PMT Shielding

The major source of radiation effects in the PMT are from radioactive contaminants in the faceplate, afterpulses from ionization of residual gases in the PMT, and from cosmic radiation, as discussed in section 4.2.1. Ambient background radiation in the 0-2 MeV can also produce ionization of the residual gases (2-15 PEeq), but unless the gamma flux is very high, the addition to the background count rate from this effect is small compared to the faceplate contribution and does not require shielding for this application.

The cosmic ray contribution shows up at PEeq greater than 15; it results from Cerenkov radiation as the relativistic particles pass through the faceplate material. Other than a 511 MeV annihilation peak, the energy spectrum is smooth and decreases with increasing energy. For a horizontal photocathode, the effect is to have more occurrences, because of the greater projected area but smaller events, because of the shorter path length in the faceplate. The magnitude of the events is reduced in a borosilicate envelope, because of the relatively strong UV absorption of the faceplate material. The cosmic ray flux is composed of about 70% muons and 30% electrons and energetic gamma, at about 1 to 2 per minute-cm$^2$. The electrons and energetic gammas are lower energy and can be shielded out by about 10 cm (4 in.) of lead, cutting the flux roughly in half. The muons are much more energetic; even 100 cm (40 in.) of lead will still pass 25% of the total flux, and generate showers of secondary radiation. Because the expected count rate from this source is small (less than 10 CPM) and the difficulty and cost of effective shielding are large, no radiation shielding was added to the PMT housing.

### 4.2.8 Phase II As-Built Design

The modifications described above were incorporated into the design of the Phase II probe. The overall probe, as built, is shown in **Figure 4-2,** and details of the scintillator head, the extension sections and the detection head are shown in **Figures 4-3, 4-4** and **4-5** respectively. Most of the probe components were procured from commercial sources, using or based on existing products. The detector head housing, adaptor and component mounting hardware were custom parts, used to interface and house the commercial detection components and electronics; these were fabricated in-house.

**Figure 4-1: CsI(Tl) Spectral Emission Characteristics**

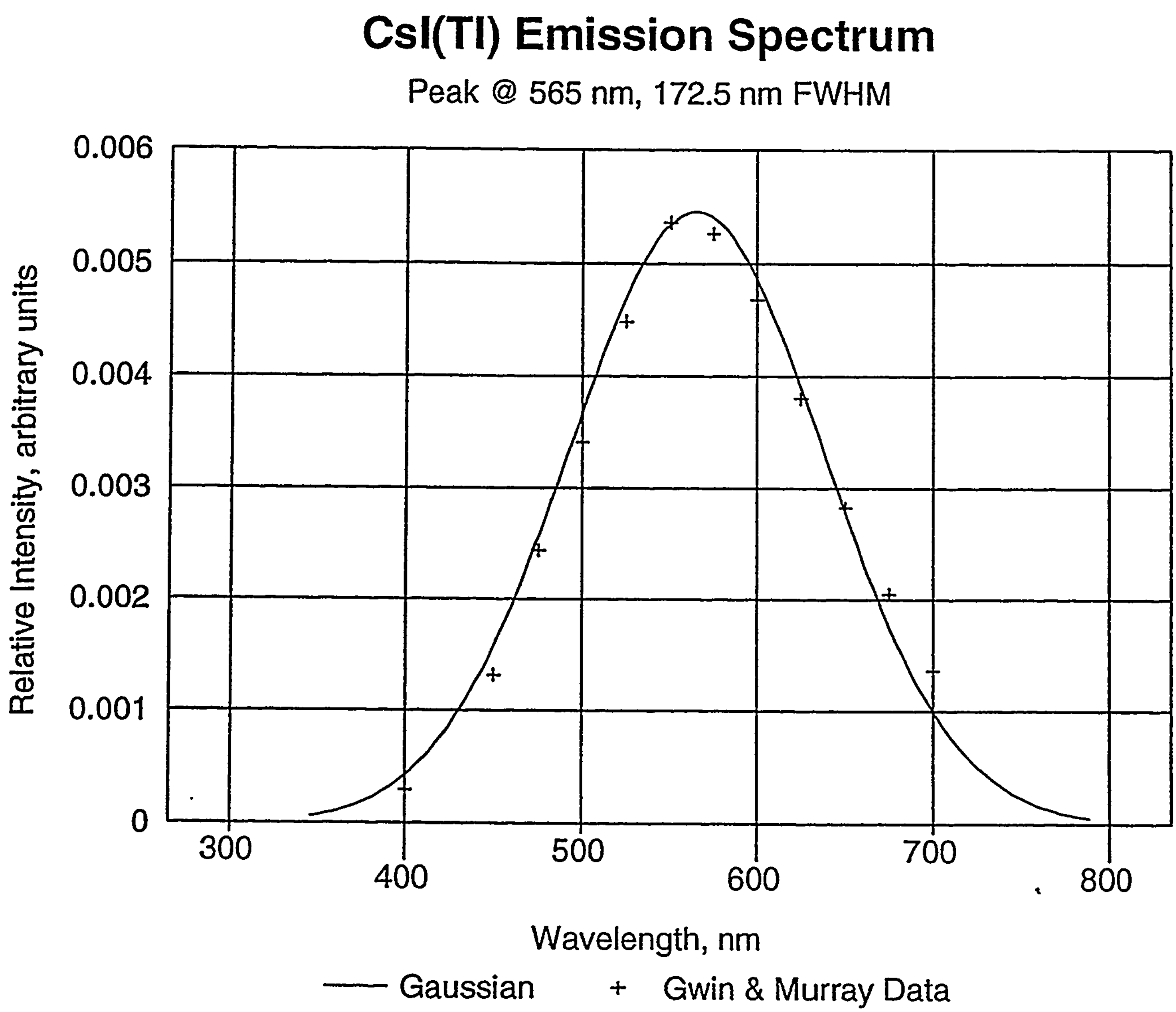


**Figure 4-2: Phase II Prototype Probe Design**

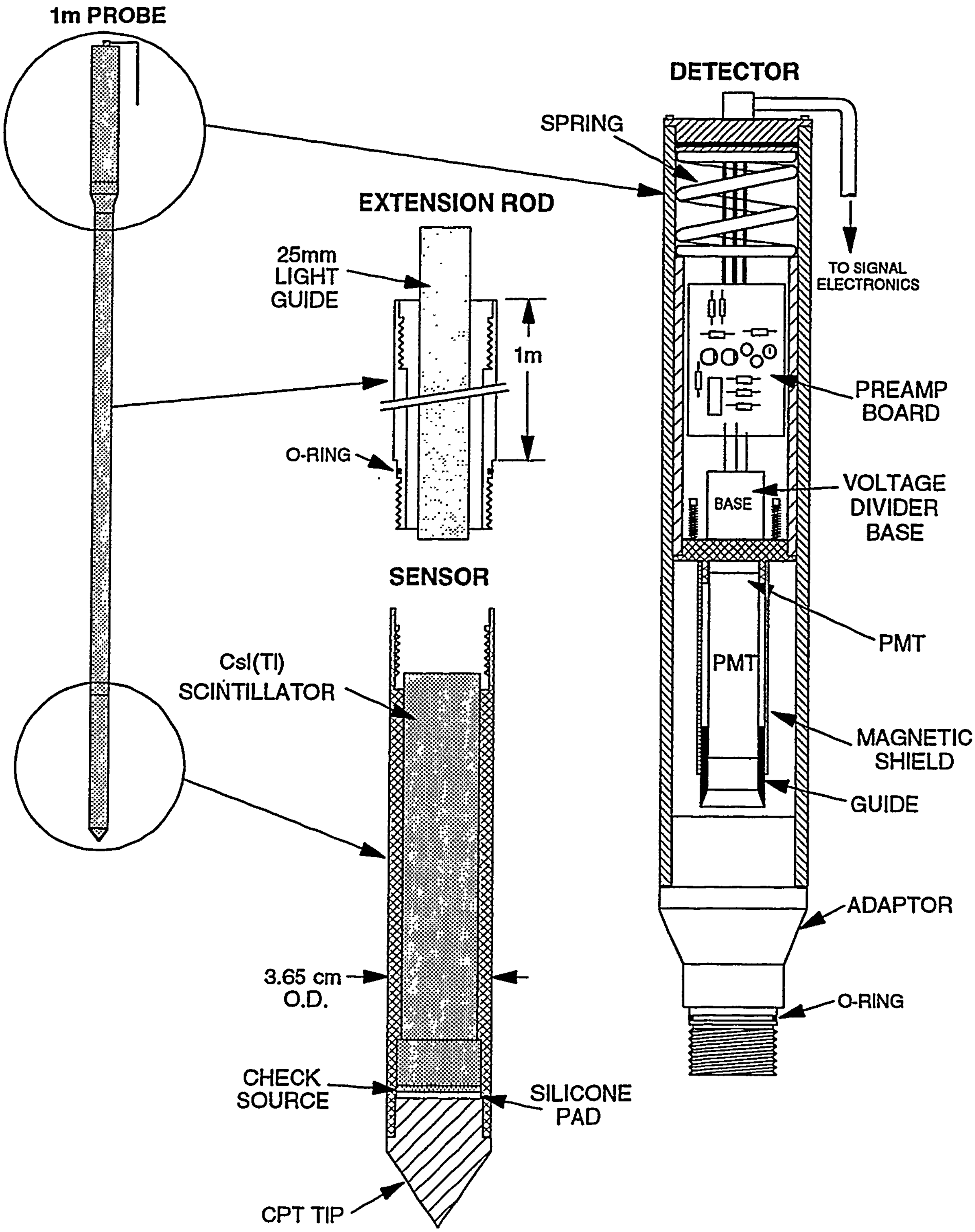


**Figure 4-3: Phase II Prototype Probe: Scintillation Head**

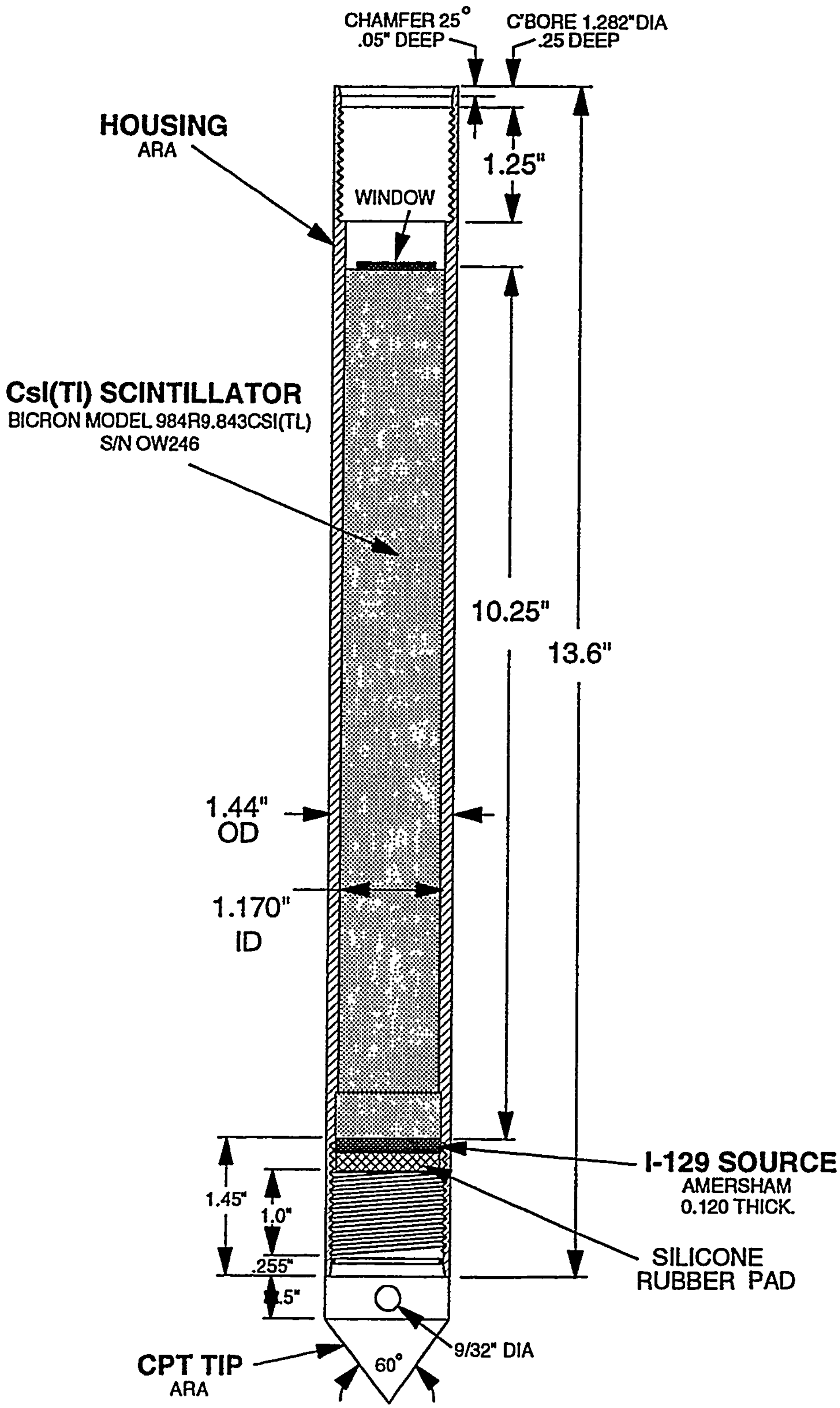


**Figure 4-4: Phase II Prototype Probe: Extension Sections**

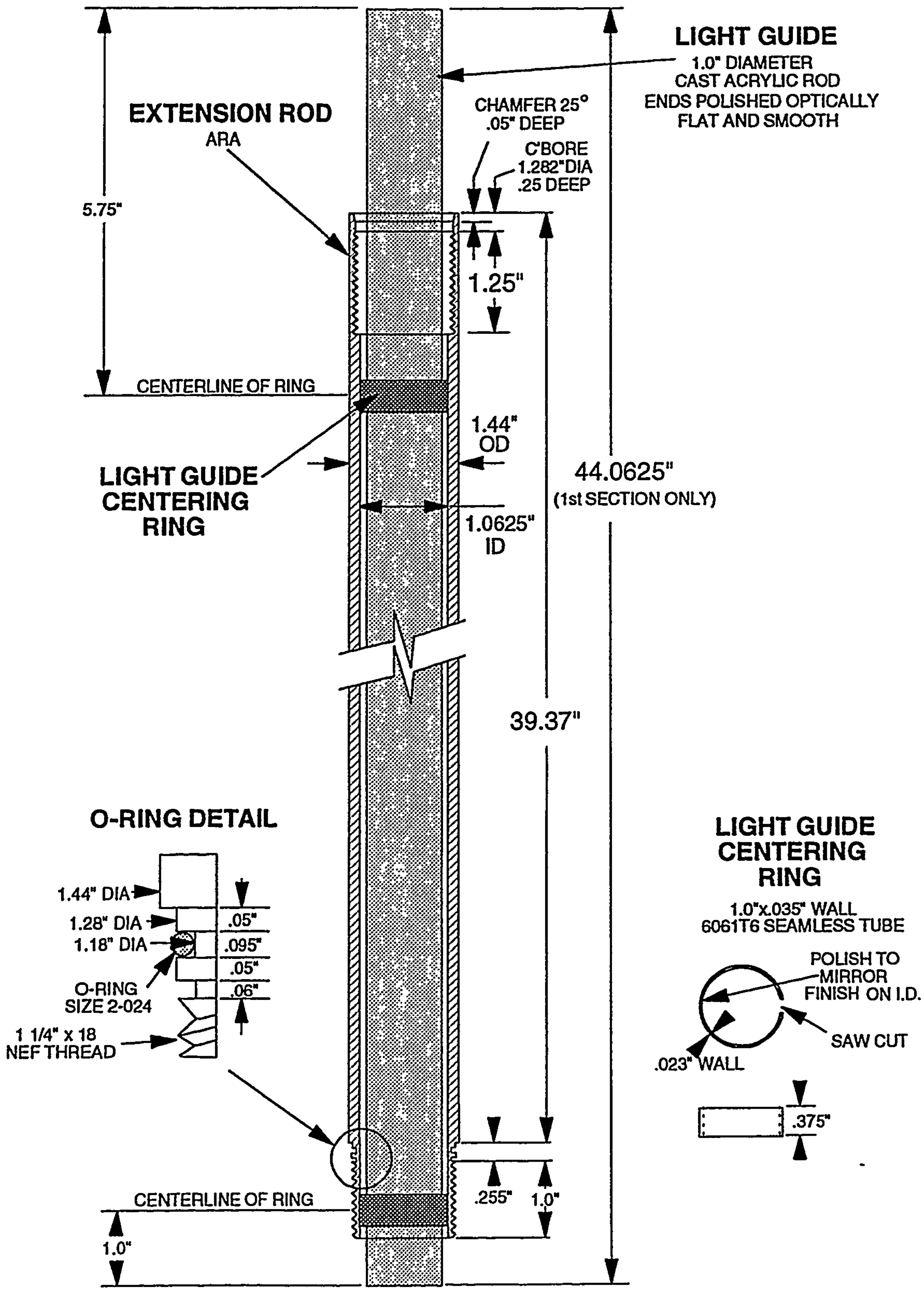
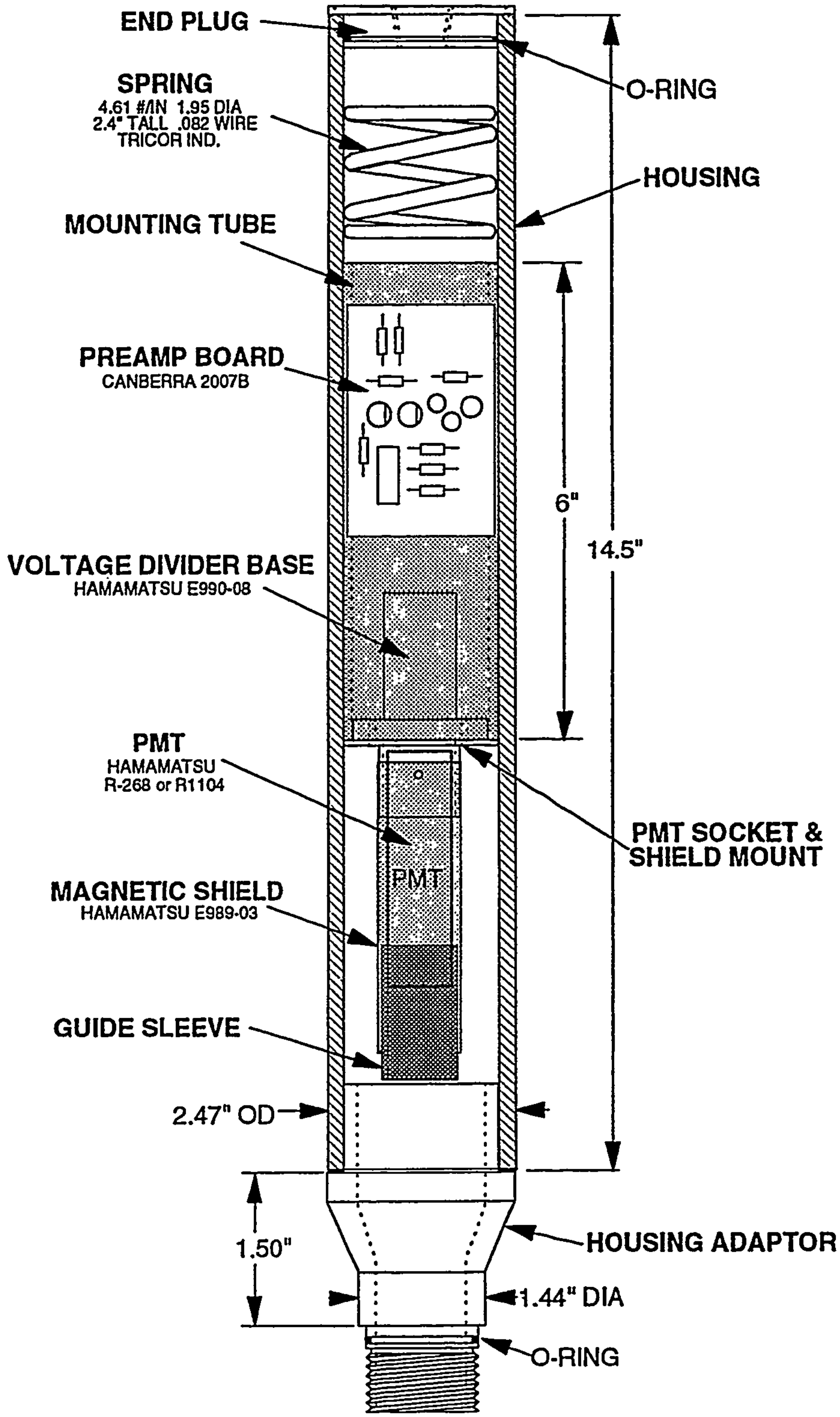


**Figure 4-5: Phase II Prototype Probe: Detection Head**



## 4.3 Probe Calibration

To make quantitative measurements, a gamma probe needs both an energy calibration and an efficiency calibration. In normal practice, a source with known isotopic content and activity, and the same geometry as the planned measurement geometry is positioned at the detector. The source is then counted for a fixed length of time. Because the isotopic content is known, the known energy lines can be used to perform the energy calibration. Because the activity levels are known and the geometry is the same as that to be measured, the efficiency calibration can also be readily performed. It was initially planned to use one of the uranium soil drums described in Section 5.3.1 to perform the efficiency calibrations for both probes, as described above. Prior to the start of testing, a review of the analyses for the soils indicated that there was too much uncertainty in the activities for these soils to permit them to be used as calibration sources. It was decided instead to calculate the efficiencies a priori, then compare the results to the approximately known analyses of the drummed soils.

### 4.3.1 Energy Calibration

For the demonstration tests, the probe will be used inside casings, completely surrounded by contaminated soil. Soil 30 cm or more away from the casing still contributes to the measured signal, as does soil above and below the probe. To duplicate the measurement geometry, the calibration source would need to be roughly the size of a 55 gallon drum (about 2 feet in diameter and about 3 feet high). This is not an available or practical calibration source geometry. Instead, the energy calibration was performed using an Amersham QCD.1 nine nuclide disc source, positioned at the center of the scintillator, side-on. This source provides 11 known energy lines which can easily be used to perform the energy calibration in the lab or field. It is not suitable for the efficiency calibration.

### 4.3.2 Efficiency Calibration

For the greatest accuracy in efficiencies calculations, the generally accepted approach is to model the geometry and determine the fate of individual photons with a Monte Carlo Neutron Photon (MCNP) analysis. For best results using this approach, a detailed knowledge of the probe and source geometries are needed, and generally an empirical verification as well. In the interest of saving time and money, we decided to calculate the efficiencies based on the soil model (spreadsheet) developed and used in Phase I of this program. (See Ref. 1, section 7 for more detail about this model.) Although this spreadsheet uses approximate methods for calculating attenuation and absorption of gamma radiation, we believed that it had sufficient detail for the calculation of peak efficiencies. The adequacy of this assumption would be checked by a comparison to the soil analyses of the test articles.

The detector efficiency as a function of energy was determined in several steps. First, the spreadsheet model of the soil, soil moisture, casing, detector can and scintillator absorption was used to determine the number of gammas absorbed within the scintillator volume for known uniform activity levels in the soil. The model also accounted for the scintillation efficiency of the scintillator, optical losses due to reflection and refraction in the scintillator and lightguide, and the PMT quantum efficiency to predict the count rate at the PMT anode for a given soil activity level. This provided a first approximation of the overall efficiency in the soil measurement geometry.

Second, the model geometry was modified to reflect the measurement geometry of an available clamshell type KUTh source, to provide an approximation of the overall efficiency in this geometry. The KUTh source is a commercially available source intended to duplicate the activities of K-40, U-238, and Th-232 in the API calibration pits in Houston; it is meant for field calibration of wireline logging tools in oil field applications (wireline logging). It is a hollow cylindrical source made in two halves, joined by a hinge on one side. It contains about 1 microCurie K-40, 0.23 microCurie natural uranium (U-238), and 0.17 microCurie natural thorium (Th-232), uniformly distributed in a polymeric matrix, inside a welded aluminum housing. The housing is about 13.5 inches long, 11 inches OD with a 4-

inch diameter bore for a probe.

A series of counts were then performed with the probe in the KUTh source using the efficiencies calculated for it, and the isotopic activities calculated. These were compared with the known activities of the isotopes in the KUTh source to generate correction factors (as a function of energy) for the calculated efficiency values. These correction factors were applied to both the KUTh efficiencies and the soil measurement efficiencies, on the assumption that because the efficiencies were calculated in the same manner that the same correction factors were needed for both. Tables of the efficiency vs energy were then stored in a computer file in the gamma spectrometer computer for use in later analysis; these efficiency values were used for the preliminary analysis of the field data.

Some of the tested soils in the field test (described in Section 5.3.1 below) had contamination levels that were reasonably well known, at least for the uranium isotopes. Data from these tests were analyzed and the predicted activities compared to the known activities. The analysis results consistently showed higher activity levels than the laboratory analyses indicating that the calculated efficiencies had been over-corrected by about 20%. The correction factors were then revised based on the field test data and the resulting efficiencies were used for all analyses.

### 4.3.3 Analysis Quantities

The energy and efficiency calibrations permit the system to identify nuclides and calculate their activities based on a library of gamma lines and yields. To calculate nuclide activities in terms of pCi/gram, the analysis quantity in grams must be known. In a counting lab, the quantity of small samples can be readily measured; in the field it cannot. Like any scintillation detector, the probe integrates counts over some sample volume; each portion of the volume contributes to the total count, but all portions do not contribute equally. For example, portions of the sample which are at large radii or steep angles relative to the scintillator contribute little to the count because they are shielded by intervening soil. To determine the sample quantities for analysis, we calculated an effective radius (30 cm) and effective view angles (±30 deg) for the probe beyond which the contribution of additional sample material is minimal. Based on these effective dimensions, we calculated the active sample volume for the probe in cubic centimeters. This volume is multiplied by the sample density to determine the analysis quantity.

For the drummed soil samples, the density could be determined reasonably accurately from the net weight and fill height. For water samples, the density was assumed to be 1 gram/cc. For the in situ measurements, the soil density was unknown and realistically, probably varied with depth. For the monitoring well (1441) in the sewage treatment plant and one of the Southfield borings (11406), the soil density was assumed to be 1.75 grams/cc. For the other Southfield boring (11423), the density was assumed to be 1.6 grams/cc; the soil at this location seemed less dense at the surface and was believed to incorporate more ash.

## 4.4 B&W Survey Tool

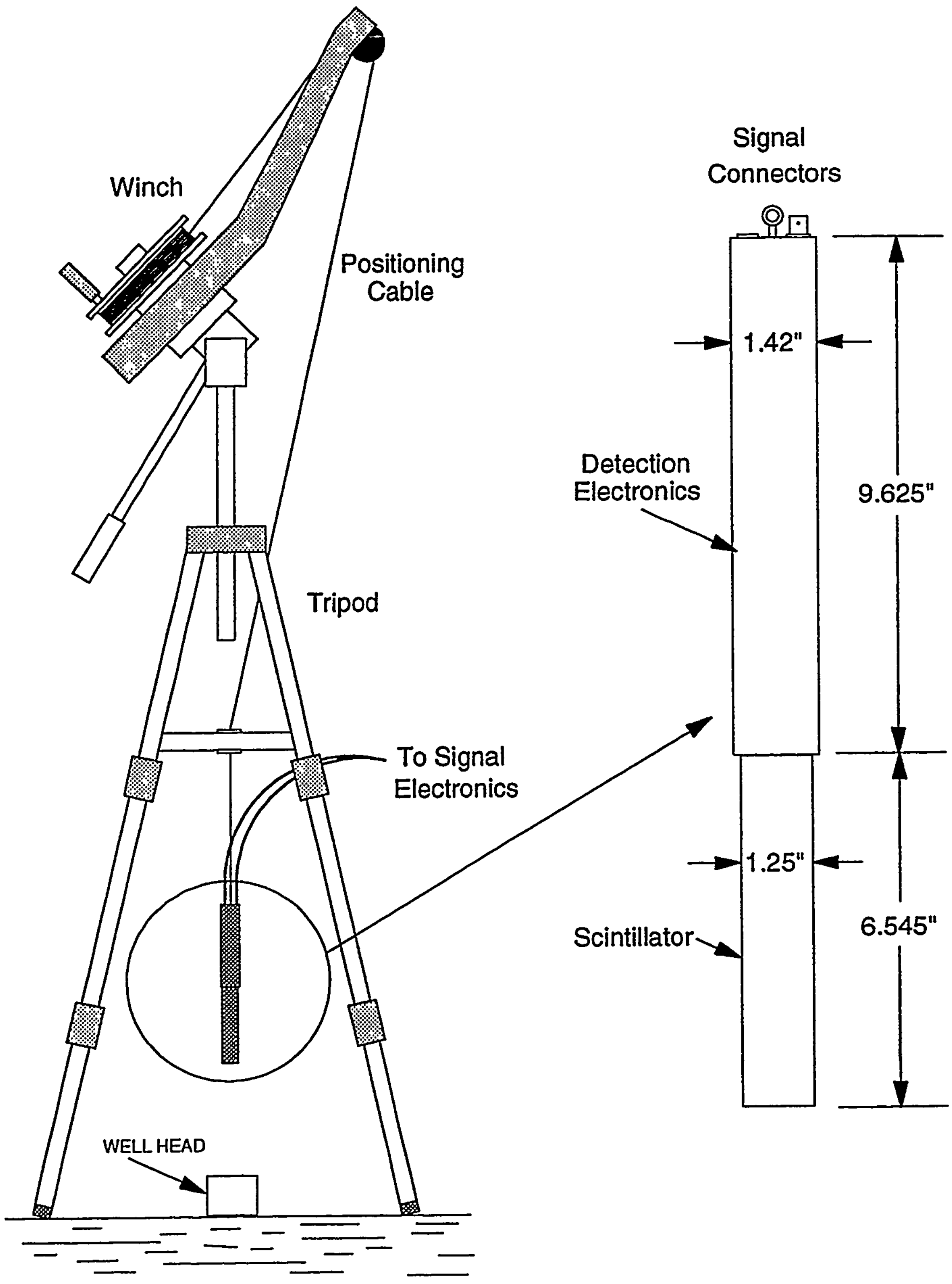
Tests were also performed using a gamma radiation B&W Survey Probe being developed by B&W. This probe, shown in **Figure 4-6**, is intended for radiation survey applications during site characterization and remediation. The probe is 1.42 inches (3.6 cm) diameter by approximately 16 inches (40 cm) long. It is designed to be lowered into a 1.5 inch diameter or larger casing on a wireline (logging mode) from a light tripod using a small hand winch. The probe contains a 1 inch (2.54 cm) diameter by 6 inch (15.3 cm) NaI(Tl) scintillator directly butt-coupled to a bialkali PMT with optical grease. The probe also contains magnetic shielding for the PMT, the voltage divider and a Cockroft-Walton high voltage power supply within a potted housing for moisture and shock resistance.

## 4.5 Gamma Spectrometer

The equipment which was used to acquire data from the two probes consists of a personal computer (PC), a monitor, a keyboard, a mouse and a printer. Power conditioning equipment, such as a constant voltage transformer and a surge suppressor, were used. The data was acquired, analyzed, stored and printed using a commercially available PC-based two channel gamma spectrometer system. The system, manufactured by Canberra Nuclear, is comprised of two acquisition interface boards (NaI+) installed in a Gateway 486-66 PC plus gamma spectroscopy software (GENIE-PC) to provide the functions of a hardware-based MCA (multi-channel analyzer). The interface boards provide a pre-amp DC power supply, an integrated HV power supply, data amplifier and a 100 MHz Wilkinson ADC (analog to digital converter).

The functions and settings of the interface board hardware are controlled from the software through a window-style graphical user interface. The software operates under an OS-2 operating system and is a true multitasking architecture; the system can thus support simultaneous and fully independent counting and analysis procedures on the two channels. In addition to hardware control, MCA control and basic gamma spectroscopy functions (such as continuum correction and peak searches), the software also performs energy and efficiency calibrations, background subtractions, nuclide identification (interference corrected), spectrum scaling or gain stabilization, calculates weighted mean activity for the nuclides detected and the MDA (minimum detectable activity) for any specified nuclide which is not located in the spectral data. The data from a count procedure is stored in a single extensible file (a Configuration Access Method or "CAM" file) which contains the spectral data, calibration information, analysis parameters, intermediate and final analysis results, setup parameters and the complete analysis library used. The selected results, including the energy spectrum if desired, of the analysis are then output in a user specified report format to a printer (Hewlett Packard Laserjet).

**Figure 4-6: B&W Survey Tool**



## 5.0 Field Demonstration Test

The purpose of the Phase II site testing was to obtain field data in contaminated soils to:

- benchmark the probe and system design methods used,
- quantify the system performance for precision, resolution and accuracy,
- provide information and field experience needed to design with a high degree of confidence the Phase III system for applicability to a variety of DOE sites.

To accomplish this purpose, four weeks of on-site field testing were planned and performed at the Fernald Environmental Management Project (FEMP) site at Fernald, Ohio, selected in Phase I. This site is a U.S. DOE site in southwestern Ohio, approximately 17 miles from Cincinnati. Uranium isotopes are the primary contaminants of concern at this site, resulting from about 35 years of processing of uranium ore concentrates into high purity uranium metal. The tests were performed between October 23 and November 17, 1994.

A detailed description of the planned tests, test articles, test requirements, site requirements and compliance documents can be found in the test plan prepared for this testing: *Demonstration Test Plan for Technology Development Project Demonstration - Development of a Long-Term Post-Closure Radiation Monitor,* contract DE-AC21-92MC29103, Revision 1, September 20, 1994. [Ref. 2]

### 5.1 Site Demonstration Scope

Two types of tests were performed: tests using drummed samples with known contamination levels and in-situ (sub-surface) tests in cased boreholes at three locations at depths up to four meters. The drummed sample tests included the following types of samples:

- Homogenized soils from the USID program: eight samples with predominantly uranium contamination at known activities from 50 to about 1750 pCi/gram (three duplicates), plus one sample of clean water which was percolated into and retained in one of the samples of contaminated soil for testing;

- Water: three samples with predominantly uranium contamination at known activities from the South plume pumping station, from the storm water retention basin and from the bio-denitrification facility;

- Sand matrix/water: one sample of sand matrix at background, plus one sample of water at a known activity level, which was percolated into and retained in the sand/gravel matrix for testing.

The in-situ tests were performed at three locations; one in an existing monitoring well, and two in boreholes available from the Cone Penetrometer Demonstration (CPD) test program which were subsequently cased with PVC.

The tests of the drummed homogenized soils (natural moisture and saturated) and the in-situ tests were of central importance to achieving the overall objectives of this development program. The overall success of the test program was judged on the basis of meeting the success criteria for each of these tests. The tests of drummed water and the sand matrix water tests were important for determining the applicability of the system being developed to additional measurement needs beyond the scope of the program. The success of these tests were judged on an individual basis.

## 5.2 Overall Test Sequence

The test sequence was based on performing the most important tests earliest in the sequence and on availability of test articles at the time of testing. The following test sequence was used:

- Homogenized soil tests (natural moisture): four drummed samples with 1-1/2" casing, tests performed indoors in Plant 8;

- In-situ test; existing monitoring well (1441): tests performed outdoors in the Sewage Treatment Plant (STP);

- Homogenized soil tests (natural moisture): three drummed samples with 2" casing, tests performed outdoors in the Southfield;

- In-situ tests: temporary boring 11406, 1-1/2" PVC by 2 meter depth, tests performed outdoors in the Southfield;

- In-situ tests: temporary boring 11423, 1-1/2" PVC by 4 meter depth, tests performed outdoors in the Southfield;

- Drummed water tests: three samples from the South Plume, Storm Water Retention Basin (SWRB) and bio-d tests performed in the SWRB valve house (indoors), on the north side of the SWRB (outdoors) and in the bio-d facility (indoors);

- Sand matrix/water tests: one sample of clean sand tested at natural moisture and saturated with water from bio-d influent, tests performed indoors in the bio-d facility;

- Homogenized soil test (natural and saturated): one drummed sample tested at natural moisture and saturated with clean water, tests performed outdoors on the Plant 8 apron (west side).

## 5.3 Test Specimens and Conditions

The test specimens for the drum tests of soils and waters, and the in-situ soils tests are described in detail below, with laboratory analysis data used for comparisons. All laboratory results have been supplied to B&W by FERMCO personnel.

### 5.3.1 Drummed Soils

The test specimens for the drummed soils tests consisted of eight 55 gallon drums of characterized soils from the USID with five different activity levels; the nominal activity levels of the soils are listed in the table below.

**Soils Samples for Drummed Soils Tests**

| Sample | Drum ID | Activity (pCi/gram) | Test ID |
|---|---|---|---|
| CP | F-392 | 51 | 1B |
| C-35 | C-389 | 95 (two drums) | 1D & 1F |
| C-100 | D-389 | 146 (two drums) | 1C & 1G |
| C-200 | E-388 | 311 (two drums) | 1E & 1H |
| --- | P011-0380 | > 1000 | 2A & 2B |

For each of the first 4 test specimens listed above, sufficient soil to fill the drums was taken from larger boxes of soil which had previously been sampled and analyzed for uranium isotopes. The analysis method used for these analyses was mass spectroscopy at Analytical Standards Level "B" (ASL B), typical of samples taken for remediation purposes. These laboratory analysis results, provided by FERMCO, have been used for the comparisons contained in this report; no analyses of the drummed soils were performed as part of this test program. The analysis results, shown in **Figure 5-1**, show considerable spread over the sampling locations within the box. The procedure used to extract the soils from the boxes and fill the drums is unknown; the analysis results thus provide only a general indication of the isotopic uranium activity of the drummed soils, not their actual content. It is believed that sample P011-0380 was taken from a similar box; we were told that this soil had been characterized with a single grab sample and showed total uranium activity greater than 1000 pCi/g; no other analysis results are available for comparison purposes.

Two additional drums were prepared: one contained an uncontaminated sand matrix, wet but not saturated, the other was used for the three water tests.

For the natural moisture tests, steel drums and lids were used. The test drum configuration for the natural moisture soils tests is shown in **Figure 5-2**; for five of the drums, a one meter section of schedule 80 PVC (1.5" ID x 1.9" OD) well casing extended from the bottom of the drum through a hole in the lid, sealed with caulk. For the other three drums (the duplicates), the casing was 2 inch schedule 80 PVC. In all drums, the bottom of the casing was capped off, the top was left open for insertion of the measuring probe. The casing was positioned radially approximately on the drum centerline.

For the tests with saturated soil or sand, and the water tests, plastic drums were used instead. The plastic test drum configuration is shown in **Figure 5-3.** Drums of this type were used for the natural moisture/saturated soil tests (2A & 2B), the sand matrix/water and the water tests. A one meter section of schedule 80 PVC (1.5" ID x 1.9" OD) well casing extends from the bottom of the drum through a hole in the lid; for the drums containing soil or sand, this was sealed with caulk, while for the water drum, it was unsealed. The bottom of the casing was capped off, the top was left open for insertion of the measuring probe. The casing was positioned radially approximately on the drum centerline. Bungs were provided in the lids and in the lower side of the drums (with valves) to fill and drain the drum.

### 5.3.2 Monitoring Well 1441 (STP)

Well 1441 is a groundwater monitoring well cased with 2 inch schedule 40 PVC, installed in 1989. The well is located in the STP at 480091.99 north and 1383021.42 east (Ohio State Planar Coordinates - OSPC). The borehole diameter was 8 inches. The completion (see **Figure 5-4**) includes a concrete cap to 6 inches below grade; a 4.5 foot bentonite seal extending to 5 feet below grade; a 13 foot sand pack extending to a Total Depth (TD) of 19 feet and a steel protective well cover which extends 2.2 feet below grade. Soil sampling was performed using a split-spoon auger for soils classification and identification of radionuclide contaminants when the well was installed. This analysis showed approximately 28 pCi/g U-238 and 4 pCi/g U-235 in the 0-6" soil interval, with significantly lower levels at the 24-30" and 60-66" intervals. Other nuclides identified in the analysis included thorium and radium isotopes, and detectable levels of cesium 137 (Cs-137), strontium 90 (Sr-90) and technetium 99 (Tc-99). It is believed that a removal action involving the 0-6" interval has been performed since the well was installed, thus the current near-surface activity levels at this well location are unknown.

### 5.3.3 Southfield Borings 11406 and 11423

Tests were performed in two temporary borings in the Southfield area, designated 11406 and 11423. Boring 11406 was located at OSPC 477907.67 North and (1)379223.26 East; Boring 11423 was located at OSPC 478030.57 North and (1)378980.09 East, assuming that the leading "1" in both eastings was inadvertently deleted from the data provided. These borings, were cased with 1-1/2 inch schedule 80 PVC; 11406 extended to just under 2 meters below grade, while 11423 extended to about 3.5 meters below grade. No procedures for the installation of these borings is available. It is our understanding that these borings were installed during the Cone Penetrometry Demonstration (CPD), as follows: a soil sampler was first used at each location to extract soil cores for laboratory analysis. The soil sampler was removed, and the WES radiation probe was then inserted into the same borehole to measure the radiation levels in-situ. The borehole was grouted to within a short distance of the surface while retracting the WES probe, using its integral grout ports. The PVC was then pushed into the grouted hole, to TD. The uranium isotopic activity results provided by FEMP are listed in the table below.

**Southfield Borings: Uranium Activity vs Depth Below Grade**

| Boring | Depth | Total U ppm | Total U pCi/g | U-234 pCi/g | U-235 pCi/g | U-236 pCi/g | U-238 pCi/g |
|---|---|---|---|---|---|---|---|
| 11406 | 0'6" | 41 | 29.82 | 15.52 | 0.615 | <.032 | 13.687 |
| | 1'6" | 120 | 87.63 | 45.55 | 1.816 | 0.205 | 40.055 |
| | 3'6" | 67 | 47.05 | 23.71 | 0.968 | <.032 | 22.372 |
| 11423 | 0'6" | 9 | 8.9 | 5.65 | 0.145 | 0.105 | 3.002 |
| | 1'6" | 13 | 0.45 | ND | 0.014 | <.032 | 0.435 |
| | 3'6" | 11 | 3.81 | ND | 0.047 | <.032 | 3.667 |
| | 6'6" | 3 | 1.05 | ND | 0.046 | <.032 | 1.001 |
| | 9'6" | 230 | 154.52 | 74.39 | 3.148 | 0.164 | 76.825 |
| | 12'6" | 3 | 1.04 | ND | 0.037 | <.032 | 1.003 |

### 5.3.4 Water Samples

The water samples for probe testing were from the South Plume, the Storm Water Retention Basin and from the bio-denitrification facility, in that order. All of the samples were drawn from influent lines, i.e. pre-treatment. Because the activity of these waters changes relatively slowly and they are routinely analyzed daily, no laboratory analysis of the drawn samples was performed. The activity for comparison was determined from the routine analyses prior and subsequent to the time the sample was drawn. The routine analyses provided only total uranium concentration; no typical isotopic ratios for these waters have been located. For the comparisons in this report, it has been assumed that the isotopic ratios are similar to those in FEMP soils, permitting the isotopic activities for U-235 and U-238 to be calculated from total U, by using their specific activities. It was assumed that 99.5% of the total uranium concentration is comprised of U-238, and that the activity of U-235 is 5% of the activity of the U-238. The South Plume analysis was reported in micrograms/liter (ppb); the analyses of the SWRB and bio-d waters were reported without units. It is assumed that the units for the SWRB analyses are ug/l (ppb) and for the bio-d analyses are mg/l (ppm). The average concentration values reported and the calculated activities are shown in the table below.

| Sample | Reported Concentration | Calculated Activities, pCi/g U-235 | U-238 |
|---|---|---|---|
| South Plume | 9.45 ug/liter | 0.00016 | 0.0032 |
| SWRB | 450.7 | 0.0076 | 0.151 |
| Bio-d | 2 | 0.034 | 0.67 |

## Figure 5-1 Laboratory Analysis of USID Soils

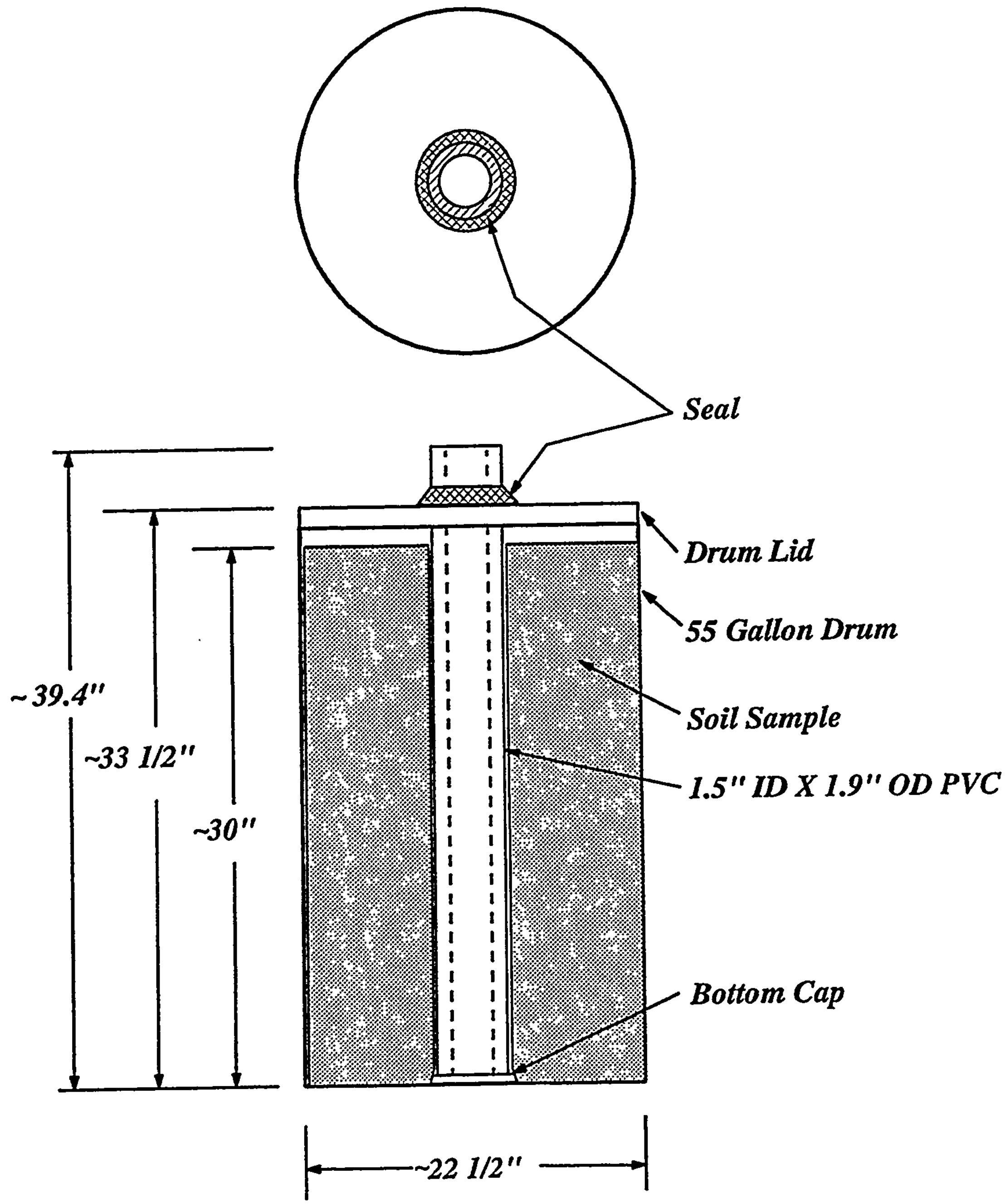
| Box C35 | Measured Isotopic Values pCi/gram | | | | | Calculated Isotopic Ratios | | | Box C35 Uranium Concentrations, ppm | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | U-234 | U-235 | U-236 | U-238 | U-Total | U234/8 | U235/8 | U236/8 | U-234 | U-235 | U-236 | U-238 | U-Total |
| NE | 47.59 | 2.06 | 0.62 | 47.06 | 97.33 | 1.0113 | 0.0438 | 0.0132 | 0.008 | 0.953 | 0.010 | 140.39 | 141.36 |
| NW | 46.22 | 1.98 | 0.60 | 44.04 | 92.84 | 1.0495 | 0.0450 | 0.0136 | 0.007 | 0.916 | 0.009 | 131.38 | 132.32 |
| SE | 46.35 | 1.98 | 0.62 | 43.70 | 92.65 | 1.0606 | 0.0453 | 0.0142 | 0.007 | 0.916 | 0.010 | 130.37 | 131.30 |
| SW | 41.25 | 1.77 | 0.56 | 40.68 | 84.26 | 1.0140 | 0.0435 | 0.0138 | 0.007 | 0.819 | 0.009 | 121.36 | 122.19 |
| C1 | 51.74 | 2.28 | 0.67 | 40.42 | 95.11 | 1.2801 | 0.0564 | 0.0166 | 0.008 | 1.055 | 0.010 | 120.58 | 121.66 |
| C2 | 47.46 | 2.11 | 0.62 | 47.06 | 97.25 | 1.0085 | 0.0448 | 0.0132 | 0.008 | 0.976 | 0.010 | 140.39 | 141.39 |
| C3 | 44.48 | 1.95 | 0.59 | 43.70 | 90.72 | 1.0178 | 0.0446 | 0.0135 | 0.007 | 0.902 | 0.009 | 130.37 | 131.29 |
| SE-A | 52.99 | 2.27 | 0.70 | 50.43 | 106.39 | 1.0508 | 0.0450 | 0.0139 | 0.008 | 1.050 | 0.011 | 150.45 | 151.52 |
| Average = | 47.260 | 2.050 | 0.623 | 44.636 | 94.569 | 1.062 | 0.046 | 0.014 | | | | | 134.128 |
| Std Dev = | 3.514 | 0.159 | 0.041 | 3.179 | 5.944 | 0.085 | 0.004 | 0.001 | | | | | 9.517 |
| SD/Avg = | 0.0744 | 0.0777 | 0.0666 | 0.0712 | 0.0628 | 0.0799 | 0.0859 | 0.0737 | | | | | 0.071 |

| Box C100 | Measured Isotopic Values pCi/gram | | | | | Calculated Isotopic Ratios | | | Box C100 Uranium Concentrations, ppm | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | U-234 | U-235 | U-236 | U-238 | U-Total | U234/8 | U235/8 | U236/8 | U-234 | U-235 | U-236 | U-238 | U-Total |
| NE | 70.07 | 3.11 | 0.88 | 70.60 | 144.66 | 0.9925 | 0.0441 | 0.0125 | 0.011 | 1.438 | 0.014 | 210.62 | 212.08 |
| NW | 75.52 | 3.29 | 0.94 | 73.96 | 153.71 | 1.0211 | 0.0445 | 0.0127 | 0.012 | 1.522 | 0.014 | 220.64 | 222.19 |
| SE | 161.42 | 7.08 | 2.06 | 158.00 | 328.56 | 1.0216 | 0.0448 | 0.0130 | 0.026 | 3.275 | 0.032 | 471.36 | 474.69 |
| SW | 77.06 | 3.41 | 0.99 | 77.32 | 158.78 | 0.9966 | 0.0441 | 0.0128 | 0.012 | 1.577 | 0.015 | 230.67 | 232.27 |
| C1 | 67.73 | 2.99 | 0.85 | 63.87 | 135.44 | 1.0604 | 0.0468 | 0.0133 | 0.011 | 1.383 | 0.013 | 190.54 | 191.95 |
| C2 | 47.97 | 2.09 | 0.60 | 60.51 | 111.17 | 0.7928 | 0.0345 | 0.0099 | 0.008 | 0.967 | 0.009 | 180.52 | 181.50 |
| C3 | 49.97 | 2.19 | 0.64 | 50.43 | 103.23 | 0.9909 | 0.0434 | 0.0127 | 0.008 | 1.013 | 0.010 | 150.45 | 151.48 |
| Average = | 78.534 | 3.451 | 0.994 | 79.241 | 162.221 | 0.982 | 0.043 | 0.012 | | | | | 238.025 |
| Std Dev = | 35.496 | 1.557 | 0.456 | 33.223 | 70.574 | 0.081 | 0.004 | 0.001 | | | | | 99.840 |
| SD/Avg = | 0.4520 | 0.4511 | 0.4583 | 0.4193 | 0.4350 | 0.0820 | 0.0848 | 0.0847 | | | | | 0.419 |

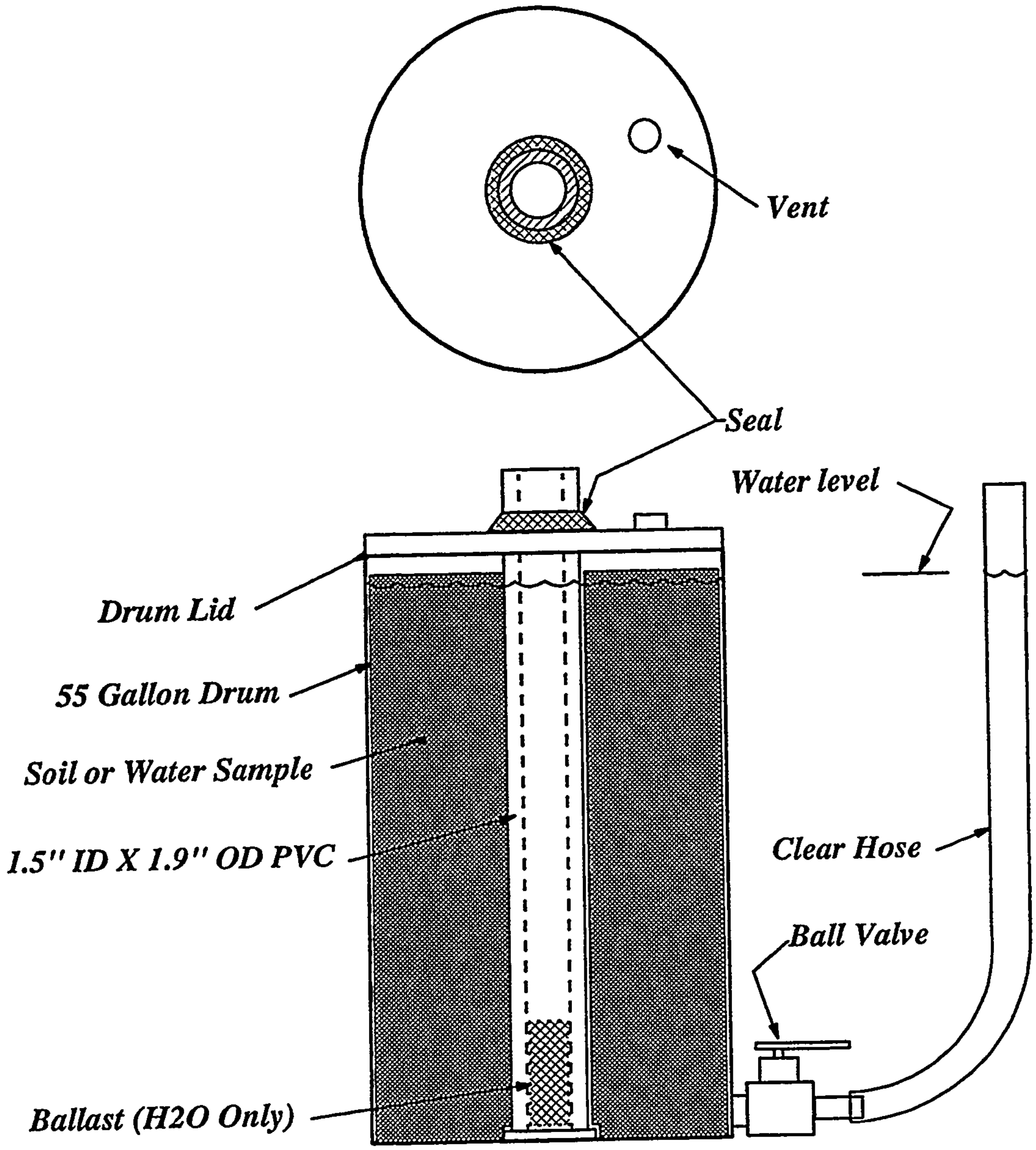
| Box C200 | Measured Isotopic Values pCi/gram | | | | | Calculated Isotopic Ratios | | | Box C200 Uranium Concentrations, ppm | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | U-234 | U-235 | U-236 | U-238 | U-Total | U234/8 | U235/8 | U236/8 | U-234 | U-235 | U-236 | U-238 | U-Total |
| NE | 148.97 | 6.84 | 1.83 | 154.64 | 312.28 | 0.9633 | 0.0442 | 0.0118 | 0.024 | 3.164 | 0.028 | 461.34 | 464.55 |
| NW | 146.80 | 6.59 | 1.75 | 147.92 | 303.06 | 0.9924 | 0.0446 | 0.0118 | 0.024 | 3.048 | 0.027 | 441.29 | 444.39 |
| SE | 160.52 | 7.15 | 2.01 | 161.36 | 331.04 | 0.9948 | 0.0443 | 0.0125 | 0.026 | 3.307 | 0.031 | 481.38 | 484.75 |
| SW | 181.71 | 8.25 | 2.20 | 188.26 | 380.42 | 0.9652 | 0.0438 | 0.0117 | 0.029 | 3.816 | 0.034 | 561.63 | 565.51 |
| C1 | 138.11 | 6.26 | 1.65 | 141.19 | 287.21 | 0.9782 | 0.0443 | 0.0117 | 0.022 | 2.895 | 0.025 | 421.21 | 424.15 |
| C2 | 106.40 | 4.85 | 1.31 | 137.83 | 250.39 | 0.7720 | 0.0352 | 0.0095 | 0.017 | 2.243 | 0.020 | 411.19 | 413.47 |
| C3 | 151.28 | 6.91 | 1.89 | 158.00 | 318.08 | 0.9575 | 0.0437 | 0.0120 | 0.024 | 3.196 | 0.029 | 471.36 | 474.61 |
| Average = | 147.684 | 6.693 | 1.806 | 155.600 | 311.783 | 0.946 | 0.043 | 0.012 | | | | | 467.348 |
| Std Dev = | 21.159 | 0.948 | 0.261 | 15.533 | 36.976 | 0.072 | 0.003 | 0.001 | | | | | 46.745 |
| SD/Avg = | 0.1433 | 0.1417 | 0.1447 | 0.0998 | 0.1186 | 0.0765 | 0.0735 | 0.0757 | | | | | 0.100 |

| Box CP | Measured Isotopic Values pCi/gram | | | | | Calculated Isotopic Ratios | | | Box CP Uranium Concentrations, ppm | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | U-234 | U-235 | U-236 | U-238 | U-Total | U234/8 | U235/8 | U236/8 | U-234 | U-235 | U-236 | U-238 | U-Total |
| NE | 40.54 | 1.66 | 0.48 | 36.98 | 79.66 | 1.0963 | 0.0449 | 0.0128 | 0.006 | 0.768 | 0.007 | 110.322 | 111.104 |
| NW | 14.39 | 0.50 | 0.17 | 11.09 | 26.15 | 1.2976 | 0.0449 | 0.0155 | 0.002 | 0.230 | 0.003 | 33.085 | 33.320 |
| SE | 22.52 | 0.63 | 0.26 | 13.45 | 36.86 | 1.6743 | 0.0468 | 0.0196 | 0.004 | 0.291 | 0.004 | 40.125 | 40.424 |
| SW | 24.47 | 0.83 | 0.29 | 17.82 | 43.41 | 1.3732 | 0.0467 | 0.0163 | 0.004 | 0.385 | 0.004 | 53.162 | 53.556 |
| C1 | 38.57 | 1.34 | 0.46 | 29.58 | 69.95 | 1.3039 | 0.0453 | 0.0154 | 0.006 | 0.620 | 0.007 | 88.246 | 88.879 |
| C2 | 29.60 | 1.01 | 0.34 | 21.85 | 52.80 | 1.3547 | 0.0462 | 0.0157 | 0.005 | 0.467 | 0.005 | 65.185 | 65.662 |
| C3 | 26.18 | 0.49 | 0.32 | 21.85 | 48.84 | 1.1982 | 0.0224 | 0.0146 | 0.004 | 0.226 | 0.005 | 65.185 | 65.420 |
| Average = | 28.039 | 0.923 | 0.331 | 21.803 | 51.095 | 1.328 | 0.042 | 0.016 | | | | | 65.481 |
| Std Dev = | 8.473 | 0.412 | 0.099 | 8.377 | 17.167 | 0.167 | 0.008 | 0.002 | | | | | 25.166 |
| SD/Avg = | 0.3022 | 0.4466 | 0.2984 | 0.3842 | 0.3360 | 0.1256 | 0.1938 | 0.1199 | | | | | 0.384 |

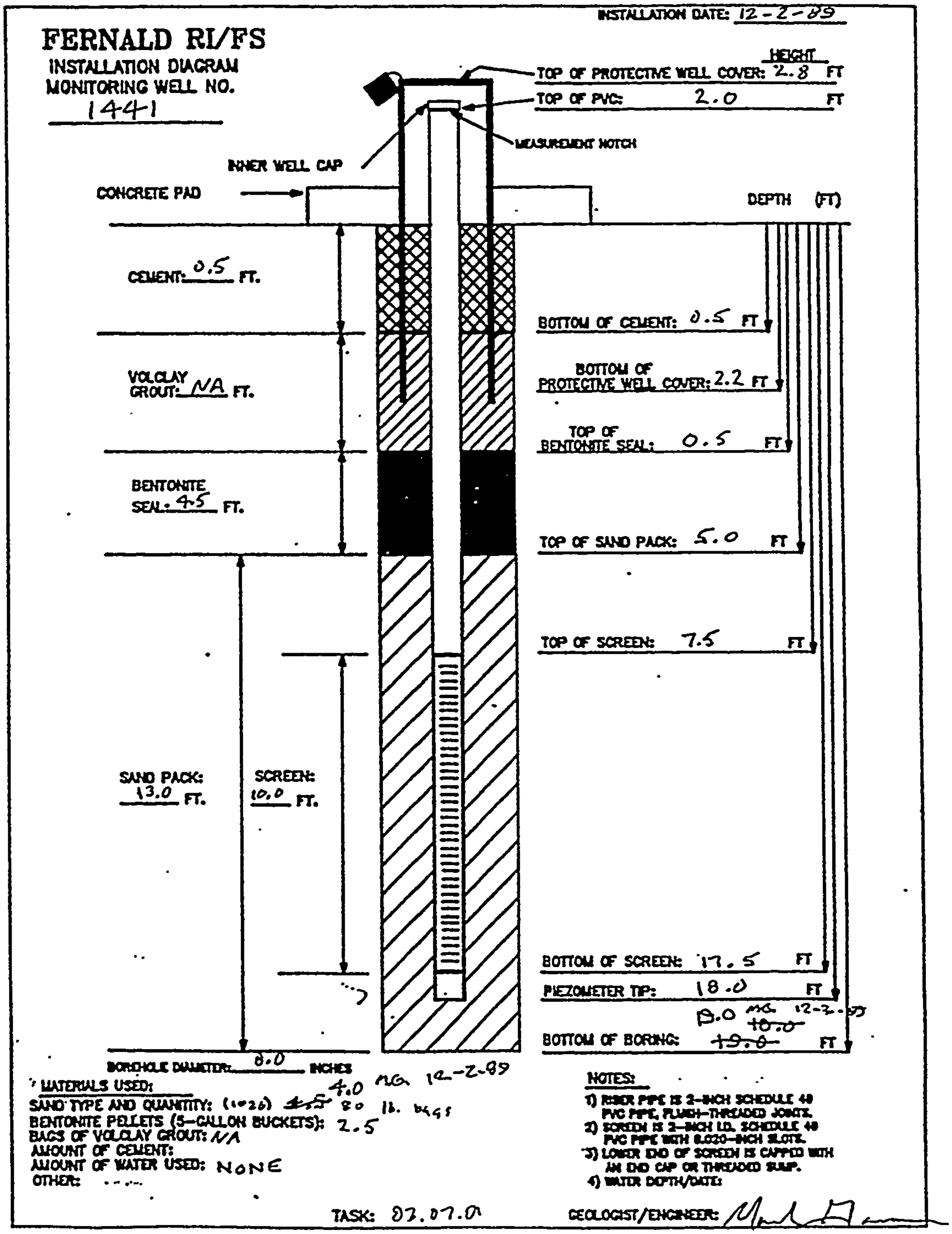
**Figure 5-2 Test Drum for Natural Moisture Soils**



## Figure 5-3 Test Drum for Saturated Soils and Water



## Figure 5-4 Well 1441 (STP) Completion



## 6.0 Field Test Results

The field tests of the long-term post-closure radiation monitor probe and system ("LPRMS probe") were conducted in parallel to tests of the B&W "Survey Probe" described in section 4.4. The functional performance of the LPRMS probe was generally fair to good. Some difficulty was encountered early in the testing with high noise counts in the energy spectrum at low energies; this problem was found to be due to lack of effective probe grounding, and was eliminated by adding a ground wire between the probe body and the gamma spectrometer in the field. After this, we were generally able to obtain the desired data without difficulty. The functional performance of the B&W Survey Probe was good to excellent; we were consistently able to obtain the desired data without difficulty, except once when the probe was accidently fully immersed in water. Once the connectors were dried out, the probe again worked normally.

All of the data analyses for this project were performed using GENIE-PC gamma analysis software, version 2.1 (Canberra Nuclear). This software incorporates algorithms for performing most of the analyses normally encountered in gamma spectroscopy, including energy and efficiency calibrations, peak location, continuum correction, peak area determination, detector efficiency correction, nuclide identification, interference correction, nuclide activity and uncertainty calculation, and minimum detectable activity (MDA) calculation. The general analysis sequence followed for each of the counts from each of the tests performed at FEMP was:

- Energy calibrate the count spectrum (counts vs keV)
- Locate the peaks in the spectrum (in keV)
- Determine the net peak areas (in detected counts)
- Efficiency correct the areas (sample counts)
- Identify nuclides by gamma lines (nuclide ID list)
- Interference correction (corrected nuclide ID list)
- Calculate total activities and uncertainties, based on nuclide gamma yields and corrected areas (pCi)

- Normalize activities and uncertainties to analysis quantity (pCi/g)
- Calculate minimum detectable activities (MDAs in pCi/g).

Each of these steps and the analysis parameters used for each are described in more detail in Appendix D.

For the survey and 1 meter LPRMS probe, the system setup (high voltage, ADC settings, discriminator settings, gain) was left constant throughout all of the tests, a period of about 4 weeks. When the LPRMS probe was in the 3 meter configuration, the gain was increased to provide approximately the same energy full scale. Ambient temperatures during this period ranged from the high 20s (F) to the low 70s, with periods of rain and fog as well as clear weather. As discussed in section 4.2.4, temperature variation is the most significant parameter affecting the performance of the scintillator/PMT combination with time, and these variations cannot readily be compensated. It is, therefore, important for the probe performance to be within acceptable limits over a range of temperatures.

The stability of the system gain was tracked by the slope of the calibration curve with time (**Figure 6-1**), and by tracking the center channels of various energy peaks in the calibration source: 662 keV (Cs-137), 1173 keV (Co-60) 1333 keV (Co-60) and 1836 keV (Y-88). For a linear PMT/scintillator combination, the tracking of a single peak is generally an adequate characterization of system gain shifts. To achieve a wider than normal energy range (<60 to >2800 keV), we used a 3rd order calibration. To evaluate effects on the nonlinearity as well as overall gain, multiple peaks were tracked. In addition, in actual analysis software, how the values are selected and calculated for this kind of monitoring can affect how well they serve as indicators of hardware changes. Tracking multiple parameters permitted us to evaluate the system performance and evaluate alternate tracking methods for this particular software package.

The two sigma variation of the calibration slope was about 9.7 percent of the average value for the LPRMS probe and only about 2.5 percent for the B&W Survey Probe over the entire test period. For the LPRMS probe, all of the slope values lie within the 2 sigma limits, while for the B&W Survey Probe, three out of 37 counts of the calibration source had values lying outside the 2 sigma limits. The B&W Survey Probe shows variations around a largely constant mean value; the LPRMS probe shows variations around a mean which increases with time. This increase of the mean calibration slope reflects a loss of sensitivity. This loss of sensitivity is believed to be due to a delamination of the optical couplant between the CsI(Tl) scintillator and the end window, internal to the scintillator housing. A partial delamination (less than 1/4 of the scintillator diameter) was observed in the field during the changeover from the 1 meter to the 3 meter configuration; a post-test examination of the LPRMS scintillator showed that during the balance of the testing, this delamination had progressed to about half of the scintillator diameter. This delamination increases optical losses, decreasing the number of photons per keV-gamma; this increases the calibration slope and decreases the resolution of the system.

The peak centroid channels showed approximately the same level of variation. **Figure 6-2** shows the variation for the 1333 keV Co-60 peak; for the LPRMS probe, the 2 sigma limits are about 8.5% of the average value while for the B&W Survey Probe the 2 sigma limits are only about 2% of the average value. As with the calibration slope, the B&W Survey Probe shows a variation around a constant mean, while the mean for the LPRMS probe is decreasing with time. The decrease in the center channel of this peak is consistent with the increase in energy calibration slope discussed above, and was typical for all the peaks monitored.

We tracked the FWHM (Full Width at Half Maximum) of the energy peaks in the calibration source as well. The FWHM is a measure of the resolution, which is directly related to the ability to separate closely spaced peaks. The average FWHM at the 662 keV Cs-137 peak was 78.45 keV for the LPRMS probe, for a resolution of 11.85%. For the B&W Survey Probe, the average FWHM was 47.9 keV for a resolution of 7.25%, comparable to the value measured in the lab and quite good for a scintillator of this size. See **Figure 6-3.** The results at 662 keV were typical of all of the peaks tracked. The increase in the FWHM of the LPRMS probe to about 105 keV (15.8%) during the period of November 10 and 11 resulted from the changeover of the probe to the 3 meter configuration.

To obtain an estimate of the variation in the overall efficiency of the probe, we analyzed the calibration counts to determine an activity for the nuclides in the calibration source. Since the efficiencies used were those for the in-situ geometry, the activities cannot be compared to the known source activities (disc geometry), but can be used to detect variations with time. This is important since the probe efficiencies are calculated and cannot readily be changed in the field to account for varying conditions. The activity variation for Cs-137 as shown in **Figure 6-4**, was about 14.2% at 2 sigma for the LPRMS probe with 1 outlier. For the B&W Survey Probe, it was 11% at 2 sigma, including a single outlier (9% without the outlier). This activity is calculated based on a single peak area. Co-60, calculated on two peaks, showed a variation of less than 8% for the B&W Survey Probe (peaks cleanly separated), but 23% for the LPRMS probe (peaks overlapped). This parameter includes variations in the positioning of the calibration source and errors which occur in the peak location and analysis software, as well as errors due to gain and resolution changes.

### 6.1 Drummed Soils

The tests in drums with 1.5" casing (1B to 1E) were run in Plant 8, which had a relatively high background count rate. Those with a 2" casing (1F to 1H) were run in the Southfield where the background rate was relatively low. The soil drum with the highest activity was tested at natural moisture (Test 2A) then saturated (Test 2B). These tests were performed on a concrete pad just outside Plant 8.

To test these samples, the first probe to be tested was calibrated and then lowered into the casing until it was approximately centered on the fill height. The count sequence for these samples was:

- Count the calibration source for 30 minutes,
- Perform ten 3-minute counts,
- Perform five 10-minute counts,
- Perform two 30-minute counts,

- Count the calibration source for 30 minutes,
- Count the background for 30 minutes.

This count sequence was then repeated for the second probe.

Each of the counts for both probes were analyzed for certain uranium, thorium and radium isotopes listed in a library (see **Figure 6-5**). In this library, the isotopes can be identified either by their own gamma emissions or by those of short half life daughters in secular equilibrium. The half lives and yields of the daughters are adjusted to provide the activity of the parent nuclide. All of the counts were analyzed using the same set of analysis parameters. All of the counts in a single test were analyzed using the same energy calibration.

### 6.1.1 51 pCi/gram Total U (Test 1B)

The analysis results for this test are summarized in **Figure 6-6** and are shown compared to the laboratory analysis results in **Figures 6-7** through **6-10**. For the LPRMS probe, all counts were performed on the same day. For the B&W Survey Probe, counts 1 through 17 were performed on one day, following the count schedule listed above. Counts 18 through 20 were performed 3 days later; count 19 was a 30 minute count, counts 18 and 20 were 90 minute counts.

**LPRMS Probe:** K-40 was found in about half of the 3 minute counts and consistently in the longer count times; increasing the count time by a factor of 10 decreased the activity uncertainty by about a factor of 3. U-235 (reference activity = 0.923 pCi/g), U-238a (Th-234) and U-238b (Pa-234m, at 21.8 pCi/g) were not identified by this probe at any count time. Ra-226 and Th-232 were detected and quantified at near background levels (1 pCi/g) in one count of 30 minutes.

**B&W Survey Probe:** K-40 was consistently found in all counts; increasing the count time by a factor of 10 decreased the activity uncertainty by about a factor of 3. At 3 and 10 minute count times, U-235 (reference activity = 0.923 pCi/g) and U-238b (Pa-234m, at 21.8 pCi/g) were not detected. U-238a (Th-234) was detected some of the time, but not consistently; this isotope has low energy gamma lines with many interferences and is not a preferred choice for quantifying U-238 - the U-238 activities calculated from this isotope are consistently over-predicted. With a 30 or 90 minute count time, U-238b could be detected and quantified reasonably well, although not 100% of the time. Ra-226 and Th-232 were reliably detected and quantified at roughly background levels with count times of 30 minutes or longer; with 10 minute counts they were generally detected and quantified; with 3 minute counts they were generally not detected.

### 6.1.2 95 pCi/gram Total U (Test 1D and 1F)

The analysis results for this test are summarized in **Figure 6-11** (1D) and **6-16** (1F), and are shown compared to the laboratory analysis results in **Figures 6-12** through **6-15** (1D) and **6-17** through **6-20** (1F). A total of 17 counts were performed with each probe in test 1D (1.5" casing) and 18 counts with each probe (1 extra 30 minute count) in test 1F (2.0" casing).

**LPRMS Probe:** K-40 was consistently found and quantified in all but one of the counts; increased count times decreased the uncertainty. In test **1D**, U-235 (at 2 pCi/g) was found in only one of the counts, and had a large uncertainty in the quantity. U-238 was not identified with this probe in any of the counts of this sample. Ra-226 and Th-232 were detected and quantified at near background levels (1 pCi/g) in two counts. In test **1F**, U-235 was found in a total of 5 counts, including two of the 3 minute counts; the 2 sigma uncertainties overlapped the reference activity, but were considerably larger than the reference uncertainty. U-238 was not identified with this probe in any of the counts of this sample. Ra-226 and Th-232 were detected and quantified at near background levels (1 pCi/g) in two counts.

**B&W Survey Probe:** K-40 was consistently found and quantified in all counts; increased count times reduced the uncertainty. In test **1D:** U-235 (at 2 pCi/g) was generally found (80% of the time) and accurately quantified even in the 3 minute counts. U-238a (Th-234) was also generally found at 3 minutes, but typically over-predicted the activity of U-238; U-238b (Pa-234m) was generally found with counts of 10 minutes or longer and quantified the U-238 reasonably well. Ra-226 and Th-232 were generally detected and quantified at background activity levels. In test **1F:** The quantitative results for 1F (run 11/8/94) compared well with those from 1D (run 10/27/94); the consistency in detecting U-235 (100%) and U-238a and U-238b were better than in test 1D. U-238a (Th-234) consistently over-predicted the U-238, while Pa-234m did reasonably well. The improved results are probably the result of a reduced background count rate and a more stable temperature environment.

### 6.1.3 162 pCi/gram Total U (Test 1C and 1G)

The analysis results for this test are summarized in **Figure 6-21** (1C) and **6-26** (1G), and are shown compared to the laboratory analysis results in **Figures 6-22** through **6-25** (1C) and **6-27** through **6-30** (1G). With the LPRMS probe, a total of 17 counts were performed in test 1C (1.5" casing) and 18 counts (1 extra 30 minute count) in test 1G (2.0" casing); with the B&W Survey Probe, 18 counts (1 extra 30 minute count) were performed in both test 1C and test 1G.

**LPRMS Probe:** K-40 was consistently found and quantified in most counts. U-235 (at 3.4 pCi/gram) was sometimes found and quantified in test 1C (4/17) and more often found and quantified in 1G (9/18). U-238 (at 79.2 pCi/g) was only rarely found and quantified (3/35) by Pa-234m, and never by Th-234. Ra-226 and Th-232 at background levels were occasionally found and quantified, more frequently in test 1G where the background was lower.

**B&W Survey Probe:** K-40 and U-235 (at 3.4 pCi/gram) were consistently found and quantified in all counts; increased count times improved the uncertainty. U-238 (at 79.2 pCi/g) was always detected with count times of 10 minutes or greater with both Th-234 and Pa-234m; as before, Th-234 was more readily detectable at short count times and Pa-234m provided a better quantitative estimate of the U-238 when detected. As the U-238 activity levels increase, the comparison between Th-234 and Pa-234m improves. Ra-226 and Th-232 were generally detected and quantified at background activity levels. Consistency of detection for U-238a and the Ra-226 and Th-232 background isotopes was somewhat better for the 3 minute counts in the 1G test run in the Southfield compared to the 1C tests run in Plant 8. The quantitative agreement between the two tests was very good.

### 6.1.4 311 pCi/gram Total U (Test 1E and 1H)

The analysis results for this test are summarized in **Figure 6-31** (1E) and **6-36** (1H), and are shown compared to the laboratory analysis results in **Figures 6-32** through **6-35** (1E) and **6-37** through **6-40** (1H). A total of 20 counts were performed with the LPRMS probe in test 1E; 17 were performed on October 28 and 3 (a 30 minute, a 60 minute and a 90 minute) were performed on November 16; in test 1H, 18 counts were performed (1 extra 30 minute). For the B&W Survey Probe, a total of 19 counts were performed in test 1E (1.5" casing) (1 extra 30 minute count and a 90 minute count) and 18 counts (1 extra 30 minute count) in test 1G (2.0" casing).

**LPRMS Probe:** K-40 was found and quantified generally (17/20) in test 1E and sometimes (11/18) in test 1H. U-235 (at 6.7 pCi/g) was also found and quantified generally (17/20) in 1E and sometimes (7/18) in 1H. U-238b (Pa-234m) at 156 pCi/g was found and quantified in about half of the counts; U-238a (Th-234) was not identified at all. Ra-226 and Th-232 at background activity levels were occasionally found and quantified. For the counts where U isotopes were found, the agreement between the tests run in Plant 8 and those run in the Southfield was good.

**B&W Survey Probe:** K-40, U-235 (at 6.7 pCi/g), U-238a (Th-234) and U-238b (Pa-234m) (at 156 pCi/g) were all consistently detected at all count times. Ra-226 and Th-232 were generally detected and quantified at background activity levels. Calculating U-238 activity based on Th-234 activity under-predicted the U-238 activity, while the Pa-234m quantified the U-238 well. Comparison between the tests run in Plant 8 to those in the Southfield was good.

### 6.1.5 >1000 pCi/gram Total U (Test 2A and 2B)

This drum of soil was first tested (test 2A, 18 counts with each probe) in the natural moisture condition like the other drums. The soil was then saturated with clean water to see how much effect moisture content had on the results (test 2B, 18 counts with each probe). No laboratory analysis results were available for this drum of soil, so the comparisons are done to the data mean and 2 sigma values. The analysis results for this test are summarized in **Figure 6-41** (2A) and **6-46** (2B), and are shown compared to the mean and 2 sigma for all counts in **Figures 6-42** through **6-45** (2A) and **6-47** through **6-50** (2B).

**LPRMS Probe:** K-40, U-235 and U-238b were all generally detected and quantified at all count times, in both the natural moisture and saturated conditions. In test 2B but not 2A, Th-232 was generally detected and quantified at activity levels somewhat elevated over normal background levels. The U-235 and U-238 activities of test 2B showed unusually large variations from count to count (although the energy spectra did not) indicating difficulty in the analysis software in locating and quantifying the peaks.

When the soil was saturated in test 2B, the calculated activities of all the nuclides are expected to decrease because of the additional attenuation of the water. With the LPRMS probe, this was not the case. The calculated activities of both K-40 and U-235 increased, while the activity of U-238 decreased, but not as much as expected. In part, this is because an expected difference of 10-20% cannot be readily seen when the count 2 sigma uncertainty values are on the order of 30% of the mean value. The cause of this appears to be related to the difficulties encountered in the analysis software in locating and determining peak areas; comparison of the energy spectra for runs 2A and 2B shows that both the background and peak counts are reduced as expected when the water is added.

**B&W Survey Probe:** K-40, U-235 (at 33 pCi/g), U-238a (Th-234) and U-238b (Pa-234m) (at 830 pCi/g) were all consistently detected at all count times, in both the natural moisture and saturated conditions. Th-232 was generally detected and quantified at activity levels somewhat elevated over normal background levels. In test 2A, the Th-234 and Pa-234m calculations for U-238 activity were in fairly good agreement.

When the soil was saturated in test 2B, the calculated activities of all nuclides decreased, because of the additional attenuation of the water. In general, the decrease was between about 10 and 20 percent, or just about in the same proportion as the weight ratio. The Th-234 lines showed the largest decrease; this trend was expected because the energy lines are less than 100 keV where the attenuation coefficient of water is highest, but the magnitude of the decrease was larger than expected. Th-234 activities showed relatively large uncertainties in both tests, about 15 to 25% of the activity (vs 5 to 8% for other nuclides), and the uncertainties did not decrease with increased count times. In both runs, the 63 and 93 keV lines were both typically found and the ID confidence was high. The cause for this is unknown, but it underscores the difficulties of using this nuclide and the desirability of using Pa-234m (if it is found) to calculate U-238 activity.

### 6.2 Sewage Treatment Plant (Test 5B)

These tests were performed in an existing PVC-cased 2" monitoring well (1441) in the Sewage Treatment Plant. While a soil analysis was performed at the time the well was put in, there had been a removal action of surface soils in the STP which probably involved this well. Thus, no reliable analysis was available for this well. In addition, the well had a steel protective well cover which extended down to over 2 feet below grade, and an 8 inch diameter cement cap (to 6" below grade) and a bentonite grout collar (to 5 feet below grade). The cement, steel and bentonite all cause additional attenuation of the gamma, reducing efficiency of the detector.

Ten in-situ counts (5 30 minute, 3 90 minute, 2 180 minute) were performed with the LPRMS, all with the top of the scintillator about 34.5" below the top of the plastic casing, about 15-1/4 inches below grade. With the B&W Survey Probe, 4 90 minute counts were performed at two different depths in the well (3 at 3" and 1 at 18" below grade); three additional 30 minute counts were performed of the near-surface soils at several locations where it was thought the removal action might have left some material - one location was adjacent to a culvert about 3 feet away from the well head (2 counts at 30 and 90 minutes), the other location was under the edge of the concrete pad around the well head (1 count at 30 minutes).

**LPRMS Probe:** The probe efficiencies were modified to account for the additional attenuation of the concrete and the data was analyzed using the same analysis parameters as the drummed soil analyses. K-40, Ra-226 and Th-232 were generally detected in all of the counts; no uranium isotopes were identified. K-40 activity was typical of background levels, about 11 pCi/g; Ra-226 and Th-232 activities were somewhat above normal background levels, approximately 5 pCi/g each.

**B&W Survey Probe:** The probe efficiencies for the in-situ counts were modified to account for the additional attenuation of the concrete. For the surface counts, the original efficiencies were used, but the analysis quantities were adjusted to reflect the fact that the probe was only looking at about half as much sample. The results of these counts are summarized in **Figure 6-52** and are shown graphically in **Figures 6-53** through **6-55**. Counts C01 to C03 are in the well at 3" depth, C04 is at 18" depth. K-40 was detected at about the expected activity levels; U-235 and U-238b were not detected at all. U-238a (Th-234) showed up in 2 of the counts, but the quantity is dubious: if U-238 and Th-234 were present at 270 pCi/g, Pa-234m would also be present at this activity. The MDA for Pa-234m is about 77 pCi/g for the counts in the well, so it should have been detected. It's more likely that the Th-234 was present, but that the activity of U-238 is overestimated. Ra-226 and Th-232 were consistently detected and quantified at activity levels somewhat elevated over normal background levels - 2.5 to 5 pCi/g.

The surface counts with the B&W Survey Probe all detected both U-235 and U-238. At the culvert (location "A", counts C05 and C06), U-235 ran about 2.3 pCi/g and U-238 about 50 pCi/g (by Th-234) to 70 pCi/g (by Pa-234m). Ra-226 was about at normal background and Th-232 was slightly elevated. At the location under the edge of the pad (location "B", count C17), the U-235 activity was about 1.5 pCi/g and the U-238 about 108 pCi/g (by Th-234) or 34 pCi/g (by Pa-234m). Since the average U-235/U-238 ratio for soils at this site is about 4.8%, these activities look reasonable.

### 6.3 Southfield Borings

Two borings were available in the Southfield area, designated as 11406 and 11423. These consisted of 1.5 inch PVC casing which was pushed by ARA during the CPD. Boring 11406 was 2 meters deep with about 9 inches of stick-out; boring 11423 was 4 meters deep with about 18 inches of stick-out. Because no data was available on the expected isotopes or profiles with depth, we first vertically profiled these borings with the B&W Survey Probe based on gross count rate, using 100 second counts over an energy range of 0 to 3 MeV. In boring 11406, the count rate peaked at a depth of about 31 inches below grade, at a count rate of over 1000 counts per second. In boring 11423, the count rate peaked at a depth of about 9 feet below grade, at a count rate of about 800 counts per second. The count rate profiles obtained are shown in **Figure 6-56.**

#### 6.3.1 Boring 11406

In boring 11406, 8 counts were taken with the LPRMS at three depths: with the scintillator centerline 5" below grade (1 30 minute), 15" below grade (2 30 minute) and at 31" below grade (3 30 minute and 2 90 minute), the point of maximum count rate. With the B&W Survey Probe, a series of 30 minute counts were performed at one foot intervals in boring 11406: 3", 15", 27", 39", 51" and 63" below grade (all 30 minute counts. Two additional counts were performed at 31" below grade, 1 30 minute and 1 90 minute count.

**LPRMS Probe:** K-40 was identified and quantified in all counts, at an activity of about 10 pCi/g, typical for this area. Ra-226 was identified and quantified at background levels in the counts 5" below grade. Ra-226 and Th-232 were identified in the counts 15" below grade, at about background levels. At 31" depth, Th-232 was identified and quantified in all counts, at activities of about 4.8 pCi/g. No uranium isotopes were identified in any of these counts.

**B&W Survey Probe:** Analysis of the data from 11406 showed that the activity of K-40 was approximately constant with depth at about 7-10 pCi/gram (typical for this area), but showed variability typical of disturbed soils. Both Ra-226 and Th-232 were also detected; the Ra-226 activity increased from about 0.5 pCi/gram near the surface to just over 1 pCi/gram at the peak depth, while the Th-232 increased from about 0.5 pCi/gram near the surface to about 4.5 pCi/gram at the peak depth. Expected values for background for this location are about 0.5 pCi/gram for Ra-226 and about 0.8 to 1.0 pCi/gram based on a survey done in 1988. These isotopes thus show elevated levels over background, varying with depth and tracking the gross count rate data; see **Figure 6-57**. No uranium isotopes were identified in any of these counts.

Based on the laboratory analyses of the soil samples (see section 5.3.3), U-235 and U-238 should have been present at 1.8 and 40 pCi/g at 18" below grade; these levels are comparable to those of test 1D, where even three minute counts with the B&W Survey Probe could generally identify and quantify these isotopes. The activities at 3'6" depth were comparable to those of test 1B; these were reliably detected with 30 minute counts, although not with shorter counts. It is not known why these isotopes were not identified in any of the counts in this boring, when the count times used were more than adequate to both identify and quantify them.

### 6.3.2 Boring 11423

In boring 11423, counts were performed with the probes' centerline at three different depths: 2.25 feet, 5.5 feet and 9 feet below grade. With the LPRMS probe, 4 counts (3 30 minute, 1 90 minute) were performed at the 2.25 foot depth with the probe in the 1 meter configuration. The probe was then reconfigured to the 3 meter configuration and 6 counts (2 each 30, 60 and 90 minutes) were performed at both 5.5 feet and 9 feet. With the B&W Survey Probe, four counts (2 30 minute, 1 60 minute and 1 90 minute) were performed at each of the same three depths.

**LPRMS Probe:** K-40 was found at the 2.25 and 5.5 foot depths, but not at 9 feet; the activity level was somewhat lower than found in boring 11406. Ra-226 and Th-232 were identified and quantified at about normal background (or slightly elevated) levels at the 2.25 foot depth. Th-232 was also identified at 5.5 and 9 feet, at approximately the same levels as at 2.25 feet. U-235 was identified in 1 of 6 counts at 5.5 feet (6.6 pCi/g), and in 2 of 6 counts at 9 feet (8.7 pCi/g); U-238 was not identified in any of the counts at any depth in this boring.

**B&W Survey Probe:** Analysis of the data showed somewhat lower results than in 11406 for K-40, 5-8 pCi/gram with similar variability. Ra-226 was found at all three depths counted, at an activity of about 1.5 pCi/gram. Th-232 activity at 2.25 feet below grade was about 1.5 pCi/gram, increasing to about 2.5 pCi/gram at 5.25 and 9.25 feet below grade. At 9.25 feet below grade, U-235 was detected at an activity of about 3 pCi/gram, and U-238 was detected at an activity of about 75 pCi/gram; see **Figure 6-58** and **6-59**. No U-235 or U-238 were detected at the shallower depths.

The laboratory analyses of the soil samples from this boring (see section 5.3.3) shows that the U-235 activity is less than .15 pCi/g and the U-238 activity is less than 4 pCi/g at all depths except 9'6". At 9'6", the U-235 activity was 3.15 pCi/g and the U-238 activity was 76.83 pCi/g. The B&W Survey Probe results compare well to these results.

## 6.4 Drummed Water (Tests 6A, 6B, 6C)

Three samples of water in drums were counted. The drums had a piece of 1.5" casing in the center like the soil drums. Lab analyses of the water were not available at the time of testing, but were later obtained (see section 5.3.4). The expected activities (lab analyses) were:

| | Expected | (Actual) |
|---|---|---|
| South Plume | 0.02 pCi/g U-238 | (0.003 pCi/g) |
| SWRB | 1.60 pCi/g U-238 | (0.151 pCi/g) |
| Bio-d | 6.00 pCi/g U-238 | (0.670 pCi/g). |

With the expected activities, the activities of the South Plume and SWRB water were expected to be below the detectable threshold, the activity of the bio-d water above the threshold; with the actual activities roughly an order of magnitude lower, none of the samples would be expected to be above the detection threshold. Three counts were performed in each drum: one each at 30, 60 and 90 minutes, with each of the probes.

**LPRMS Probe:** The results of these counts are shown in **Figures 6-60** to **6-62.** No nuclides were detected in the South Plume water (6A). In SWRB water (6B), K-40 was identified in the longest count (0.67 pCi/g); U-238 was identified in the shortest count (activity = 15.5 ±6.67 pCi/g), but this was not confirmed in the longer counts. The counts in SWRB water were repeated with the probe directly immersed in the water sample (no casing); K-40 (0.87 pCi/g) was detected in all three counts, but no other isotopes were detected in any counts. K-40 was also the only isotope detected in water from Bio-d (0.4 pCi/g), only at the 90 minute count time. As discussed below, the K-40 detected is likely to be an artifact, not an isotope present in the water.

**B&W Survey Probe:** The results are shown in **Figures 6-63** to **6-65.** Low levels of K-40 were detected in most of the counts, and Ra-226 in some (6A only). It's probable that most of the detected amount was actually attenuated background. A background count of the detector (out of the water drum) for test 6A showed K-40 at an activity of about 3.8 pCi/gram-water and Ra-226b (Bi-214) at about 0.24 pCi/gram-water. At 1.5 MeV (K-40 = 1.46 MeV), 25 cm of water attenuates about 80% of the incident gamma, so the in-water measurement would be expected to show about 20% of the activity of the background if there were no K-40 in the water sample itself. This is about what was observed, so it's likely the K-40 is an artifact (also for tests 6B and 6C). Some of the Ra-226 count in 6A is attributable to this as well. The Bi-214 peak which was detected is at 609 keV; at this energy, the water will pass about 8% of the incident gamma, so an activity of about .02 pCi/gram (0.08 x .24 pCi/g) would be expected from the background. The detected Ra-226 shows an activity about 10 times this, with 2 sigma uncertainty of about 35% of the mean. It's likely that this is contamination in the water. No uranium isotopes were detected in any of the counts for any of these three tests.

## 6.5 Drummed Sand and Water (3A, 3B)

In this test, a drum filled with clean sand (no contaminants) was first counted with each probe (3 counts each, 1 each at 30, 60 and 90 minutes) to establish a background (Test 3A). The sand was then saturated with water (98 lbs) from Bio-d, and then counted again with each probe (Test 3B: 3 counts each, 1 each at 30, 60 and 90 minutes). The results for the clean sand counts are shown in **Figures 6-66** and **6-67**. For clean sand + Bio-d water, the results are shown in **Figures 6-68** through **6-70**.

**LPRMS Probe:** K-40 and Ra-226 were detected in the counts in both the clean sand and saturated sand, at levels consistent with background. No other isotopes were detected, and the differences between the two counts are small and not statistically significant.

**B&W Survey Probe:** Normal K-40, Ra-226 and Th-232 background nuclides were detected in the clean sand; the activity levels agree well with those detected with the LPRMS probe. In the saturated sand, the detected levels of K-40, Ra-226 and Th-232 are reduced by the added mass of water, but the differences are not significant at 2 sigma. U-238a (Th-234) is now detected as well. Although the uncertainty of each measurement is large (about 60% of the activity at 2 sigma), the values are consistent from count to count. The activity calculated for U-238 is about 6.2 pCi/g, considerably larger than the lab analysis value of 0.67 pCi/g for this water, not surprising given the noted unreliability of Th-234 for quantifying U-238 in previous tests.

## 6.6 Alternate Analysis for Tests 6A, 6B and 6C

In the test of contaminated bio-d water in sand (test 3B), the Th-234 peak was identified in the B&W Survey Probe counts. In the test with bio-d water only (test 6C), this peak was not found, even though the count rate should be higher because of the absence of the sand attenuation. In an examination of the spectral data, it appeared that a peak was in fact present, at least at 93 keV line. The data from the 3 tests with drummed water (6A, 6B, 6C) were re-analyzed using "User Specified ROIs" in which we specified the areas of the energy spectrum where we wanted the peak search. The specified ROIs (regions of interest) were at the K-40, U-235 and U-238 energy lines. Analyzing the data in this way disables some of the statistical tests normally performed on the data.

**LPRMS Probe:** The summary results for the re-analyses are shown in **Figures 6-71** through **6-73.** The K-40 activities are comparable to those obtained using the standard analysis methods, but K-40 is found more frequently. The U-238a (Th-234) lines are now also detected in tests 6A and 6B. These lines have energies of 63 and 93 keV where 25 cm of water will pass less than 1.5% of the incident gamma; attenuated background levels would be well below the detection threshold. No U-235 or U-238b lines were detected in any of these three tests, and no Th-234 was detected in test 6C.

**B&W Survey Probe:** The summary results of the re-analyses are shown in **Figures 6-74** through **6-76.** As before, K-40 is found at levels consistent with attenuated background in all three runs. The U-238a (Th-234) lines are now also detected, in all counts in tests 6A and 6C, and in the longest count of 6B. No U-235 or Pa-234m lines were detected in any of tests. The activities calculated for Th-234 in tests 6A and 6C are below the background level, but are consistently higher than expected from an attenuated background, indicating that the U-238a is in fact present in the water. The activities calculated are higher than would be expected based on the contamination levels reported to us. This is not surprising since quantification of U-238 based on Th-234 activity has not been reliable in these tests.

## 6.7 Alternate Analyses for LPRMS Data

Based on the improvement in identifying nuclides seen in tests 6A, 6B and 6C, the count data for all of the LPRMS counts were re-analyzed using user-specified ROIs for K-40, U-235, U-238a (Th-234) and U-238b (Pa-234m). These analysis results are included in Appendix A. Use of this analysis method significantly improved the ability of the analysis software to identify uranium isotopes based on counts from the LPRMS probe.

For example, the drummed soil of test 1D had 94.6 pCi/g total uranium: 44.6 pCi/g U-238 and 2.05 pCi/g U-235. Using the standard analysis methods, only K-40 was consistently identified; U-235 was identified in only 1 count of 17 (see **Figures 6-11** through **6-15**), and U-238 not at all. With user-specified ROIs, U-235 was identified in 16/17 counts, U-238a in 17/17 counts and U-238b in 4/17 counts (see **Figures 6-77** through **6-81**). As with the analysis results from the B&W Survey Probe data, quantification of U-238 based on Th-234 was poor; Pa-234m, when found, provided accurate quantification of the U-238.

With this analysis method, the results for nuclide identification are almost as good as those for the B&W Survey Probe, although the LPRMS probe still did not identify U-235 or U-238b in test 1B, while the B&W Survey Probe did (at 30 minute count times). The measurement uncertainties are considerably larger, resulting in greater uncertainty in the calculated activities of nuclides detected.

## 6.8 Performance Results - LPRMS and Survey Tool

### 6.8.1 Minimum Detectable Activity (Detection Limits)

The normal procedure for determining the lower detection limits (LDL) by isotope for a system measuring radioactive nuclides is to count and analyze the Minimum Detectable Activity (MDA) for a "blank", a sample identical to the unknowns in geometry, background nuclides (such as K-40) and absorption characteristics, but with no other isotopic activity. The count protocols and analysis parameters used are identical to those used to count and analyze unknowns. A blank soil sample was not available for the tests performed at FEMP. However, one of the test runs provided a reasonably close match to a blank: run 3A, a drum of clean sand with K-40 activity of 6.4 pCi/g.

For this test, both the LPRMS probe and the B&W Survey Probe had been used to perform 30, 60 and 90 minute counts. The LPRMS probe was in the 1 meter configuration for test 3A. A Genie-PC nuclide library was prepared which included all of the gamma emitting isotopes from the list, prepared in Phase I, of nuclides found on DOE lands. This library included short half-life daughters which could reasonably be expected to be in secular equilibrium with the parent, with yields and half lives adjusted to provide the MDA of the parent, based on detection of the daughter. An MDA analysis was performed for both of the probes for test 3A using this library. This analysis was performed uusing Genie-PC, which uses the method of Currie for MDA calculation, at 95% confidence. A listing of the MDA library and the isotopic MDAs for each of the probes are included in Appendix C. The table below shows the MDA values for uranium isotopes from this appendix, for 30 minute and 90 minute count times. The isotopic MDA is defined as the lowest line MDA for any of the isotope's gamma lines.

**LDLs for Uranium Isotopes, 30 & 90 Minute Counts: Test 3A**

| | Survey Probe | | LPRMS Probe (1 m) | |
|---|---|---|---|---|
| | 30 min | 90 min | 30 min | 90 min |
| U-233 | 130.8 | 75.5 pCi/g | 219.1 | 126.7 pCi/g |
| U-234 | 207.8 | 119.6 pCi/g | 23320 | 13472 pCi/g |
| U-235 | 0.39 | 0.23 pCi/g | 0.52 | 0.30 pCi/g |
| U-236 | 207.5 | 69.4 pCi/g | 2436 | 1408 pCi/g |
| U-237 | 0.68 | 0.39 pCi/g | 1.27 | 0.74 pCi/g |
| U-238 | 4.38 | 2.53 pCi/g | 10.5 | 6.10 pCi/g |

This table shows that the LDLs for the LPRMS probe are generally about twice those of the survey probe, except for isotopes which only have low energy gamma lines. Both probes show LDLs for U-235, U-237 and U-238 which are potentially useful for monitoring applications; the ratio of the 30 and 90 minute count LDLs shows that the LDLs are dominated by count statistics, and that longer count times could be expected to further reduce the LDL. For reliable measurement, it's desirable for the activity to be roughly a factor of 5 to 10 or more above the lower detection limit. With the isotopic ratios typical for FEMP, this corresponds to about 50 pCi/g total U for the survey probe and about 125 pCi/g total U for the LPRMS probe for a 90 minute count time (based on U-238). For 30 minute count times, the LDLs correspond to about 90 pCi/g total U for the Survey Probe and about 200 pCi/g total U for the LPRMS probe, based on U-238.

### 6.8.2 Precision

Precision is typically determined and stated by isotope for an activity which is 10 times the MDA in a particular measurement situation. Because of the limited number of test articles and their generally low uranium activity levels, the precision values for the LPRMS and Survey probes are stated in the table below at isotopic activities of about 5 times the MDA, or roughly 6 to 10 times the LDL. The values listed in the table are for single 30 minute counts rather than an average of multiple counts. The activities listed in the table are isotopic activities. The precision values given are relative uncertainties; to calculate these values, the measurement uncertainty (at 1 standard deviation) for an activity determination is divided by the activity, and multiplied by 100 to give a percentage (relative precision). All of the measurement uncertainties were calculated using Genie-PC, as part of the analysis sequence.

**Precision for Uranium Isotopes: Activities ~5 x MDA**

| | Survey Probe | | LPRMS Probe (1 m) | |
|---|---|---|---|---|
| | Precision | Activity | Precision | Activity |
| U-235 | 5.6% | 3.451 pCi/g | 7.3% | 6.693 pCi/g |
| U-238a(Th-234) | 25.0% | 21.80 pCi/g | nf | |
| U-238b(Pa-234m) | 4.7% | 155.6 pCi/g | 7.4% | 155.6 pCi/g |

### 6.8.3 Bias

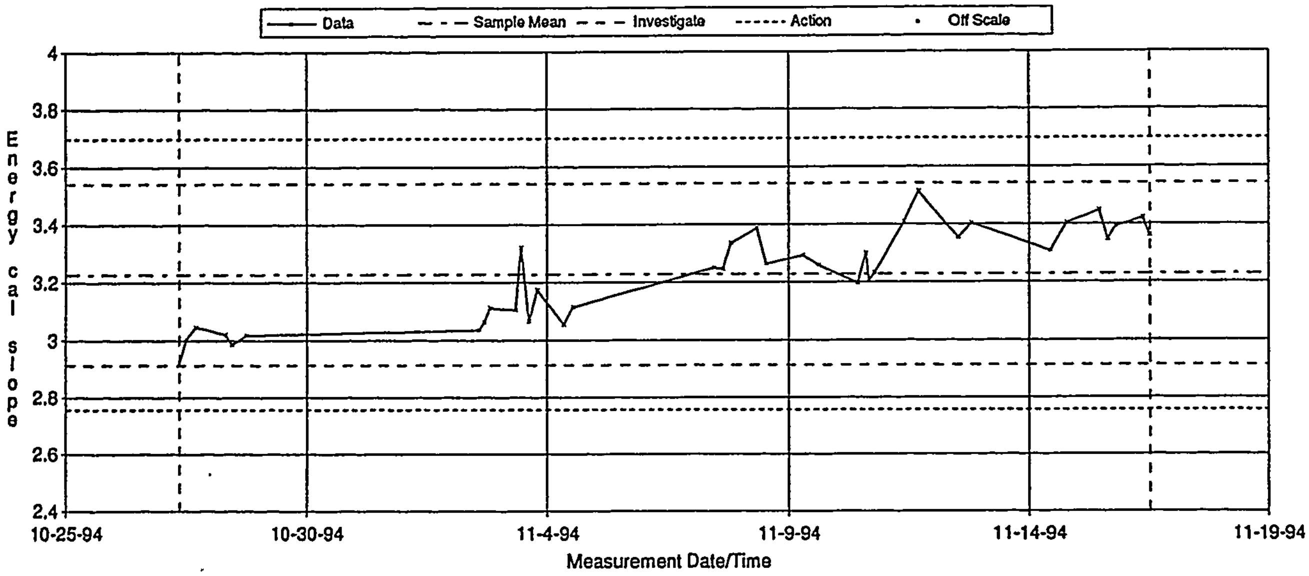
To determine the bias of an activity measurement, the measurement is compared to a known activity level in an analyte. Typically, the difference between the measurement and known activities is divided by the known activity and the result is multiplied by 100 to give bias as a percentage (relative bias). For the tests at FEMP, the activities in the test drums were only approximately known (see Figure 5-1). The bias values shown in the table below were calculated using the average isotopic activities for the boxes of USID soils as the "known" value, although there will be some unknown bias due to the sampling involved with removing the soils from the boxes and placing them in the drums, and due to the unknown uncertainties of the reference analyses themselves. The bias values were calculated for the same 30 minute counts used in the determination of precision, above.

**Bias for Uranium Isotopes: Activities ~5 x MDA**

| | Survey Probe | | LPRMS Probe (1 m) | |
|---|---|---|---|---|
| | Bias | Activity | Bias | Activity |
| U-235 | +3.2% | 3.451 pCi/g | +78.2% | 6.693 pCi/g |
| U-238a(Th-234) | +382% | 21.80 pCi/g | nf | |
| U-238b(Pa-234m) | +8.9% | 155.6 pCi/g | +5.2% | 155.6 pCi/g |

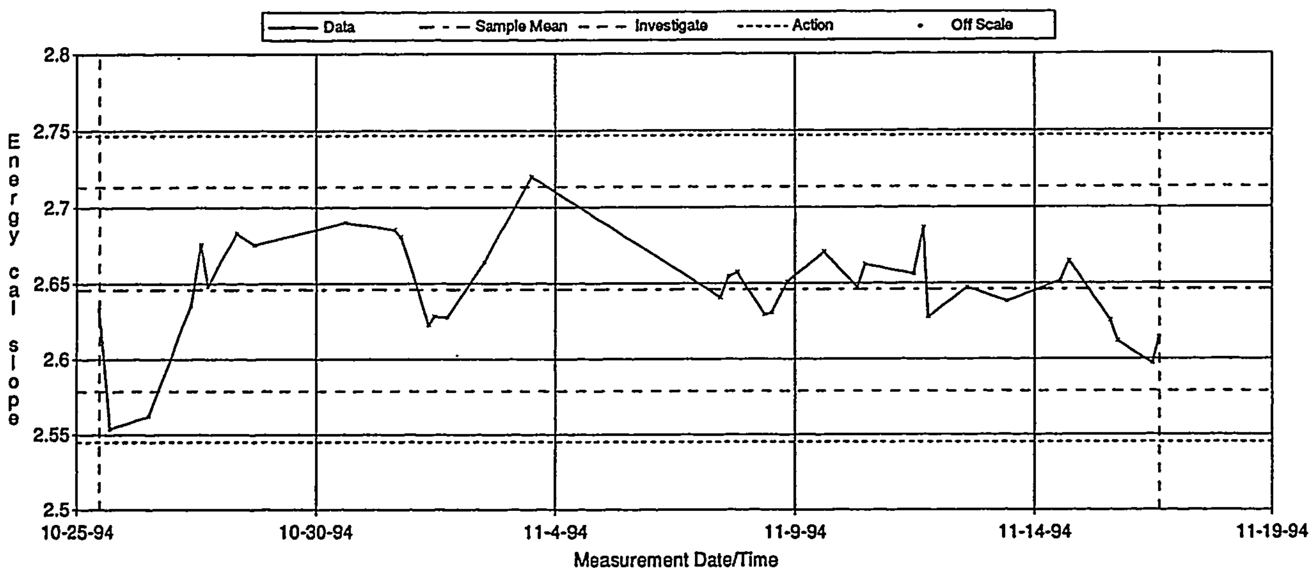
## Figure 6-1 Calibration Slope vs Time

### LPRMS Probe




QA Filename : C:\GENIEPC\CAMFILES\DOECAL.QAF
Parameter Description : Energy cal slope
Selection Dates : 10-27-94 8:19:21 AM - 11-16-94 11:29:03 AM
Sample Mean +-Std Dev : 3.226 +- 0.157

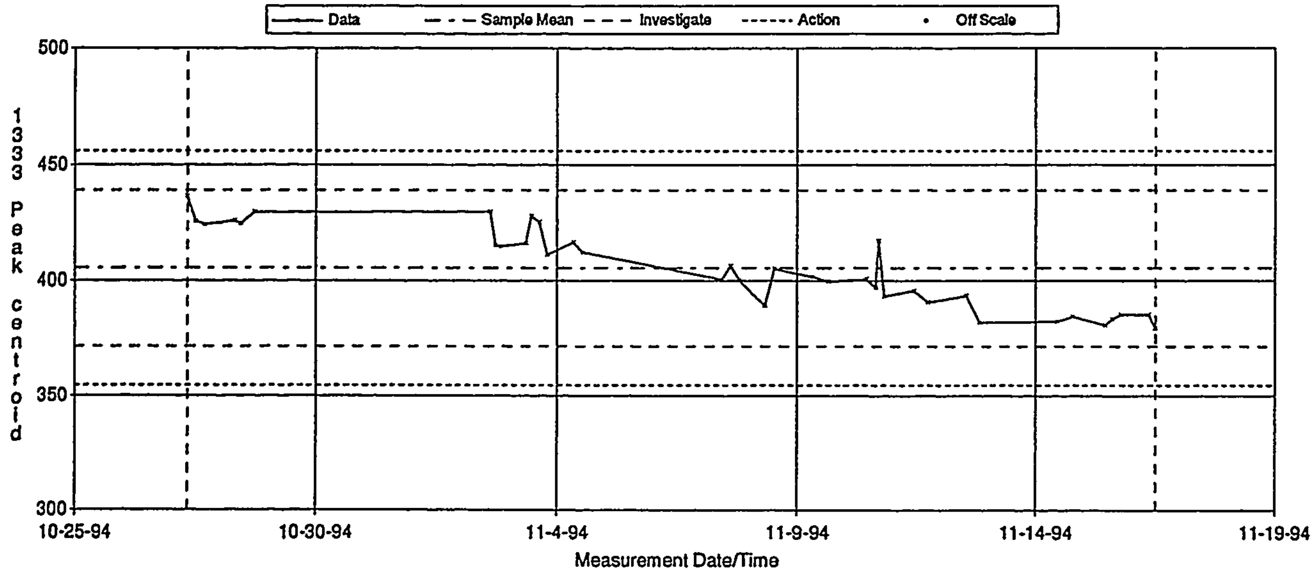
### Survey Probe




QA Filename : C:\GENIEPC\CAMFILES\NESICAL.QAF
Parameter Description : Energy cal slope
Selection Dates : 10-25-94 11:02:00 AM - 11-16-94 2:23:38 PM
Sample Mean +-Std Dev : 2.646 +- 0.034

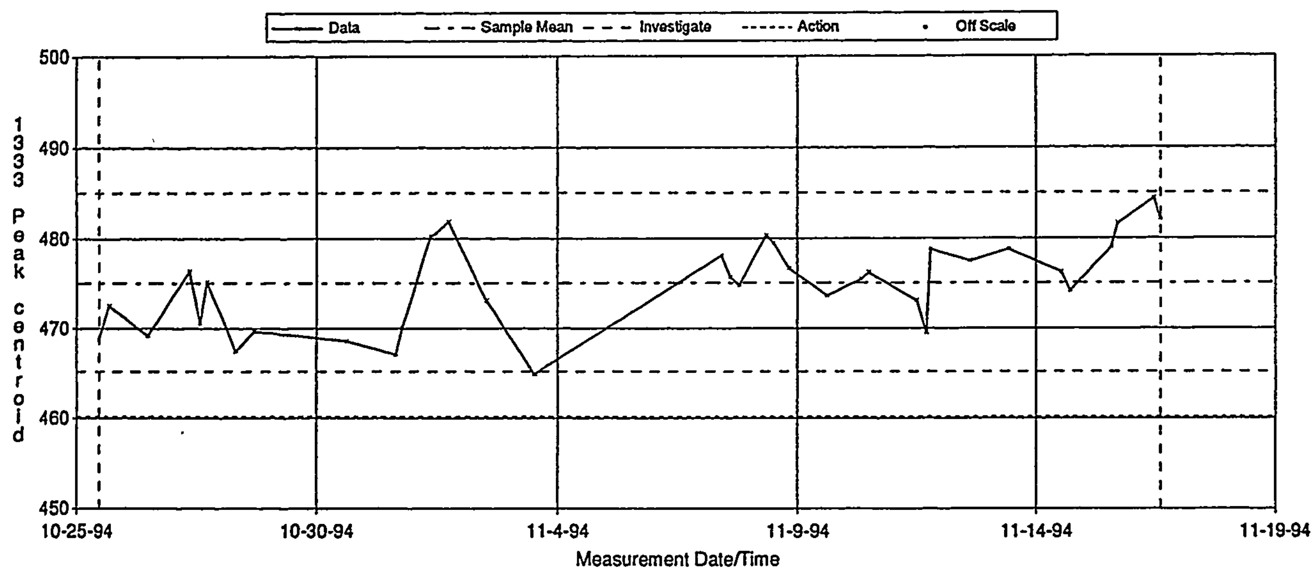
## Figure 6-2 Co-60 Peak (1333 keV) Channel vs Time

### LPRMS Probe




QA Filename : C:\GENIEPC\CAMFILES\DOECAL.QAF
Parameter Description : 1333 Peak centroid (ch)
Selection Dates : 10-27-94 8:19:21 AM - 11-16-94 11:29:03 AM
Sample Mean +-Std Dev : 405.146 +-16.883

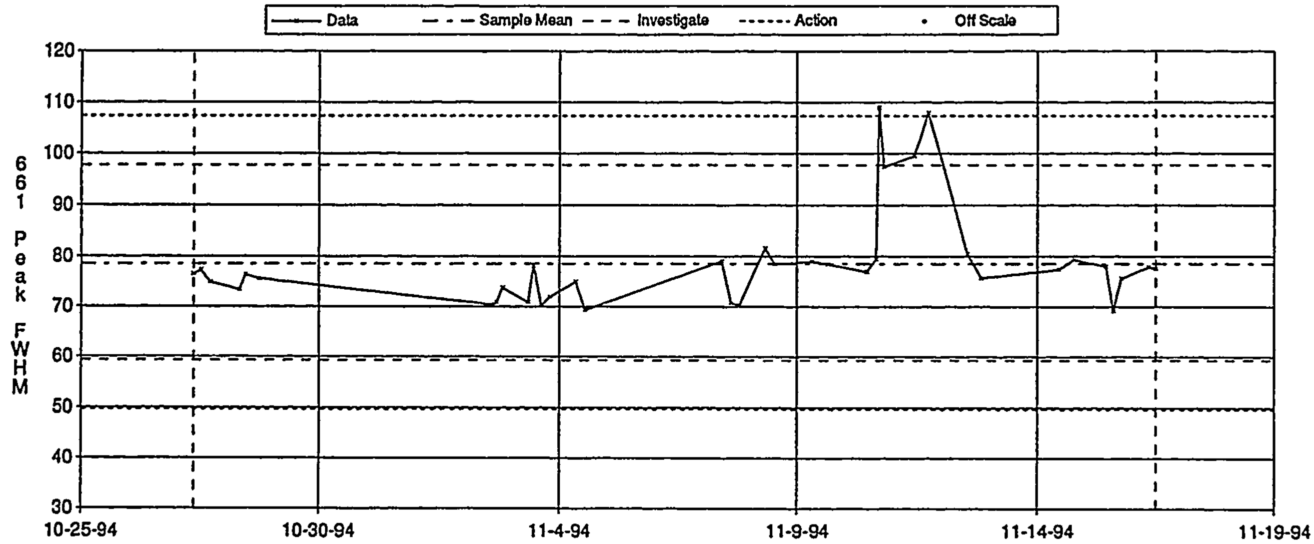
### Survey Probe




QA Filename : C:\GENIEPC\CAMFILES\NESICAL.QAF
Parameter Description : 1333 Peak centroid (ch)
Selection Dates : 10-25-94 11:02:00 AM - 11-16-94 2:23:38 PM
Sample Mean +-Std Dev : 475.044 +- 4.966

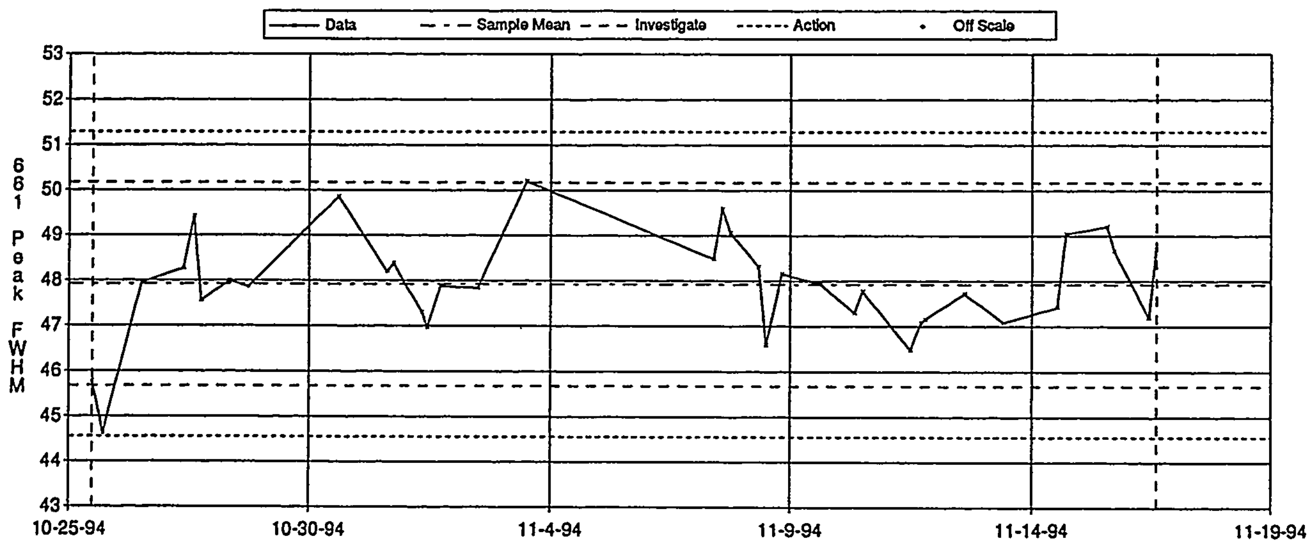
## Figure 6-3 FWHM at 661 KeV vs Time

### LPRMS Probe




QA Filename : C:\GENIEPC\CAMFILES\DOECAL.QAF
Parameter Description : 661 Peak FWHM (keV)
Selection Dates : 10-27-94 8:19:21 AM - 11-16-94 11:29:03 AM
Sample Mean +-Std Dev : 78.447 +- 9.604

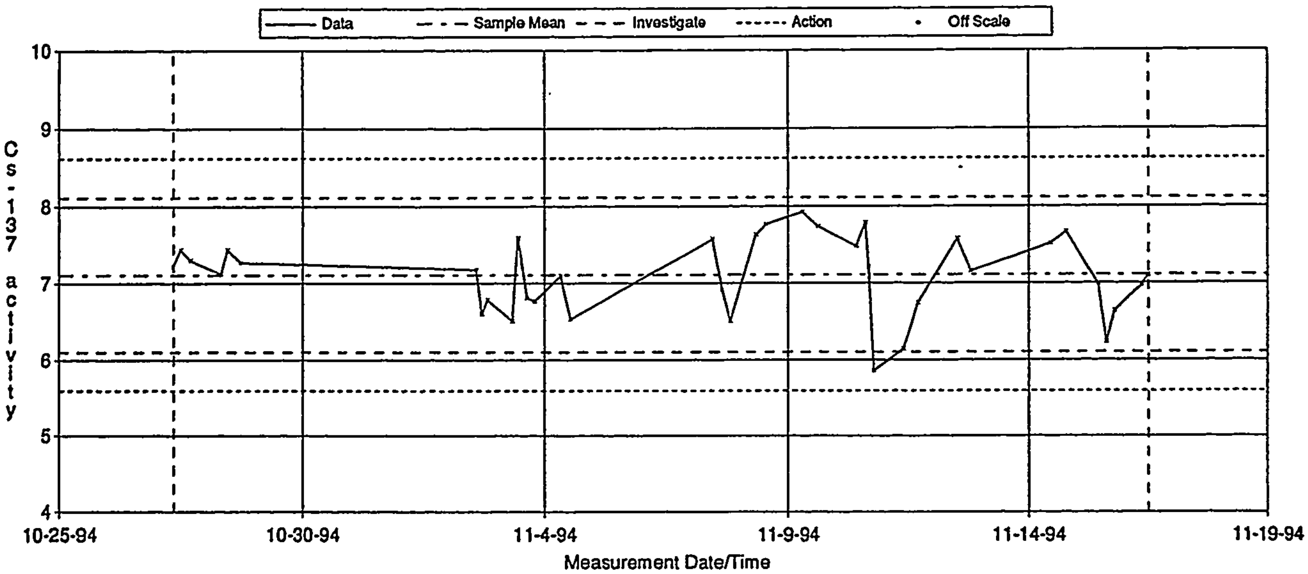
### Survey Probe




QA Filename : C:\GENIEPC\CAMFILES\NESICAL.QAF
Parameter Description : 661 Peak FWHM (keV)
Selection Dates : 10-25-94 11:02:00 AM - 11-16-94 2:23:38 PM
Sample Mean +-Std Dev : 47.917 +- 1.123

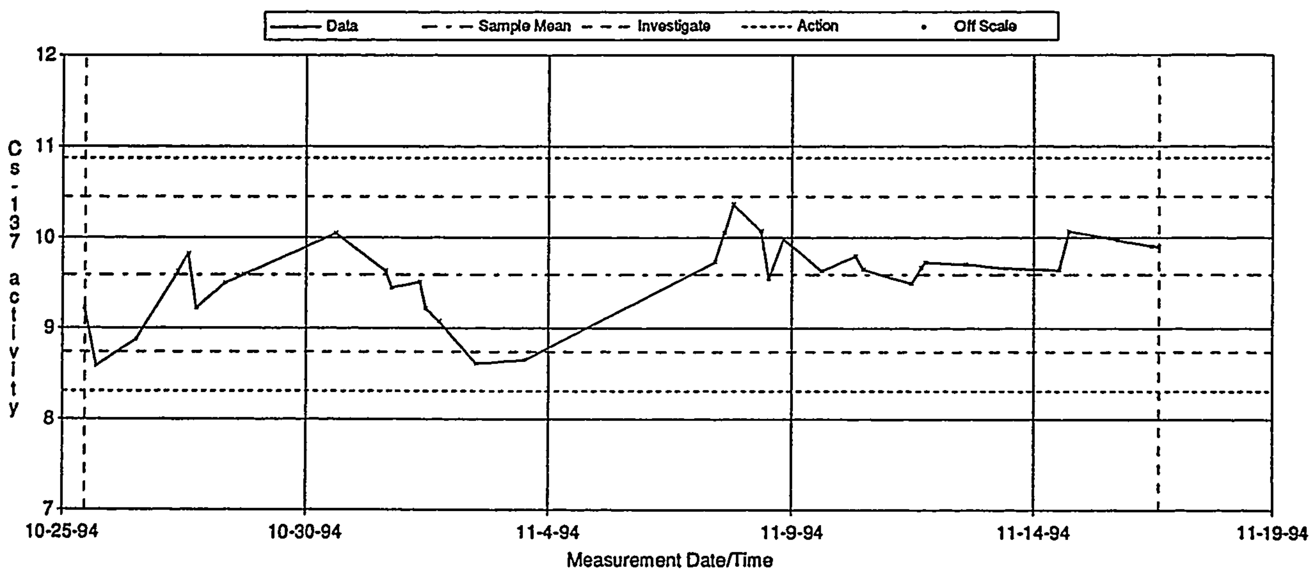
## Figure 6-4 Cs-137 Calculated Activity vs Time

### LPRMS Probe




QA Filename : C:\GENIEPC\CAMFILES\DOECAL.QAF
Parameter Description : Cs-137 activity (uCi/unit)
Selection Dates : 10-27-94 8:19:21 AM - 11-16-94 11:29:03 AM
Sample Mean +-Std Dev : 7.103 +- 0.504

### Survey Probe




QA Filename : C:\GENIEPC\CAMFILES\NESICAL.QAF
Parameter Description : Cs-137 activity (uCi/unit)
Selection Dates : 10-25-94 11:02:00 AM - 11-16-94 2:23:38 PM
Sample Mean +-Std Dev : 9.589 +- 0.427

## Figure 6-5 Analysis Library (PARENT2D.nlb)

```
*************************************************************************
*****          L I B R A R Y   L I S T I N G   R E P O R T        *****
*************************************************************************
```

Nuclide Library Title: Parent Library (PARENT2D.NLB)

Nuclide Library Description: Parent Library based on Combined

| Nuclide Name | Half-Life (Seconds) | Energy (keV ) | Energy Uncert. (keV ) | Yield (%) | Yield Uncert.(Abs.+-) |
|---|---|---|---|---|---|
| K-40 | 4.030E+16 | 1460.750* | 0.060 | 10.67 | 0.11 |
| Ra-226a | 5.049E+10 | 295.213 | 0.008 | 18.50 | 0.30 |
| | | 351.921* | 0.008 | 35.80 | 0.50 |
| Ra-226b | 5.049E+10 | 609.312* | 0.007 | 44.80 | 0.50 |
| | | 1120.287 | 0.010 | 14.80 | 0.20 |
| | | 1764.494 | 0.014 | 15.36 | 0.20 |
| Th-232a | 4.433E+17 | 911.205* | 0.004 | 26.60 | 0.70 |
| Th-232ai | 4.433E+17 | 89.950 | 0.020 | 2.13 | 0.54 |
| | | 967.964* | 0.020 | 21.31 | 0.54 |
| Th-232b | 4.433E+17 | 87.300 | 0.010 | 8.03 | 0.10 |
| | | 115.190 | 0.010 | 0.60 | 0.11 |
| | | 238.633* | 0.004 | 43.60 | 1.30 |
| | | 300.087 | 0.010 | 3.34 | 0.11 |
| Th-232c | 4.433E+17 | 727.180* | 0.060 | 6.65 | 0.15 |
| | | 1620.560 | 0.070 | 1.51 | 0.05 |
| Th-232d | 4.433E+17 | 583.140 | 0.013 | 30.26 | 0.00 |
| | | 2614.533* | 0.013 | 35.63 | 0.00 |
| U-235 | 2.221E+16 | 109.140 | 0.020 | 1.50 | 0.10 |
| | | 143.760 | 0.020 | 10.90 | 0.23 |
| | | 185.715* | 0.005 | 57.50 | 1.10 |
| U-235i | 2.221E+16 | 89.950 | 0.002 | 2.73 | 0.10 |
| | | 93.350 | 0.002 | 4.50 | 0.10 |
| | | 163.330 | 0.020 | 5.00 | 0.12 |
| | | 205.311 | 0.010 | 5.00 | 0.21 |
| U-238a | 1.410E+17 | 63.290 | 0.020 | 4.50 | 0.90 |
| | | 92.590* | 0.030 | 5.20 | 1.20 |
| U-238b | 1.410E+17 | 765.000 | 0.000 | 0.21 | 0.00 |
| | | 1001.000* | 0.000 | 0.59 | 0.00 |

* = key line

TOTALS: 12 Nuclides 28 Energy Lines

## Figure 6-6 Results Summary: Test 1B (51 pCi/g Total U)

### LPRMS Probe

Test D1B: Nominal Activity = 51.1 pCi/g Total U — Efficiencies from 01/30/95

| Count USID | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0.923 | 0.41 | | | 21.803 | 8.38 | | | | | | | | |
| C01 | <17.2 | | <4.4 | | <87 | | <263 | | | | | | | | | |
| C02 | 11.42 | 2.16 | <4.4 | | <87 | | <262 | | | | | | | | | |
| C03 | <17.1 | | <4.4 | | <87 | | <262 | | | | | | | | | |
| C04 | <17.3 | | <4.4 | | <87 | | <261 | | | | | | | | | |
| C05 | 12.87 | 2.20 | <4.4 | | <87 | | <260 | | | | | | | | | |
| C06 | 11.74 | 2.14 | <4.4 | | <87 | | <262 | | | | | | | | | |
| C07 | <16.8 | | <4.4 | | <87 | | <262 | | | | | | | | | |
| C08 | <16.9 | | <4.4 | | <87 | | <261 | | | | | | | | | |
| C09 | <17.0 | | <4.4 | | <87 | | <262 | | | | | | | | | |
| C10 | 12.70 | 2.18 | <4.4 | | <87 | | <260 | | | | | | | | | |
| C11 | 14.11 | 1.21 | <2.4 | | <48 | | <142 | | | | | | | | | |
| C12 | 15.17 | 1.19 | <2.4 | | <48 | | <142 | | | | | | | | | |
| C13 | 11.87 | 1.19 | <2.4 | | <48 | | <142 | | | | | | | | | |
| C14 | 13.34 | 1.20 | <2.4 | | <48 | | <143 | | | | | | | | | |
| C15 | 16.28 | 1.20 | <2.4 | | <48 | | <142 | | | | 0.74 | 0.22 | | | 1.19 | 0.13 |
| C16 | 11.57 | 0.70 | <1.4 | | <28 | | <82 | | | | | | | | | |
| C17 | 11.96 | 0.71 | <1.4 | | <28 | | <82 | | | | | | | | | |
| Avg | 13.00 | 1.52 | | | | | | | | | 0.74 | 0.00 | | | 1.19 | 0.00 |

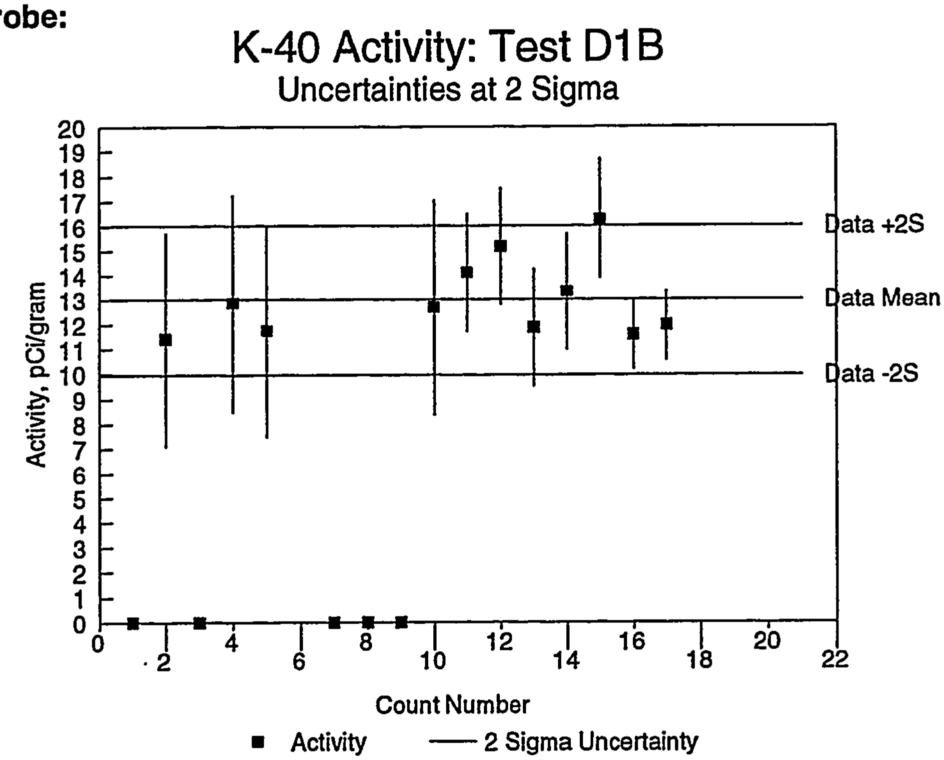
### Survey Probe

Test N1B: Nominal Activity = 51.1 pCi/g — Efficiencies from 01/30/95

| Count USID | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0.923 | 0.41 | | | 21.803 | 8.38 | | | | | | | | |
| C01 | 9.29 | 1.88 | <3.5 | | <42 | | <208 | | | | | | | | | |
| C02 | 11.93 | 2.31 | <3.5 | | <42 | | <207 | | | | | | | | | |
| C03 | 7.71 | 1.84 | <3.5 | | <42 | | <208 | | | | | | | | | |
| C04 | 10.59 | 1.82 | <3.5 | | <42 | | <208 | | | | | | | | | |
| C05 | 14.05 | 1.99 | <3.5 | | <42 | | <208 | | | | | | | | 1.16 | 0.43 |
| C06 | 13.50 | 1.91 | <3.5 | | 31.99 | 16.02 | <210 | | | | 0.97 | 0.29 | | | | |
| C07 | 12.83 | 1.91 | <3.5 | | 53.11 | 16.05 | <212 | | | | | | | | 1.30 | 0.43 |
| C08 | 9.59 | 1.84 | <3.5 | | <42 | | <211 | | | | | | | | | |
| C09 | 13.09 | 1.96 | <3.5 | | 74.64 | 18.83 | <211 | | 1.32 | 0.42 | | | | | | |
| C10 | 12.78 | 1.90 | <3.5 | | <42 | | <212 | | | | | | | | | |
| C11 | 10.49 | 1.05 | <1.9 | | <23 | | <115 | | | | | | | | | |
| C12 | 12.50 | 1.07 | <1.9 | | 37.65 | 13.10 | <115 | | | | 0.52 | 0.17 | | | 0.87 | 0.25 |
| C13 | 11.20 | 1.05 | <1.9 | | 34.12 | 11.52 | <114 | | | | | | 0.57 | 0.29 | 1.01 | 0.24 |
| C14 | 12.38 | 1.06 | <1.9 | | <23 | | <114 | | | | 0.57 | 0.16 | | | | |
| C15 | 13.92 | 1.07 | <1.9 | | 57.13 | 14.85 | <114 | | 1.04 | 0.17 | 0.74 | 0.22 | 0.69 | 0.26 | 0.72 | 0.24 |
| C16 | 11.37 | 0.62 | <1.1 | | 42.90 | 12.63 | < 66 | | 0.52 | 0.13 | 0.51 | 0.09 | | | 0.81 | 0.15 |
| C17 | 11.67 | 0.62 | <1.1 | | <13 | | 27.37 | 8.94 | 0.54 | 0.13 | 0.53 | 0.09 | 0.41 | 0.17 | 1.01 | 0.15 |
| C19 | 10.04 | 0.87 | 1.11 | 0.32 | 105.06 | 26.25 | 32.58 | 7.88 | 0.68 | 0.16 | 0.96 | 0.10 | 0.75 | 0.23 | | |
| C18 | 11.04 | 0.68 | 1.27 | 0.23 | 102.88 | 25.49 | <38 | | 0.57 | 0.11 | 0.94 | 0.06 | 0.67 | 0.13 | | |
| C20 | 10.18 | 0.78 | 1.39 | 0.22 | 103.82 | 25.45 | 21.09 | 4.90 | 0.37 | 0.09 | 0.99 | 0.06 | 0.59 | 0.15 | | |
| Avg | 11.51 | 1.63 | 1.26 | 0.11 | 64.33 | 28.49 | 27.01 | 4.70 | 0.72 | 0.31 | 0.75 | 0.20 | 0.61 | 0.11 | 0.98 | 0.19 |

**Figure 6-7 K-40 Activity: Test 1B (51 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

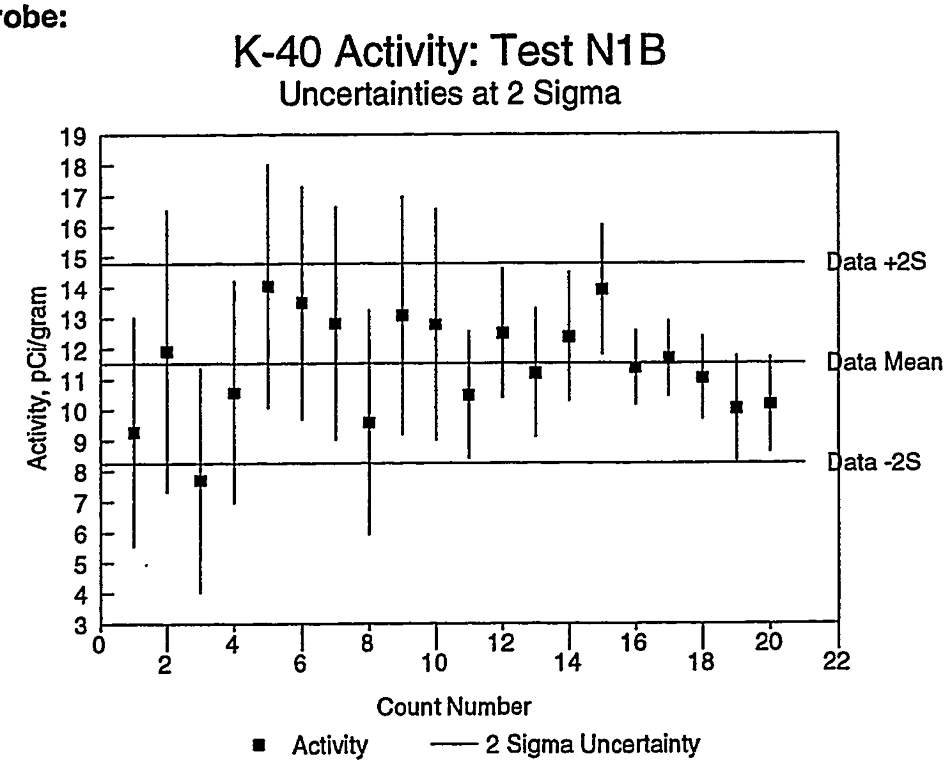
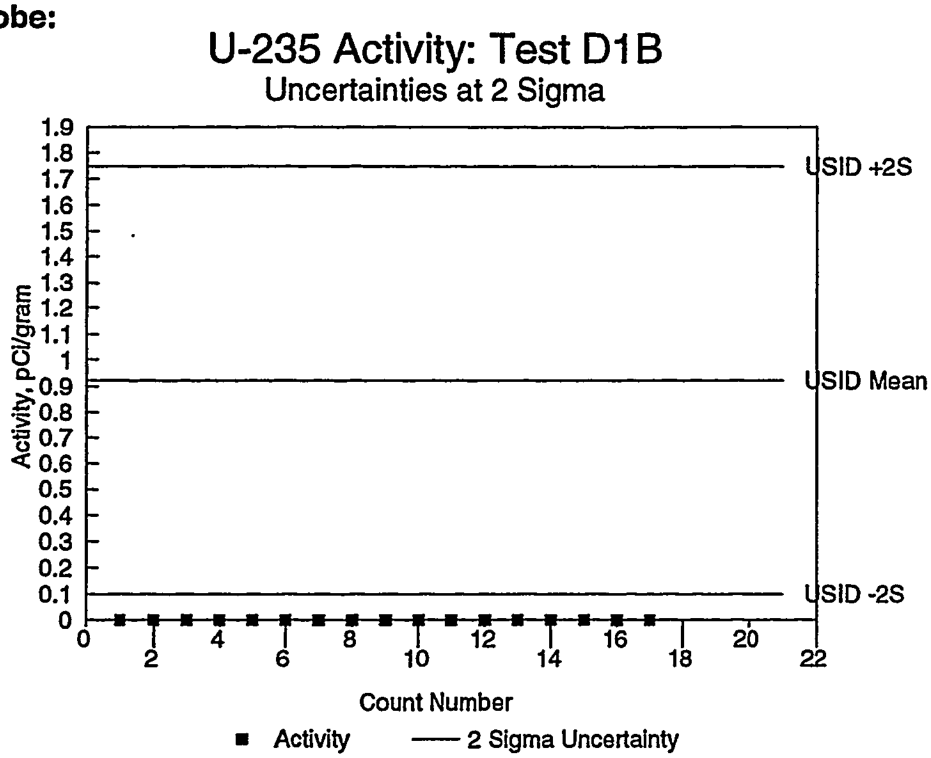


**Figure 6-8 U-235 Activity: Test 1B (51 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

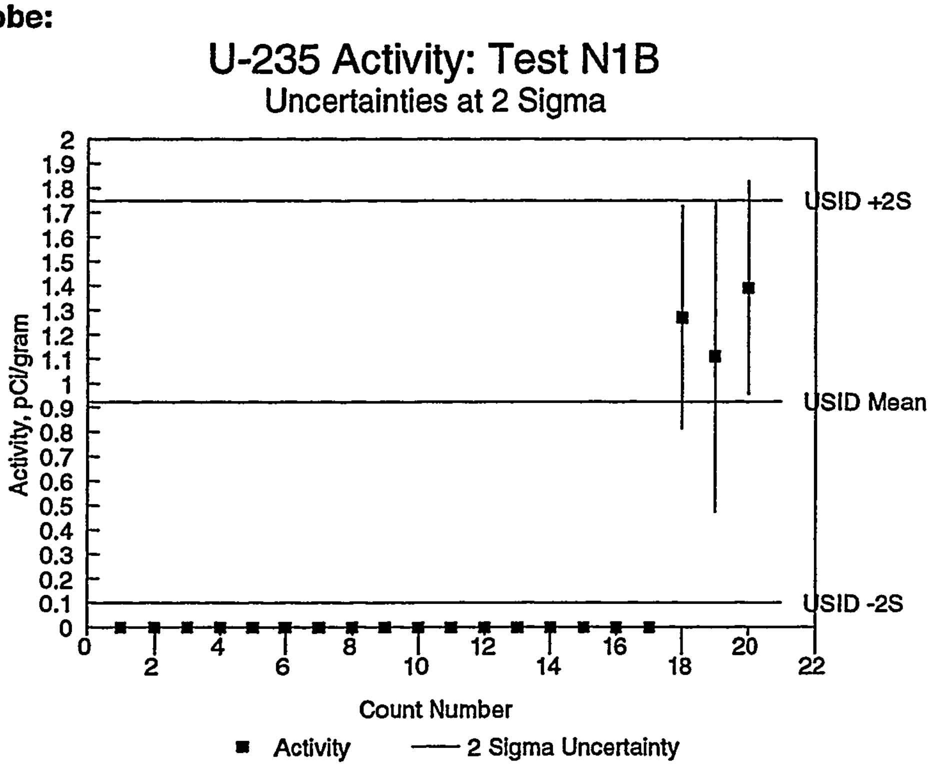
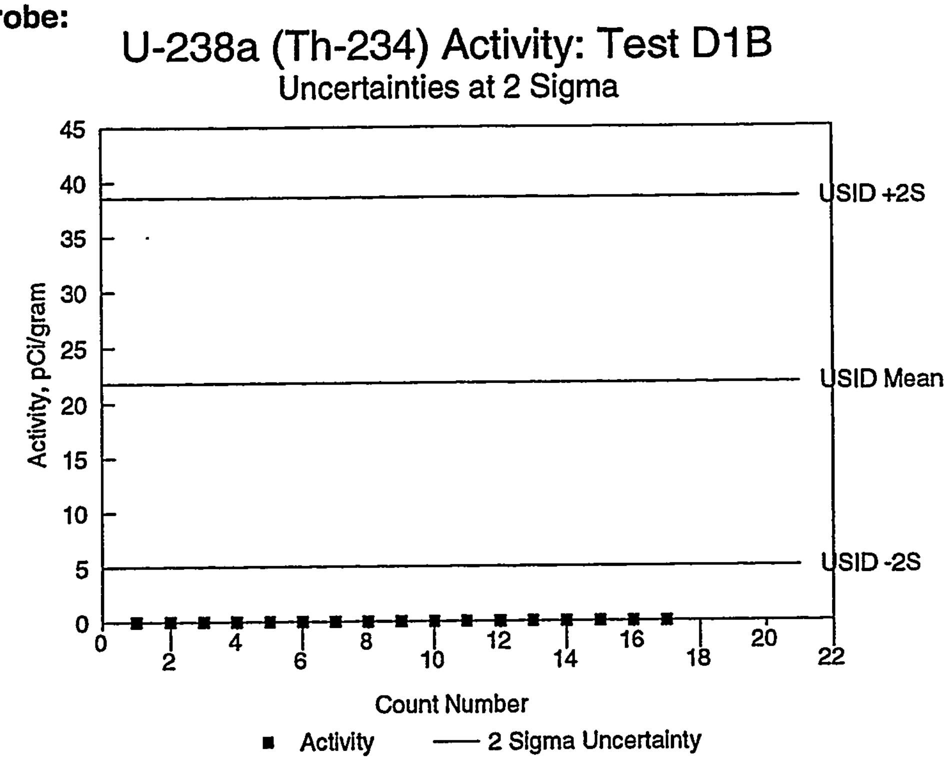


**Figure 6-9 U-238a (Th-234) Activity: Test 1B (51 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

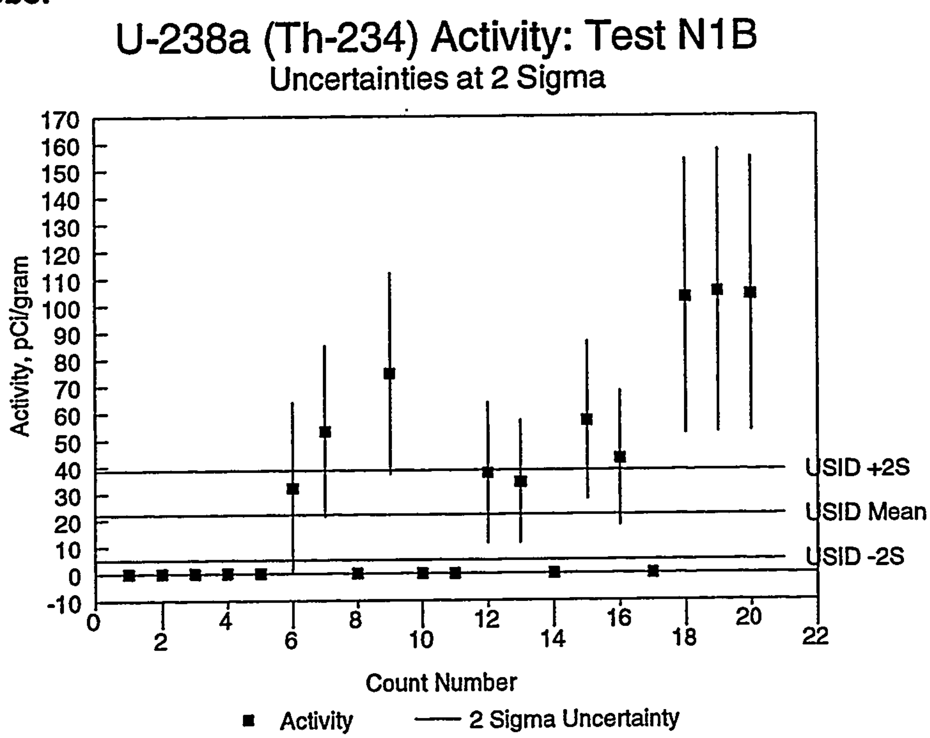
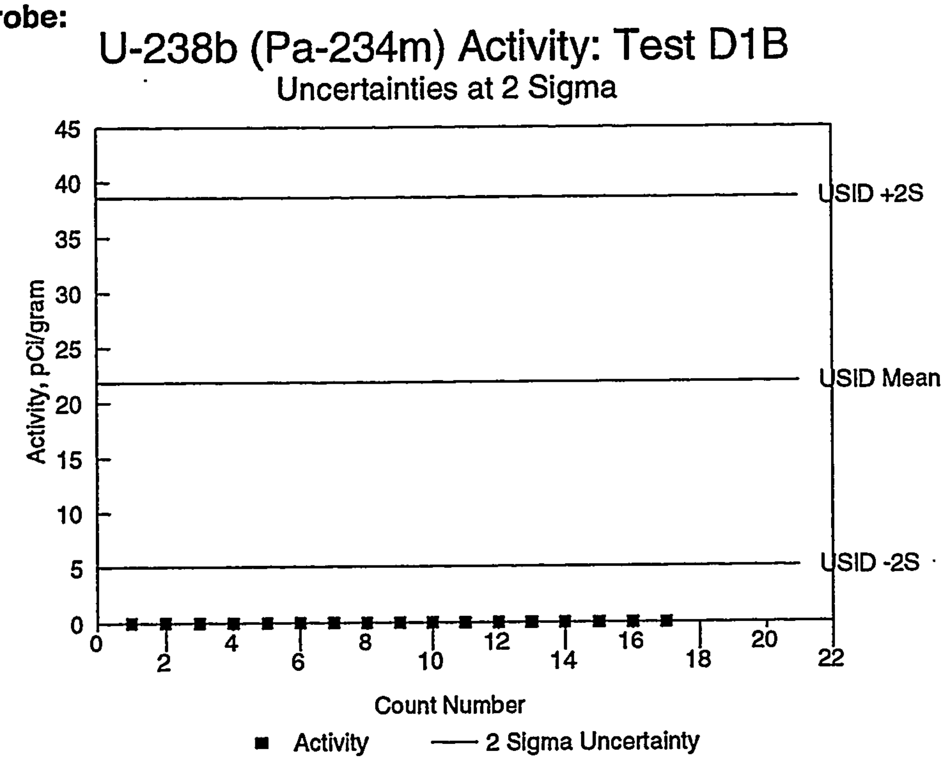
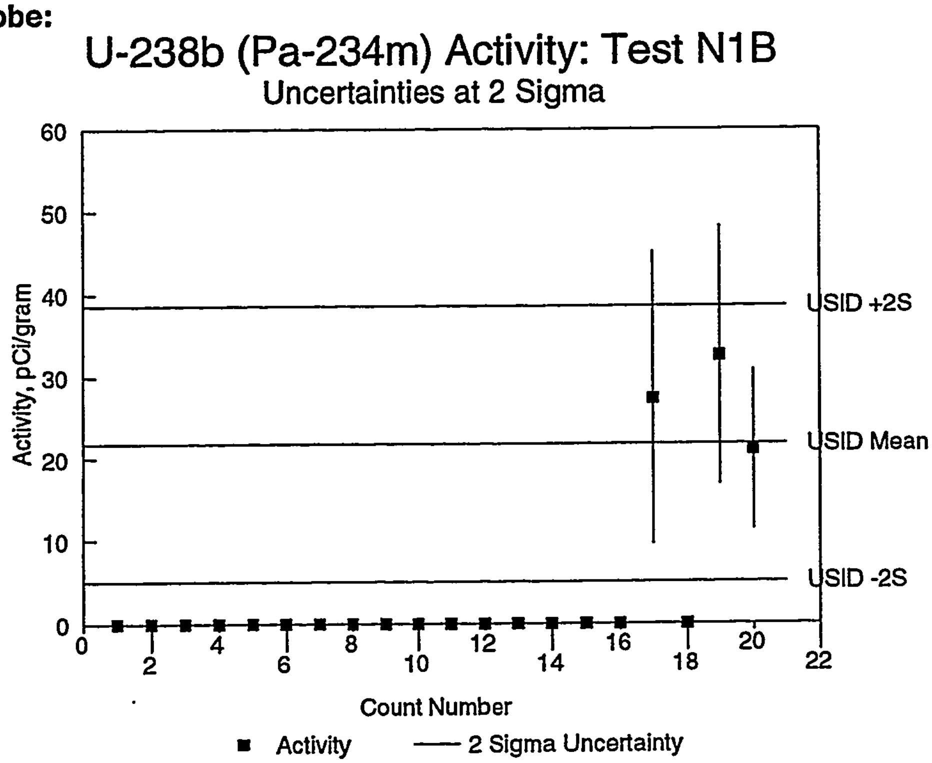


**Figure 6-10 U-238b (Pa-234m) Activity: Test 1B (51 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**



## Figure 6-11 Results Summary: Test 1D (95 pCi/g Total U)

### LPRMS Probe

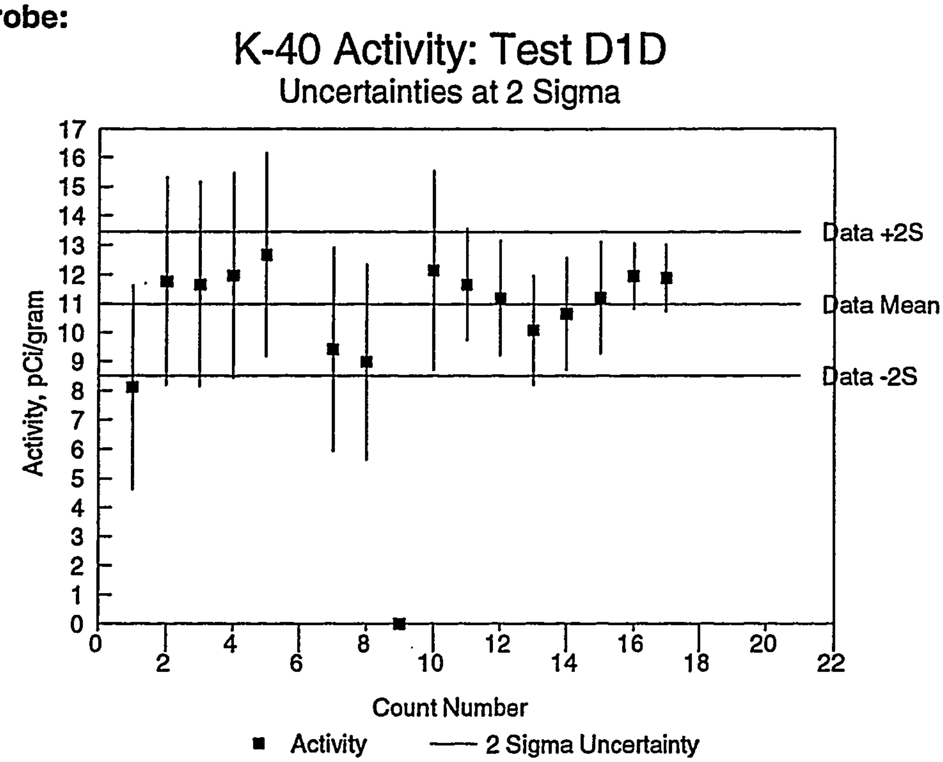
| Test D1D: Nominal Activity = 94.6 pCi/g Total U | | | | | | | Efficiencies from 01/30/95 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Count USID | K-40 | +- | U-235 2.05 | +- 0.16 | U-238a | +- | U-238b 44.636 | +- 3.18 | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
| C01 | 8.13 | 1.76 | <3.9 | | <79 | | <216 | | | | | | | | | |
| C02 | 11.76 | 1.79 | <3.9 | | <79 | | <216 | | | | | | | | | |
| C03 | 11.66 | 1.76 | <3.9 | | <79 | | <216 | | | | | | | | | |
| C04 | 10.39 | 1.73 | <3.9 | | <79 | | <216 | | | | | | | | | |
| C05 | 11.96 | 1.77 | 6.19 | 1.79 | <79 | | <213 | | | | | | | | | |
| C06 | 12.66 | 1.75 | <3.9 | | <79 | | <216 | | | | | | | | | |
| C07 | 9.42 | 1.75 | <3.9 | | <79 | | <214 | | | | | | | | 1.53 | 0.49 |
| C08 | 8.99 | 1.68 | <3.9 | | <79 | | <216 | | | | 1.02 | 0.33 | | | | |
| C09 | <13.6 | | <3.9 | | <79 | | <216 | | | | | | | | | |
| C10 | 12.14 | 1.72 | <3.9 | | <79 | | <215 | | | | | | | | | |
| C11 | 11.66 | 0.97 | <2.1 | | <43 | | <117 | | | | | | | | | |
| C12 | 11.17 | 1.00 | <2.1 | | <43 | | <117 | | | | | | | | | |
| C13 | 10.08 | 0.95 | <2.1 | | <43 | | <117 | | | | | | | | | |
| C14 | 10.64 | 0.97 | <2.1 | | <43 | | <117 | | | | | | | | | |
| C15 | 11.19 | 0.97 | <2.1 | | <43 | | <117 | | | | | | | | | |
| C16 | 11.94 | 0.57 | <1.2 | | <25 | | <68 | | | | | | | | | |
| C17 | 11.89 | 0.58 | <1.2 | | <25 | | <68 | | | | 0.55 | 0.15 | | | 0.95 | 0.11 |
| Avg. | 10.98 | 1.23 | 6.19 | 0.00 | | | | | | | 0.79 | 0.24 | | | 1.24 | 0.29 |

### Survey Probe

| Test N1D: Nominal Activity = 94.6 pCi/g Total U | | | | | | | Efficiencies from 01/30/95 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Count USID | K-40 | +- | U-235 2.05 | +- 0.16 | U-238a | +- | U-238b 44.636 | +- 3.18 | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
| C01 | 11.36 | 1.58 | 1.43 | 0.50 | 107.02 | 26.96 | 70.23 | 22.99 | 0.91 | 0.39 | | | | | 1.72 | 0.31 |
| C02 | 9.78 | 1.61 | 2.39 | 0.43 | 110.28 | 27.44 | <179 | | | | | | | | | |
| C03 | 10.89 | 1.65 | 1.64 | 0.64 | 118.67 | 28.93 | <179 | | 1.62 | 0.25 | 0.90 | 0.26 | 1.39 | 0.59 | | |
| C04 | 14.35 | 1.76 | 1.26 | 0.43 | 115.46 | 27.76 | <179 | | | | 0.79 | 0.26 | | | | |
| C05 | 12.66 | 1.69 | <3.4 | | <39 | | <179 | | | | 1.01 | 0.27 | | | | |
| C06 | 10.42 | 1.62 | 1.44 | 0.43 | 115.60 | 28.11 | <179 | | 0.96 | 0.39 | | | | | | |
| C07 | 9.06 | 1.61 | 1.39 | 0.49 | 104.28 | 26.64 | <179 | | | | 0.72 | 0.26 | 1.48 | 0.32 | | |
| C08 | 10.50 | 1.65 | 2:17 | 0.49 | 114.75 | 27.75 | <179 | | | | | | 1.11 | 0.54 | | |
| C09 | 9.65 | 1.64 | 1.01 | 0.43 | 110.61 | 27.01 | 89.13 | 23.22 | | | 0.89 | 0.26 | | | | |
| C10 | 11.51 | 1.70 | <3.4 | | 120.30 | 30.44 | <180 | | | | | | | | | |
| C11 | 11.97 | 0.96 | 2.26 | 0.27 | 121.06 | 29.67 | <98 | | 0.96 | 0.25 | 0.82 | 0.15 | 0.78 | 0.32 | | |
| C12 | 12.26 | 0.92 | 1.82 | 0.30 | <21 | | 39.22 | 12.39 | | | 0.84 | 0.15 | 1.05 | 0.30 | | |
| C13 | 10.70 | 0.93 | 1.99 | 0.41 | 110.68 | 26.97 | <98 | | 0.65 | 0.22 | 0.73 | 0.15 | | | | |
| C14 | 11.32 | 0.90 | 2.16 | 0.38 | 111.56 | 27.41 | 36.10 | 12.47 | | | 0.75 | 0.14 | | | | |
| C15 | 10.96 | 1.00 | 2.28 | 0.38 | 101.60 | 10.21 | <98 | | 0.80 | 0.15 | 0.63 | 0.15 | 1.39 | 0.61 | | |
| C16 | 11.80 | 0.63 | 2.96 | 0.30 | 111.95 | 27.10 | 34.68 | 6.66 | | | 0.70 | 0.08 | | | | |
| C17 | 11.11 | 0.57 | 2.17 | 0.29 | 111.11 | 26.87 | 50.03 | 6.90 | 0.50 | 0.12 | 0.77 | 0.08 | 0.35 | 0.11 | | |
| Avg | 11.19 | 1.21 | 1.89 | 0.51 | 112.33 | 5.33 | 53.23 | 20.09 | 0.91 | 0.33 | 0.80 | 0.10 | 1.08 | 0.37 | 1.72 | 0.00 |

**Figure 6-12 K-40 Activity: Test 1D (95 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

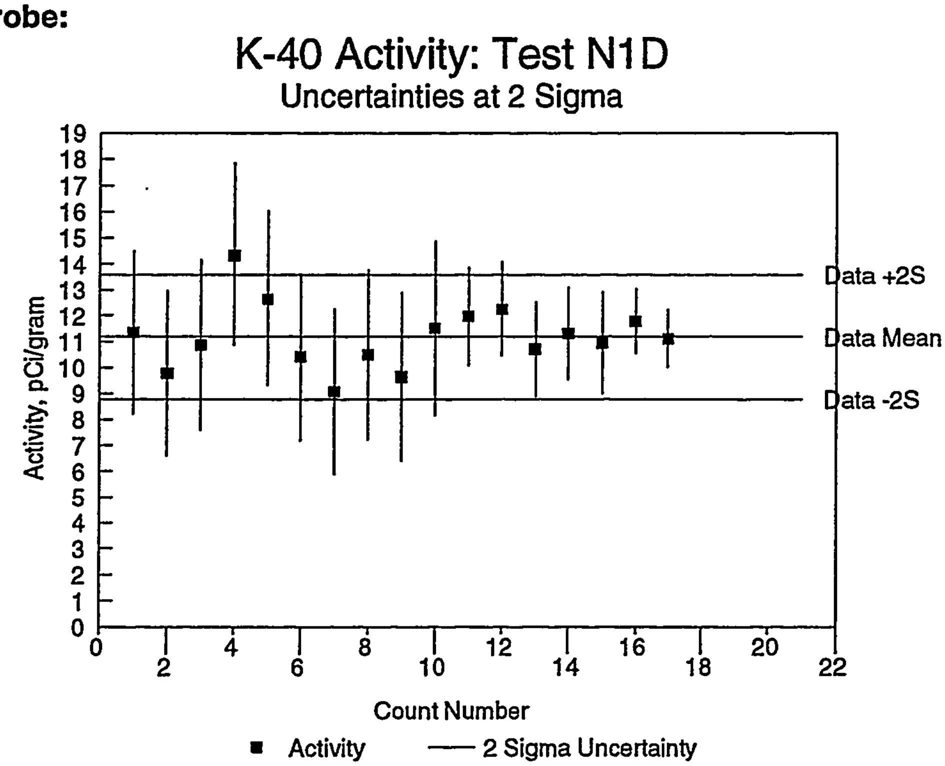
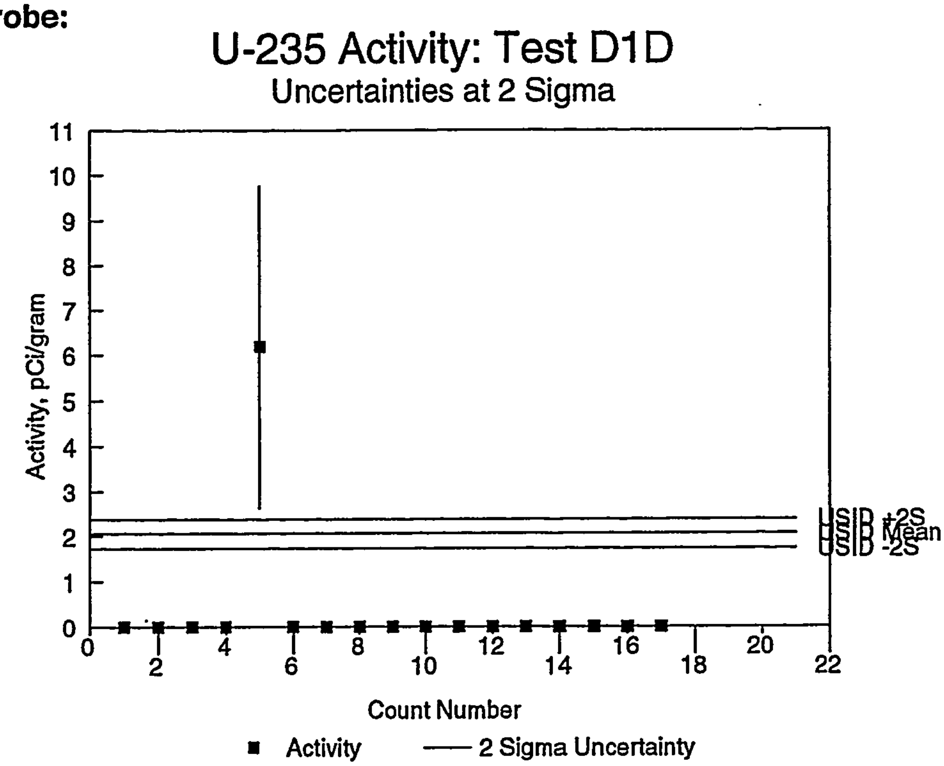


**Figure 6-13 U-235 Activity: Test 1D (95 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

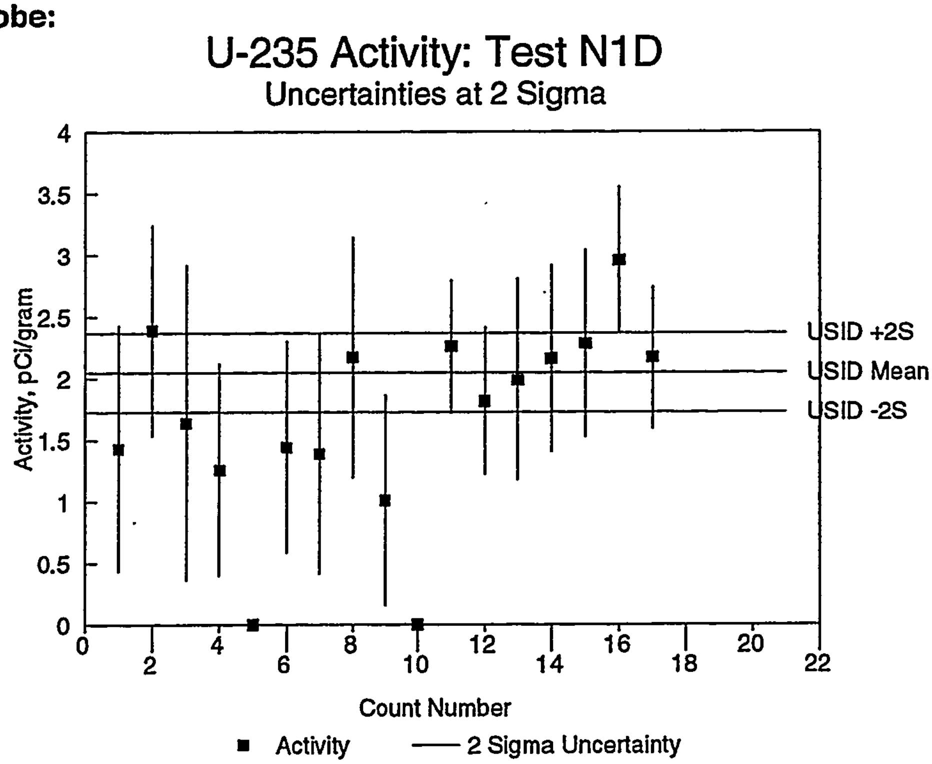
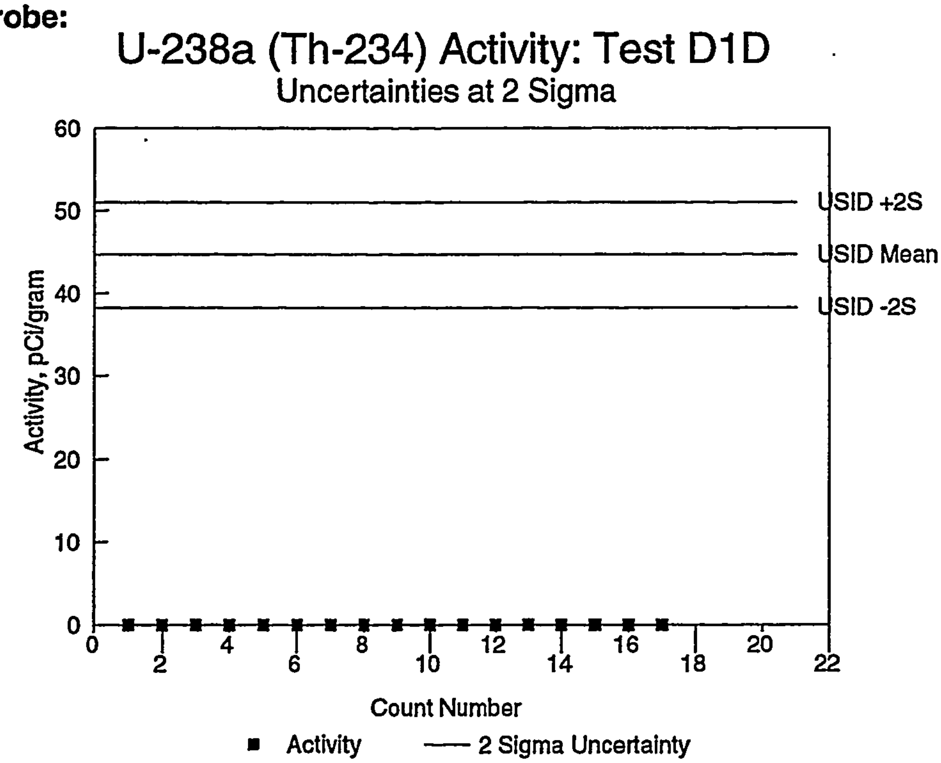


**Figure 6-14 U-238a (Th-234) Activity: Test 1D (95 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

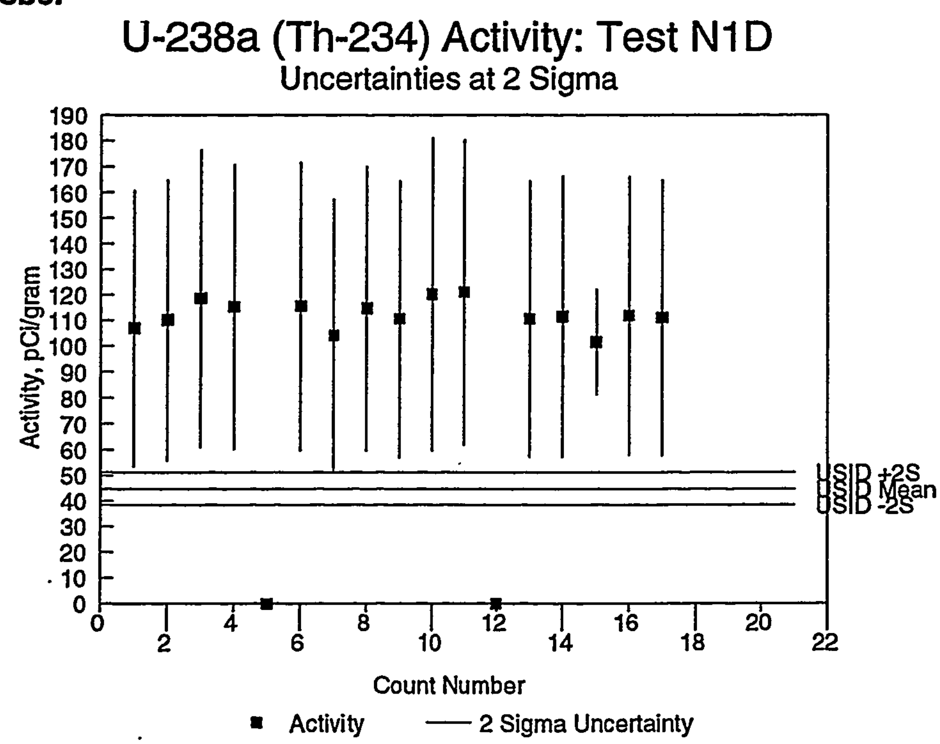
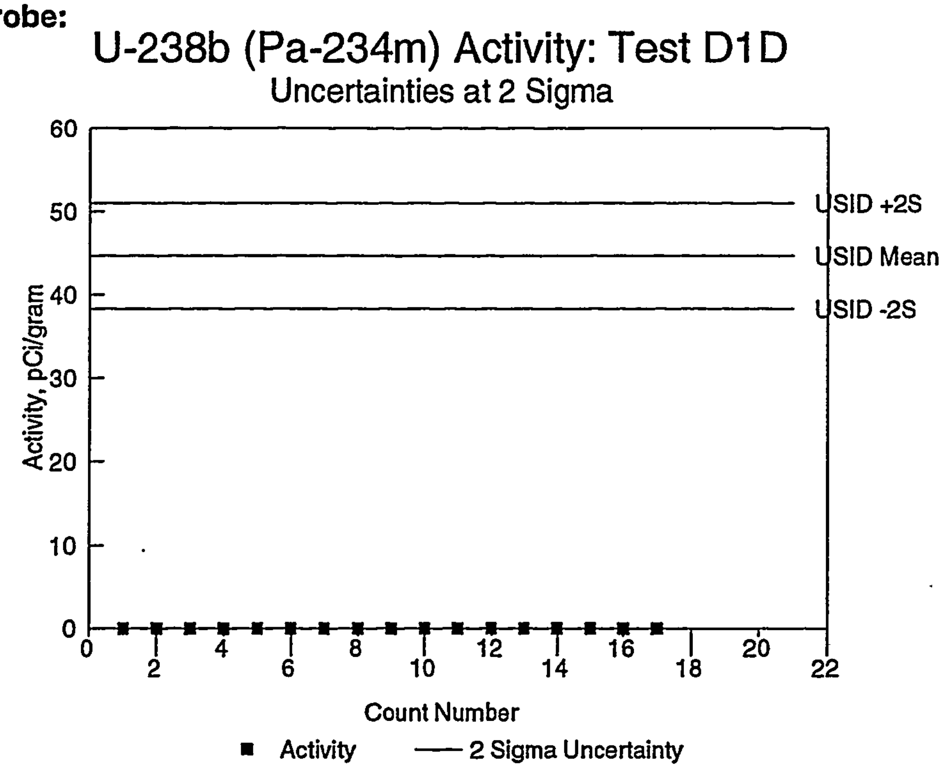
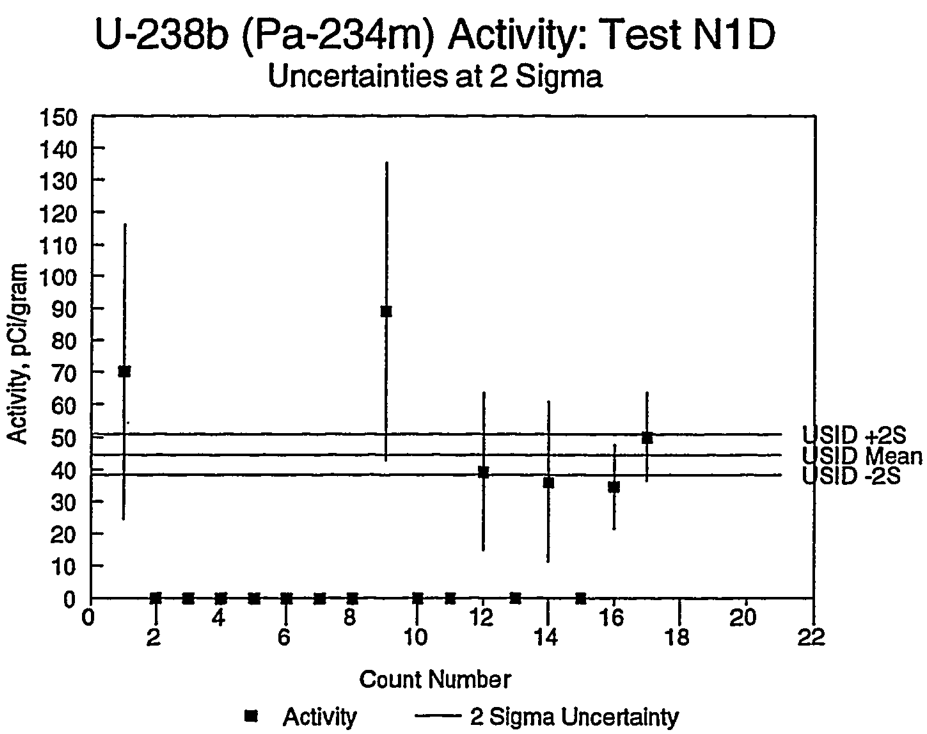


**Figure 6-15 U-238b (Pa-234m) Activity: Test 1D (95 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**



## Figure 6-16 Results Summary: Test 1F (95 pCi/g Total U)

### LPRMS Probe

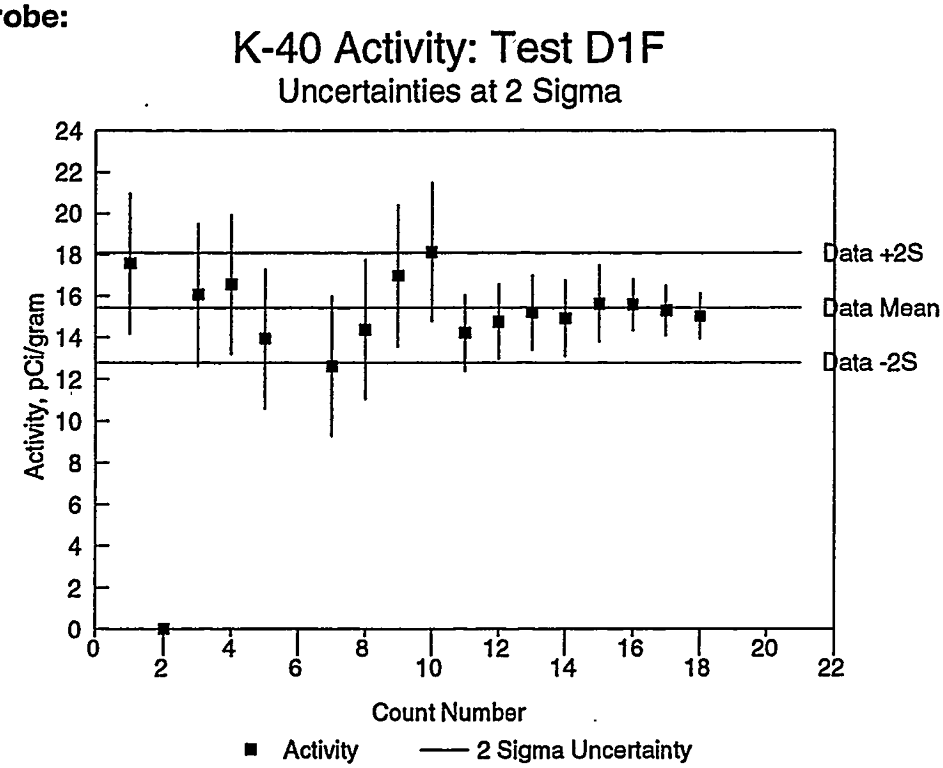
| Test D1F: Nominal Activity = 94.6 pCi/g Total U | | | | | | | Efficiencies from 01/12/95 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Count | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
| USID | | | 2.05 | 0.16 | | | 44.636 | 3.18 | | | | | | | | |
| C01 | 17.58 | 1.71 | 5.39 | 1.73 | | <73 | | <199 | | | | | | | | |
| C02 | | <12.6 | 1.41 | 0.57 | | <72 | | <201 | | | | | | | | |
| C03 | 16.07 | 1.73 | | <3.6 | | <73 | | <199 | | | | | | | | |
| C04 | 15.72 | 1.68 | | <3.6 | | <73 | | <200 | | | | | | | | |
| C05 | 16.57 | 1.70 | | <3.6 | | <73 | | <198 | | | | | | | | |
| C06 | 13.94 | 1.69 | | <3.6 | | <73 | | <200 | | | | | | | | |
| C07 | 12.62 | 1.68 | | <3.6 | | <73 | | <201 | | | | | | | | |
| C08 | 14.38 | 1.69 | | <3.6 | | <73 | | <196 | | | | | | | | |
| C09 | 16.97 | 1.73 | | <3.6 | | <73 | | <197 | | | | | | | | |
| C10 | 18.12 | 1.69 | | <3.6 | | <73 | | <200 | | | | | | | | |
| C11 | 14.22 | 0.93 | | <2.0 | | <40 | | <108 | | | 0.50 | 0.17 | | | | |
| C12 | 14.76 | 0.92 | | <2.0 | | <40 | | <108 | | | | | | | 1.06 | 0.24 |
| C13 | 15.20 | 0.92 | | <2.0 | | <40 | | <108 | | | | | | | 0.72 | 0.24 |
| C14 | 14.93 | 0.93 | 3.85 | 0.98 | | <40 | | <108 | 1.17 | 0.74 | | | 5.17 | 1.71 | 0.70 | 0.13 |
| C15 | 15.63 | 0.94 | | <2.0 | | <40 | | <109 | | | | | | | 0.80 | 0.24 |
| C16 | 15.59 | 0.62 | 3.30 | 0.75 | | <23 | | <62 | | | | | | | 0.49 | 0.19 |
| C17 | 15.31 | 0.61 | | <1.1 | | <23 | | <62 | | | | | | | 1.10 | 0.10 |
| C18 | 15.05 | 0.56 | 2.40 | 0.65 | | <23 | | <62 | | | | | | | 0.84 | 0.22 |
| Avg | 15.45 | 1.32 | 3.27 | 1.35 | | | | | 1.17 | | 0.50 | 0.00 | 5.17 | 0.00 | 0.82 | 0.20 |

### Survey Probe

| Test N1F: Nominal Activity = 94.6 pCi/g Total U | | | | | | | Efficiencies from 01/30/95 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Count | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
| USID | | | 2.05 | 0.16 | | | 44.636 | 3.18 | | | | | | | | |
| C01 | 15.25 | 1.67 | 2.03 | 0.66 | 97.46 | 10.26 | 69.34 | 21.42 | | | 1.22 | 0.25 | 0.92 | 0.48 | | |
| C02 | 12.36 | 1.54 | 1.77 | 0.44 | 96.11 | 23.92 | | <167 | | | 1.14 | 0.25 | 1.54 | 0.52 | | |
| C03 | 10.69 | 1.53 | 1.98 | 0.40 | | <36 | 83.80 | 22.11 | | | 1.19 | 0.25 | | | | |
| C04 | 13.69 | 1.53 | 3.22 | 0.66 | 72.87 | 12.05 | | <167 | | | 0.89 | 0.25 | 0.97 | 0.43 | | |
| C05 | 14.62 | 1.58 | 1.68 | 0.40 | 89.33 | 22.27 | 63.78 | 21.62 | | | | | | | | |
| C06 | 12.07 | 1.53 | 1.67 | 0.39 | 98.04 | 24.79 | | <169 | | | 0.63 | 0.24 | | | | |
| C07 | 13.20 | 1.69 | 1.52 | 0.44 | 99.01 | 24.11 | | <166 | | | | | | | | |
| C08 | 14.55 | 1.56 | 1.86 | 0.40 | 26.09 | 7.02 | | <168 | | | | | | | | |
| C09 | 10.44 | 1.50 | 1.43 | 0.46 | 85.08 | 21.04 | | <168 | | | 1.18 | 0.24 | | | | |
| C10 | 11.00 | 1.55 | 1.18 | 0.41 | 96.08 | 23.62 | | <167 | | | | | | | | |
| C11 | 13.72 | 0.96 | 1.49 | 0.25 | 90.72 | 22.06 | 36.25 | 11.65 | 0.45 | 0.19 | 0.69 | 0.14 | | | | |
| C12 | 13.43 | 0.89 | 2.70 | 0.33 | 95.34 | 23.19 | 52.49 | 10.81 | 0.84 | 0.19 | 0.58 | 0.14 | 0.49 | 0.26 | 0.49 | 0.21 |
| C13 | 12.53 | 0.88 | 1:98 | 0.31 | 96.98 | 23.59 | 65.63 | 13.62 | 0.88 | 0.14 | 0.80 | 0.13 | 0.54 | 0.26 | | |
| C14 | 12.25 | 0.89 | 2.12 | 0.33 | 96.85 | 23.37 | 60.98 | 10.90 | | | 0.70 | 0.13 | 0.48 | 0.26 | 0.69 | 0.14 |
| C15 | 13.82 | 0.97 | 2.81 | 0.33 | 81.44 | 22.51 | 60.05 | 12.02 | 0.73 | 0.19 | 0.56 | 0.13 | 1.07 | 0.26 | | |
| C16 | 13.93 | 0.66 | 2.30 | 0.24 | 96.00 | 22.90 | 32.79 | 6.77 | 0.61 | 0.11 | 0.80 | 0.07 | 0.79 | 0.15 | | |
| C17 | 12.64 | 0.61 | 1.85 | 0.22 | 97.98 | 23.47 | 57.78 | 6.39 | 0.82 | 0.13 | 0.82 | 0.08 | 0.45 | 0.15 | | |
| C18 | 14.41 | 0.64 | 2.33 | 0.22 | 95.27 | 22.93 | 67.61 | 6.40 | 0.72 | 0.11 | 0.86 | 0.07 | | | | |
| Avg | 13.03 | 1.35 | 2.00 | 0.51 | 88.86 | 17.12 | 59.14 | 13.87 | 0.72 | 0.14 | 0.86 | 0.22 | 0.81 | 0.34 | 0.59 | 0.10 |

**Figure 6-17 K-40 Activity: Test 1F (95 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

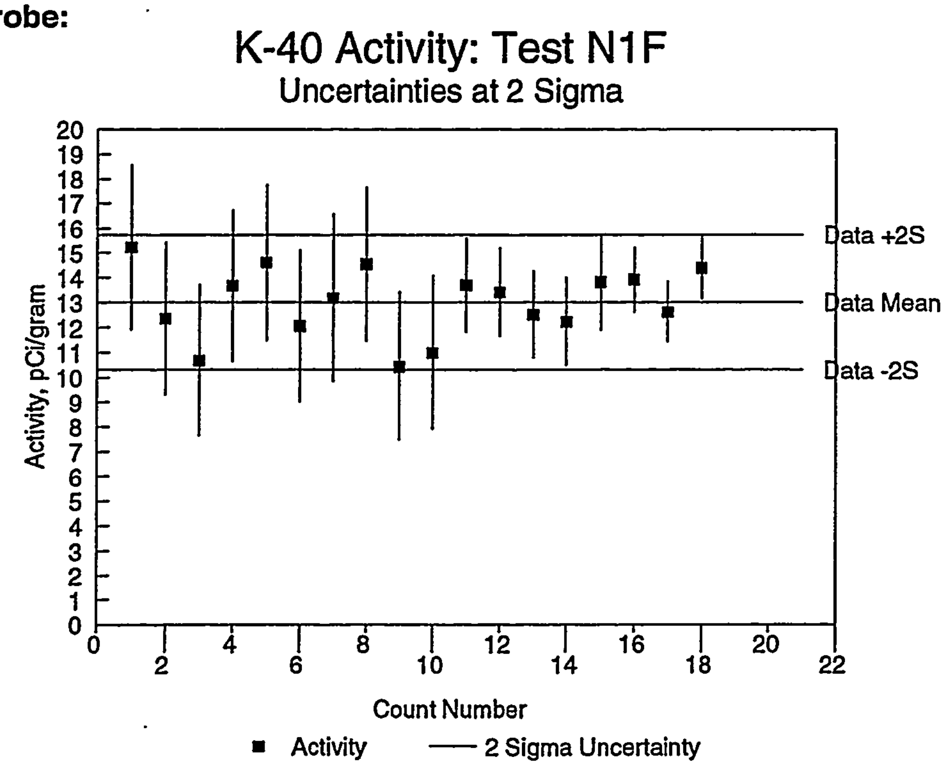
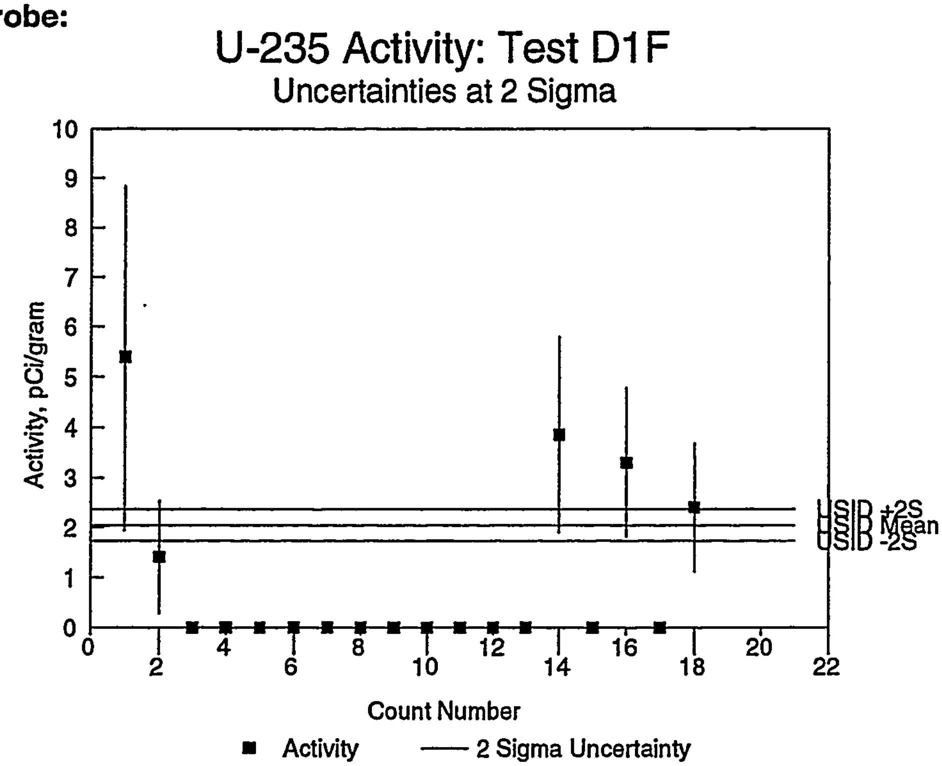


**Figure 6-18 U-235 Activity: Test 1F (95 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

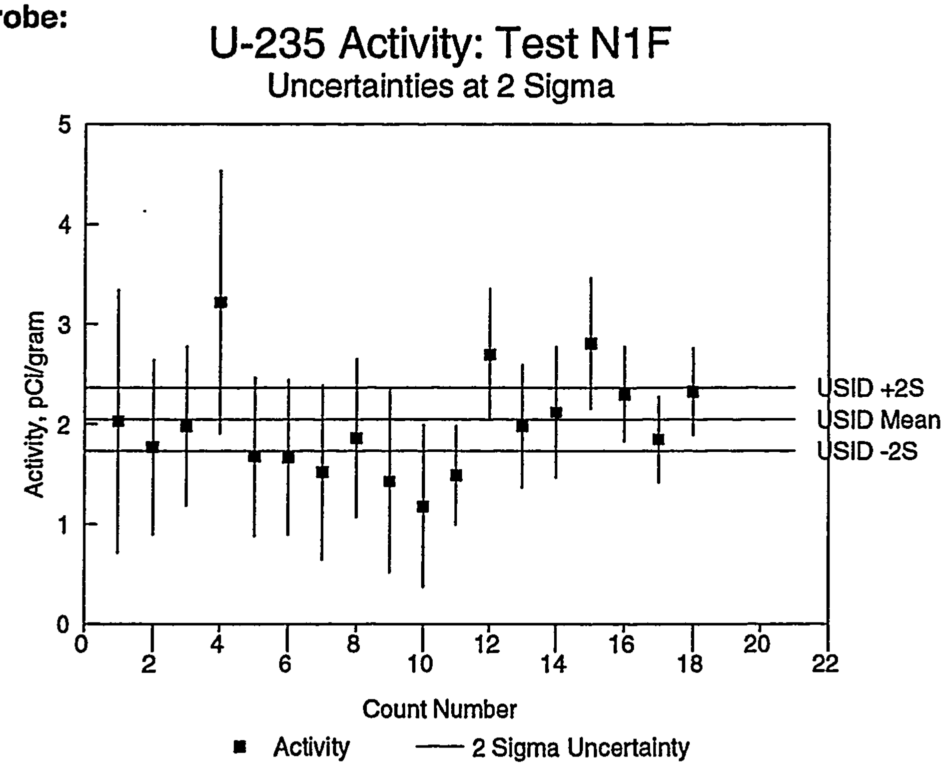
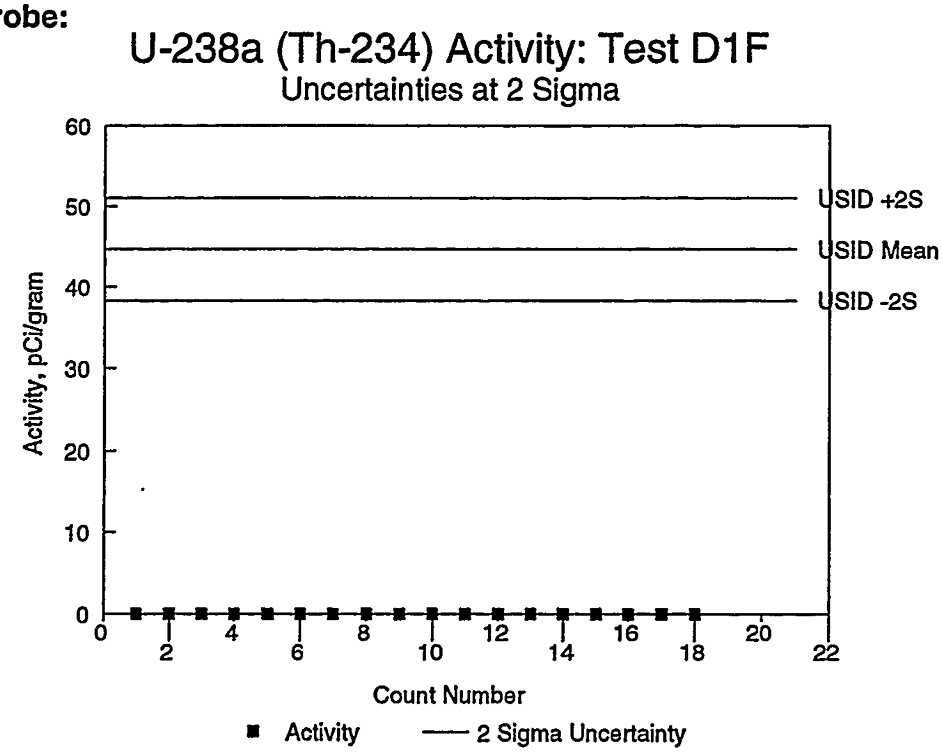


**Figure 6-19 U-238a (Th-234) Activity: Test 1F (95 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

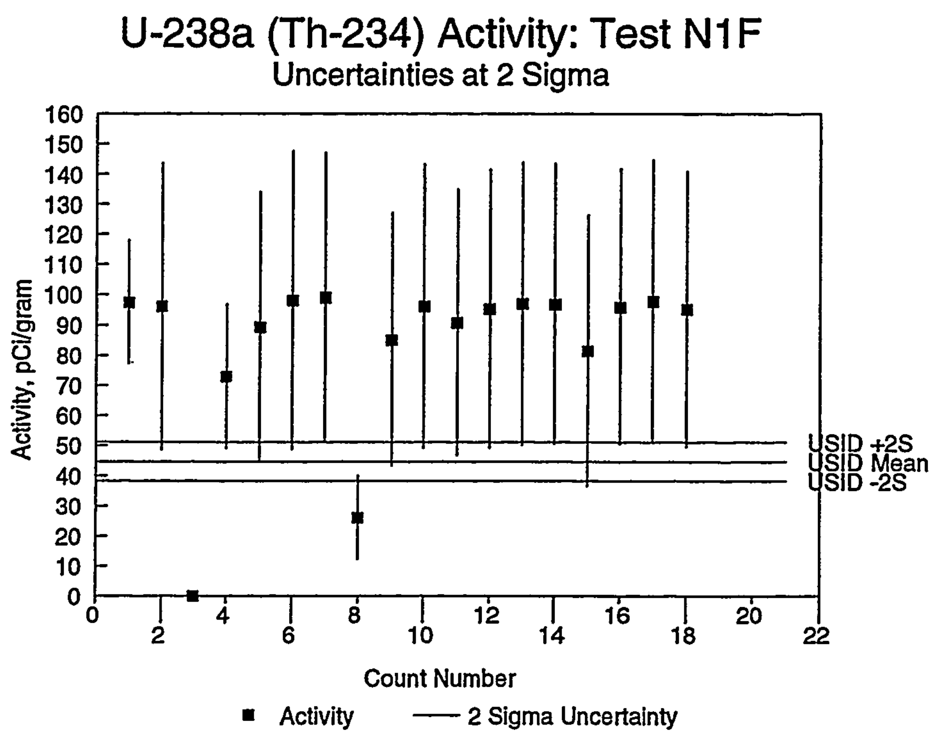
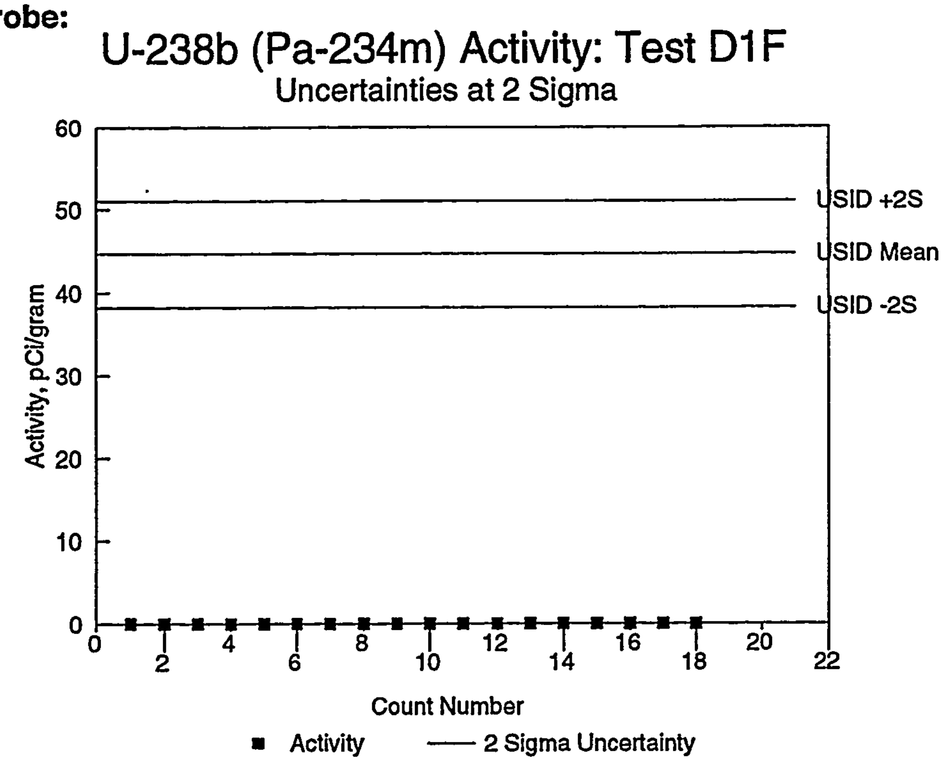
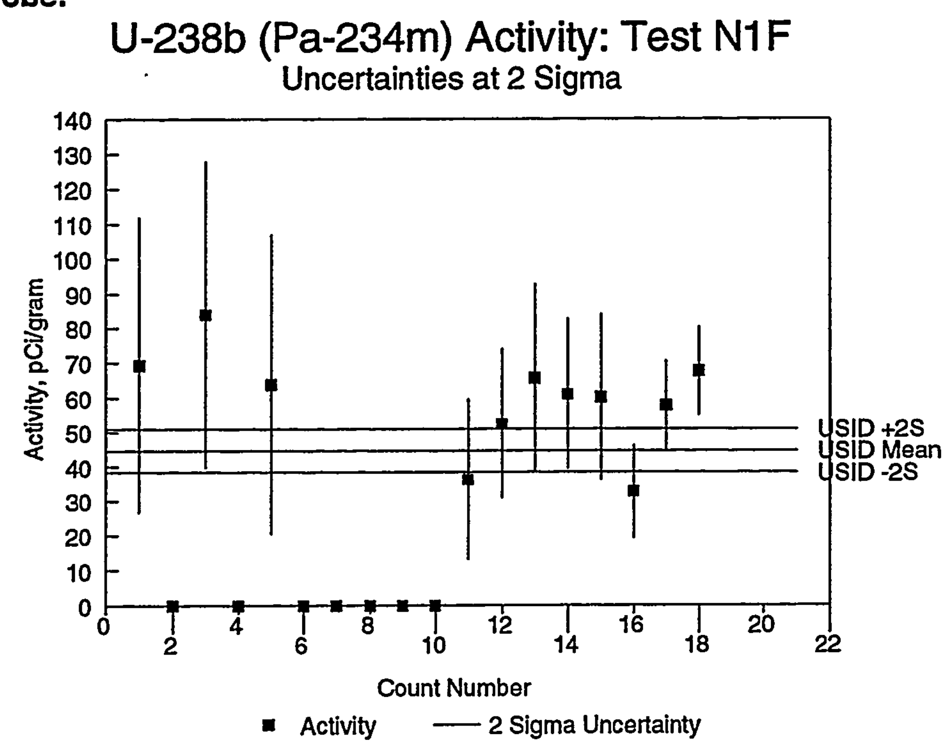


**Figure 6-20 U-238b (Pa-234m) Activity: Test 1F (95 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**



## Figure 6-21 Results Summary: Test 1C (162 pCi/g Total U)

### LPRMS Probe

Test D1C: Nominal Activity = 162.2 pCi/g Total U — Efficiencies from 01/30/95

| Count USID | K-40 | +- | U-235 3.451 | +- 1.56 | U-238a | +- | U-238b 79.241 | +- 33.2 | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C01 | 13.72 | 1.91 | <4.4 | | <88 | | <244 | | | | | | | | | |
| C02 | 15.11 | 1.85 | 2.49 | 1.78 | <88 | | <243 | | | | | | | | | |
| C03 | <15.5 | | <4.4 | | <88 | | <245 | | | | | | | | | |
| C04 | 13.51 | 1.89 | <4.4 | | <89 | | <244 | | | | | | | | | |
| C05 | 13.78 | 1.92 | <4.4 | | <89 | | <244 | | | | | | | | | |
| C06 | 17.68 | 1.96 | <4.4 | | <89 | | <243 | | | | 1.31 | 0.36 | | | | |
| C07 | <15.5 | | <4.4 | | <89 | | <245 | | | | | | | | | |
| C08 | 13.12 | 1.91 | <4.4 | | <89 | | <245 | | | | | | | | | |
| C09 | 13.75 | 1.94 | <4.4 | | <88 | | <243 | | | | | | | | | |
| C10 | 16.87 | 1.96 | <4.4 | | <89 | | <246 | | | | | | | | | |
| C11 | 14.58 | 1.08 | <2.4 | | <48 | | <134 | | | | 0.63 | 0.20 | | | | |
| C12 | 15.29 | 1.07 | 2.08 | 1.26 | <49 | | 82.09 | 16.38 | | | | | | | | |
| C13 | 15.77 | 1.07 | <2.4 | | <49 | | <134 | | | | | | | | | |
| C14 | 14.32 | 1.07 | <2.4 | | <49 | | <133 | | | | | | | | | |
| C15 | 14.83 | 1.07 | <2.4 | | <49 | | <133 | | | | | | | | | |
| C16 | 14.55 | 0.73 | 2.02 | 1.15 | <28 | | <77 | | | | | | | | 0.76 | 0.20 |
| C17 | 14.99 | 0.81 | 1.46 | 0.78 | <28 | | <76 | | | | | | | | 0.58 | 0.17 |
| Avg | 14.79 | 1.21 | 2:01 | 0.37 | | | 82.09 | | | | 0.97 | 0.34 | | | 0.67 | 0.09 |

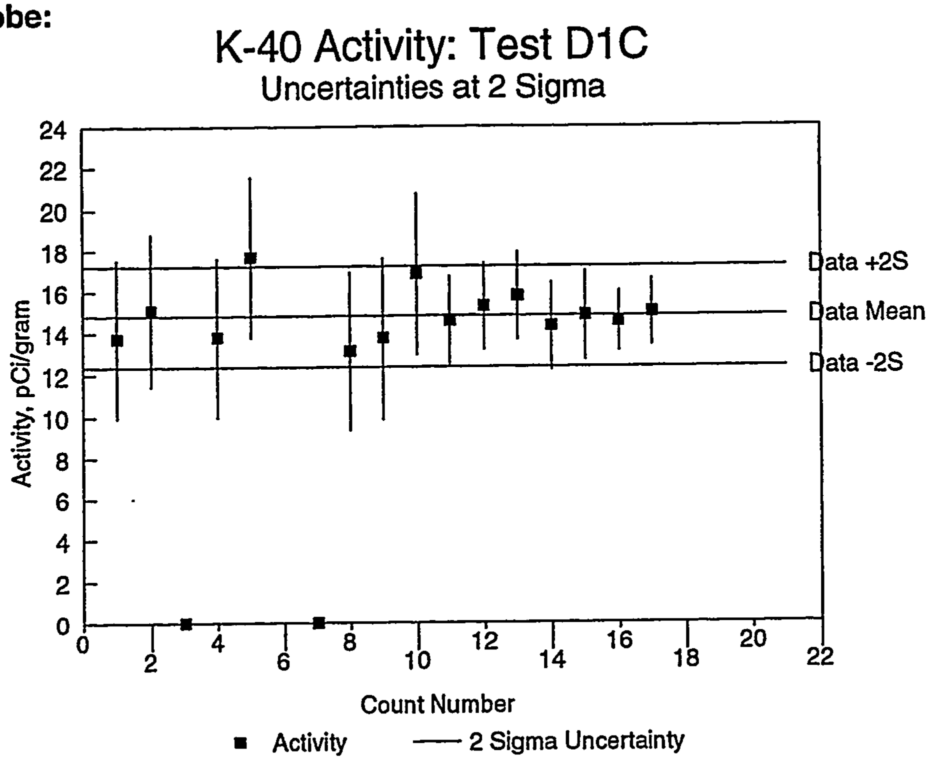
### Survey Probe

Test N1C: Nominal Activity = 162.2 pCi/g Total U — Efficiencies from 01/30/95

| Count USID | K-40 | +- | U-235 3.451 | +- 1.56 | U-238a | +- | U-238b 79.241 | +- 33.2 | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C01 | 9.92 | 1.93 | 3.38 | 0.52 | <46 | | 111.53 | 26.87 | | | | | 1.82 | 0.55 | | |
| C02 | 14.03 | 1.85 | 3.40 | 0.53 | <46 | | <210 | | | | 1.21 | 0.29 | | | | |
| C03 | 15.48 | 1.79 | 3.38 | 0.52 | <46 | | 66.87 | 24.64 | | | 0.89 | 0.29 | | | | |
| C04 | 16.80 | 1.91 | 3.28 | 0.52 | <46 | | 120.83 | 26.62 | | | | | | | | |
| C05 | 17.20 | 1.86 | 2.91 | 0.48 | <46 | | 129.83 | 26.08 | | | | | | | 1.17 | 0.43 |
| C06 | 15.06 | 1.79 | 3.59 | 0.52 | 109.91 | 30.70 | 78.30 | 25.85 | | | 1.12 | 0.29 | 1.72 | 0.35 | | |
| C07 | 15.33 | 1.76 | 3.24 | 0.48 | <46 | | <209 | | | | | | | | | |
| C08 | 15.06 | 1.77 | 3.82 | 0.66 | 94.49 | 25.54 | 83.75 | 26.24 | | | 0.95 | 0.28 | | | | |
| C09 | 14.11 | 1.77 | 3.02 | 0.48 | 89.08 | 27.71 | 78.25 | 26.53 | | | | | | | | |
| C10 | 13.22 | 1.85 | 2.92 | 0.49 | 83.62 | 28.47 | 80.74 | 26.63 | | | | | | | | |
| C11 | 13.74 | 1.16 | 3.24 | 0.30 | 94.14 | 25.87 | 62.14 | 14.14 | 0.54 | 0.23 | 0.54 | 0.17 | | | 0.65 | 0.26 |
| C12 | 15.66 | 1.04 | 3.48 | 0.29 | 98.38 | 27.27 | 78.19 | 13.37 | | | | | 0.98 | 0.30 | 0.88 | 0.23 |
| C13 | 14.71 | 1.11 | 3.00 | 0.29 | 95.72 | 27.08 | 97.77 | 13.23 | | | 0.48 | 0.17 | 0.76 | 0.19 | 0.58 | 0.25 |
| C14 | 12.38 | 1.16 | 3.01 | 0.30 | 89.17 | 24.56 | 78.09 | 14.30 | | | 0.64 | 0.16 | 0.60 | 0.30 | | |
| C15 | 13.49 | 1.04 | 3.64 | 0.29 | 100.88 | 28.19 | 67.35 | 14.47 | | | | | 0.56 | 0.19 | 0.76 | 0.23 |
| C16 | 15.66 | 0.73 | 3.78 | 0.20 | 100.08 | 27.29 | 75.73 | 7.68 | 0.57 | 0.13 | 0.65 | 0.09 | 0.55 | 0.17 | 0.88 | 0.15 |
| C17 | 13.46 | 0.75 | 3.56 | 0.20 | 96.61 | 27.19 | 89.83 | 8.73 | 0.71 | 0.13 | 0.65 | 0.09 | 0.87 | 0.19 | 0.51 | 0.15 |
| C18 | 11.37 | 0.96 | 4.61 | 0.31 | 18.27 | 7.30 | 85.92 | 8.13 | 0.50 | 0.14 | 1.04 | 0.10 | 0.61 | 0.20 | | |
| Avg | 14.26 | 1.77 | 3.40 | 0.40 | 89.20 | 22.32 | 86.57 | 18.71 | 0.58 | 0.08 | 0.82 | 0.24 | 0.94 | 0.46 | 0.78 | 0.21 |

**Figure 6-22 K-40 Activity: Test 1C (162 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

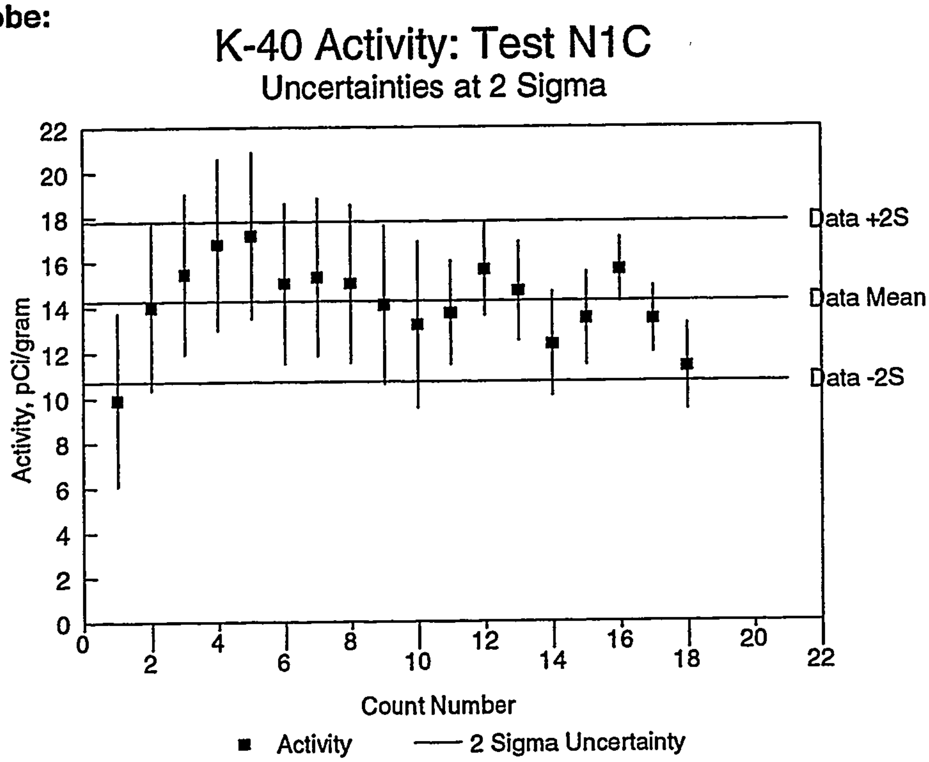
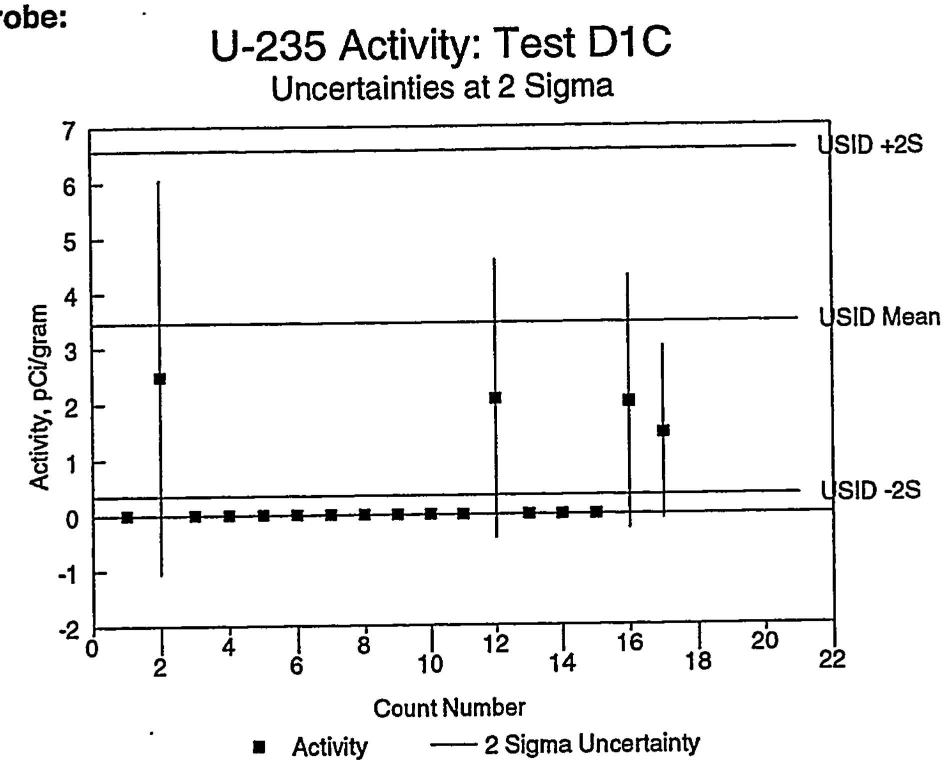


**Figure 6-23 U-235 Activity: Test 1C (162 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

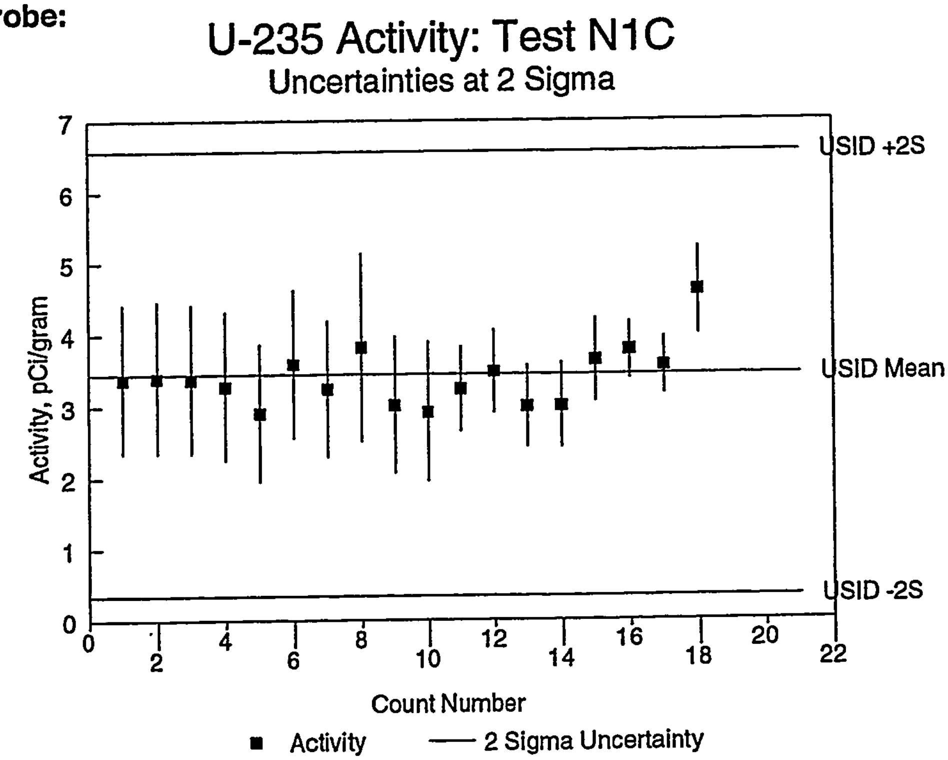
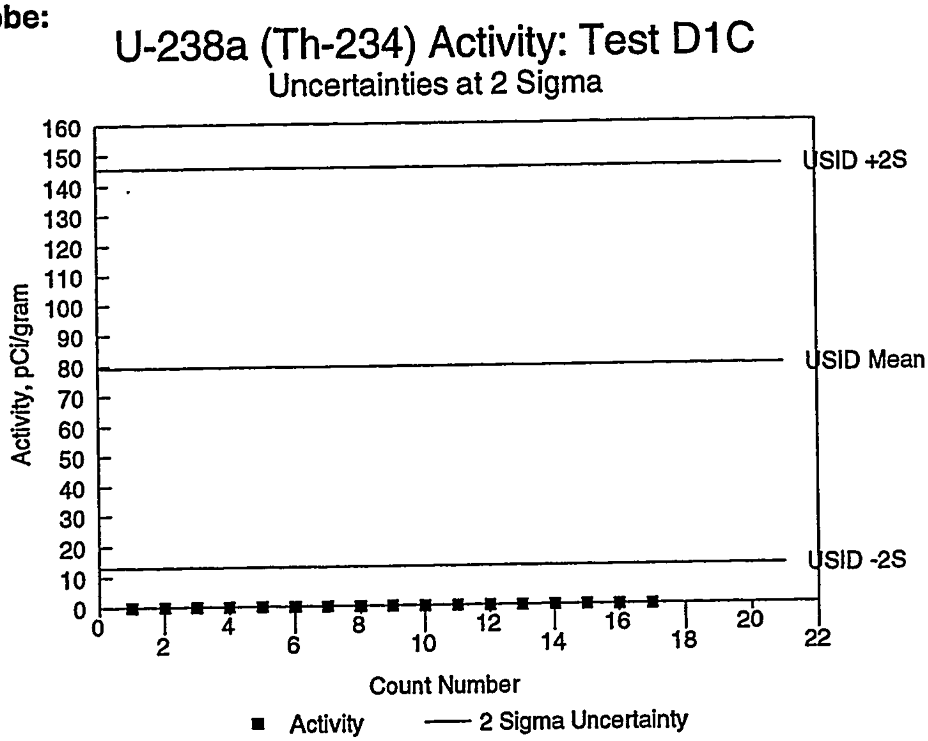


**Figure 6-24 U-238a (Th-234) Activity: Test 1C (162 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

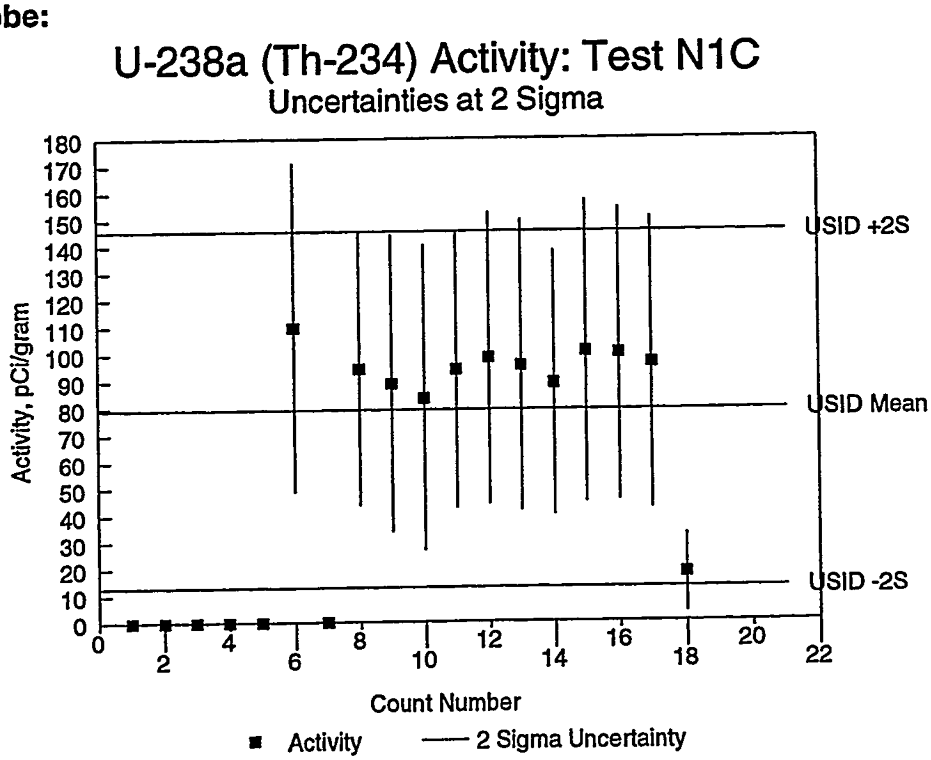
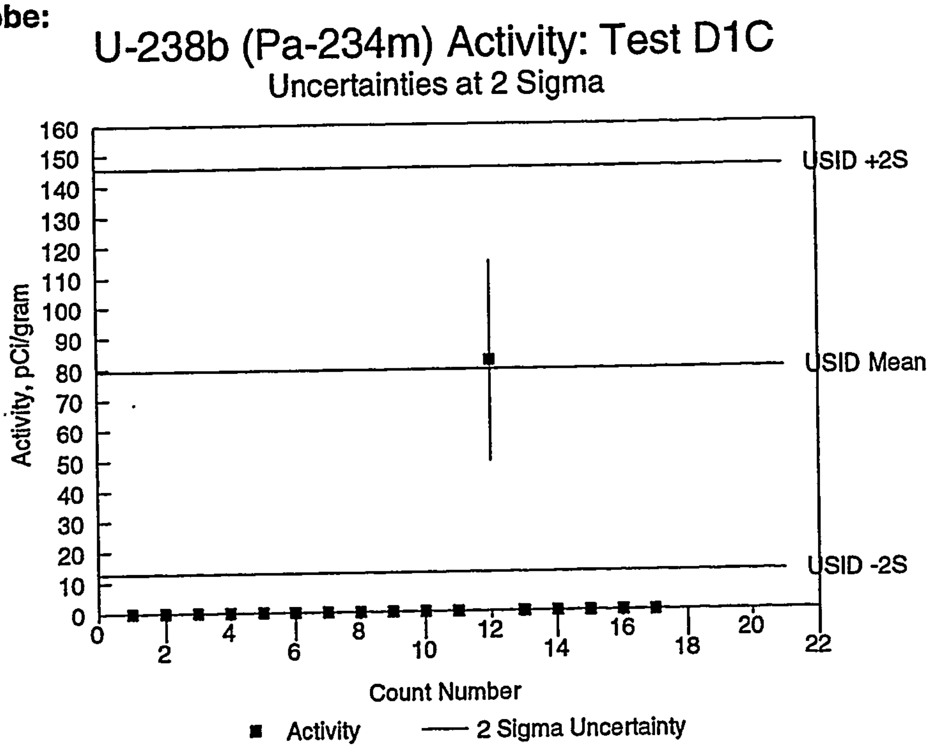
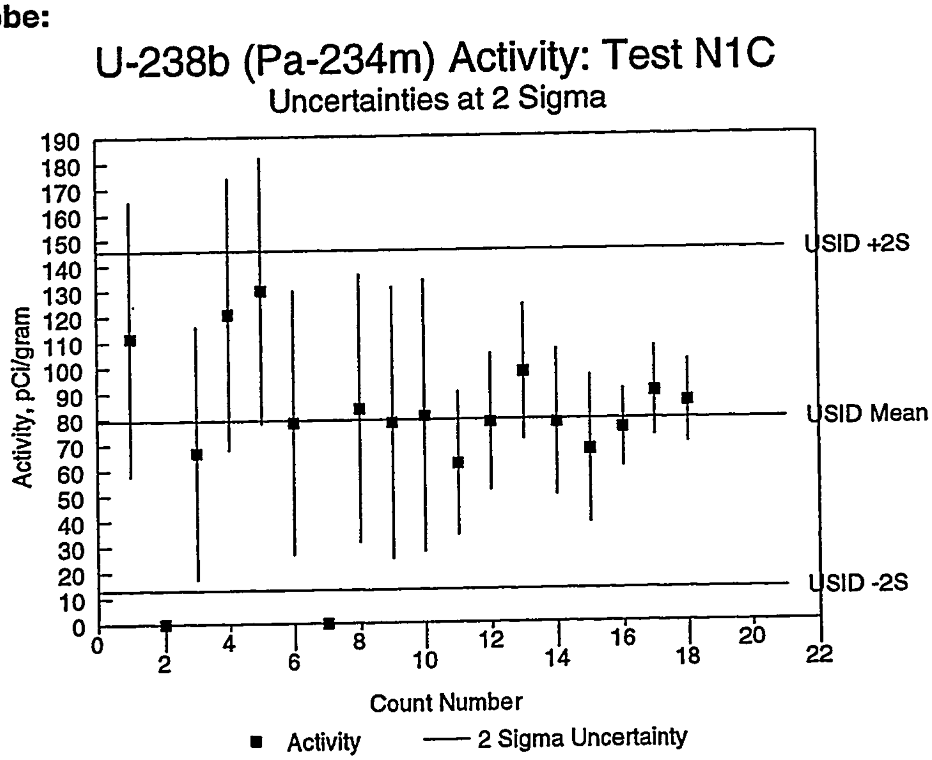


**Figure 6-25 U-238b (Pa-234m) Activity: Test 1C (162 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**



## Figure 6-26 Results Summary: Test 1G (162 pCi/g Total U)

### LPRMS Probe

Test D1G: Nominal Activity = 162.2 pCi/g Total U — Efficiencies from 01/12/95

| Count USID | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 3.451 | 1.56 | | | 79.241 | 33.2 | | | | | | | | |
| C01 | 16.03 | 1.56 | | <3.4 | | <69 | | <183 | | | | | | | | |
| C02 | 11.12 | 1.49 | | <3.3 | | <69 | | <180 | | | | | | | | |
| C03 | 12.40 | 1.54 | 1.48 | 0.49 | | <69 | | <181 | | | | | | | | |
| C04 | 11.98 | 1.59 | 1.86 | 0.49 | | <69 | | <181 | | | 1.09 | 0.28 | | | | |
| C05 | 11.10 | 1.58 | | <3.3 | | <69 | 82.48 | 22.73 | | | | | | | | |
| C06 | 11.73 | 1.52 | 1.74 | 0.54 | | <69 | | <180 | | | | | | | | |
| C07 | 14.33 | 1.50 | | <3.3 | | <69 | | <178 | | | | | | | | |
| C08 | | <11.1 | | <3.3 | | <69 | | <182 | | | | | | | | |
| C09 | 12.69 | 1.52 | 3.20 | 0.98 | | <69 | | <183 | | | | | | | | |
| C10 | 15.54 | 1.58 | 1.57 | 0.49 | | <69 | | <181 | | | | | | | | |
| C11 | 12.41 | 0.86 | | <1.8 | | <38 | | <100 | | | 0.46 | 0.15 | | | | |
| C12 | 10.77 | 0.84 | | <1.8 | | <38 | 59.15 | 12.86 | | | | | | | 0.73 | 0.22 |
| C13 | 10.73 | 0.91 | | <1.8 | | <38 | | <98 | | | | | | | 0.92 | 0.23 |
| C14 | 11.17 | 0.88 | 2.60 | 0.96 | | <38 | | <98 | | | | | | | | |
| C15 | 11.70 | 0.90 | 1.04 | 0.36 | | <38 | | <98 | | | | | | | 0.70 | 0.22 |
| C16 | 10.58 | 0.74 | 1.01 | 0.34 | | <22 | | <56 | | | 0.52 | 0.10 | | | | |
| C17 | 10.82 | 0.71 | | <1.1 | | <22 | | <56 | | | | | | | 0.68 | 0.13 |
| C18 | 11.64 | 0.65 | 1.06 | 0.34 | | <22 | | <57 | 0.51 | 0.10 | 0.48 | 0.09 | | | | |
| Avg | 12.16 | 1.60 | 1.73 | 0.70 | | | 70.82 | 11.67 | 0.51 | 0.00 | 0.64 | 0.26 | | | 0.76 | 0.10 |

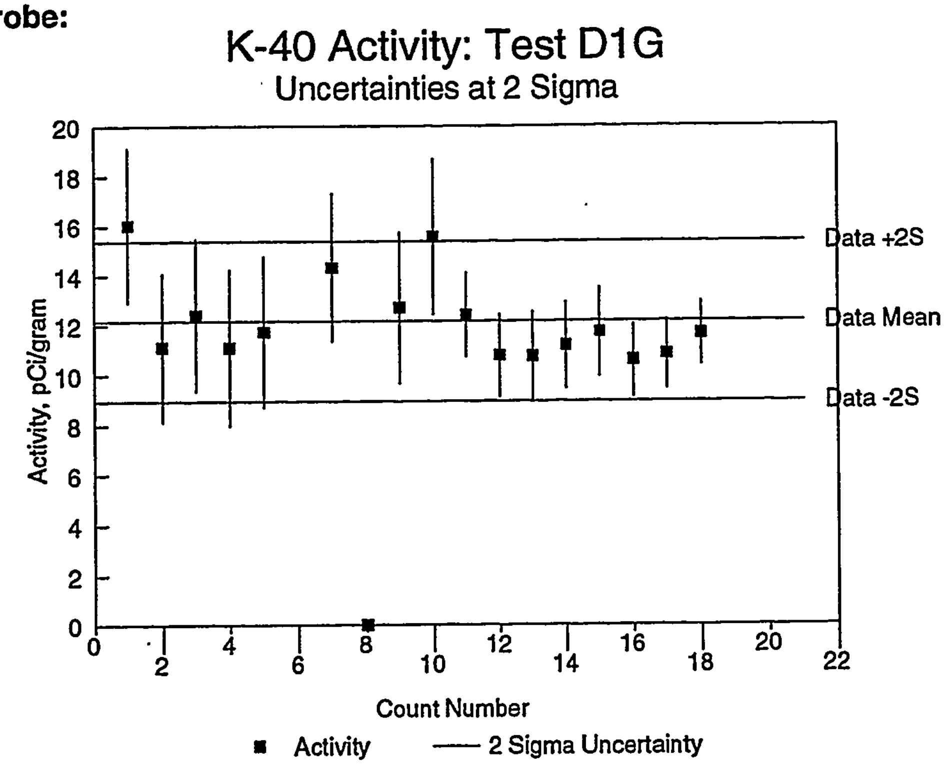
### Survey Probe

Test N1G: Nominal Activity = 162.2 pCi/g Total U — Efficiencies from 01/30/95

| Count USID | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 3.451 | 1.56 | | | 79.241 | 33.2 | | | | | | | | |
| C01 | 12.16 | 1.47 | 3.18 | 0.51 | 52.02 | 12.51 | | <165 | | | 0.61 | 0.23 | 1.62 | 0.49 | | |
| C02 | 14.81 | 1.43 | 3.55 | 0.41 | 118.98 | 30.41 | 98.70 | 20.93 | 0.85 | 0.33 | | | | | | |
| C03 | 11.19 | 1.40 | 3.44 | 0.46 | 136.28 | 32.25 | 61.20 | 21.31 | | | | | | | | |
| C04 | 10.59 | 1.36 | 3.92 | 0.42 | 153.16 | 36.27 | 99.28 | 21.38 | 1.17 | 0.33 | 0.73 | 0.24 | | | | |
| C05 | 12.37 | 1.52 | 3.38 | 0.45 | 138.50 | 33.42 | 102.94 | 20.74 | | | | | | | | |
| C06 | 15.62 | 1.51 | 5.39 | 0.58 | 132.26 | 9.60 | | <164 | | | | | | | | |
| C07 | 15.71 | 1.60 | 2.75 | 0.46 | 140.22 | 33.50 | | <163 | 1.14 | 0.34 | 1.11 | 0.26 | 0.95 | 0.49 | | |
| C08 | 11.94 | 1.49 | 3.51 | 0.54 | 158.31 | 37.41 | | <164 | | | 0.77 | 0.23 | | | | |
| C09 | 14.90 | 1.58 | 4.01 | 0.41 | 25.79 | 8.17 | 66.97 | 20.99 | | | 1.07 | 0.24 | | | | |
| C10 | 10.95 | 1.49 | 3.59 | 0.46 | 153.96 | 36.61 | | <161 | | | 1.20 | 0.24 | 1.18 | 0.48 | | |
| C11 | 11.50 | 0.84 | 3.19 | 0.31 | 146.05 | 34.49 | 77.90 | 10.81 | 0.67 | 0.18 | 0.82 | 0.12 | | | | |
| C12 | 14.10 | 0.91 | 2.80 | 0.36 | 149.07 | 35.47 | 68.03 | 11.08 | | | 0.85 | 0.13 | | | | |
| C13 | 13.95 | 0.83 | 4.18 | 0.38 | 16.16 | 6.73 | 80.24 | 10.83 | 0.83 | 0.19 | 0.78 | 0.13 | 0.54 | 0.27 | | |
| C14 | 12.64 | 0.83 | 4.45 | 0.40 | 39.26 | 8.84 | 72.74 | 10.87 | | | 0.71 | 0.13 | | | | |
| C15 | 12.58 | 0.87 | 4.00 | 0.40 | 81.26 | 5.92 | 72.39 | 11.13 | 0.49 | 0.19 | 0.78 | 0.12 | 0.75 | 0.27 | | |
| C16 | 13.24 | 0.67 | 4.29 | 0.30 | 15.92 | 6.74 | 66.39 | 6.21 | 0.81 | 0.08 | 0.84 | 0.07 | 0.45 | 0.16 | | |
| C17 | 12.31 | 0.74 | 4.44 | 0.28 | 139.05 | 8.98 | 81.49 | 6.32 | 0.70 | 0.11 | 0.71 | 0.07 | 1.19 | 0.38 | | |
| C18 | 11.75 | 0.79 | 4.11 | 0.31 | 138.96 | 7.72 | 71.86 | 6.25 | 0.36 | 0.11 | 0.74 | 0.07 | 1.30 | 0.36 | | |
| Avg | 12.91 | 1.55 | 3.79 | 0.64 | 107.51 | 51.35 | 78.47 | 13.16 | 0.78 | 0.25 | 0.84 | 0.16 | 1.00 | 0.37 | | |

**Figure 6-27 K-40 Activity: Test 1G (162 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

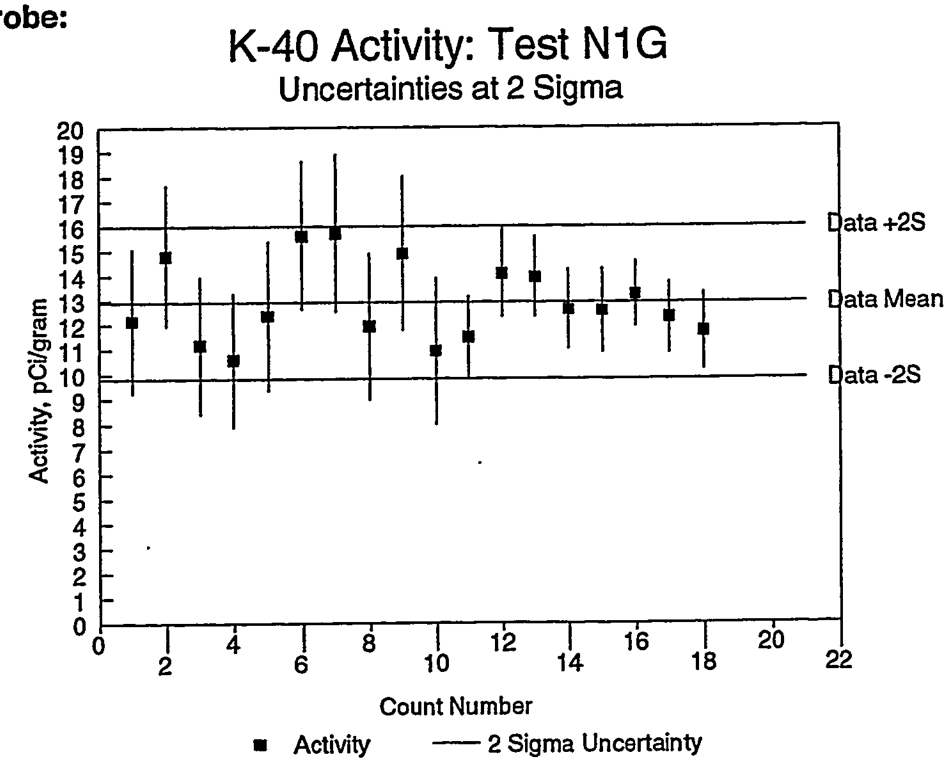
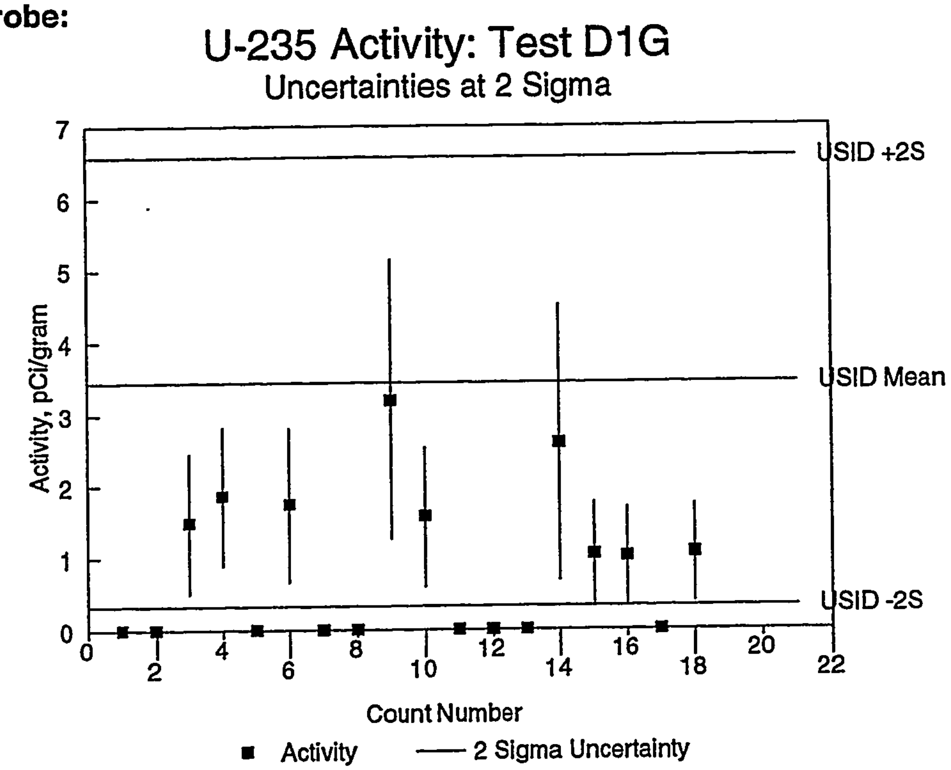


**Figure 6-28 U-235 Activity: Test 1G (162 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

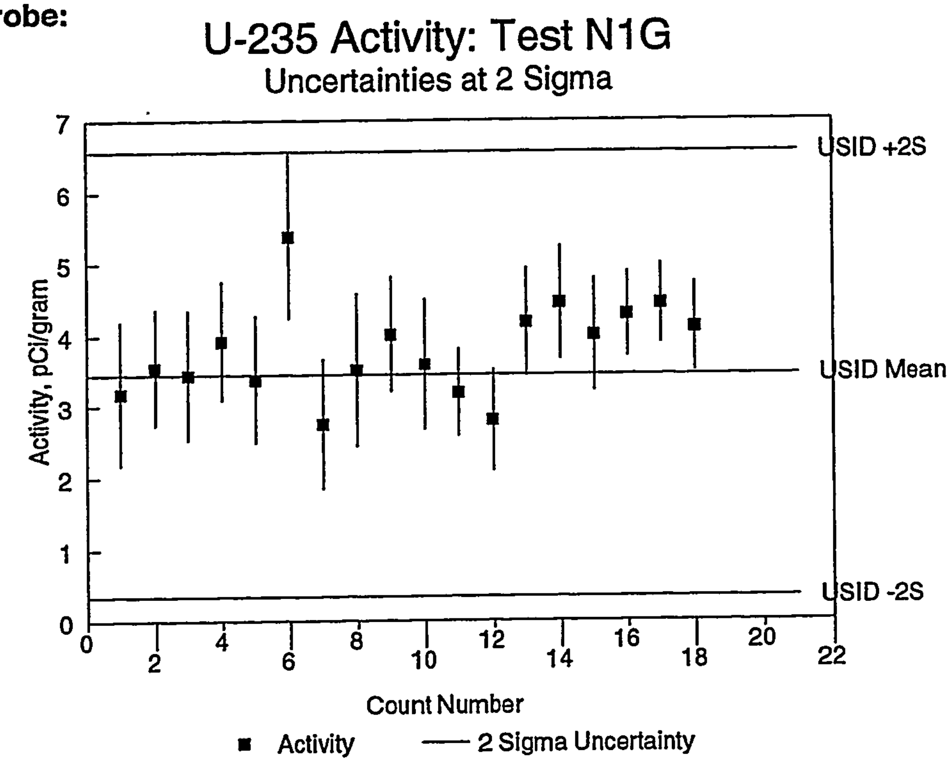
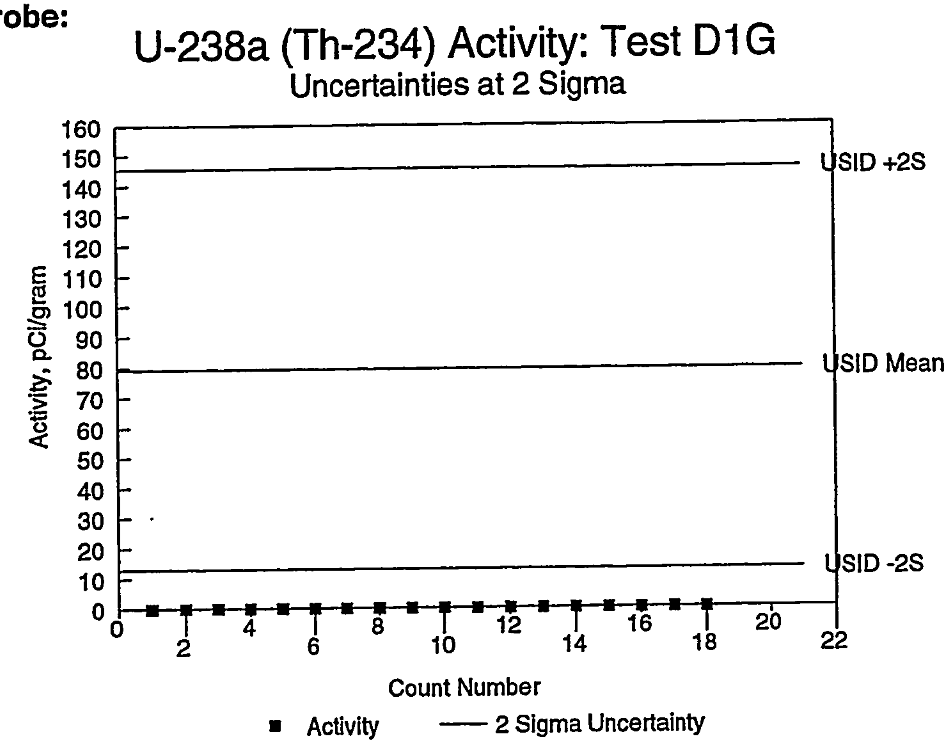


**Figure 6-29 U-238a (Th-234) Activity: Test 1G (162 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

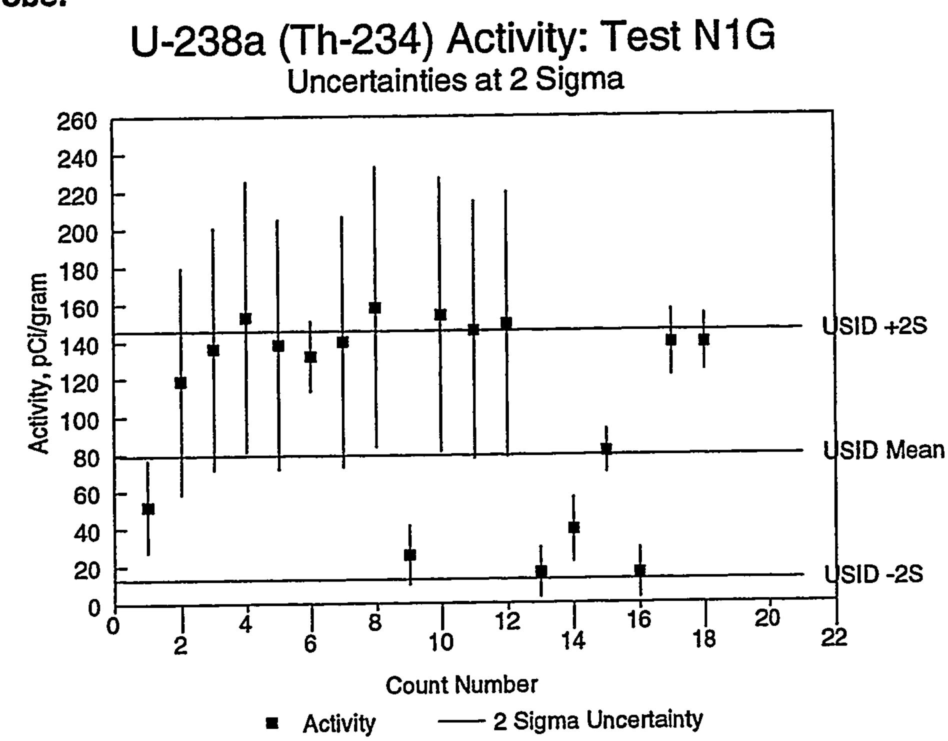
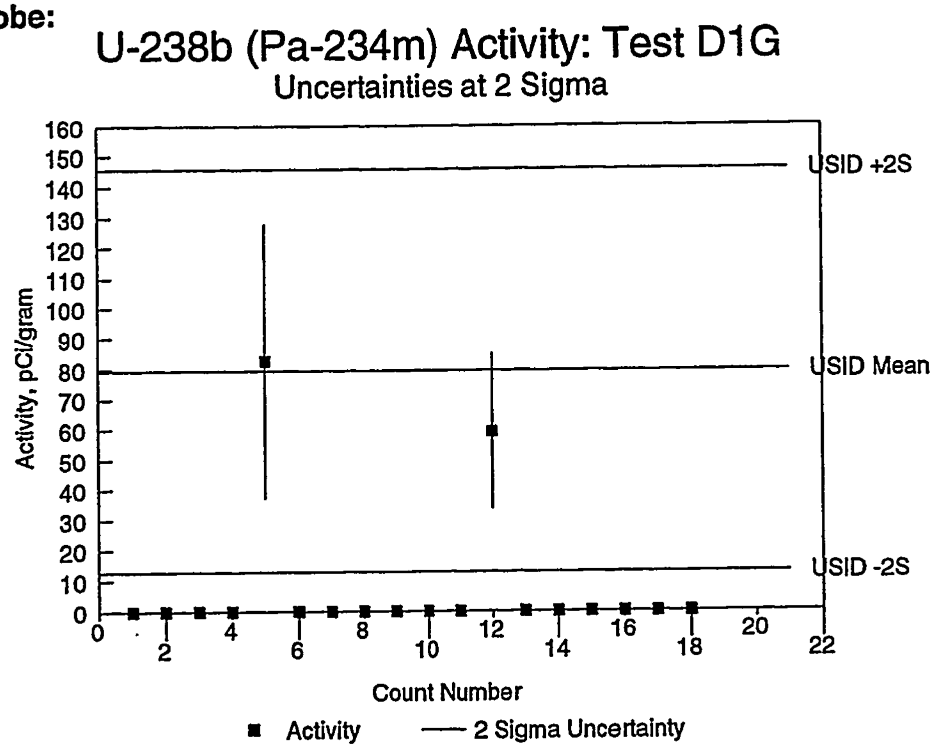
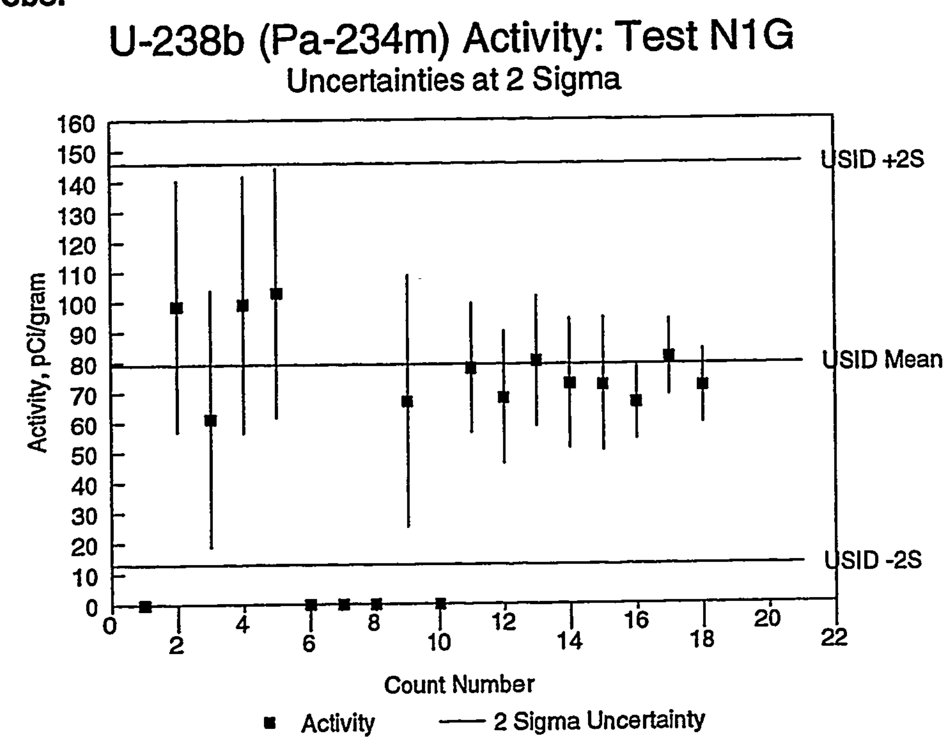


**Figure 6-30 U-238b (Pa-234m) Activity: Test 1G (162 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**



## Figure 6-31 Results Summary: Test 1E (311 pCi/g Total U)

### LPRMS Probe

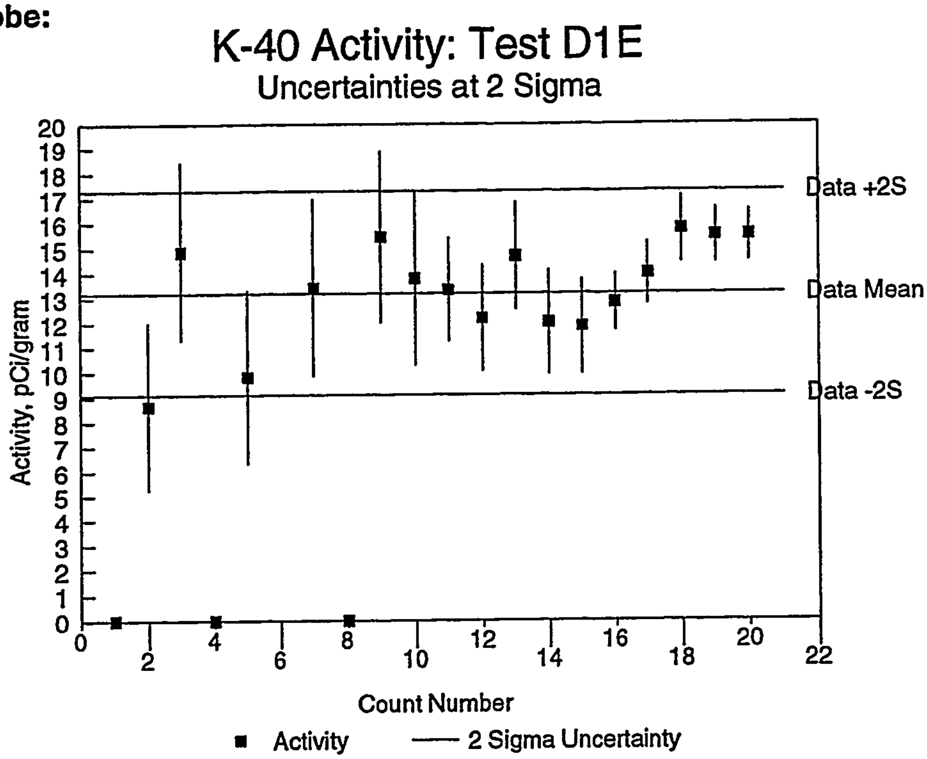
| Test D1E: Nominal Activity = 311.8 pCi/g Total U Count USID | K-40 | +- | U-235 6.693 | +- 0.95 | U-238a | +- | U-238b 155.6 (Efficiencies from 01/30/95) | +- 15.5 | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C01 | <13.7 | | 5.37 | 0.78 | <93 | | 90.04 | 39.73 | | | | | | | | |
| C02 | 8.63 | 1.70 | 2.47 | 0.89 | <93 | | <233 | | | | | | | | | |
| C03 | 14.86 | 1.79 | <4.6 | | <94 | | 192.96 | 27.68 | | | | | | | | |
| C04 | 10.67 | 1.75 | 4.18 | 0.89 | <93 | | <235 | | | | | | | | | |
| C05 | <13.8 | | 13.85 | 1.98 | <94 | | <235 | | | | | | | | | |
| C06 | 9.82 | 1.75 | 5.03 | 0.70 | <93 | | <234 | | | | | | | | | |
| C07 | 13.41 | 1.78 | <4.6 | | <94 | | <234 | | | | | | | | | |
| C08 | <13.7 | | 4.64 | 0.95 | <93 | | <232 | | | | | | | | 1.57 | 0.53 |
| C09 | 15.44 | 1.71 | 5.06 | 0.82 | <93 | | <233 | | | | | | | | | |
| C10 | 13.78 | 1.76 | 4.08 | 0.82 | <93 | | 190.60 | 60.60 | 1.95 | 0.40 | | | | | | |
| C11 | 13.33 | 1.04 | 5.39 | 0.59 | <51 | | 162.21 | 18.00 | | | | | | | | |
| C12 | 12.19 | 1.08 | 4.28 | 0.63 | <51 | | <127 | | | | | | | | 0.91 | 0.29 |
| C13 | 14.68 | 1.08 | 5.10 | 0.60 | <51 | | <128 | | | | 0.76 | 0.22 | | | | |
| C14 | 12.02 | 1.06 | 4.67 | 0.55 | <51 | | <127 | | | | | | | | | |
| C15 | 11.84 | 0.96 | 4.20 | 0.65 | <51 | | <128 | | | | | | | | | |
| C16 | 12.82 | 0.58 | <1.5 | | <29 | | 154.51 | 10.26 | | | 0.45 | 0.13 | | | | |
| C17 | 13.99 | 0.63 | 11.93 | 0.87 | <29 | | 163.75 | 12.16 | | | 0.47 | 0.13 | | | | |
| C18 | 15.76 | 0.67 | 2.86 | 0.35 | <29 | | 149.16 | 13.02 | | | 0.49 | 0.14 | | | | |
| C19 | 15.49 | 0.55 | 2.70 | 0.40 | <20 | | 155.60 | 8.98 | | | 0.58 | 0.06 | | | | |
| C20 | 15.51 | 0.51 | 2.85 | 0.42 | <17 | | 156.71 | 7.70 | | | | | | | 0.68 | 0.07 |
| Avg | 13.19 | 2.05 | 5.22 | 2.97 | | | 157.28 | 27.98 | 1.95 | | 0.55 | 0.11 | | | 1.05 | 0.38 |

### Survey Probe

| Test N1E: Nominal Activity = 311.8 pCi/g Total U Count USID | K-40 | +- | U-235 6.693 | +- 0.95 | U-238a | +- | U-238b 155.6 (Efficiencies from 01/30/95) | +- 15.5 | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C01 | 10.97 | 1.62 | 7.80 | 0.56 | 268.83 | 65.44 | 140.80 | 24.87 | | | | | | | | |
| C02 | 9.00 | 1.55 | 8.16 | 0.62 | 66.70 | 17.13 | 188.53 | 26.69 | | | | | | | | |
| C03 | 12.22 | 1.67 | 6.87 | 0.55 | 112.60 | 25.90 | 121.09 | 25.30 | | | | | | | 1.24 | 0.43 |
| C04 | 13.86 | 1.71 | 8.21 | 0.60 | 108.42 | 22.81 | 136.64 | 26.70 | | | | | 1.69 | 0.59 | | |
| C05 | 13.87 | 1.58 | 7.29 | 0.57 | 111.44 | 23.64 | 191.64 | 24.09 | | | 1.36 | 0.29 | | | | |
| C06 | 10.52 | 1.60 | 8.64 | 0.83 | 137.52 | 11.80 | 212.27 | 19.43 | | | | | | | | |
| C07 | 12.52 | 1.55 | 9.01 | 0.91 | 102.65 | 22.12 | 143.28 | 26.10 | 1.00 | 0.40 | 0.80 | 0.29 | | | | |
| C08 | 13.49 | 1.67 | 6.92 | 0.55 | 84.65 | 19.61 | 220.55 | 26.95 | | | | | | | 1.43 | 0.43 |
| C09 | 10.98 | 1.60 | 7.34 | 0.54 | 104.22 | 22.65 | 175.70 | 23.79 | | | 0.97 | 0.31 | | | 1.14 | 0.32 |
| C10 | 13.17 | 1.68 | 7.54 | 0.55 | 99.09 | 22.05 | 173.82 | 24.18 | | | | | | | | |
| C11 | 13.78 | 0.92 | 7.56 | 0.29 | 85.90 | 19.38 | 165.40 | 13.63 | 0.96 | 0.17 | 0.49 | 0.17 | | | 0.95 | 0.15 |
| C12 | 12.18 | 0.95 | 7.79 | 0.48 | 107.70 | 24.39 | 177.47 | 13.65 | | | 0.84 | 0.17 | | | 1.03 | 0.15 |
| C13 | 10.39 | 1.11 | 7.65 | 0.45 | 104.28 | 21.92 | 180.98 | 13.24 | 0.87 | 0.17 | 0.70 | 0.16 | | | | |
| C14 | 9.36 | 0.95 | 9.58 | 0.57 | 207.93 | 12.05 | 169.68 | 13.30 | | | 0.70 | 0.16 | 1.63 | 0.67 | | |
| C15 | 11.96 | 1.05 | 7.89 | 0.42 | 114.79 | 25.57 | 178.05 | 13.27 | 0.78 | 0.23 | 0.64 | 0.16 | | | | |
| C16 | 12.77 | 0.72 | 9.28 | 0.33 | 166.30 | 10.81 | 160.98 | 9.05 | 0.42 | 0.13 | 0.83 | 0.09 | 1.37 | 0.39 | 1.08 | 0.08 |
| C17 | 12.30 | 0.64 | 9.06 | 0.40 | 92.83 | 20.16 | 169.51 | 7.95 | 0.45 | 0.13 | 0.59 | 0.09 | 0.37 | 0.19 | 1.19 | 0.09 |
| C18 | 10.52 | 0.89 | 9.25 | 0.49 | 122.04 | 9.13 | 154.23 | 9.00 | 0.60 | 0.10 | 0.93 | 0.09 | 1.69 | 0.41 | | |
| C19 | 10.83 | 0.81 | 9.16 | 0.41 | 120.83 | 8.94 | 168.29 | 8.26 | 0.60 | 0.08 | 0.66 | 0.06 | 1.62 | 0.37 | 0.97 | 0.06 |
| Avg | 11.83 | 1.46 | 8.16 | 0.83 | 122.04 | 45.84 | 169.94 | 23.92 | 0.71 | 0.21 | 0.79 | 0.22 | 1.40 | 0.47 | 1.13 | 0.15 |

**Figure 6-32 K-40 Activity: Test 1E (311 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

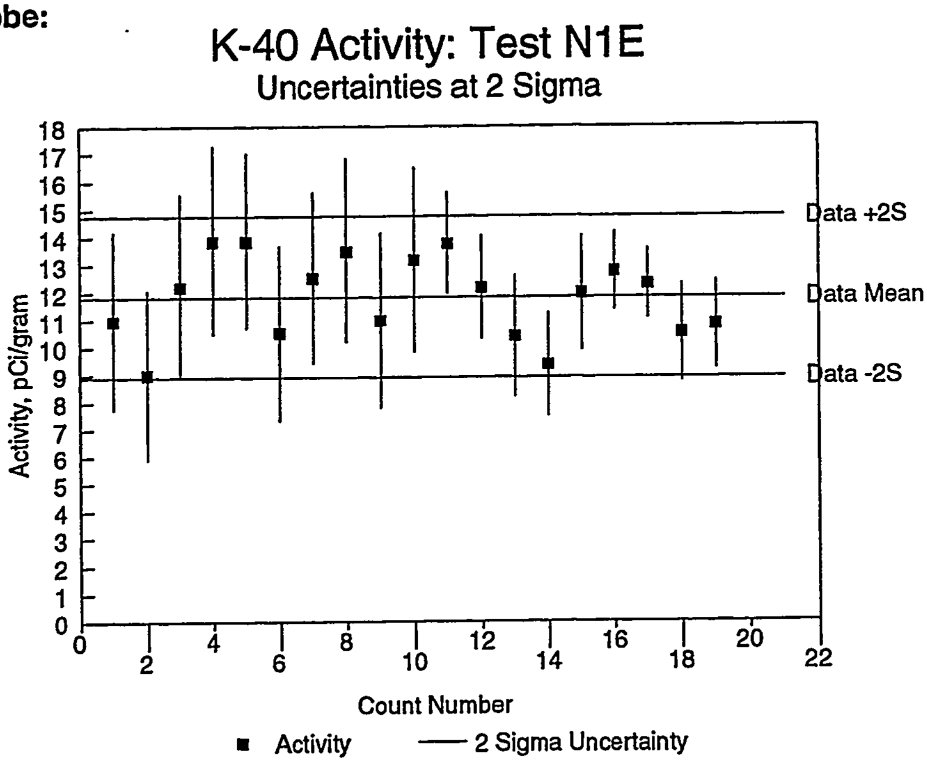
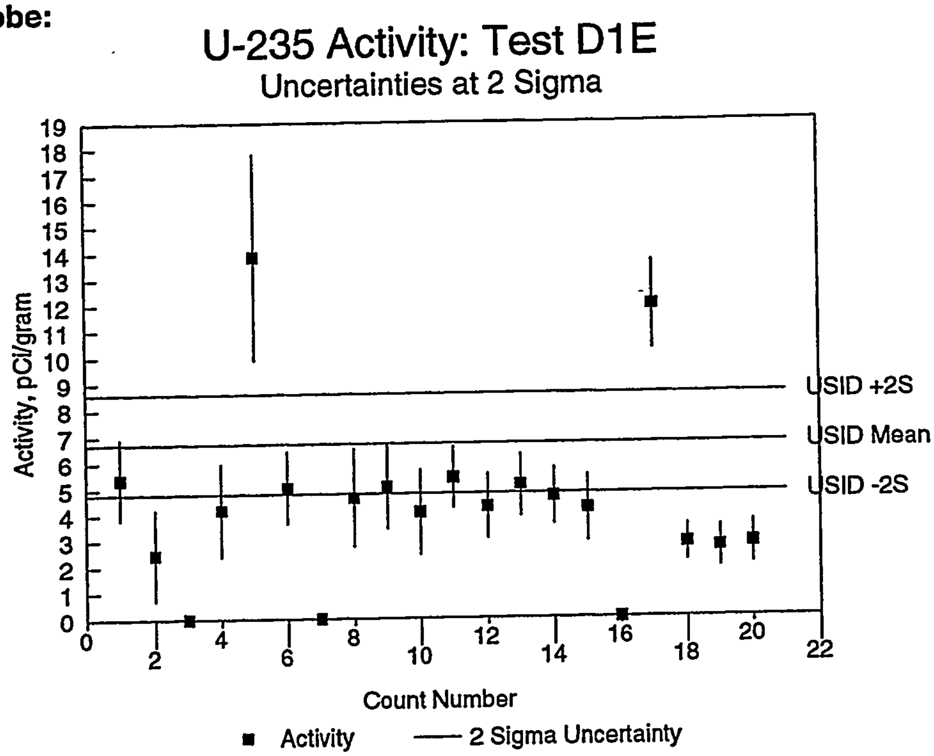


**Figure 6-33 U-235 Activity: Test 1E (311 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

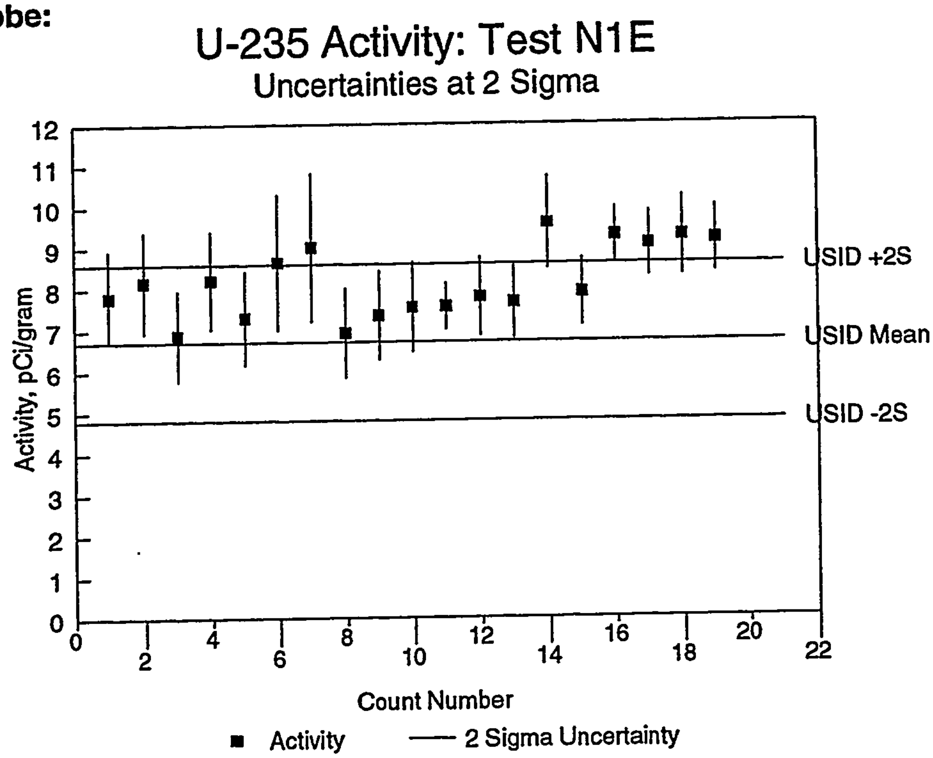
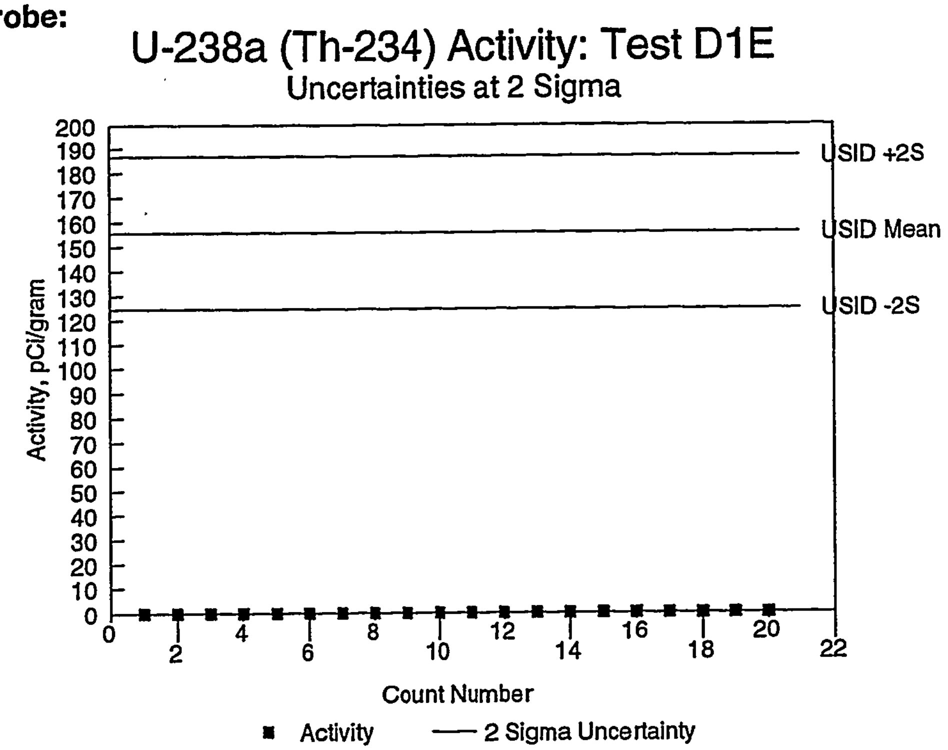


**Figure 6-34 U-238a (Th-234) Activity: Test 1E (311 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

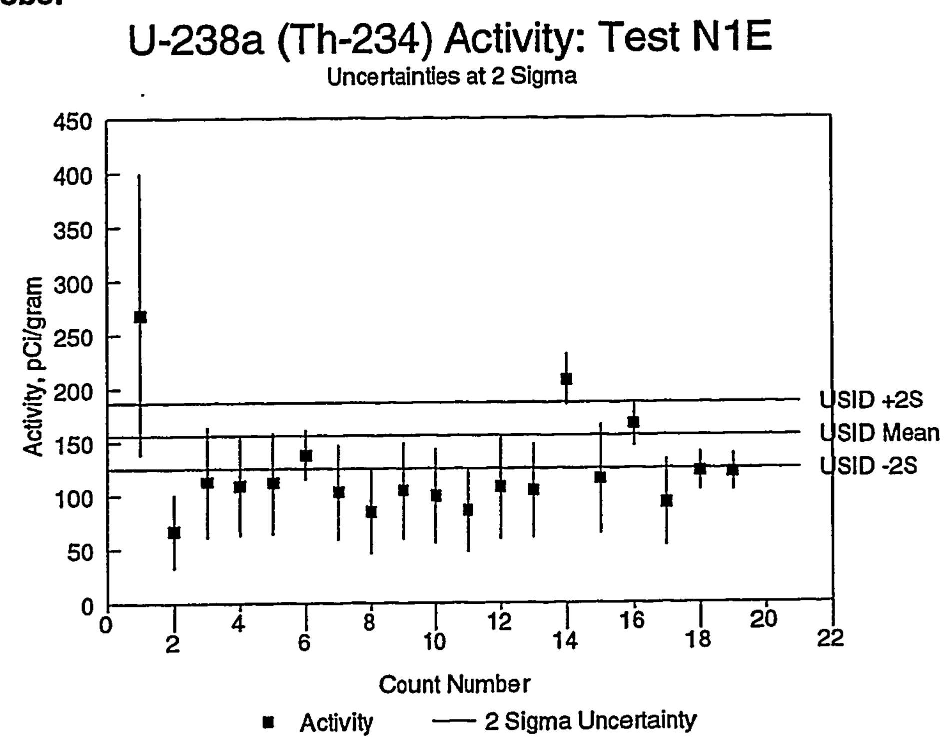
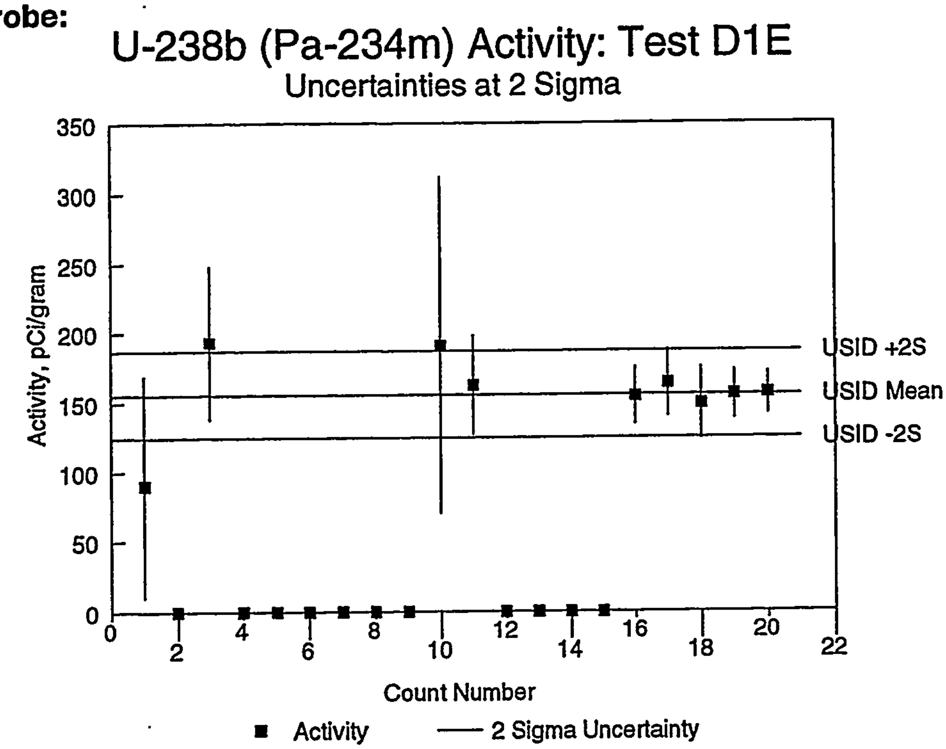
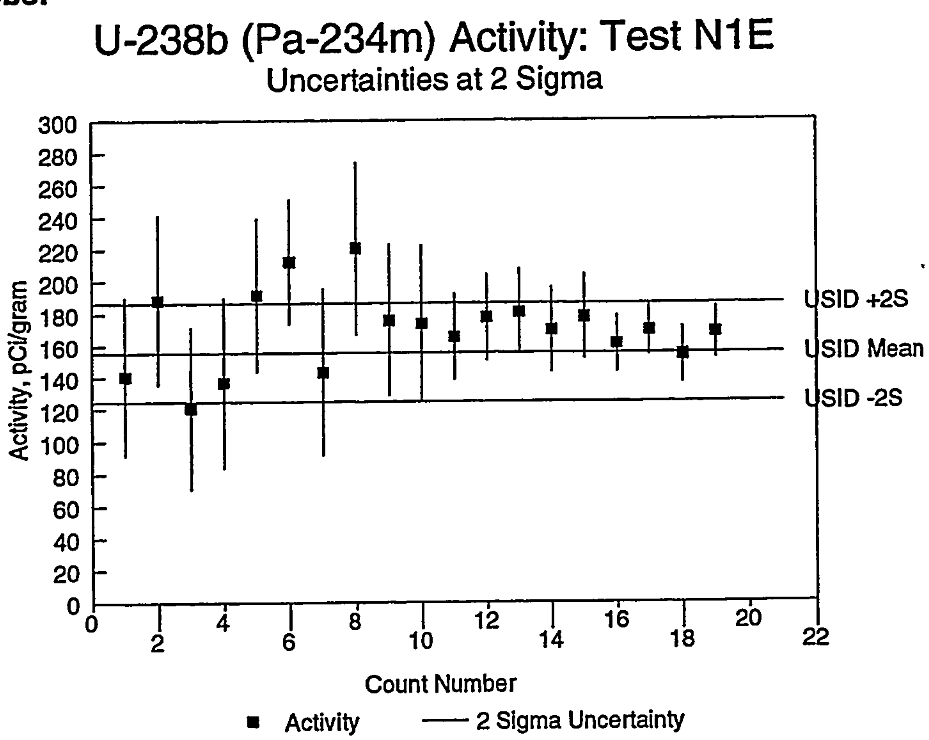


**Figure 6-35 U-238b (Pa-234m) Activity: Test 1E (311 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**



# Figure 6-36 Results Summary: Test 1H (311 pCi/g Total U)

## LPRMS Probe

Test D1H: Nominal Activity = 311.8 pCi/g Total U — Efficiencies from 01/12/95

| Count USID | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 6.693 | 0.95 | | | 155.6 | 15.5 | | | | | | | | |
| C01 | <11.5 | | <3.6 | | <74 | | <195 | | | | | | | | | |
| C02 | <11.5 | | 3.64 | 0.56 | <74 | | 94.25 | 24.41 | | | | | | | | |
| C03 | <11.3 | | <3.6 | | <74 | | <193 | | | | | | | | | |
| C04 | <11.3 | | <3.6 | | <74 | | 136.81 | 24.32 | | | | | | | | |
| C05 | <11.4 | | <3.6 | | <73 | | <195 | | | | | | | | | |
| C06 | <11.3 | | <3.6 | | <74 | | <193 | | | | | | | | | |
| C07 | 10.03 | 1.45 | <3.6 | | <74 | | <194 | | | | | | | | | |
| C08 | 10.29 | 1.45 | <3.6 | | <74 | | <195 | | | | | | | | | |
| C09 | <11.3 | | 3.64 | 0.80 | <74 | | <194 | | | | | | | | | |
| C10 | 8.87 | 1.43 | <3.6 | | <74 | | 139.87 | 23.40 | | | | | | | | |
| C11 | 12.31 | 0.81 | 3.38 | 0.64 | <40 | | 152.67 | 12.36 | | | | | | | | |
| C12 | 10.89 | 0.79 | <2.0 | | <40 | | 160.91 | 13.40 | | | | | | | | |
| C13 | 11.34 | 0.81 | 12.29 | 1.50 | <40 | | 162.16 | 12.37 | | | 0.80 | 0.19 | 1.28 | 1.20 | | |
| C14 | 10.85 | 0.78 | <2.0 | | <41 | | 137.55 | 17.56 | | | 0.70 | 0.19 | | | | |
| C15 | 12.62 | 0.87 | <2.0 | | <41 | | <104 | | | | | | | | | |
| C16 | 12.29 | 0.47 | 13.32 | 0.97 | <23 | | 125.99 | 10.27 | | | 0.39 | 0.11 | 0.85 | 0.65 | | |
| C17 | 11.81 | 0.50 | 8.10 | 0.76 | <23 | | <60 | | | | 0.52 | 0.11 | | | | |
| C18 | 12.36 | 0.47 | 7.31 | 0.79 | | | 113.08 | 8.84 | | | | | | | 0.85 | 0.07 |
| C19 | | | | | | | | | | | | | | | | |
| C20 | | | | | | | | | | | | | | | | |
| Avg | 11.24 | 1.13 | 7.38 | 3.85 | | | 135.92 | 21.00 | | | 0.60 | 0.16 | 1.07 | 0.22 | 0.85 | |

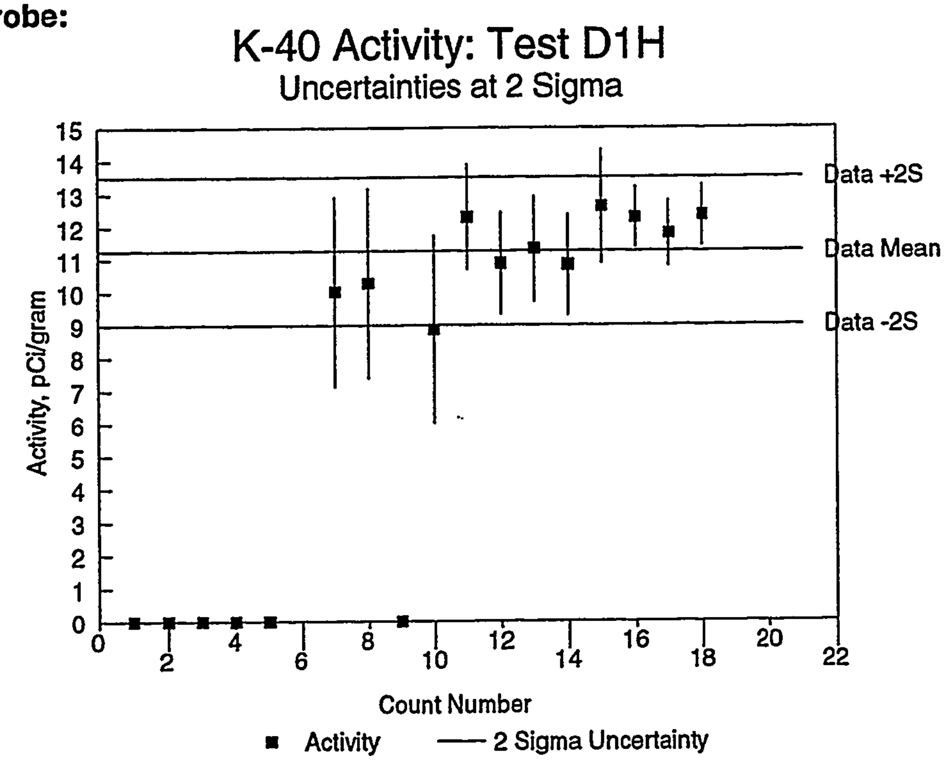
## Survey Probe

Test N1H: Nominal Activity = 311.8 pCi/g Total U — Efficiencies from 01/30/95

| Count USID | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 6.693 | 0.95 | | | 155.6 | 15.5 | | | | | | | | |
| C01 | 13.41 | 1.50 | 6.80 | 0.52 | 60.00 | 13.49 | 107.60 | 20.93 | | | | | | | 1.22 | 0.34 |
| C02 | 10.19 | 1.32 | 6.08 | 0.48 | 64.75 | 13.97 | 159.42 | 19.66 | | | | | | | 1.30 | 0.34 |
| C03 | 10.76 | 1.32 | 6.12 | 0.44 | 104.22 | 22.12 | 141.00 | 19.29 | | | 1.11 | 0.25 | | | | |
| C04 | 12.28 | 1.33 | 5.37 | 0.44 | 89.35 | 19.04 | 126.50 | 20.48 | | | 0.79 | 0.23 | | | | |
| C05 | 9.05 | 1.24 | 5.80 | 0.50 | 82.55 | 18.45 | 131.05 | 20.73 | | | | | | | | |
| C06 | 11.35 | 1.29 | 6.40 | 0.45 | 48.76 | 12.30 | 162.06 | 21.20 | | | | | | | | |
| C07 | 9.71 | 1.25 | 6.76 | 0.50 | 52.33 | 12.71 | 128.60 | 20.35 | | | 0.65 | 0.23 | 1.21 | 0.49 | | |
| C08 | 9.77 | 1.22 | 5.89 | 0.49 | 99.72 | 20.53 | 141.87 | 19.22 | | | | | | | | |
| C09 | 11.98 | 1.27 | 6.61 | 0.44 | 65.38 | 13.72 | 138.80 | 20.39 | | | | | | | | |
| C10 | 11.37 | 1.32 | 5.89 | 0.55 | 88.70 | 19.94 | 136.91 | 19.49 | | | | | | | 1.26 | 0.36 |
| C11 | 11.21 | 0.72 | 6.00 | 0.26 | 88.87 | 17.47 | 145.70 | 10.79 | | | 0.73 | 0.13 | 1.07 | 0.27 | | |
| C12 | 10.87 | 0.72 | 7.00 | 0.31 | 108.98 | 19.76 | 135.21 | 11.01 | | | | | 1.32 | 0.27 | 1.00 | 0.12 |
| C13 | 11.55 | 0.74 | 6.35 | 0.38 | 82.78 | 17.42 | 120.38 | 10.67 | 1.03 | 0.13 | | | | | 0.80 | 0.12 |
| C14 | 11.09 | 0.72 | 6.25 | 0.35 | 93.11 | 17.91 | 131.21 | 10.64 | 0.46 | 0.18 | 0.89 | 0.13 | | | | |
| C15 | 9.73 | 0.71 | 5.63 | 0.38 | 102.47 | 19.52 | 131.07 | 10.73 | | | 0.70 | 0.12 | | | | |
| C16 | 12.00 | 0.44 | 6.62 | 0.24 | 76.79 | 16.28 | 143.38 | 7.17 | 0.39 | 0.10 | 0.52 | 0.07 | 1.07 | 0.16 | 0.74 | 0.08 |
| C17 | 11.26 | 0.45 | 6.83 | 0.25 | 84.31 | 16.21 | 140.73 | 6.24 | 0.58 | 0.10 | 0.39 | 0.07 | 1.22 | 0.15 | 0.97 | 0.06 |
| C18 | 10.43 | 0.42 | 7.16 | 0.24 | 88.75 | 16.04 | 137.79 | 6.24 | 0.57 | 0.10 | 0.54 | 0.08 | 1.20 | 0.15 | 1.00 | 0.07 |
| C19 | | | | | | | | | | | | | | | | |
| C20 | | | | | | | | | | | | | | | | |
| Avg | 11.00 | 1.05 | 6.31 | 0.49 | 82.32 | 17.23 | 136.63 | 12.32 | 0.61 | 0.22 | 0.70 | 0.20 | 1.18 | 0.09 | 1.04 | 0.19 |

**Figure 6-37 K-40 Activity: Test 1H (311 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

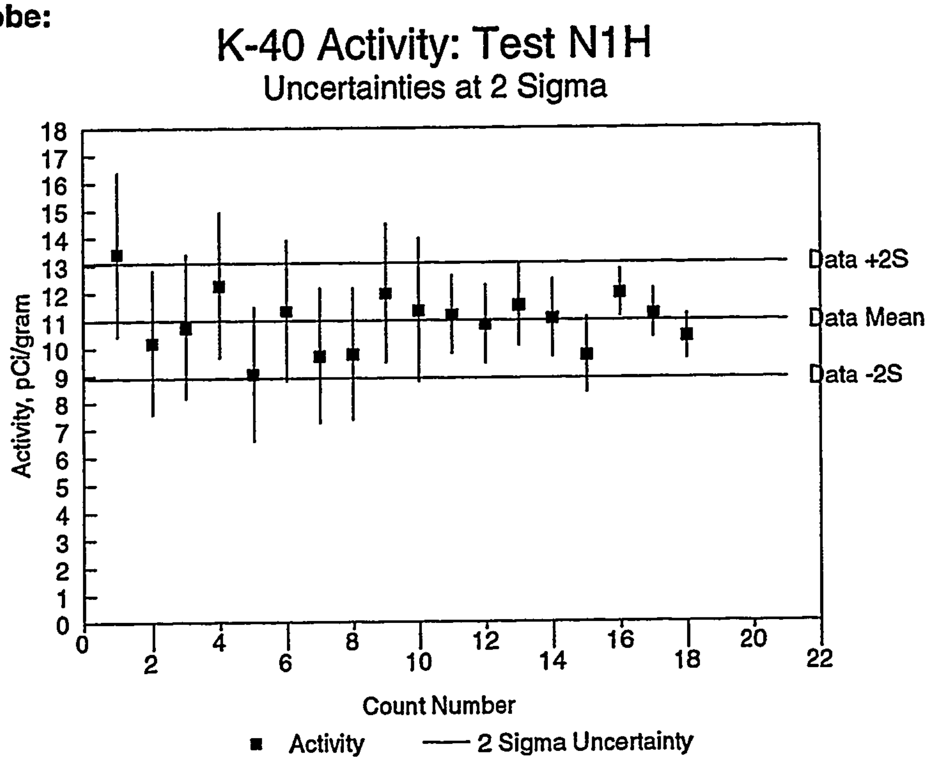
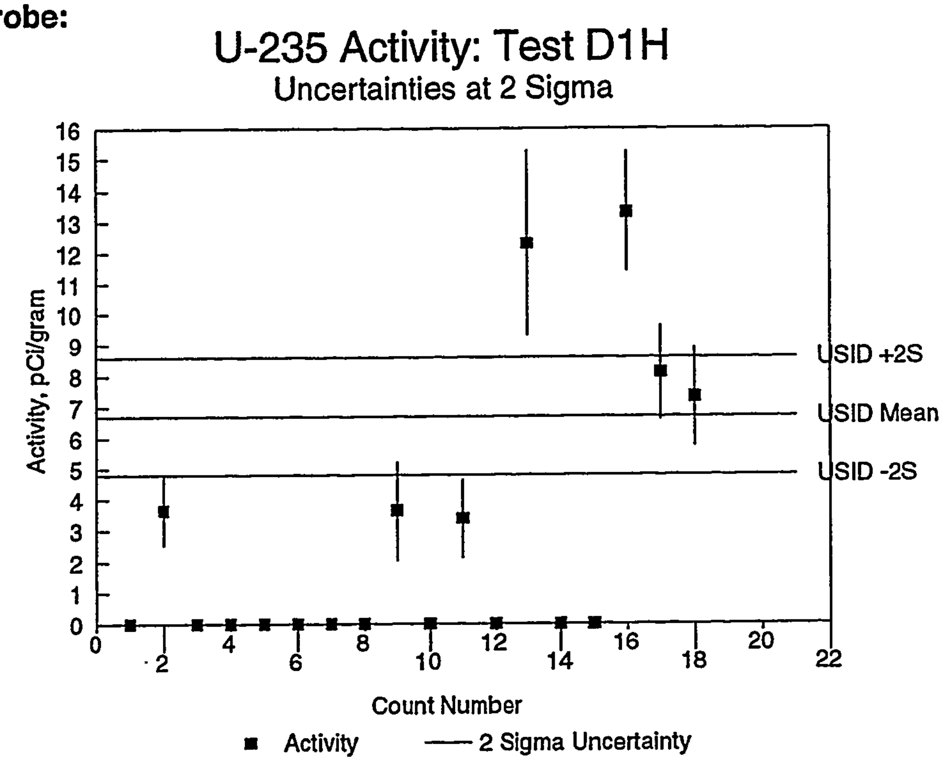
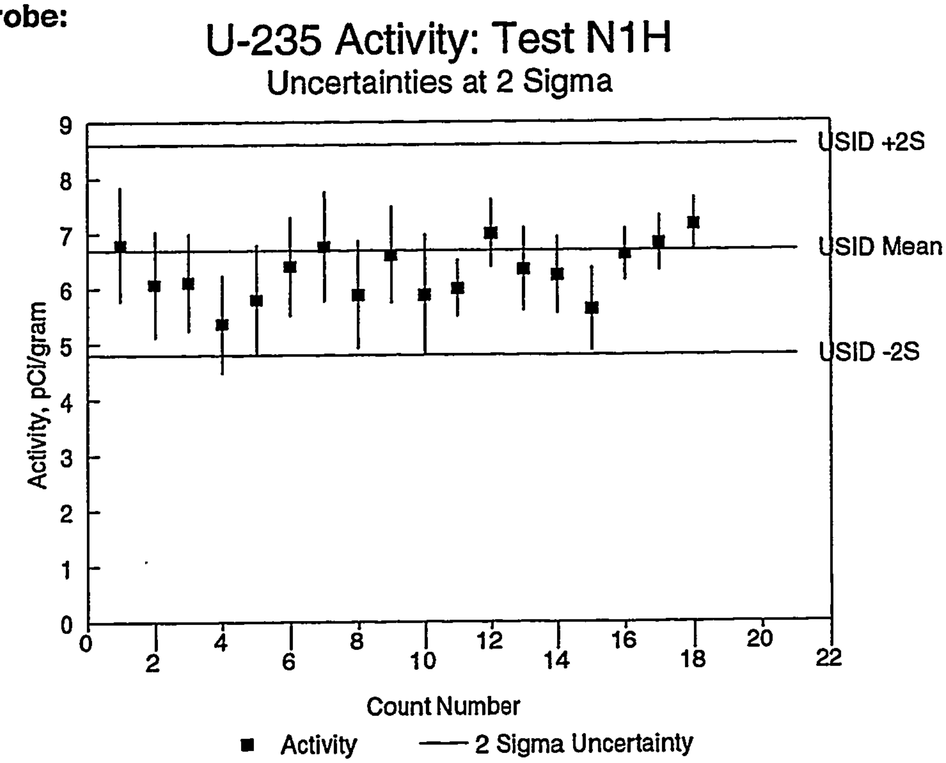


**Figure 6-38 U-235 Activity: Test 1H (311 pCi/g total U)**

**LPRMS Probe:**



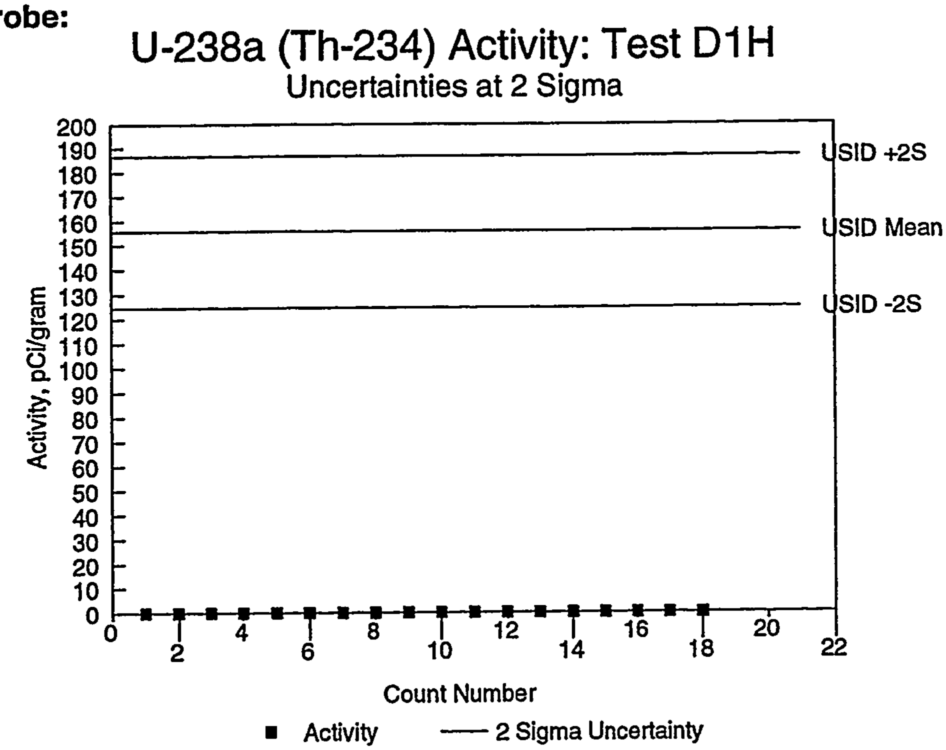

**Survey Probe:**




-116-

**Figure 6-39 U-238a (Th-234) Activity: Test 1H (311 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

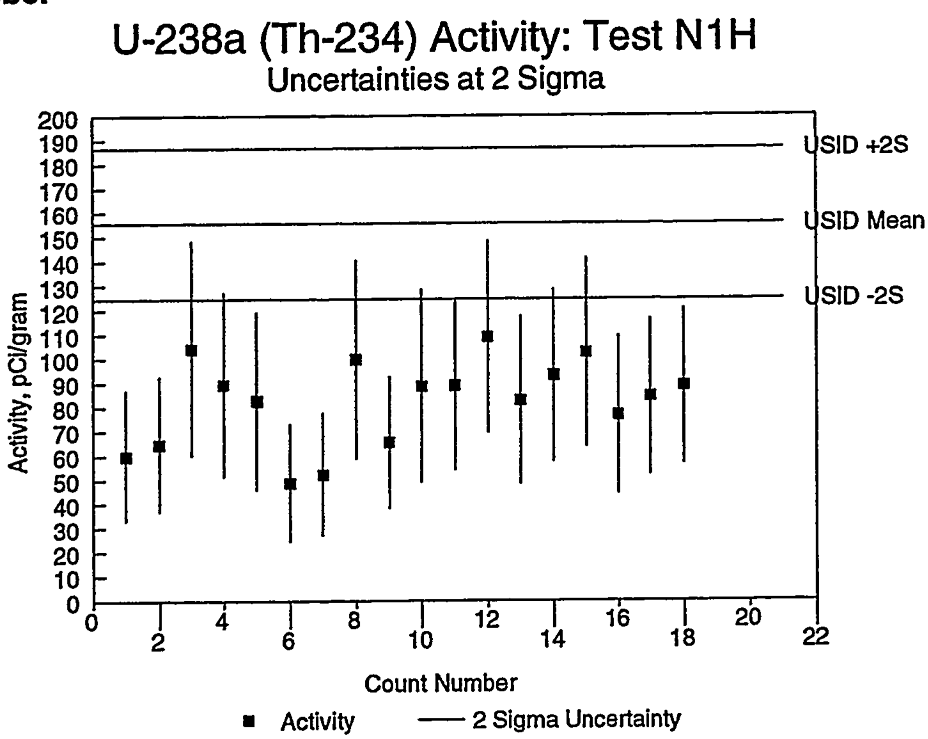
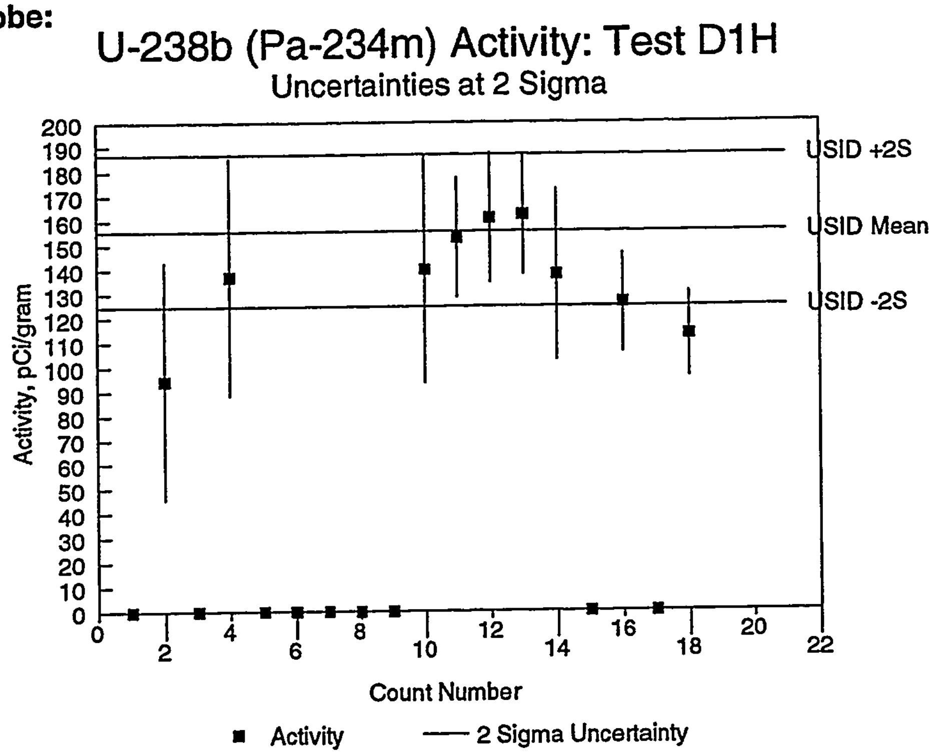
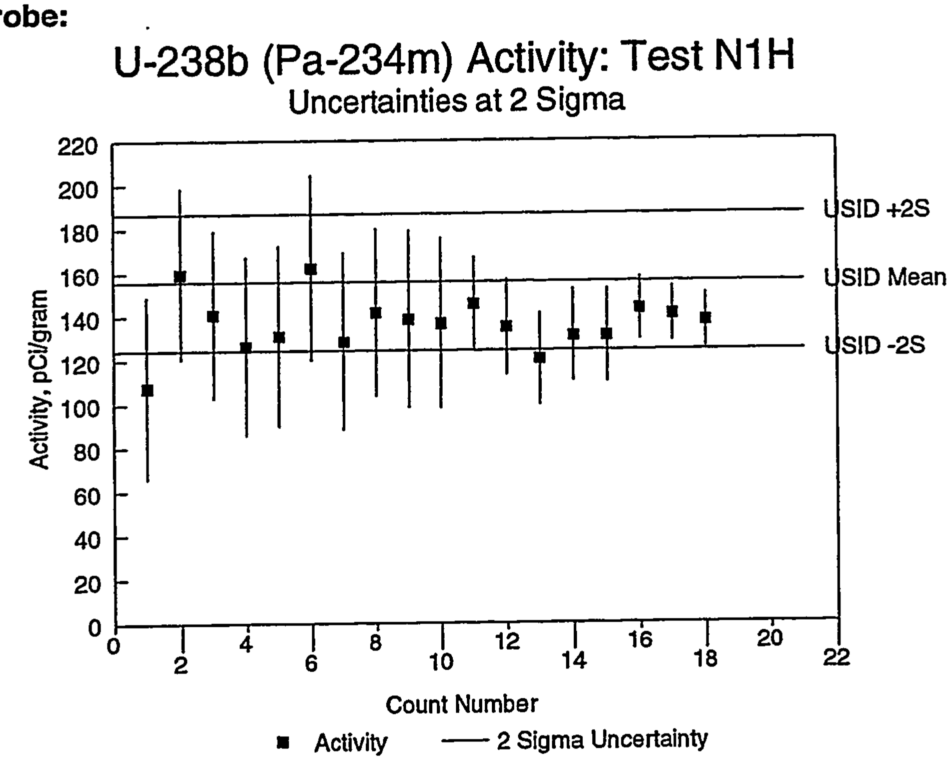


**Figure 6-40 U-238b (Pa-234m) Activity: Test 1H (311 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**



## Figure 6-41 Results Summary: Test 2A (>1000 pCi/g U)

### LPRMS Probe

Test D2A: Nominal Activity = 1750 pCi/g Total U Efficiencies from 01/30/95

| Count USID | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232c | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 36.26 | 0 | (Th-234) | | 824.25 | 0 | (Pb-214) | | | | | | (Bi-212) | |
| C01 | 13.14 | 2.44 | 17.39 | 1.57 | <155 | | <381 | | | | | | | | | |
| C02 | 10.96 | 2.36 | 17.45 | 1.17 | <155 | | <382 | | | | | | | | | |
| C03 | <21 | | 20.79 | 1.60 | <154 | | 738.95 | 51.68 | | | | | | | | |
| C04 | 16.88 | 2.41 | 23.03 | 1.24 | <154 | | 695.20 | 51.11 | 3.36 | 0.65 | | | | | | |
| C05 | 13.90 | 2.35 | 20.54 | 1.13 | <154 | | 668.78 | 49.22 | | | | | | | | |
| C06 | <21 | | 21.34 | 1.21 | <153 | | 603.19 | 48.05 | | | | | | | | |
| C07 | <21 | | 21.12 | 1.13 | <153 | | 729.98 | 52.73 | | | | | | | | |
| C08 | 12.67 | 2.40 | 21.37 | 1.14 | <153 | | 624.95 | 49.21 | | | | | | | | |
| C09 | 8.22 | 2.39 | 20.21 | 1.25 | <153 | | 737.92 | 49.84 | | | | | | | | |
| C10 | 11.50 | 2.38 | 19.85 | 1.17 | <153 | | 687.50 | 49.51 | | | | | | | | |
| C11 | 9.10 | 1.31 | 19.70 | 0.88 | <84 | | 697.79 | 34.32 | | | | | | | | |
| C12 | 10.89 | 1.41 | 23.92 | 2.32 | <84 | | 681.83 | 34.54 | | | | | | | | |
| C13 | 12.95 | 1.33 | 18.98 | 0.70 | <84 | | 698.70 | 38.92 | | | | | | | | |
| C14 | 10.41 | 1.43 | 20.01 | 0.91 | <84 | | 718.78 | 34.98 | | | | | | | | |
| C15 | 10.71 | 1.57 | 18.22 | 0.93 | <84 | | 666.14 | 34.82 | | | | | | | | |
| C16 | 12.10 | 0.93 | 20.96 | 0.66 | <48 | | 747.73 | 28.86 | | | | | | | | |
| C17 | 11.39 | 0.89 | 20.93 | 0.59 | <34 | | 753.22 | 25.32 | | | 0.40 | 0.14 | | | | |
| C18 | 11.46 | 0.86 | 18.99 | 0.57 | <28 | | 753.43 | 24.84 | | | 0.34 | 0.12 | | | | |
| Avg | 11.75 | 1.99 | 20.27 | 1.66 | | | 700.26 | 43.17 | 3.36 | | 0.37 | 0.03 | | | | |

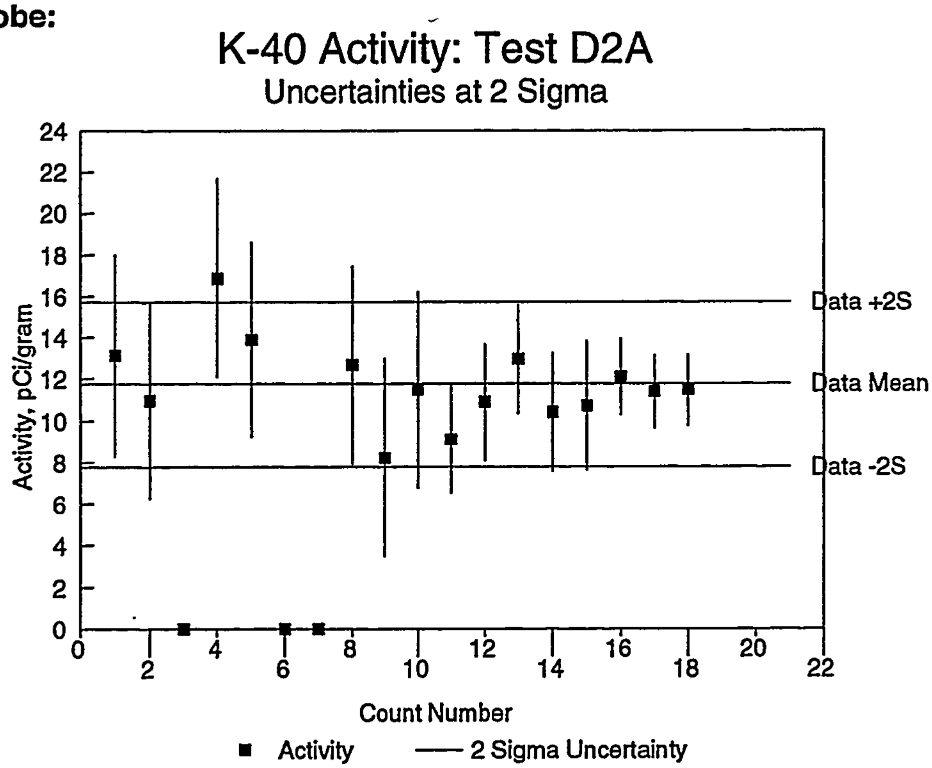
### Survey Probe

Test N2A: Nominal Activity = 1750 pCi/g Total U Efficiencies from 01/30/95

| Count USID | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232c | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 36.26 | 0 | (Th-234) | | 824.25 | 0 | (Pb-214) | | | | | | (Bi-212) | |
| C01 | 13.74 | 2.23 | 36.16 | 1.71 | 391.62 | 95.8 | 790.91 | 43.83 | | | | | | | | |
| C02 | 12.86 | 2.21 | 32.84 | 1.83 | 651.97 | 142.0 | 834.76 | 45.69 | | | | | | | | |
| C03 | 16.09 | 2.29 | 32.75 | 1.64 | 834.79 | 174.0 | 793.48 | 43.55 | | | 1.75 | 0.55 | | | | |
| C04 | 13.16 | 2.16 | 36.67 | 1.83 | 883.84 | 172.5 | 801.81 | 43.69 | | | | | | | | |
| C05 | 14.49 | 2.26 | 33.63 | 1.96 | 718.83 | 145.6 | 806.46 | 44.42 | | | | | | | | |
| C06 | 12.35 | 2.13 | 34.68 | 1.83 | 791.02 | 156.2 | 844.23 | 43.96 | | | | | | | 13.88 | 3.63 |
| C07 | 16.32 | 2.18 | 34.81 | 1.59 | 797.36 | 158.3 | 887.07 | 44.61 | | | | | | | | |
| C08 | 17.27 | 2.30 | 32.96 | 1.99 | 801.21 | 165.0 | 819.81 | 43.67 | | | | | | | 12.37 | 3.58 |
| C09 | 15.77 | 2.28 | 32.98 | 2.38 | 885.62 | 179.4 | 794.42 | 46.01 | | | | | | | 15.37 | 3.59 |
| C10 | 13.37 | 2.19 | 32.27 | 1.92 | 870.42 | 172.8 | 775.73 | 46.08 | | | | | | | | |
| C11 | 15.14 | 1.24 | 34.11 | 1.94 | 859.17 | 161.6 | 803.98 | 24.75 | | | | | | | 11.37 | 1.97 |
| C12 | 12.91 | 1.23 | 32.07 | 2.25 | 864.49 | 172.0 | 830.47 | 25.59 | | | | | | | 14.73 | 1.99 |
| C13 | 14.87 | 1.38 | 33.29 | 2.09 | 839.66 | 168.6 | 811.55 | 28.55 | | | | | | | 9.38 | 1.97 |
| C14 | 15.21 | 1.25 | 32.82 | 2.29 | 885.97 | 180.4 | 706.39 | 25.19 | | | | | | | 11.96 | 2.03 |
| C15 | 14.26 | 1.31 | 33.61 | 2.54 | 961.79 | 184.5 | 681.82 | 28.17 | | | | | | | 11.71 | 1.99 |
| C16 | 14.65 | 0.86 | 33.15 | 2.44 | 930.01 | 178.0 | 700.27 | 16.28 | | | | | | | 11.75 | 1.23 |
| C17 | 14.72 | 0.64 | 33.57 | 2.70 | 1007.08 | 194.0 | 751.81 | 13.39 | 0.50 | 0.11 | | | | | 11.08 | 0.95 |
| C18 | 14.84 | 0.57 | 33.17 | 2.51 | 916.19 | 171.8 | 775.76 | 10.85 | 0.44 | 0.13 | | | | | 10.91 | 0.78 |
| Avg | 14.56 | 1.29 | 33.64 | 1.20 | 827.28 | 133.0 | 789.49 | 50.88 | 0.47 | 0.03 | 1.75 | | | | 12.23 | 1.69 |

**Figure 6-42 K-40 Activity: Test 2A (>1000 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

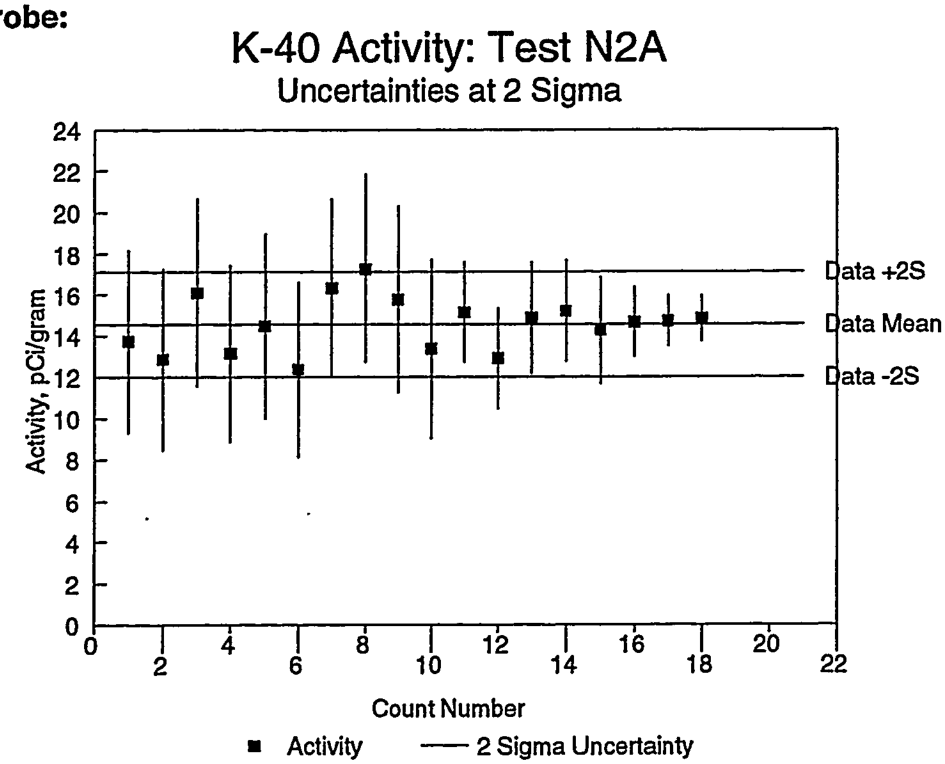
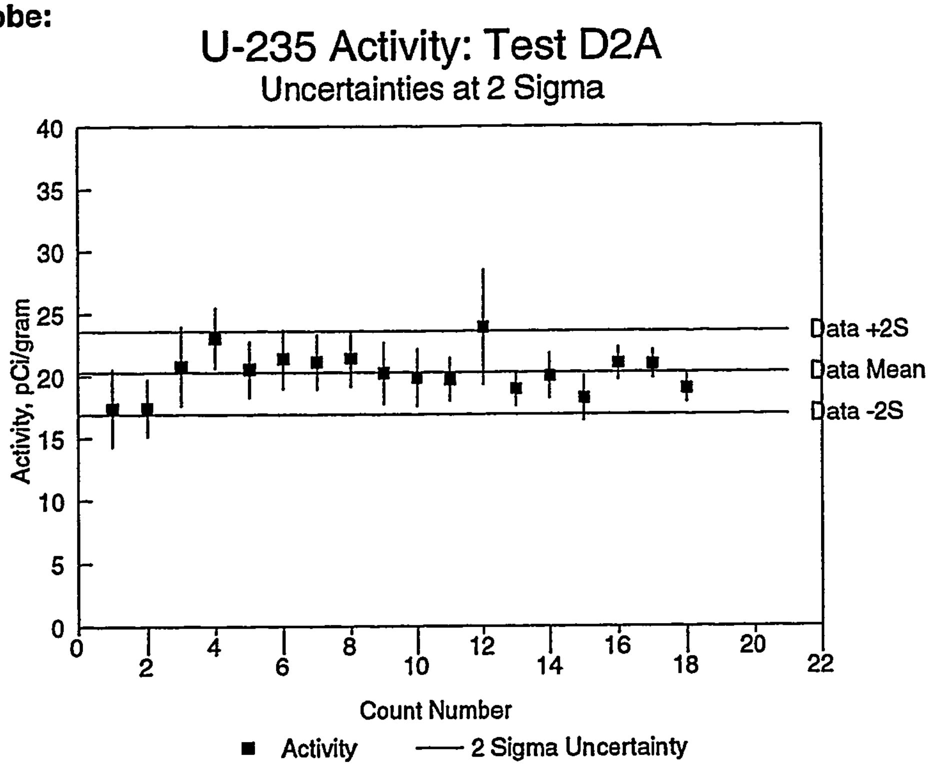


**Figure 6-43 U-235 Activity: Test 2A (>1000 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

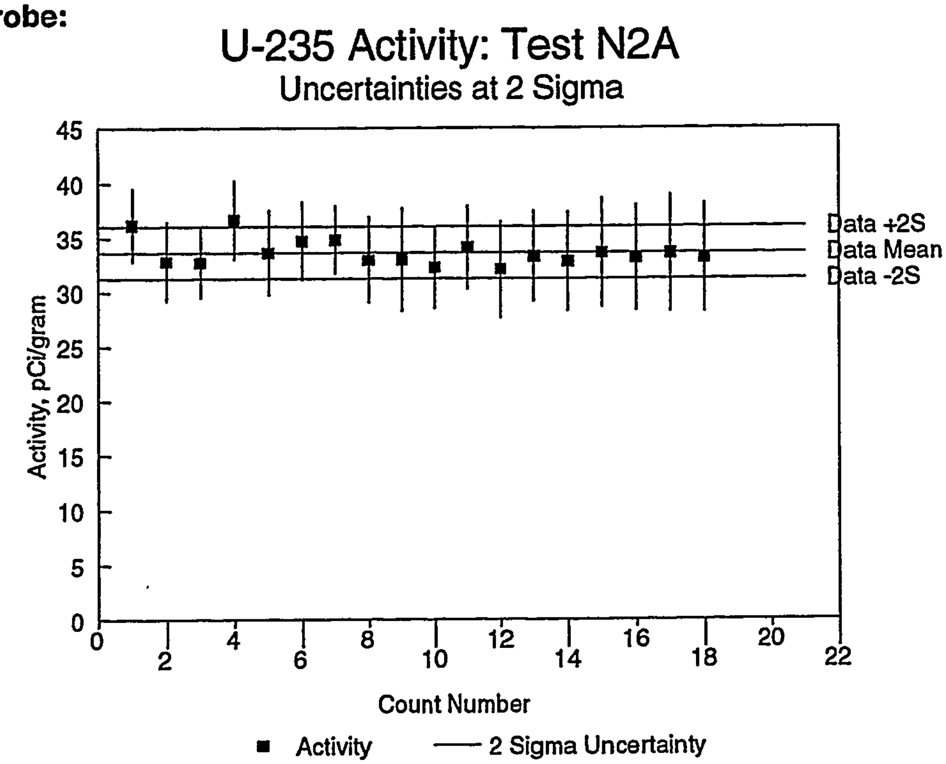
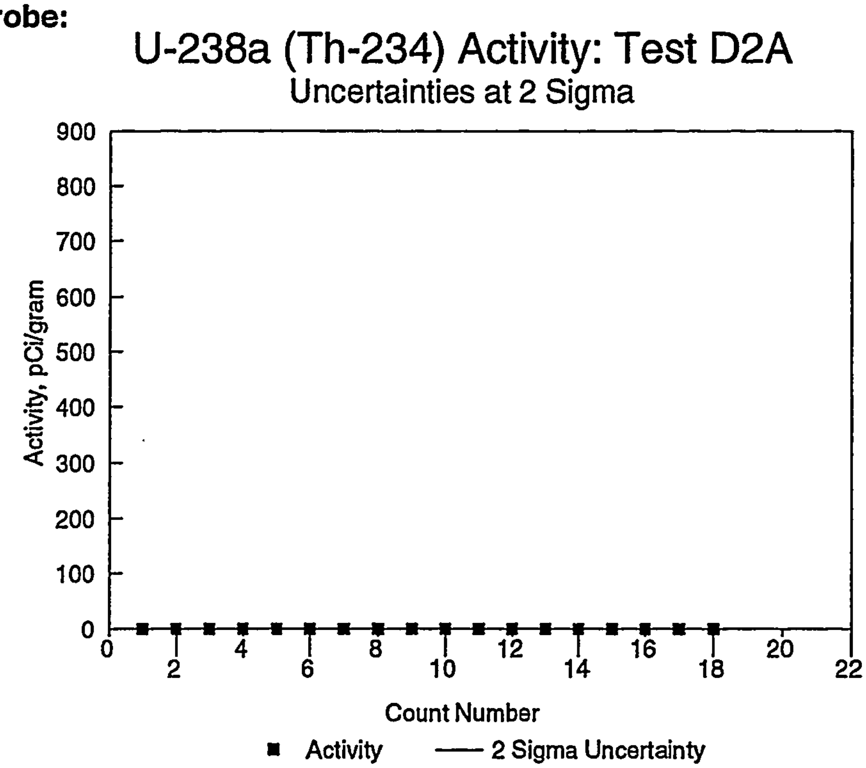


**Figure 6-44 U-238a (Th-234) Activity: Test 2A (>1000 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

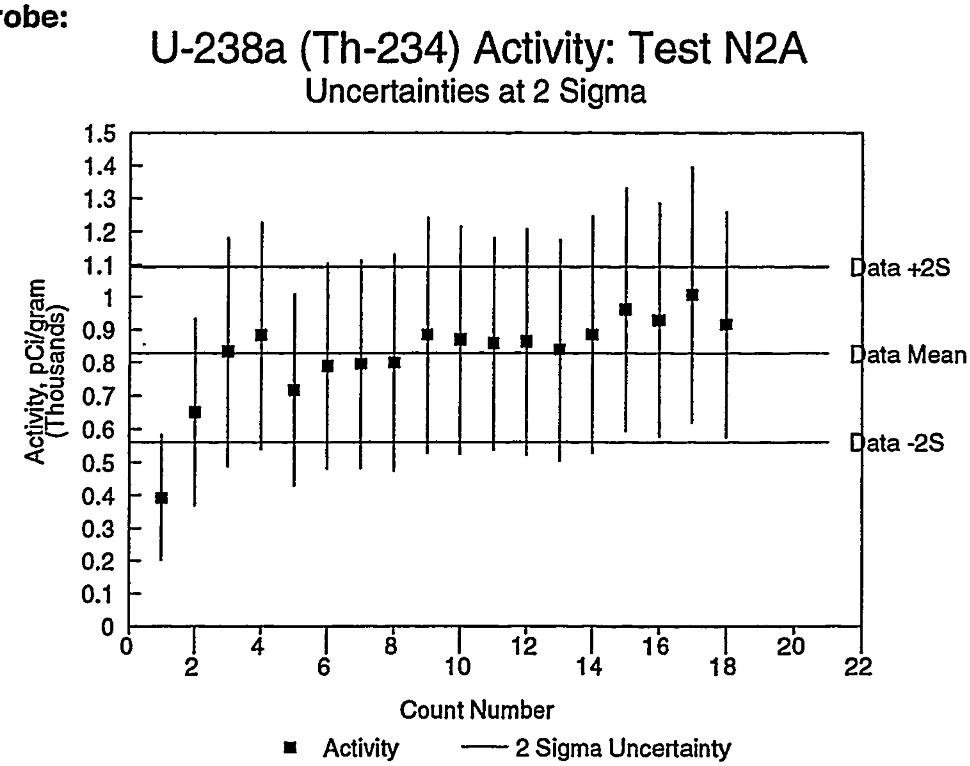
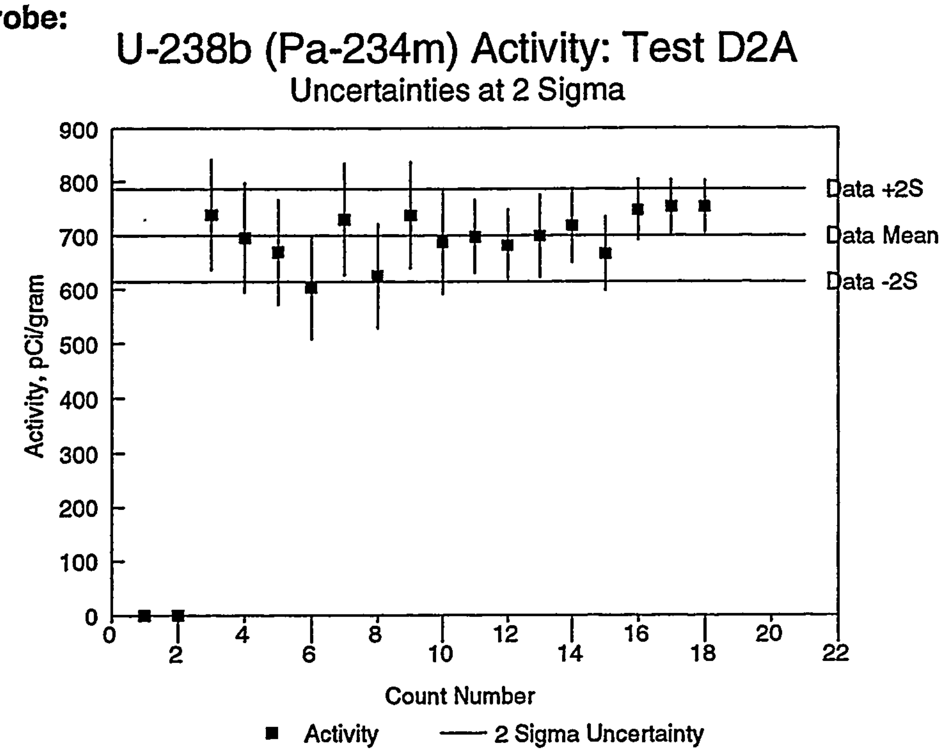
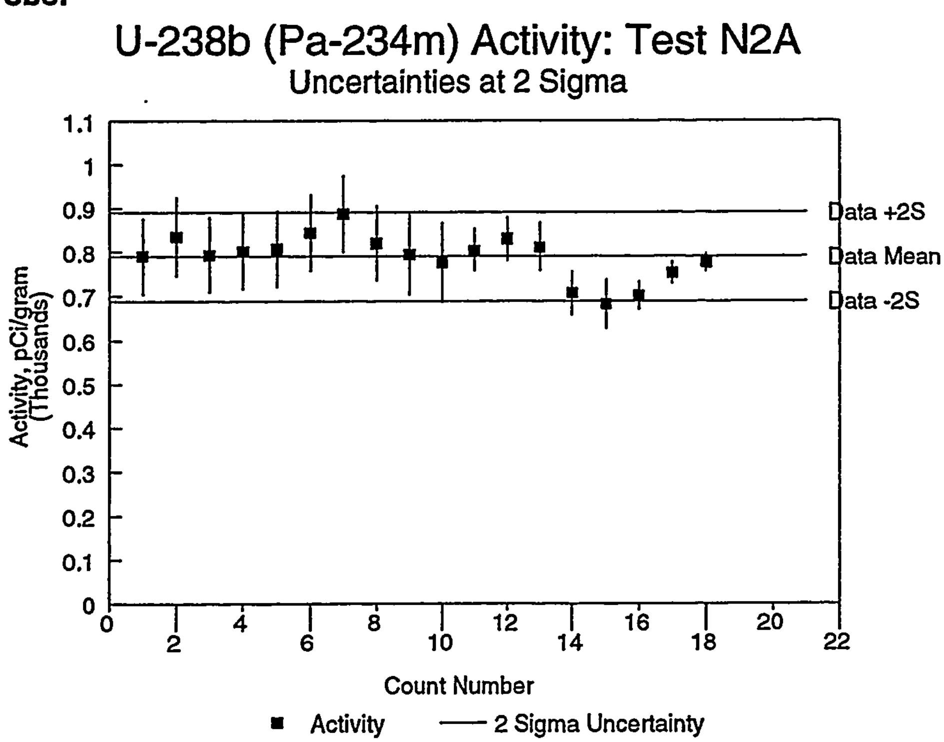


**Figure 6-45 U-238b (Pa-234m) Activity: Test 2A (>1000 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**



## Figure 6-46 Results Summary: Test 2B (>1000 pCi/g U)

### LPRMS Probe

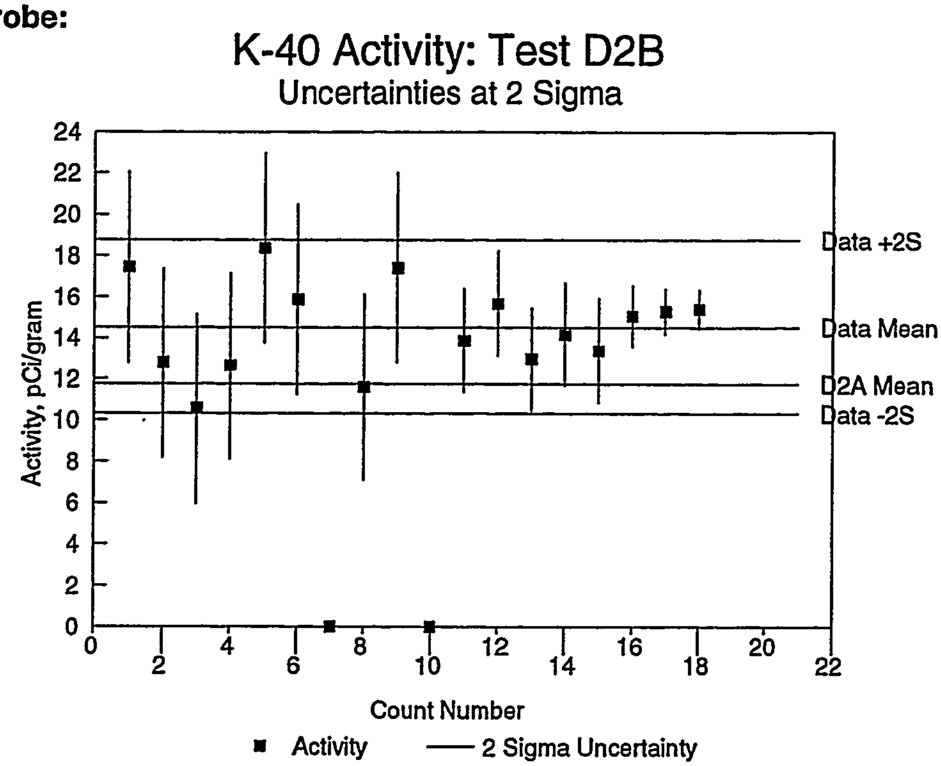
| Test D2B: Nominal Activity = 1750 pCi/g Total U | | | | | | | Efficiencies from 01/30/95 | | | | | | (Pb-212) | | (Bi-212) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Count | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232c | +- |
| D2A | 11.75 | 1.99 | 20.27 | 1.66 | | | 700.26 | 43.2 | 3.36 | 0.65 | | | | | 12.23 | 1.69 |
| C01 | 17.44 | 2.33 | 13.77 | 2.28 | | <154 | | <372 | | | | | | | 22.72 | 4.08 |
| C02 | 12.79 | 2.31 | 32.29 | 4.64 | | <154 | 515.09 | 63.07 | | | | | | | 14.51 | 5.07 |
| C03 | 10.57 | 2.31 | 14.64 | 2.48 | | <153 | 571.34 | 61.18 | | | | | | | | |
| C04 | 12.65 | 2.28 | 36.70 | 3.92 | | <153 | | <375 | | | | | | | | |
| C05 | 18.37 | 2.32 | 30.21 | 4.39 | | <153 | | <375 | | | | | | | | |
| C06 | 15.87 | 2.32 | 31.83 | 4.12 | | <153 | 758.19 | 48.31 | | | | | | | | |
| C07 | | <19.8 | 13.81 | 1.59 | | <153 | | <377 | | | | | | | | |
| C08 | 11.63 | 2.27 | 33.89 | 4.09 | | <153 | 697.43 | 44.83 | | | | | | | | |
| C09 | 17.41 | 2.33 | 34.52 | 3.71 | | <152 | 668.09 | 45.17 | | | | | | | | |
| C10 | | <19.9 | 32.66 | 3.38 | | <153 | | <377 | | | | | | | | |
| C11 | 13.89 | 1.28 | | <4.2 | | <84 | 677.81 | 33.98 | | | | | | | | |
| C12 | 15.68 | 1.29 | 32.12 | 3.32 | | <84 | 617.24 | 33.80 | | | | | | | | |
| C13 | 12.97 | 1.27 | 16.92 | 1.21 | | <83 | 696.21 | 25.70 | | | | | | | | |
| C14 | 14.17 | 1.27 | | <4.2 | | <84 | 677.85 | 33.87 | | | | | | | | |
| C15 | 13.39 | 1.28 | 34.70 | 3.56 | | <83 | 684.58 | 34.54 | | | | | | | | |
| C16 | 15.08 | 0.76 | 15.29 | 1.73 | | <48 | 775.09 | 17.87 | | | | | | | | |
| C17 | 15.30 | 0.56 | 15.81 | 1.91 | | <34 | 787.17 | 14.26 | | | | | | | | |
| C18 | 15.41 | 0.48 | 33.13 | 1.69 | | <28 | 751.43 | 14.26 | | | | | | | | |
| Avg | 14.54 | 2.11 | 26.39 | 8.93 | | | 682.89 | 76.11 | | | | | | | 18.62 | 4.10 |
| D2B/D2A | 1.24 | | 1.30 | | | | 0.98 | | | | | | | | 1.52 | |

### Survey Probe

| Test N2B: Nominal Activity = 1750 pCi/g Total U | | | | | | | Efficiencies from 01/30/95 | | | | | | (Pb-212) | | (Bi-212) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Count | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232c | +- |
| N2A | 14.56 | 1.29 | 33.64 | 1.2 | 827.28 | 133 | 789.49 | 50.9 | (Pb-214) | | | | | | 12.23 | 1.69 |
| C01 | 11.66 | 2.00 | 28.37 | 1.08 | 297.53 | 60.55 | 575.48 | 41.33 | | | | | | | | |
| C02 | 11.88 | 2.01 | 28.58 | 0.95 | 225.52 | 50.72 | 565.90 | 41.78 | | | | | | | | |
| C03 | 11.83 | 2.10 | 31.17 | 1.28 | 207.00 | 42.68 | 666.88 | 42.55 | | | | | 1.65 | 0.54 | | |
| C04 | 17.69 | 2.04 | 29.10 | 1.20 | 272.84 | 52.93 | 636.88 | 42.05 | | | | | | | 9.36 | 3.35 |
| C05 | 9.84 | 2.02 | 28.69 | 1.20 | 351.97 | 67.48 | 603.36 | 41.75 | | | | | | | 10.47 | 3.27 |
| C06 | 12.60 | 1.98 | 30.97 | 0.99 | 353.30 | 64.59 | 602.12 | 39.09 | | | | | 2.82 | 0.89 | 10.59 | 3.27 |
| C07 | 11.81 | 2.09 | 28.54 | 1.23 | 353.28 | 67.36 | 691.59 | 42.27 | | | | | | | | |
| C08 | 13.52 | 2.09 | 30.88 | 1.24 | 217.13 | 49.52 | 579.48 | 41.81 | | | | | | | | |
| C09 | 8.65 | 2.00 | 28.47 | 1.05 | 306.61 | 61.99 | 577.39 | 41.50 | | | | | | | 11.89 | 3.23 |
| C10 | 15.84 | 2.08 | 30.92 | 1.21 | 375.23 | 68.73 | 620.56 | 41.15 | | | | | 2.42 | 0.90 | | |
| C11 | 13.55 | 1.15 | 29.66 | 0.64 | 323.25 | 63.77 | 693.11 | 25.12 | | | | | 1.89 | 0.49 | 8.16 | 1.78 |
| C12 | 14.00 | 1.13 | 27.86 | 1.03 | 317.72 | 61.56 | 616.51 | 23.18 | | | | | | | 7.66 | 1.79 |
| C13 | 15.00 | 1.30 | 28.74 | 0.84 | 332.24 | 65.10 | 615.58 | 23.48 | | | | | | | 7.87 | 1.78 |
| C14 | 12.85 | 1.18 | 28.08 | 0.92 | 322.89 | 61.53 | 596.84 | 23.52 | | | | | | | 7.01 | 1.79 |
| C15 | 11.78 | 1.16 | 28.13 | 0.96 | 383.81 | 67.98 | 620.40 | 23.05 | | | | | | | | |
| C16 | 12.02 | 0.84 | 27.78 | 0.84 | 347.74 | 63.64 | 732.27 | 19.26 | | | | | | | 10.16 | 1.17 |
| C17 | 12.66 | 0.73 | 29.32 | 0.72 | 341.77 | 62.30 | 725.75 | 12.60 | | | | | 1.23 | 0.21 | 11.13 | 0.77 |
| C18 | 12.58 | 0.71 | 29.49 | 0.77 | 335.83 | 61.49 | 692.61 | 11.40 | | | | | 1.16 | 0.20 | 10.74 | 0.72 |
| Avg | 12.76 | 2.00 | 29.15 | 1.10 | 314.76 | 50.95 | 634.04 | 51.64 | | | | | 1.86 | 0.60 | 9.55 | 1.55 |
| N2B/N2A | 0.88 | | 0.87 | | 0.38 | | 0.80 | | | | | | | | 0.78 | |

**Figure 6-47 K-40 Activity: Test 2B (>1000 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

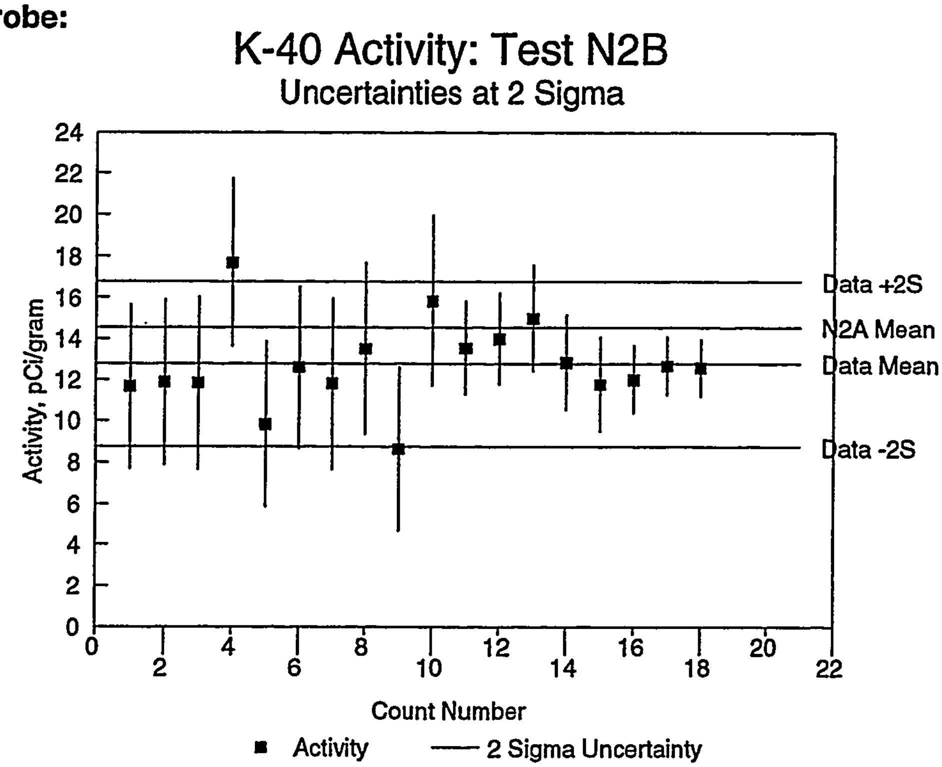
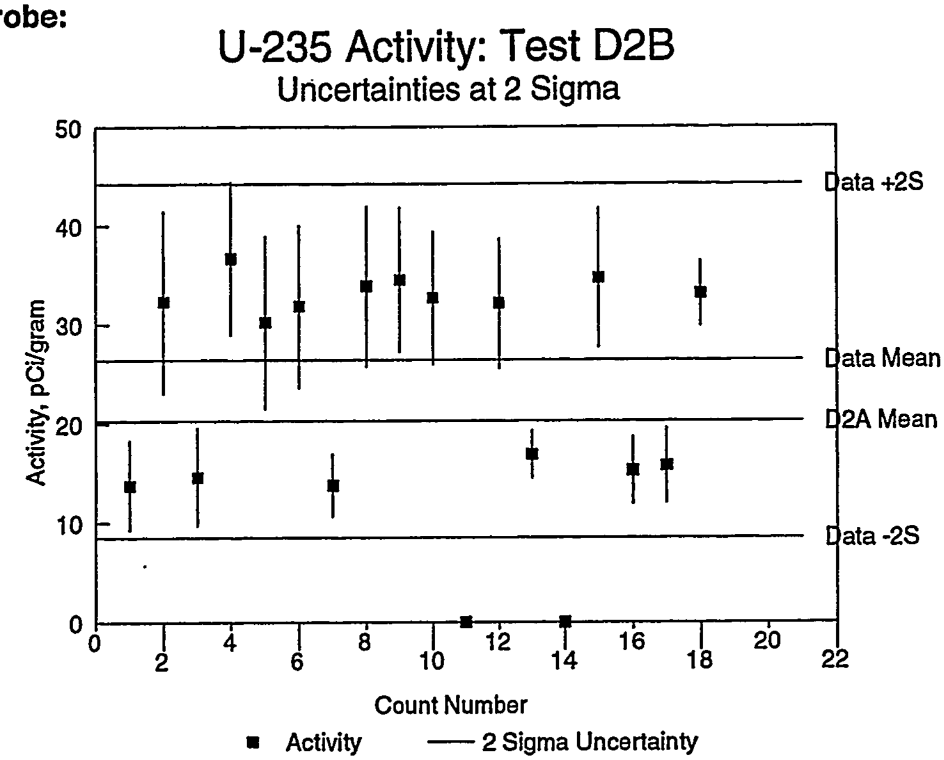


**Figure 6-48 U-235 Activity: Test 2B (>1000 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

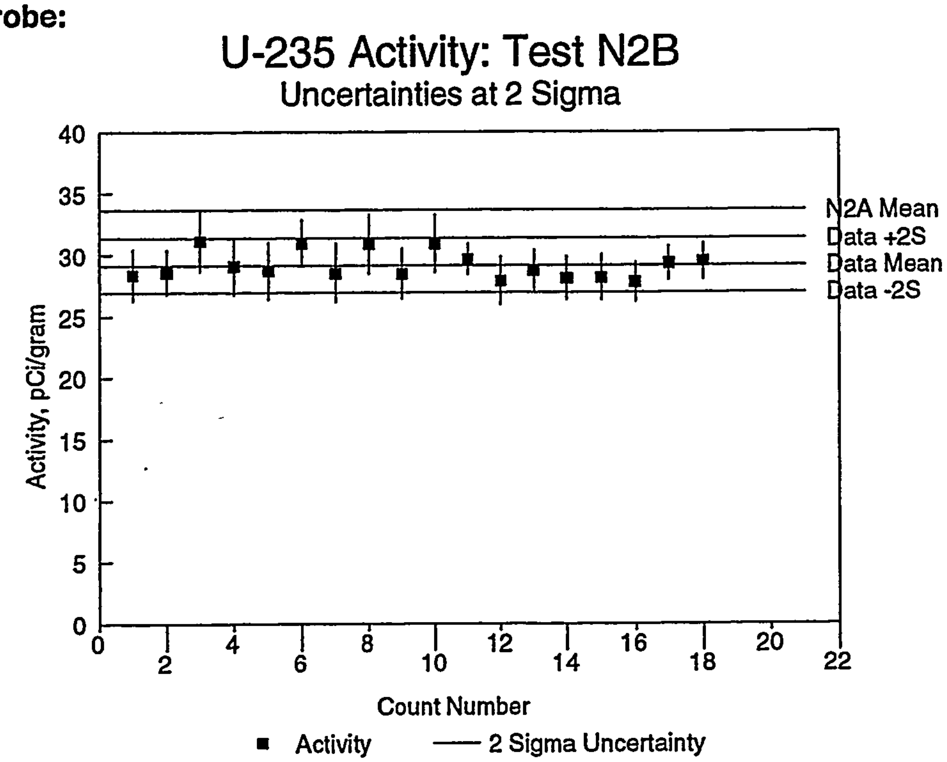
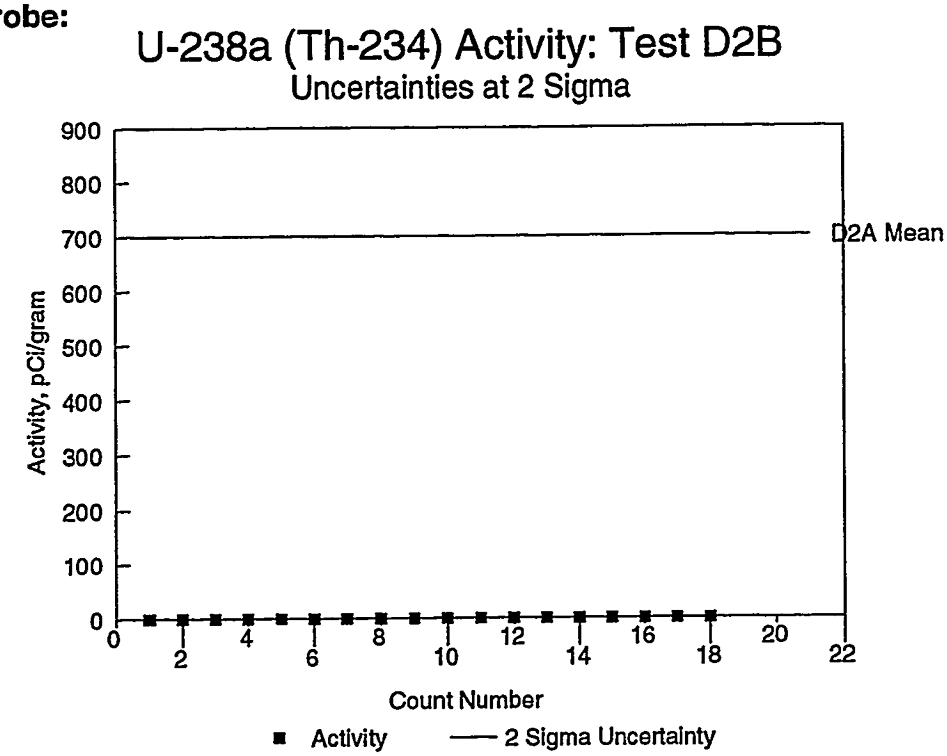


**Figure 6-49 U-238a (Th-234) Activity: Test 2B (>1000 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**

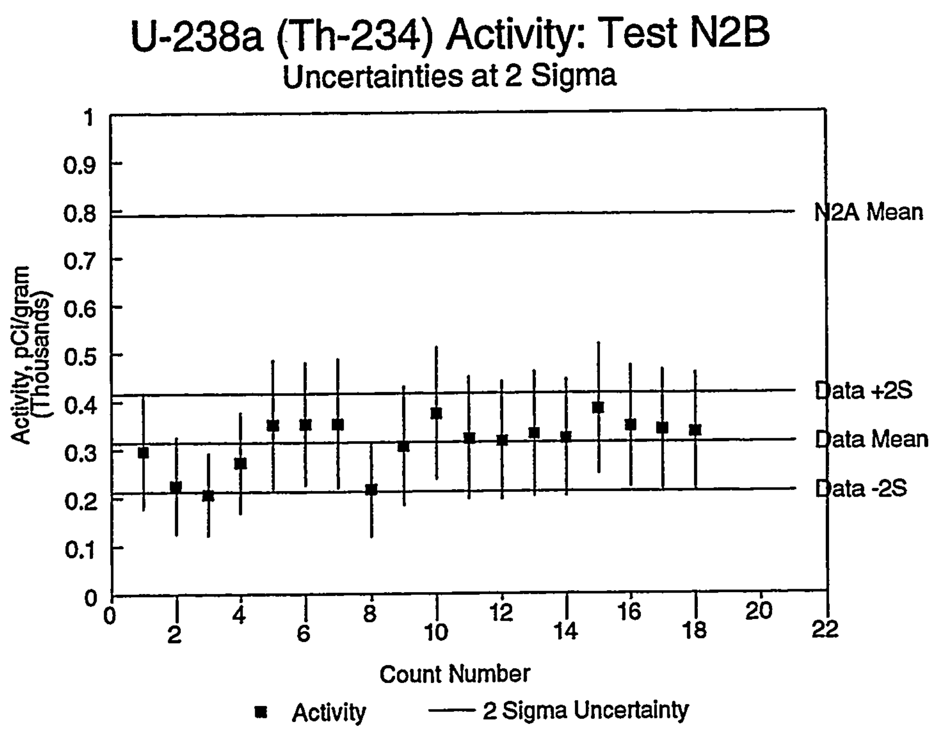
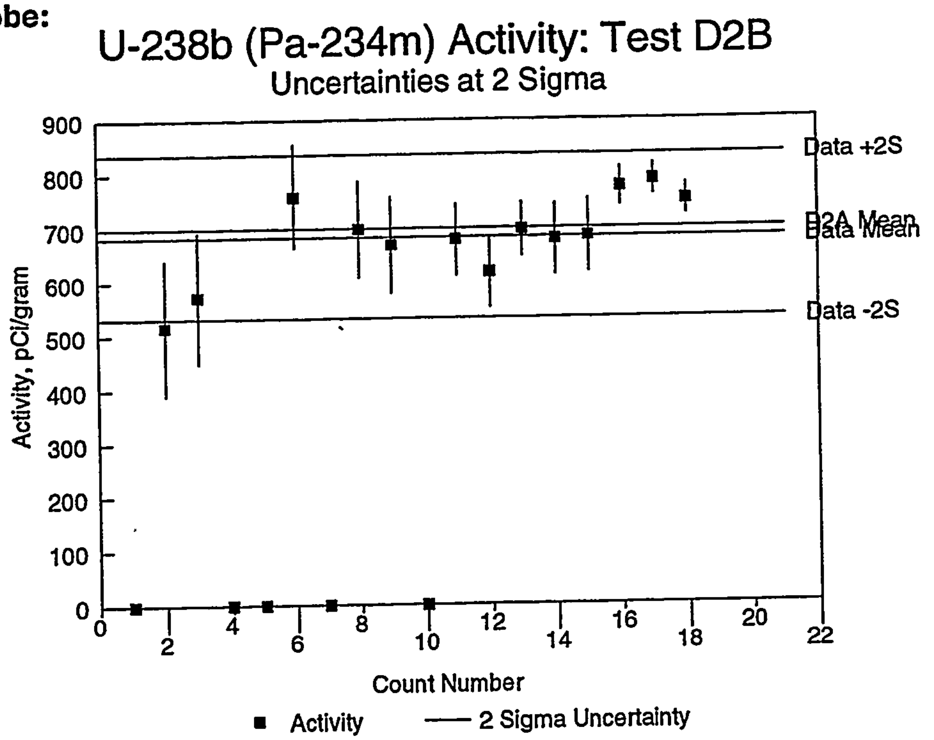
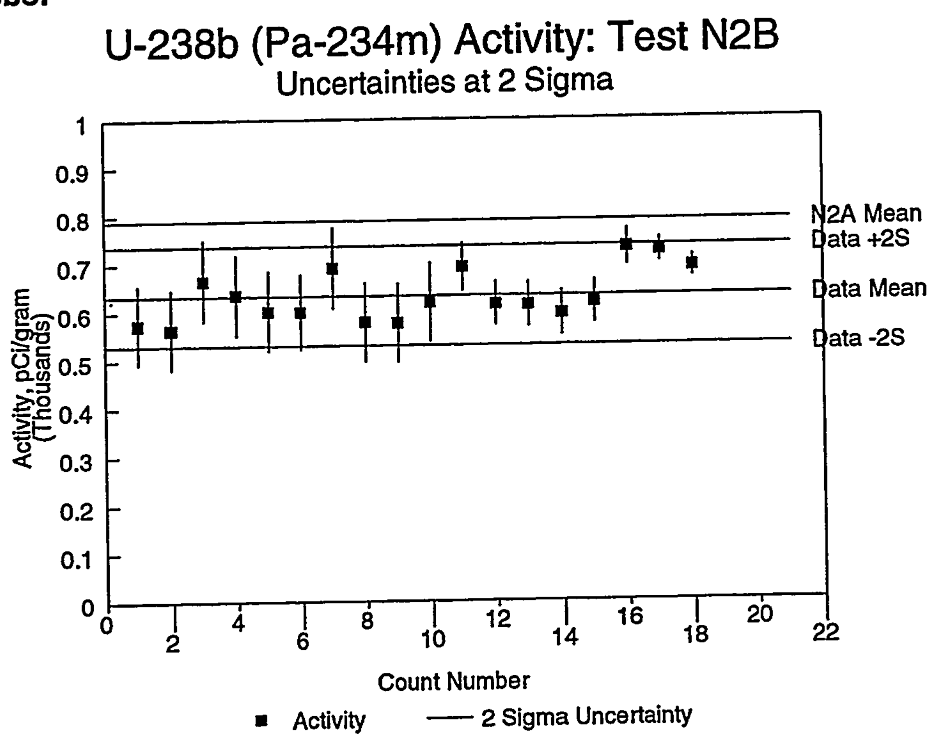


**Figure 6-50 U-238b (Pa-234m) Activity: Test 2B (>1000 pCi/g total U)**

**LPRMS Probe:**




**Survey Probe:**



# Figure 6-51 Results Summary: Test 5B (STP In situ)

## LPRMS Probe

Test D5B: Nominal Activity = ???: STP Well 1441 Efficiencies from 1/30/95

| Count | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a (Pb-214) | +- | Ra-226b (Bi-214) | +- | Th-232b (Pb-212) | +- | Th-232c (Bi-212) | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C01 | 2.75 | 0.76 | <6.7 | | <242 | | <102 | | | | | | | | | |
| C02 | 13.91 | 0.81 | <6.8 | | <236 | | <108 | | | | 3.17 | 0.24 | | | | |
| C03 | 13.40 | 0.80 | <6.8 | | <238 | | <106 | | | | 5.23 | 0.33 | 2.47 | 2.22 | | |
| C04 | 12.34 | 1.47 | <12 | | <415 | | <178 | | | | 6.69 | 0.64 | | | | |
| C05 | 9.59 | 1.72 | <12 | | <417 | | <177 | | 4.82 | 0.73 | 5.47 | 0.63 | 6.65 | 1.92 | 7.77 | 3.75 |
| C06 | | <8.5 | <12 | | <420 | | <176 | | | | 4.13 | 0.92 | | | 9.78 | 4.16 |
| C07 | 6.35 | 1.05 | <4.7 | | <168 | | <72 | | | | | | | | | |
| C08 | 12.72 | 1.25 | <12 | | <406 | | <183 | | | | 2.85 | 0.56 | | | | |
| C10 | 15.66 | 0.83 | <4.7 | | <163 | | <80 | | 1.25 | 0.59 | 1.35 | 0.19 | | | | |
| C11 | 12.86 | 1.41 | <12 | | <399 | | <196 | | | | | | | | | |
| Avg | 11.06 | 3.88 | | | | | | | 3.04 | 1.79 | 4.13 | 1.68 | 4.56 | 2.09 | 8.78 | 1.00 |

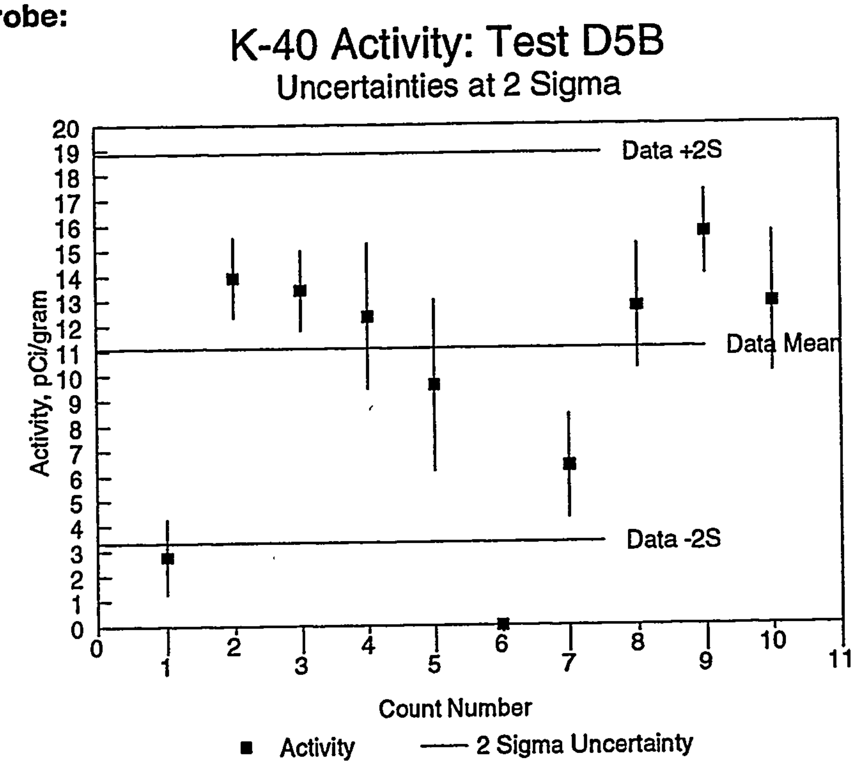
## Survey Probe

Test N5B: Nominal Activity = ???: STP Well 1441 Efficiencies from 1/30/95

| Count | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a (Pb-214) | +- | Ra-226b (Bi-214) | +- | Th-232b (Pb-212) | +- | Th-232c (Bi-212) | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C01 | 13.20 | 1.12 | <5.1 | | 286.12 | 68.66 | <77.6 | | 2.68 | 0.38 | 2.43 | 0.16 | 5.57 | 0.90 | | |
| C02 | 15.57 | 0.62 | <4.9 | | <88 | | <76.1 | | 2.36 | 0.36 | 2.00 | 0.14 | 4.67 | 0.64 | | |
| C03 | 15.27 | 0.65 | <5.0 | | 264.05 | 62.48 | <76.1 | | 2.26 | 0.37 | 2.17 | 0.15 | 4.20 | 0.81 | | |
| C04 | 9.86 | 1.41 | <6.3 | | <113.5 | | <95.8 | | 8.16 | 0.75 | 7.43 | 0.36 | 15.46 | 2.15 | | |
| C05 | 9.38 | 0.71 | 1.90 | 0.23 | 53.88 | 11.50 | | | 0.41 | 0.18 | 0.80 | 0.13 | 2.37 | 0.26 | | |
| C06 | 7.68 | 0.59 | 2.73 | 0.18 | 45.58 | 10.27 | 71.28 | 11.23 | 0.51 | 0.10 | 1.06 | 0.08 | 2.45 | 0.17 | | |
| C17 | 17.53 | 0.84 | 1.49 | 0.27 | 107.74 | 27.52 | 34.27 | 12.66 | 1.12 | 0.19 | 1.09 | 0.14 | 3.19 | 0.29 | | |
| Avg | 12.64 | 3.44 | 2.04 | 0.52 | 151.47 | 103.4 | 52.78 | 18.51 | 2.50 | 2.46 | 2.43 | 2.12 | 5.42 | 4.24 | | |

**Figure 6-52 K-40 Activity: Test 5B (STP In situ)**

**LPRMS Probe:**




**Survey Probe:**

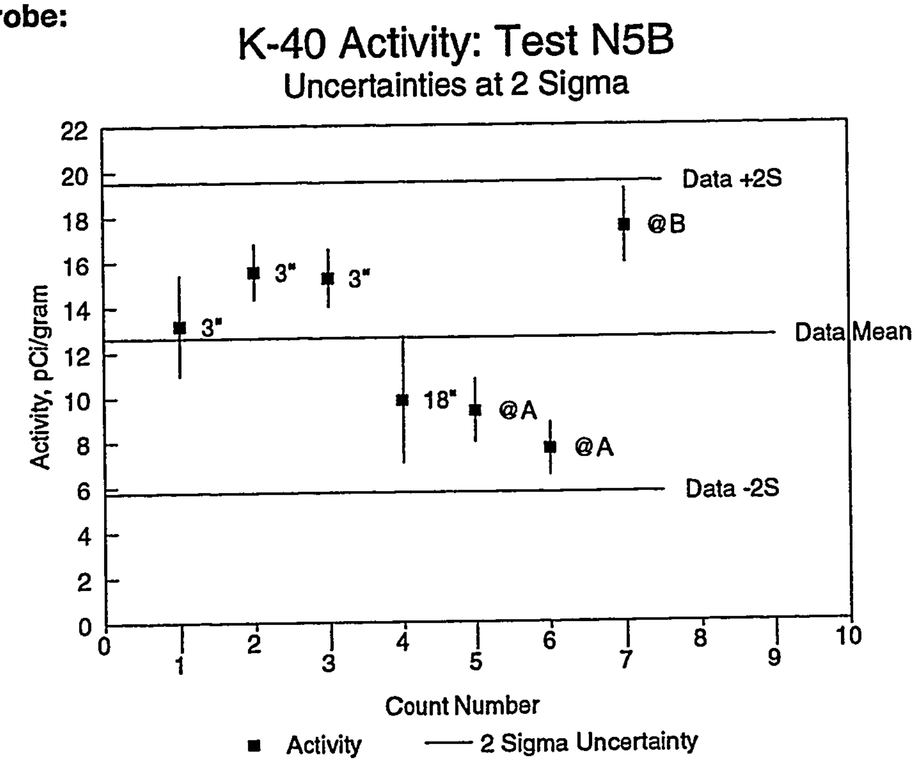
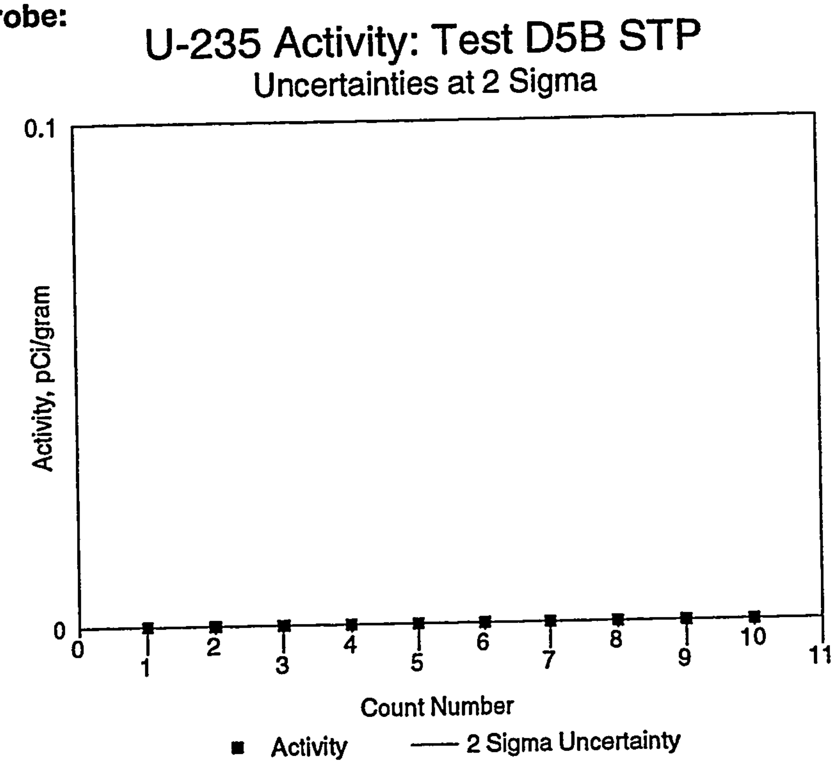


**Figure 6-53 U-235 Activity: Test 5B (STP In situ)**

**LPRMS Probe:**




**Survey Probe:**

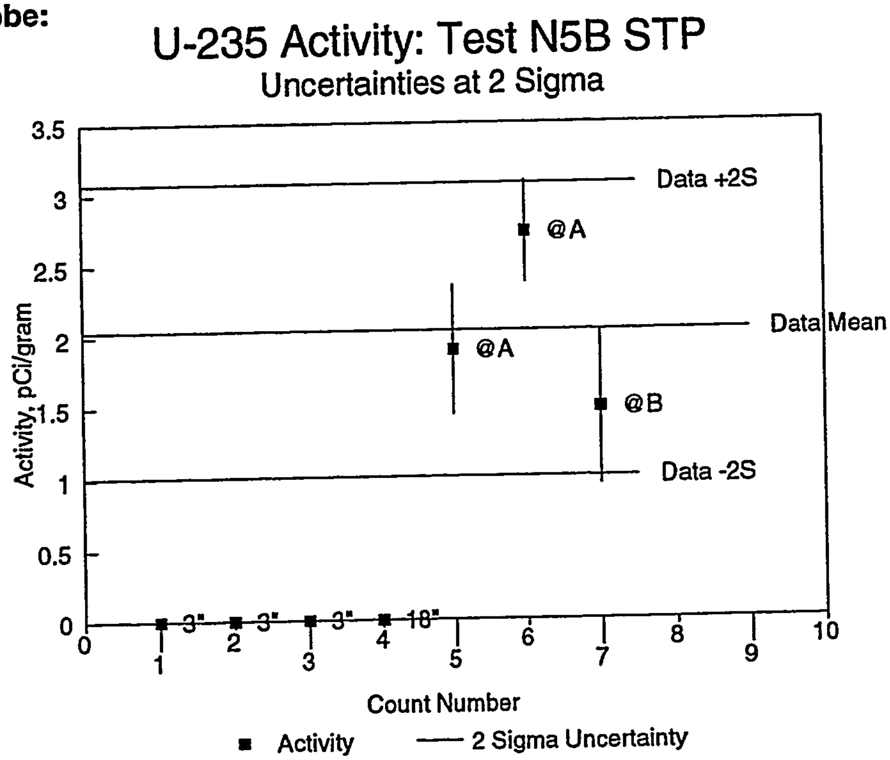
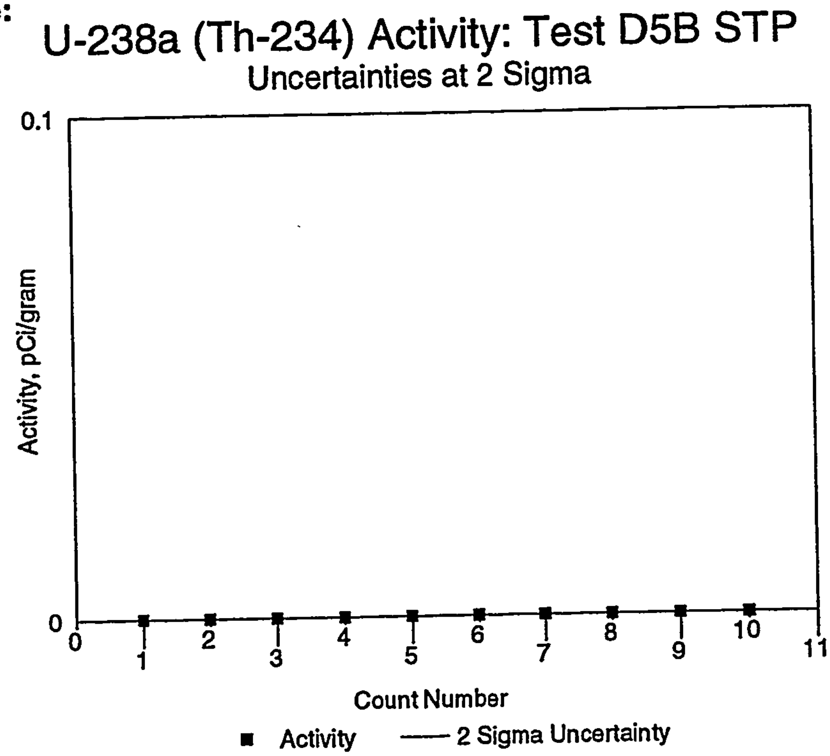
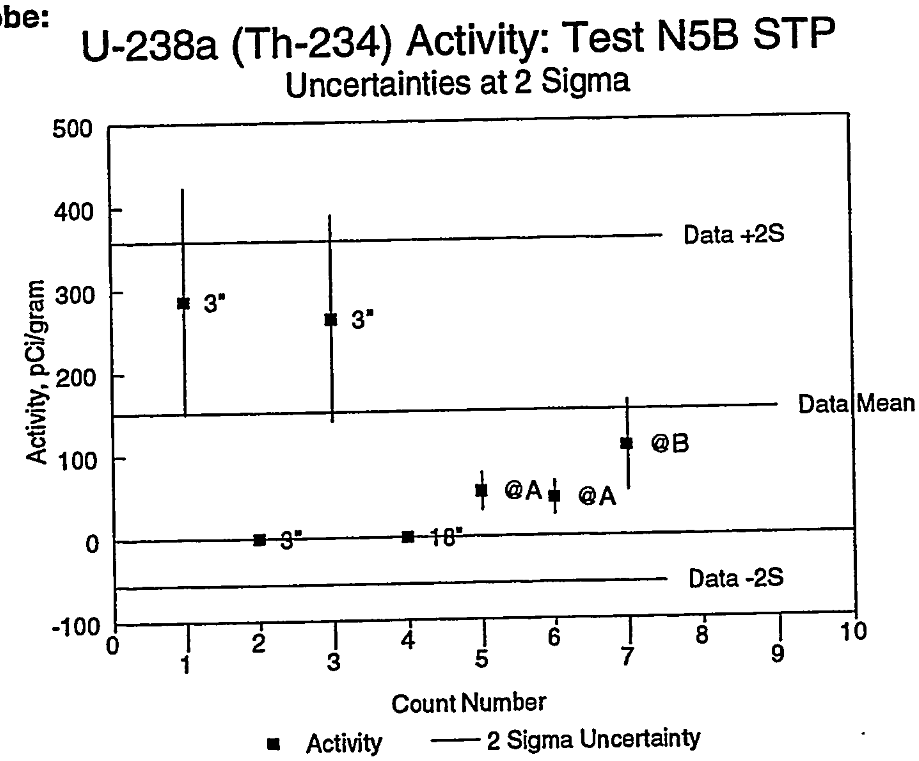


**Figure 6-54 U-238a (Th-234) Activity: Test 5B (STP In situ)**

**LPRMS Probe:**



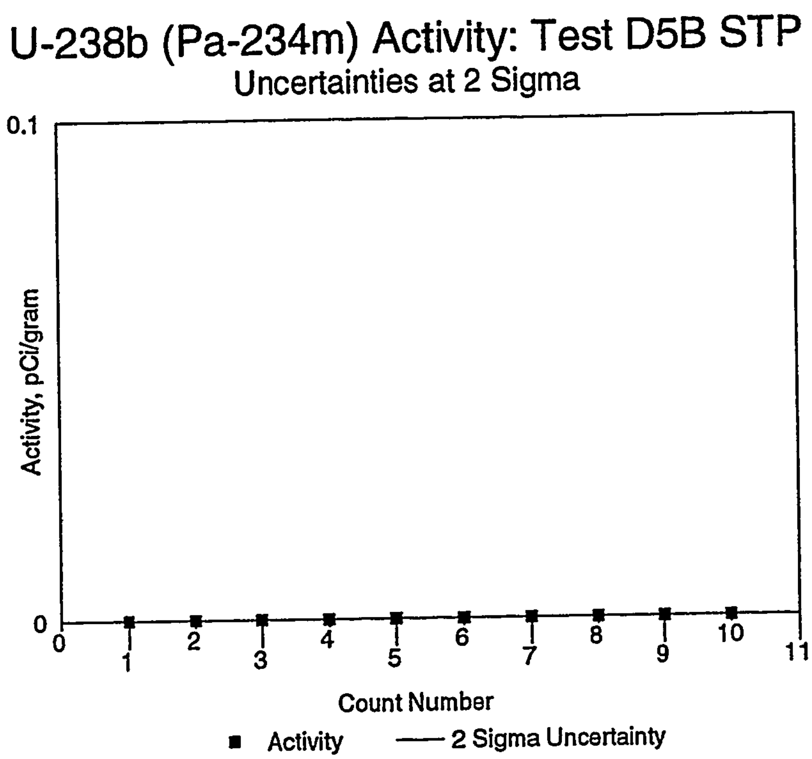

**Survey Probe:**




-132-

**Figure 6-55 U-238b (Pa-234m) Activity: Test 5B (STP In situ)**

**LPRMS Probe:**




**Survey Probe:**

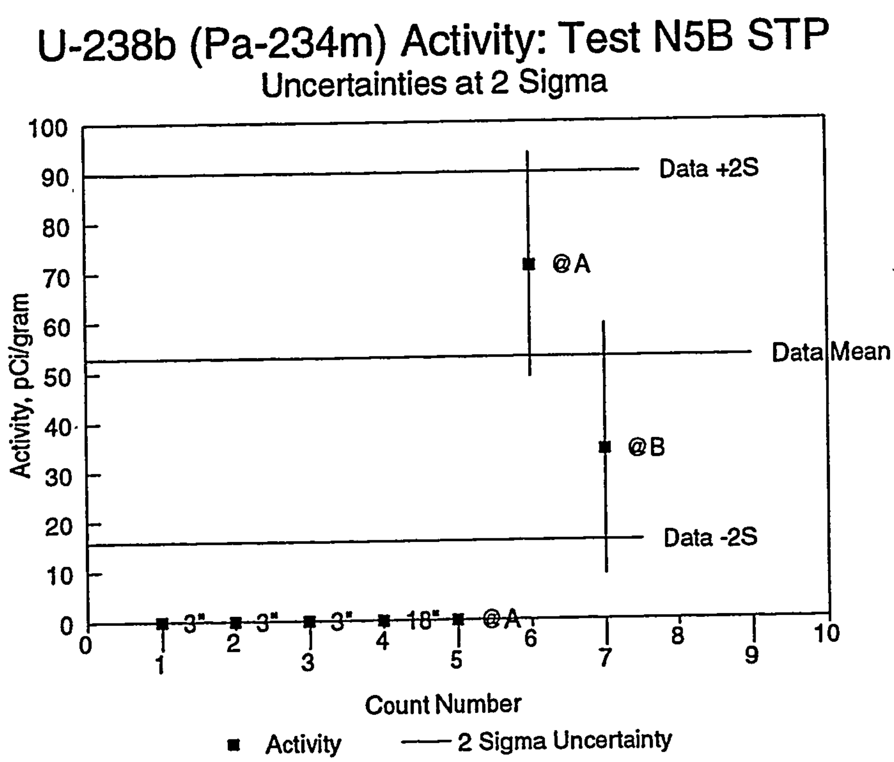
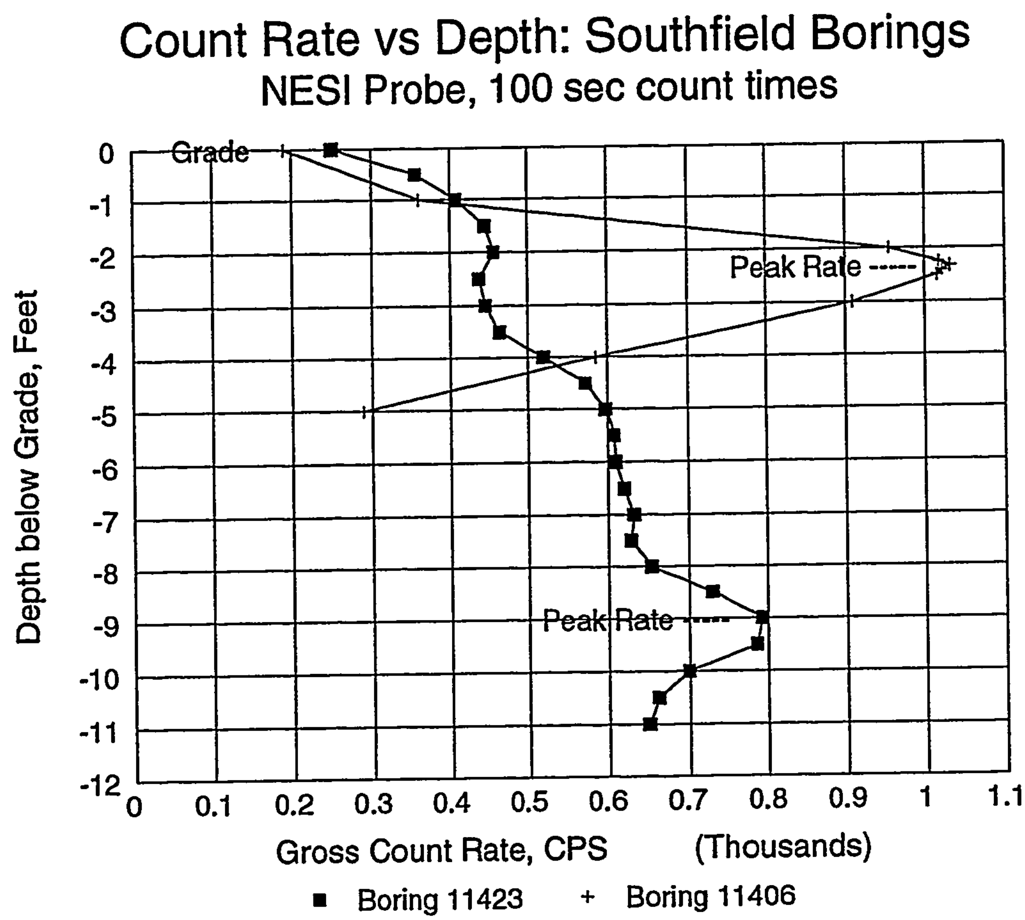
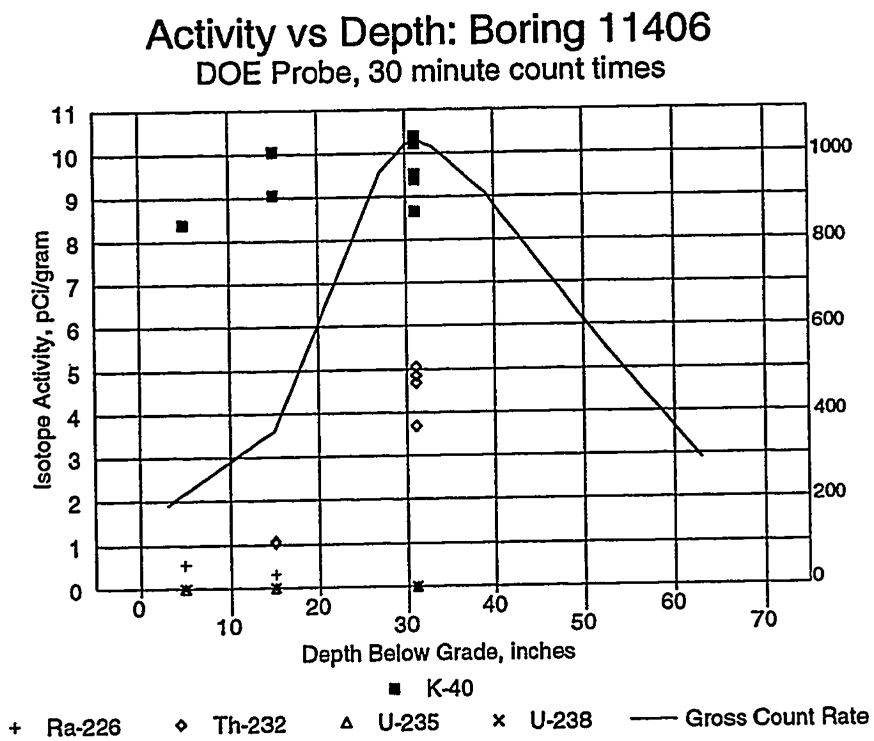


**Figure 6-56 Gross Count Rate vs Depth (Borings 11406 & 11423)**



## Figure 6-57 Boring 11406 Isotopic Activity vs Depth

**LPRMS Probe:**




**Survey Probe:**

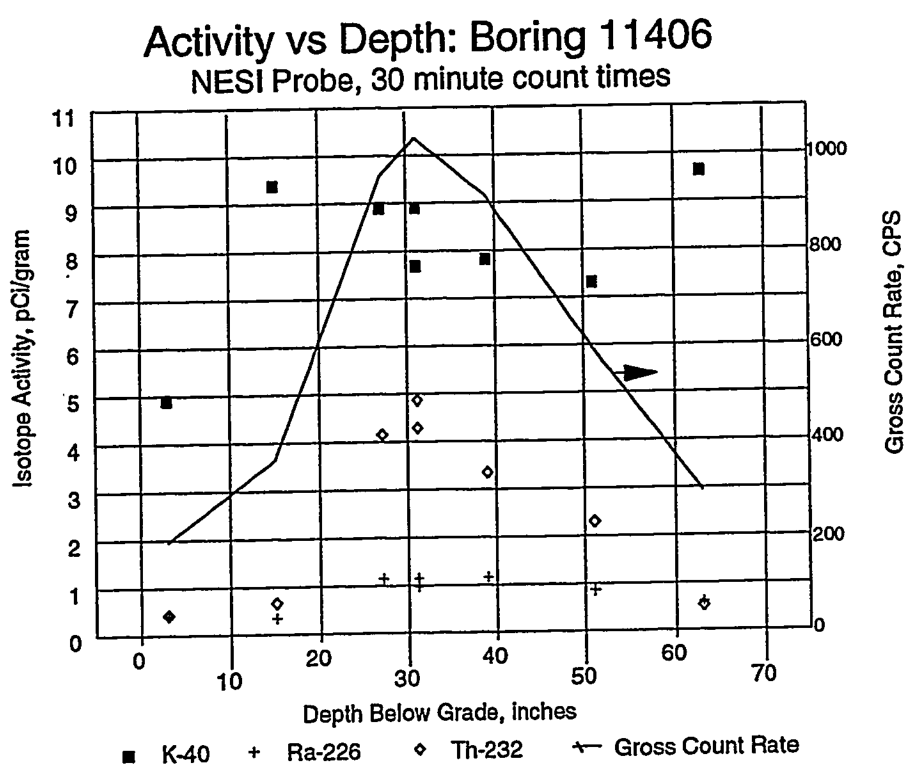
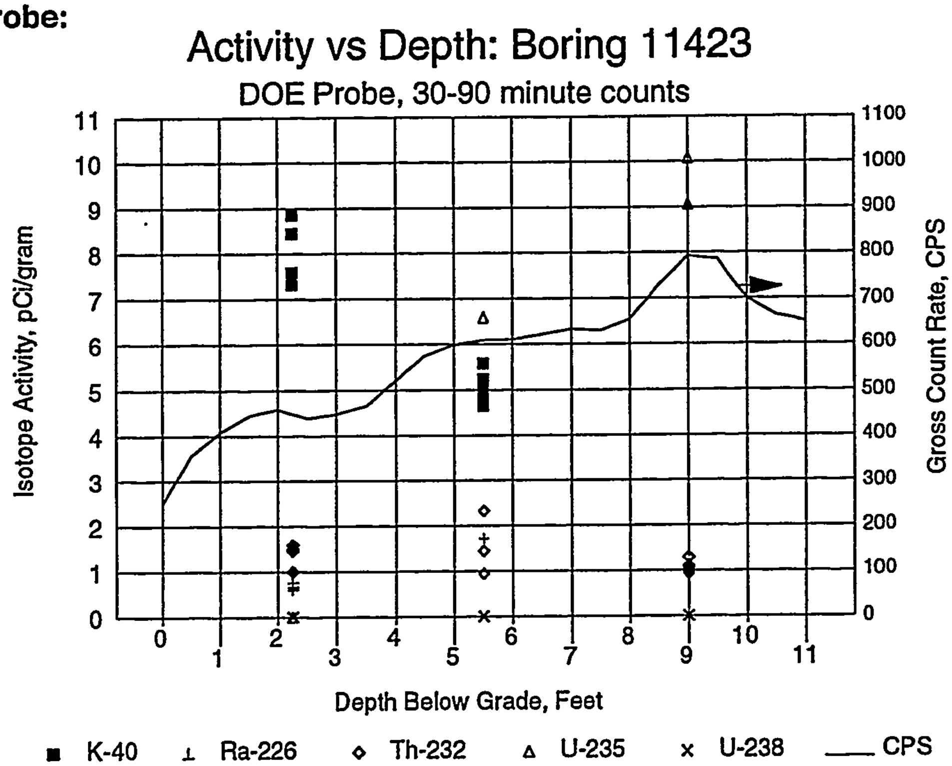


**Figure 6-58 Boring 11423 Isotopic Activity vs Depth**

**LPRMS Probe:**




**Survey Probe:**

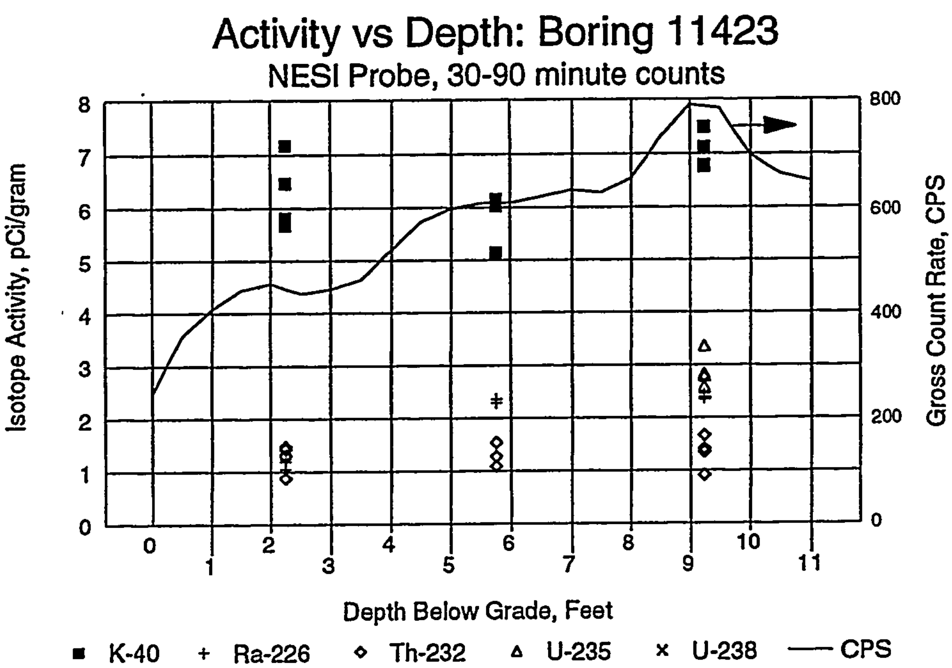
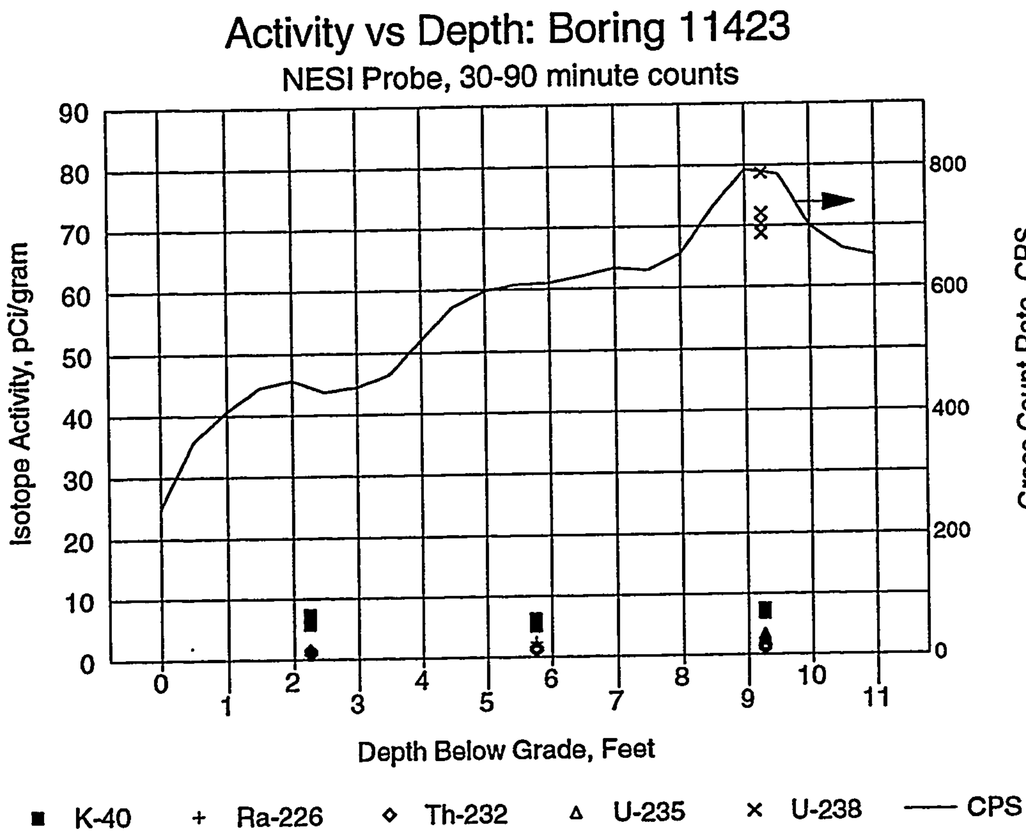


**Figure 6-59 Boring 11423 Isotopic Activity vs Depth**



## Figure 6-60 Results Summary: Test 6A (South Plume) LPRMS Probe

| Test D6A: Nominal Activity = Unknown South Plume Water | | | | | | | Efficiencies from 01/30/95 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Count USID | K-40 | +- | U-235 | +- | U-238a (Th-234) | +- | U-238b (Pa-234m) | +- | Ra-226a (Pb-214) | +- | Ra-226b (Bi-214) | +- |
| C01 | <1.54 | | <0.64 | | <13.8 | | <24.8 | | | | | |
| C02 | <1.06 | | <0.45 | | <9.7 | | <17.1 | | | | | |
| C03 | <0.86 | | <0.37 | | <7.9 | | <13.8 | | | | | |
| C04 | | | | | | | | | | | | |
| C05 | | | | | | | | | | | | |
| Avg | | | | | | | | | | | | |

## Figure 6-61 Results Summary: Test 6B (SWRB Water) LPRMS Probe

| Test D6B: Nominal Activity = Unknown: SWRB Water | | | | | | | Efficiencies from 01/30/95 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Count USID | K-40 | +- | U-235 | +- | U-238a (Th-234) | +- | U-238b (Pa-234m) | +- | Ra-226a (Pb-214) | +- | Ra-226b (Bi-214) | +- |
| C01 | <1.5 | | <0.55 | | <13.5 | | 15.50 | 6.67 | | | | |
| C02 | <1.1 | | <0.39 | | <9.5 | | <17 | | | | | |
| C03 | 0.67 | 0.11 | <0.32 | | <7.8 | | <14 | | | | | |
| C04 | | | | | | | | | | | | |
| C05 | | | | | | | | | | | | |
| Avg | 0.67 | | | | | | 15.50 | | | | | |

## Figure 6-62 Results Summary: Test 6C (Bio-d Water) LPRMS Probe

| Test D6C: Nominal Activity = Unknown: Bio-D Water | | | | | | | Efficiencies from 01/30/95 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Count USID | K-40 | +- | U-235 | +- | U-238a (Th-234) | +- | U-238b (Pa-234m) | +- | Ra-226a (Pb-214) | +- | Ra-226b (Bi-214) | +- |
| C01 | <1.4 | | <0.58 | | <13.1 | | <22.3 | | | | | |
| C02 | <0.98 | | <0.41 | | <9.2 | | <15.8 | | | | | |
| C03 | 0.41 | 0.10 | <0.33 | | <7.5 | | <12.8 | | | | | |
| C04 | | | | | | | | | | | | |
| C05 | | | | | | | | | | | | |
| Avg | 0.41 | | | | | | | | | | | |

## Figure 6-63 Results Summary: Test 6A (South Plume) Survey Probe

Test N6A: Nominal Activity = Unknown South Plume Water Efficiencies from 01/30/95

| Count USID | K-40 | +- | U-235 | +- | U-238a (Th-234) | +- | U-238b (Pa-234m) | +- | Ra-226a (Pb-214) | +- | Ra-226b (Bi-214) | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C01 | 0.62 | 0.18 | <0.37 | | <4.8 | | <20.5 | | 0.22 | 0.04 | 0.12 | 0.03 |
| C02 | 0.58 | 0.13 | <0.26 | | <3.4 | | <14.4 | | 0.15 | 0.03 | 0.14 | 0.02 |
| C03 | 0.71 | 0.10 | <0.21 | | <2.7 | | <11.7 | | 0.18 | 0.03 | 0.13 | 0.02 |
| C04 | | | | | | | | | | | | |
| C05 | | | | | | | | | | | | |
| Avg | 0.64 | 0.05 | | | | | | | 0.18 | 0.03 | 0.13 | 0.01 |

## Figure 6-64 Results Summary: Test 6B (SWRB Water) Survey Probe

Test N6B: Nominal Activity = Unknown: SWRB Water Efficiencies from 01/30/95

| Count USID | K-40 | +- | U-235 | +- | U-238a (Th-234) | +- | U-238b (Pa-234m) | +- | Ra-226a (Pb-214) | +- | Ra-226b (Bi-214) | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C01 | <1.5 | | <0.42 | | <5.8 | | <22.8 | | <.4 | | <.3 | |
| C02 | 1.13 | 0.14 | <0.30 | | <4.0 | | <15.8 | | <.3 | | <.2 | |
| C03 | 1.03 | 0.12 | <0.24 | | <3.2 | | <12.7 | | <.2 | | <.15 | |
| C04 | | | | | | | | | | | | |
| C05 | | | | | | | | | | | | |
| Avg | 1.08 | 0.05 | | | | | | | | | | |

## Figure 6-65 Results Summary: Test 6C (Bio-d Water) Survey Probe

Test N6C: Nominal Activity = Unknown: Bio-D Water Efficiencies from 01/30/95

| Count USID | K-40 | +- | U-235 | +- | U-238a (Th-234) | +- | U-238b (Pa-234m) | +- | Ra-226a (Pb-214) | +- | Ra-226b (Bi-214) | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C01 | <1.1 | | <0.36 | | <4.7 | | <17.9 | | <.4 | | <.2 | |
| C02 | 0.39 | 0.10 | <0.25 | | <3.3 | | <12.6 | | <.25 | | <.15 | |
| C03 | 0.51 | 0.09 | <0.20 | | <2.7 | | <10.2 | | <.20 | | <.12 | |
| C04 | | | | | | | | | | | | |
| C05 | | | | | | | | | | | | |
| Avg | 0.45 | 0.06 | | | | | | | | | | |

## Figure 6-66 Results Summary: Test 3A (Clean Sand - Dry)

### LPRMS Probe

Test D3A: Nominal Activity = 0 pCi/g Total U — Efficiencies from 01/30/95

| Count USID | K-40 | +- | U-235 | +- | U-238a (Th-234) | +- | U-238b (Pa-234m) | +- | Ra-226a (Pb-214) | +- | Ra-226b (Bi-214) | +- | Th-232b (Pb-212) | +- | Th-232c (Bi-212) | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C01 | 5.84 | 0.31 | <0.52 | | <10.6 | | <32.3 | | | | 0.27 | 0.05 | | | | |
| C02 | 6.08 | 0.24 | <0.37 | | <7.5 | | <22.7 | | | | 0.23 | 0.03 | | | | |
| C03 | 6.27 | 0.21 | <0.30 | | <6.1 | | <18.6 | | | | 0.23 | 0.03 | | | | |
| C04 | | | | | | | | | | | | | | | | |
| C05 | | | | | | | | | | | | | | | | |
| Avg | 6.06 | 0.18 | | | | | | | | | 0.24 | 0.019 | | | | |

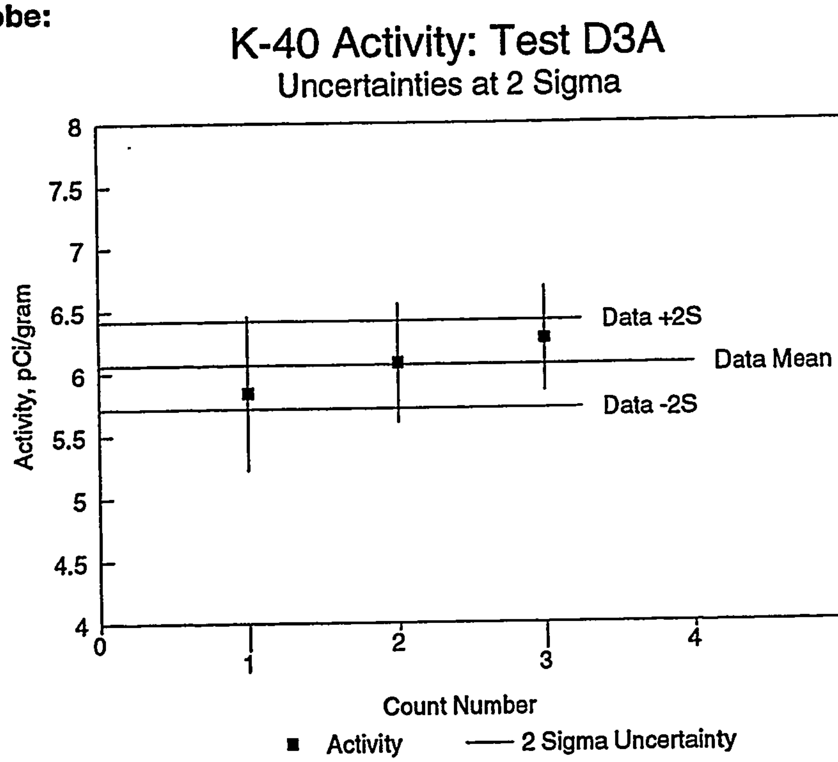
### Survey Probe

Test N3A: Nominal Activity = 0 pCi/g Total U — Efficiencies from 01/30/95

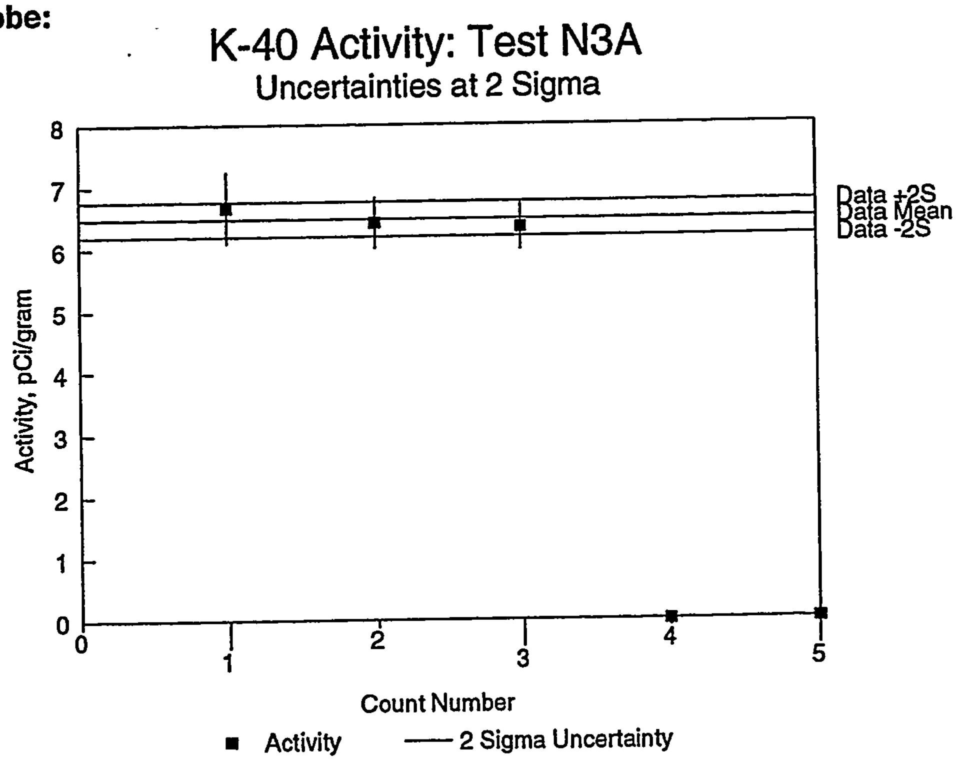
| Count USID | K-40 | +- | U-235 | +- | U-238a (Th-234) | +- | U-238b (Pa-234m) | +- | Ra-226a (Pb-214) | +- | Ra-226b (Bi-214) | +- | Th-232b (Pb-212) | +- | Th-232c (Bi-212) | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C01 | 6.67 | 0.29 | <0.37 | | <4.8 | | <20.5 | | 0.32 | 0.06 | 0.30 | 0.03 | 0.26 | 0.06 | | |
| C02 | 6.42 | 0.21 | <0.26 | | <3.4 | | <14.4 | | 0.28 | 0.04 | 0.31 | 0.02 | 0.31 | 0.05 | | |
| C03 | 6.35 | 0.19 | <0.21 | | <2.7 | | <11.7 | | 0.25 | 0.03 | 0.31 | 0.02 | 0.23 | 0.03 | | |
| Avg | 6.48 | 0.14 | | | | | | | 0.28 | 0.029 | 0.31 | 0.005 | 0.27 | 0.033 | | |

**Figure 6-67 K-40 Activity: Test 3A (Clean Sand - Dry)**

**LPRMS Probe:**




**Survey Probe:**



## Figure 6-68 Results Summary: Test 3B (Sand + Bio-d Water)

### LPRMS Probe

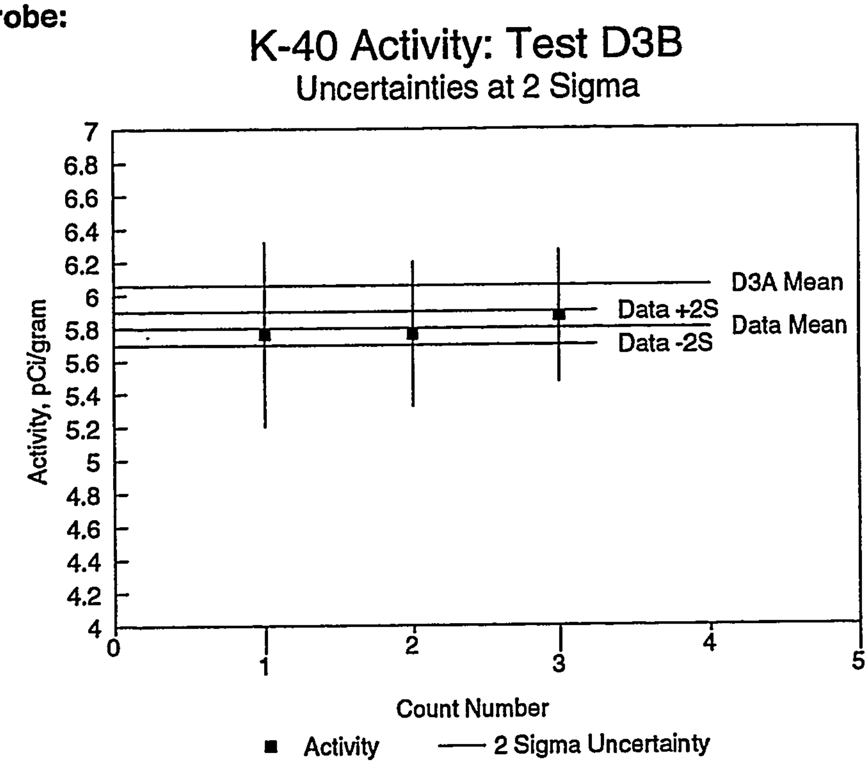
| Test D3B: Nominal Activity = Unknown Bio-d Water Efficiencies from 1/30/95 | | | | | | | | | (Pb-214) | | (Bi-214) | | (Pb-212) | | (Bi-212) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Count | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232c | +- |
| D3A | 6.06 | 0.18 | | | | | | | 0.28 | 0.03 | 0.31 | 0.00 | 0.27 | 0.03 | | |
| C01 | 5.76 | 0.28 | <0.5 | | <10.6 | | <29.5 | | | | <0.38 | | | | | |
| C02 | 5.76 | 0.22 | <0.4 | | <7.5 | | <20.8 | | | | 0.25 | 0.03 | | | | |
| C03 | 5.87 | 0.20 | <0.3 | | <6.1 | | <16.9 | | | | 0.23 | 0.02 | | | | |
| Avg | 5.80 | 0.04 | | | | | | | | | 0.24 | 0.01 | | | | |

### Survey Probe

| Test N3B: Nominal Activity = Unknown Bio-d Water Efficiencies from 1/30/95 | | | | | | | | | (Pb-214) | | (Bi-214) | | (Pb-212) | | (Bi-212) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Count | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232c | +- |
| N3A | 6.48 | 0.14 | | | | | | | 0.28 | 0.03 | 0.31 | 0.00 | 0.27 | 0.03 | | |
| C01 | 5.48 | 0.27 | <0.4 | | 6.15 | 1.94 | <25.0 | | 0.13 | 0.05 | 0.30 | 0.03 | 0.19 | 0.06 | | |
| C02 | 5.51 | 0.20 | <0.3 | | 6.07 | 1.84 | <17.6 | | 0.17 | 0.04 | 0.28 | 0.02 | 0.20 | 0.04 | | |
| C03 | 5.58 | 0.18 | <0.2 | | 6.32 | 1.86 | <14.4 | | 0.14 | 0.03 | 0.28 | 0.02 | 0.18 | 0.03 | | |
| Avg | 5.52 | 0.04 | | | 6.18 | 0.10 | | | 0.15 | 0.02 | 0.29 | 0.01 | 0.19 | 0.01 | | |

**Figure 6-69 K-40 Activity: Test 3B (Sand + Bio-d Water)**

**LPRMS Probe:**




**Survey Probe:**

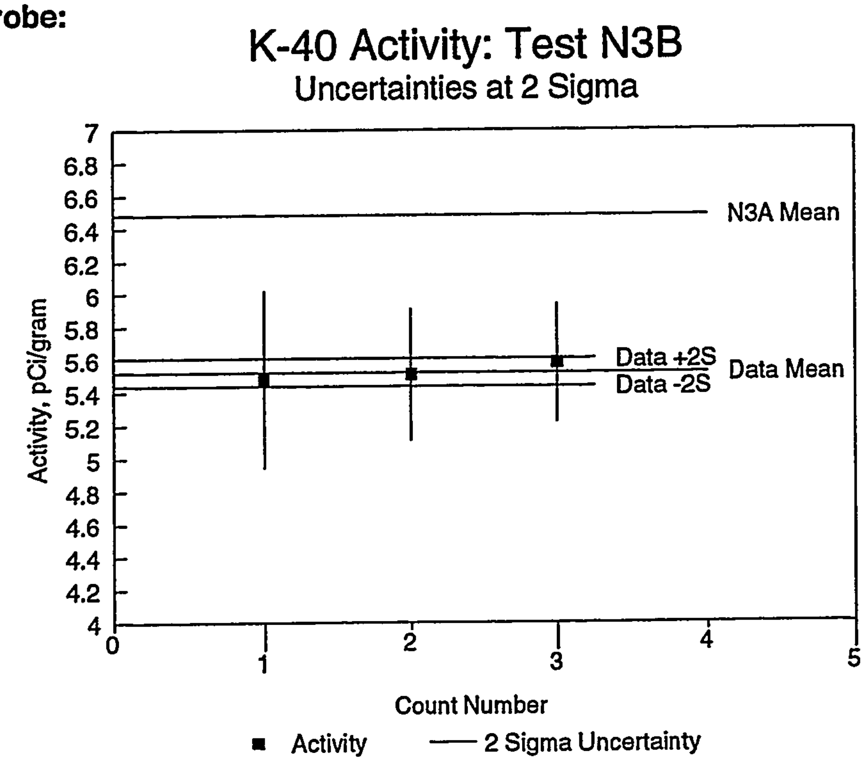
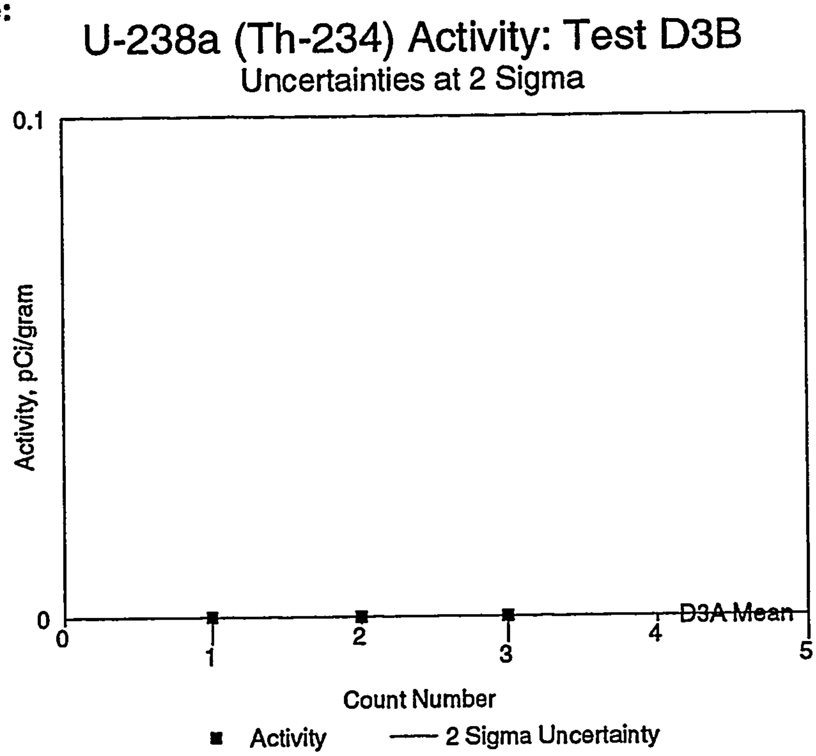
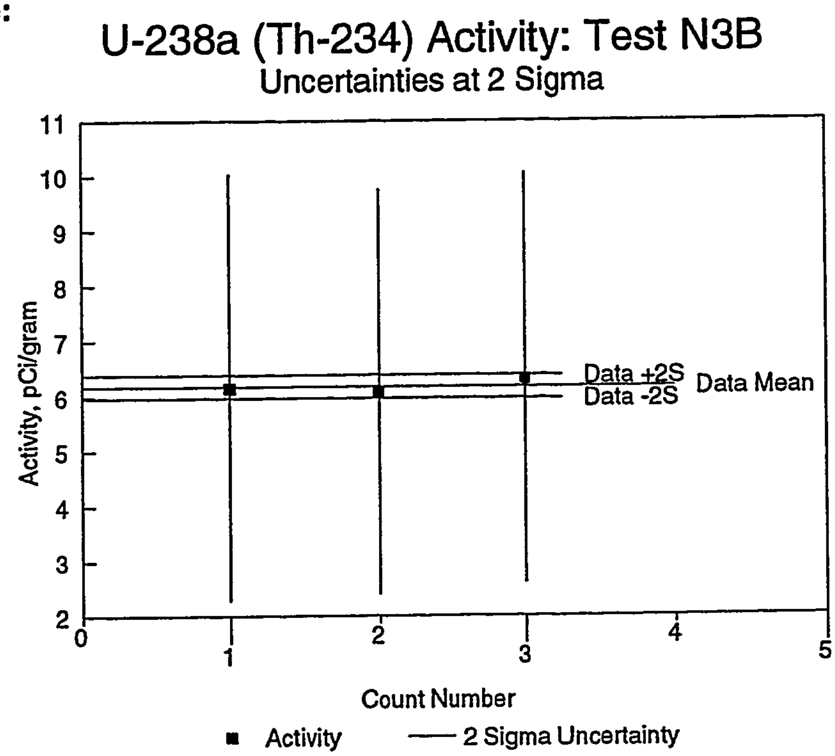


**Figure 6-70 U-238a (Th-234) Activity: Test 3B (Sand + Bio-d Water)**

**LPRMS Probe:**




**Survey Probe:**



## Figure 6-71 Re-analysis Results Summary: Test 6A (South Plume) LPRMS

Test D6AU: Nom. Activity = Unknown South Plume Water

| Count USID | K-40 | +- | U-235 | +- | U-238a (Th-234) | +- | U-238b (Pa-234m) | +- | Ra-226a (Pb-214) | +- | Ra-226b (Bi-214) | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C01 | <1.54 | | <0.64 | | 15.53 | 4.42 | <24.8 | | | | | |
| C02 | 0.59 | 0.13 | <0.45 | | 15.17 | 4.47 | <17.1 | | | | | |
| C03 | 0.48 | 0.11 | <0.37 | | 14.66 | 4.33 | <13.8 | | | | | |
| Avg | 0.54 | 0.05 | | | 15.12 | 0.36 | | | | | | |

## Figure 6-72 Re-analysis Results Summary: Test 6B (SWRB Water) LPRMS

Test D6BU: Nominal Activity = Unknown: SWRB Water

| Count USID | K-40 | +- | U-235 | +- | U-238a (Th-234) | +- | U-238b (Pa-234m) | +- | Ra-226a (Pb-214) | +- | Ra-226b (Bi-214) | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C01 | <1.5 | | <0.55 | | <13.5 | | <24.0 | | | | | |
| C02 | 0.56 | 0.13 | <0.39 | | 11.00 | 4.20 | <17 | | | | | |
| C03 | 0.67 | 0.11 | <0.32 | | 10.90 | 4.13 | <14 | | | | | |
| Avg | 0.62 | 0.05 | | | 10.95 | 0.05 | | | | | | |

## Figure 6-73 Re-analysis Results Summary: Test 6C (Bio-d Water) LPRMS

Test D6CU: Nominal Activity = Unknown: Bio-D Water

| Count USID | K-40 | +- | U-235 | +- | U-238a (Th-234) | +- | U-238b (Pa-234m) | +- | Ra-226a (Pb-214) | +- | Ra-226b (Bi-214) | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C01 | <1.4 | | <0.58 | | <13.1 | | <22.3 | | | | | |
| C02 | <0.98 | | <0.41 | | <9.2 | | <15.8 | | | | | |
| C03 | 0.41 | 0.10 | <0.33 | | <7.5 | | <12.8 | | | | | |
| Avg | 0.41 | | | | | | | | | | | |

## Figure 6-74 Re-analysis Results Summary: Test 6A (South Plume) Survey

Test N6A–USER: Unknown Activity, (South Plume) Efficiencies from 01/30/95

| Count USID | K–40 | +– | U–235 | +– | U–238a (Th–234) | +– | U–238b (Pa–234m) | +– | Ra–226a (Pb–214) | +– | Ra–226b (Bi–214) | +– |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C01 | 0.65 | 0.18 | <0.37 | | 3.62 | 1.07 | <20.5 | | 0.22 | 0.04 | 0.12 | 0.03 |
| C02 | 0.60 | 0.13 | <0.26 | | 2.70 | 0.77 | <14.4 | | 0.15 | 0.03 | 0.14 | 0.02 |
| C03 | 0.71 | 0.10 | <0.21 | | 2.90 | 0.76 | <11.7 | | 0.18 | 0.03 | 0.13 | 0.02 |
| Avg | 0.65 | 0.04 | | | 3.07 | 0.40 | | | | | | |
| Backgnd | 3.80 | 0.29 | | | 4.41 | 1.50 | | | 0.18 | 0.03 | 0.13 | 0.01 |

## Figure 6-75 Re-analysis Results Summary: Test 6B (SWRB Water) Survey

Test N6B–USER: Unknown Activity, (SWRB) Efficiencies from 01/30/95

| Count | K–40 | +– | U–235 | +– | U–238a (Th–234) | +– | U–238b (Pa–234m) | +– | Ra–226a (Pb–214) | +– | Ra–226b (Bi–214) | +– |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C01 | 0.87 | 0.20 | <0.42 | | <5.76 | | <22.8 | | | | | |
| C02 | 1.13 | 0.14 | <0.30 | | <4.01 | | <15.7 | | | | | |
| C03 | 1.03 | 0.11 | <0.24 | | 2.90 | 0.83 | <12.7 | | | | | |
| Avg | 1.01 | 0.11 | | | 2.90 | 0.83 | | | | | | |
| Backgnd | 9.08 | 0.46 | | | | | | | | | | |

## Figure 6-76 Re-analysis Results Summary: Test 6C (Bio-d Water) Survey

Test N6C–USER: Unknown Activity, (Bio–d) Efficiencies from 01/30/95

| Count | K–40 | +– | U–235 | +– | U–238a (Th–234) | +– | U–238b (Pa–234m) | +– | Ra–226a (Pb–214) | +– | Ra–226b (Bi–214) | +– |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C01 | <1.12 | | <0.36 | | 2.87 | 0.80 | <17.9 | | | | | |
| C02 | 0.39 | 0.10 | <0.25 | | 2.42 | 0.65 | <12.6 | | | | | |
| C03 | 0.51 | 0.09 | <0.20 | | 2.68 | 0.67 | <10.2 | | | | | |
| Avg | 0.45 | 0.06 | | | 2.66 | 0.18 | | | | | | |
| Backgnd | 2.46 | 0.26 | 0.36 | 0.08 | 7.11 | 1.89 | 17.04 | 3.89 | | | | |

# Figure 6-77 Re-analysis of 6A: K-40 (User Specified ROIs)

## LPRMS Probe

Test D1DU: Nominal Activity = 94.6 pCi/g Total U Effic. from 01/30/95

| Count USID | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2.05 | 0.15 | | | 44.636 | 3.17 | | | | | | | | |
| C01 | 8.66 | 1.78 | 3.79 | 1.41 | 224.25 | 65.84 | <216 | | | | | | | | | |
| C02 | 12.03 | 1.80 | 4.60 | 1.40 | 217.88 | 67.82 | <216 | | | | | | | | | |
| C03 | 12.12 | 1.77 | 4.12 | 1.40 | 234.50 | 68.67 | <216 | | | | | | | | | |
| C04 | 10.3 | 1.73 | 5.02 | 1.45 | 226.58 | 66.77 | <216 | | | | | | | | | |
| C05 | 11.45 | 1.76 | 4.24 | 1.41 | 235.31 | 68.33 | <213 | | | | | | | | | |
| C06 | 12.39 | 1.77 | 4.74 | 1.40 | 202.16 | 63.60 | <216 | | | | | | | | | |
| C07 | 9.56 | 1.76 | <3.9 | | 216.27 | 66.42 | <214 | | | | | | | | | |
| C08 | 8.70 | 1.69 | 5.99 | 1.40 | 242.09 | 71.18 | <215 | | | | | | | | | |
| C09 | 7.82 | 1.72 | 5.13 | 1.40 | 247.41 | 71.42 | <216 | | | | | | | | | |
| C10 | 12.23 | 1.73 | 5.25 | 1.41 | 209.12 | 66.08 | <215 | | | | | | | | | |
| C11 | 11.69 | 0.97 | 4.31 | 0.81 | 233.68 | 67.07 | <117 | | | | | | | | | |
| C12 | 10.99 | 1.00 | 4.60 | 0.94 | 226.58 | 66.47 | 52.79 | 14.20 | | | | | | | | |
| C13 | 10.09 | 0.96 | 3.15 | 0.95 | 218.88 | 66.46 | <117 | | | | | | | | | |
| C14 | 10.74 | 0.97 | 3.12 | 0.98 | 221.96 | 66.40 | 46.53 | 14.02 | | | | | | | | |
| C15 | 11.19 | 0.97 | 4.12 | 1.10 | 221.59 | 66.70 | <117 | | | | | | | | | |
| C16 | 11.94 | 0.57 | 4.08 | 0.64 | 224.86 | 66.75 | 35.70 | 8.18 | | | | | | | | |
| C17 | 11.90 | 0.57 | 3.76 | 0.64 | 221.60 | 66.67 | 43.28 | 8.20 | | | | | | | | |
| C18 | | | | | | | | | | | | | | | | |
| C19 | | | | | | | | | | | | | | | | |
| C20 | | | | | | | | | | | | | | | | |
| Avg | 10.81 | 1.37 | 4.38 | 0.73 | 224.98 | 10.96 | 44.58 | 6.16 | | | | | | | | |

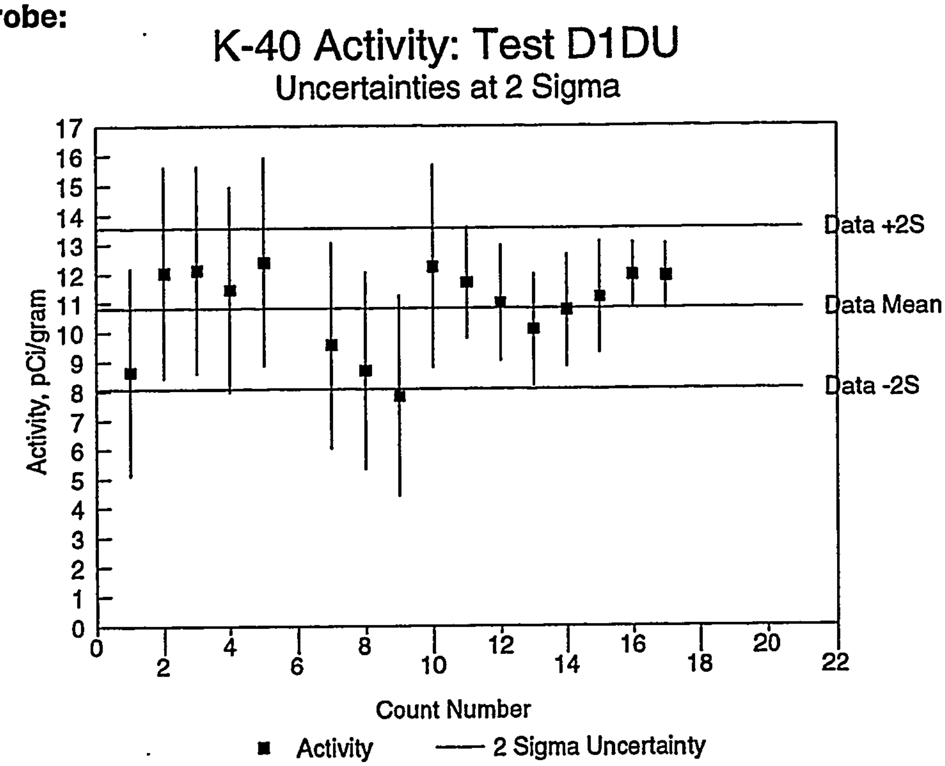
## Survey Probe

Test D1D: Nominal Activity = 94.6 pCi/g Total U Efficiencies from 01/30/95

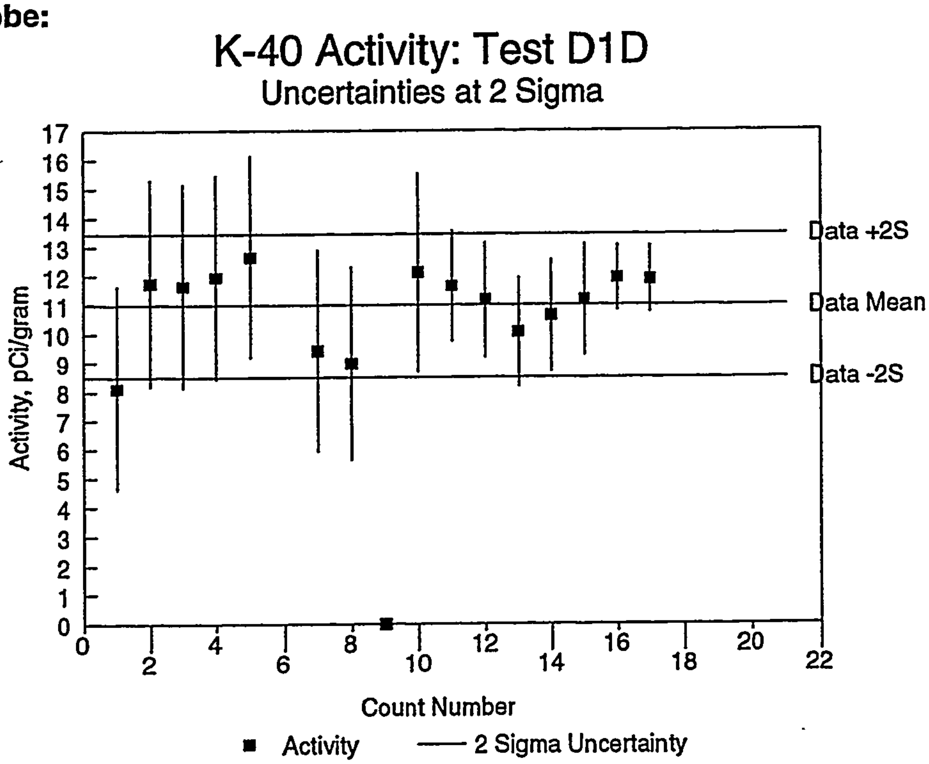
| Count USID | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2.05 | 0.15 | | | 44.636 | 3.17 | | | | | | | | |
| C01 | 8.13 | 1.76 | <3.9 | | <79 | | <216 | | | | | | | | | |
| C02 | 11.76 | 1.79 | <3.9 | | <79 | | <216 | | | | | | | | | |
| C03 | 11.66 | 1.76 | <3.9 | | <79 | | <216 | | | | | | | | | |
| C04 | 10.39 | 1.73 | <3.9 | | <79 | | <216 | | | | | | | | | |
| C05 | 11.96 | 1.77 | 6.19 | 1.79 | <79 | | <213 | | | | | | | | | |
| C06 | 12.66 | 1.75 | <3.9 | | <79 | | <216 | | | | | | | | | |
| C07 | 9.42 | 1.75 | <3.9 | | <79 | | <214 | | | | | | | | 1.53 | 0.49 |
| C08 | 8.99 | 1.68 | <3.9 | | <79 | | <216 | | | | 1.02 | 0.33 | | | | |
| C09 | <13.6 | | <3.9 | | <79 | | <216 | | | | | | | | | |
| C10 | 12.14 | 1.72 | <3.9 | | <79 | | <215 | | | | | | | | | |
| C11 | 11.66 | 0.97 | <2.1 | | <43 | | <117 | | | | | | | | | |
| C12 | 11.17 | 1.00 | <2.1 | | <43 | | <117 | | | | | | | | | |
| C13 | 10.08 | 0.95 | <2.1 | | <43 | | <117 | | | | | | | | | |
| C14 | 10.64 | 0.97 | <2.1 | | <43 | | <117 | | | | | | | | | |
| C15 | 11.19 | 0.97 | <2.1 | | <43 | | <117 | | | | | | | | | |
| C16 | 11.94 | 0.57 | <1.2 | | <25 | | <68 | | | | | | | | | |
| C17 | 11.89 | 0.58 | <1.2 | | <25 | | <68 | | | | 0.55 | 0.15 | | | 0.95 | 0.11 |
| C18 | | | | | | | | | | | | | | | | |
| C19 | | | | | | | | | | | | | | | | |
| C20 | | | | | | | | | | | | | | | | |
| Avg | 10.98 | 1.23 | 6.19 | | | | | | | | 0.79 | 0.23 | | | 1.24 | 0.29 |

**Figure 6-78 Re-analysis K-40 Activity: Test 1D (95pCi/g total U)**

**LPRMS Probe:**



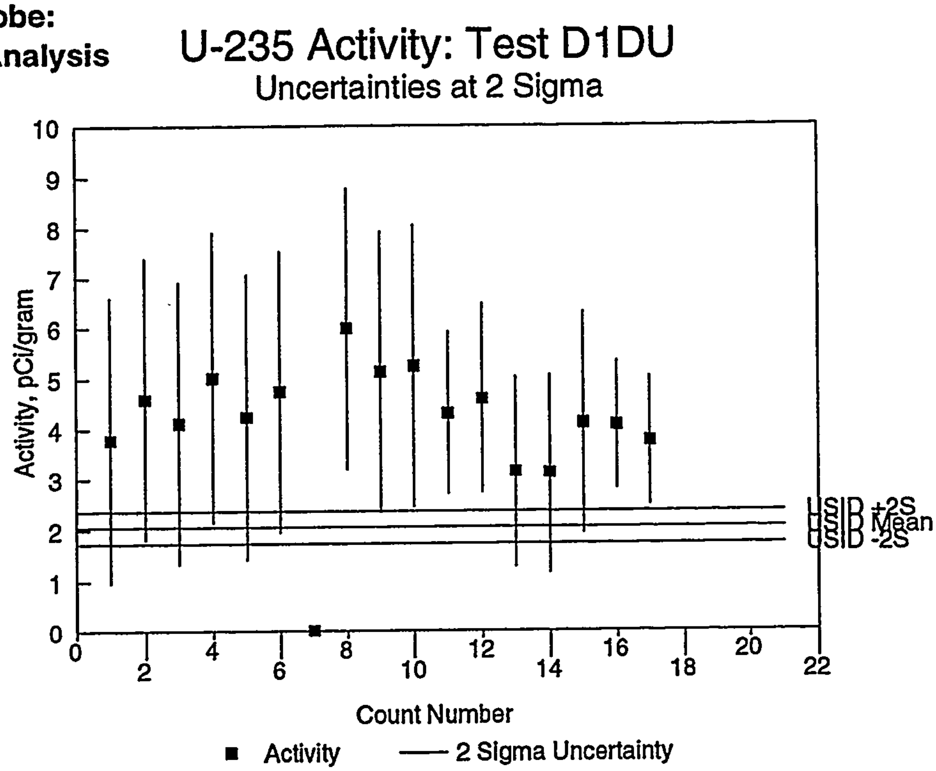

**Survey Probe:**




-148-

**Figure 6-79 Re-analysis U-235 Activity: Test 1D (95pCi/g total U)**

**LPRMS Probe:**
**User ROI Analysis**




**LPRMS Probe:**
**Library Analysis**

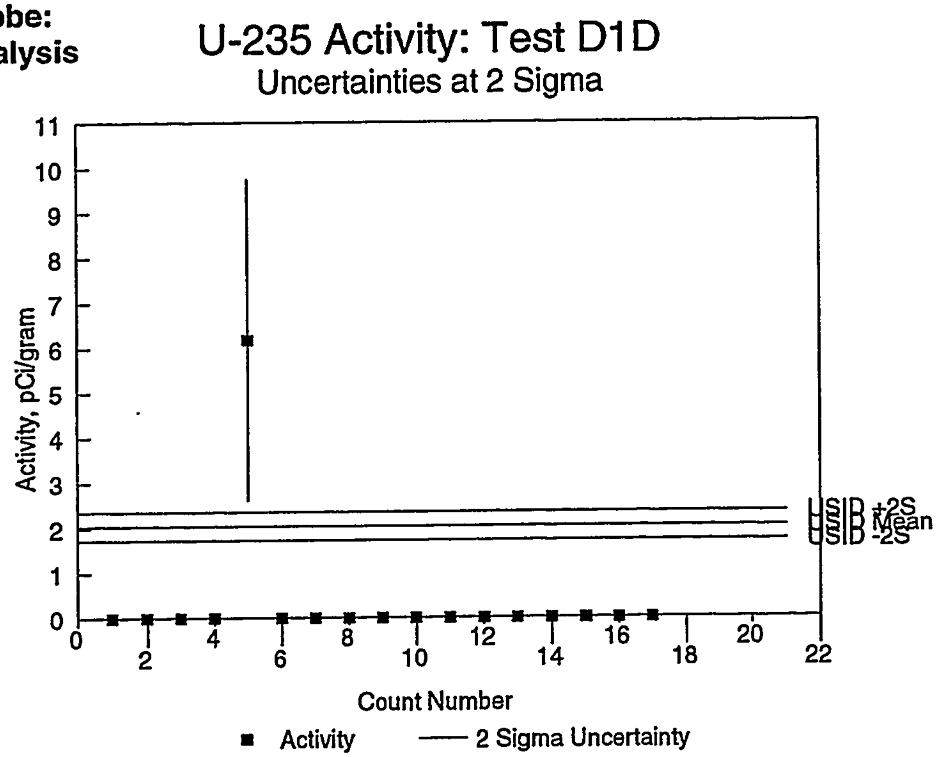
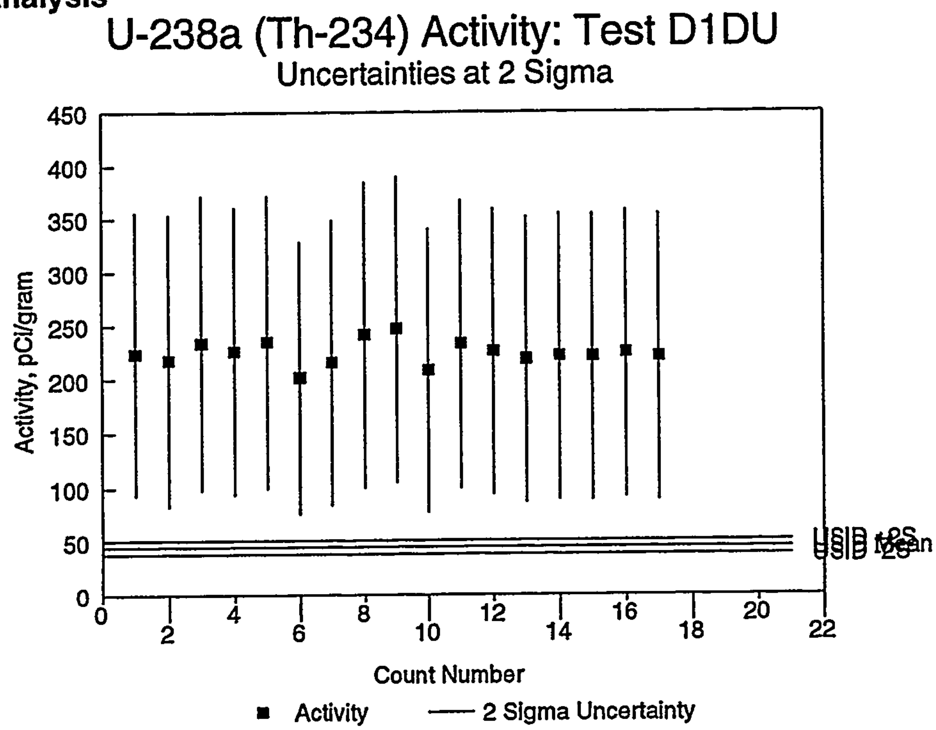


**Figure 6-80 Re-analysis U-238a (Th-234) Activity: Test 1D (95pCi/g total U)**

**LPRMS Probe:**
**User ROI Analysis**




**LPRMS Probe:**
**Library Analysis**

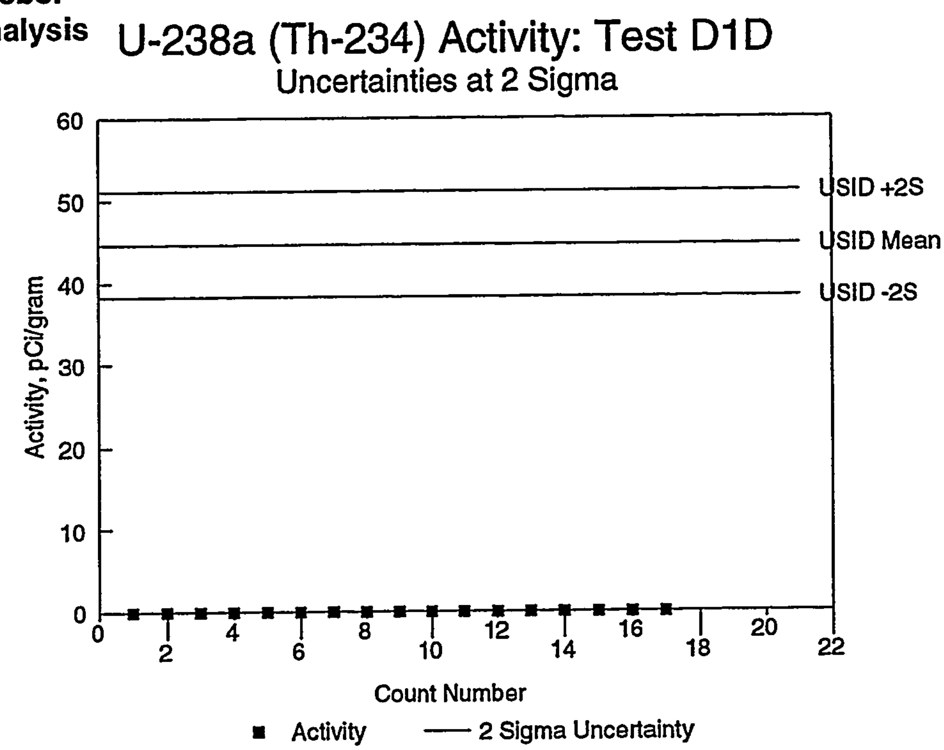
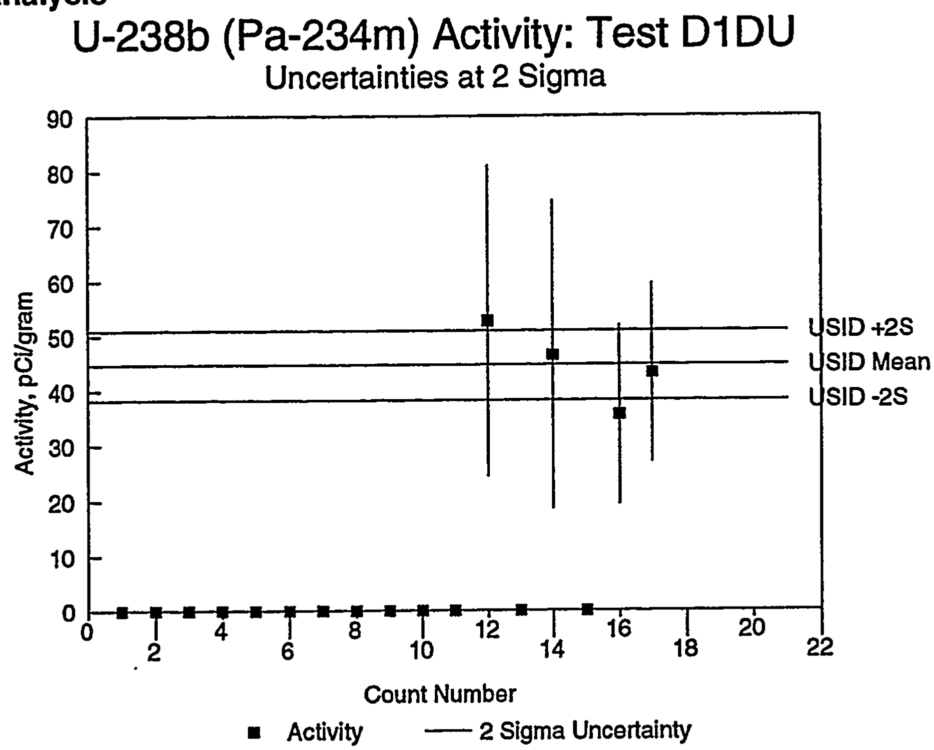
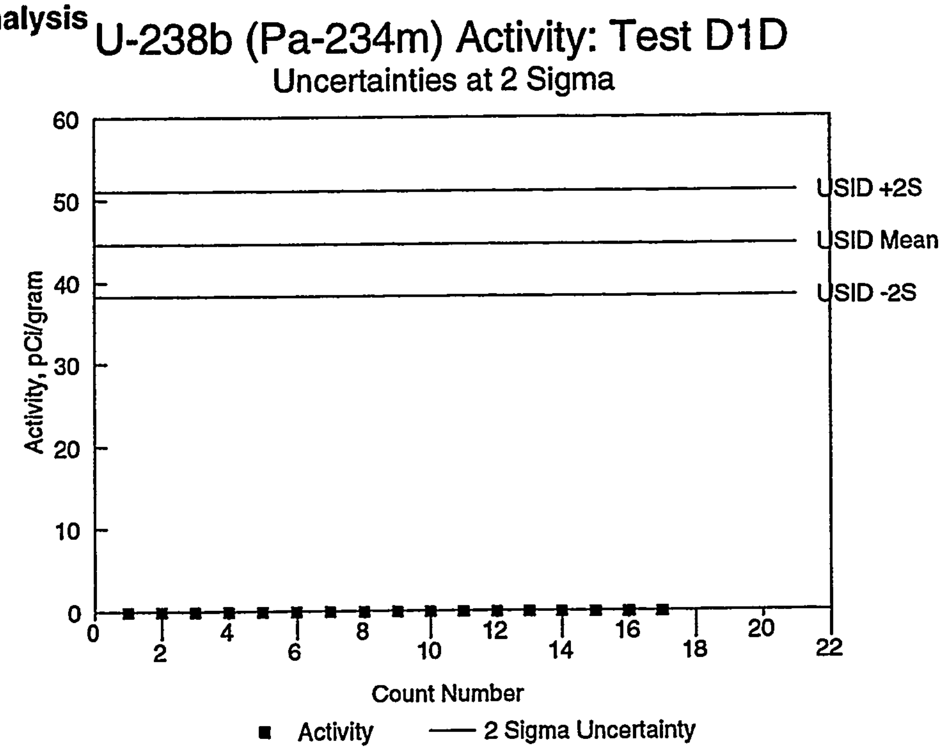


**Figure 6-81 Re-analysis U-238b (Pa-234m) Activity: Test 1D (95pCi/g total U)**

**LPRMS Probe:**
**User ROI Analysis**




**LPRMS Probe:**
**Library Analysis**



## 7.0 Conclusions and Discussion

The Phase II tests showed that the methods used in designing and analyzing the probe were adequate for calculating gamma flux, soil and water absorption, window absorption, absorption by the scintillator, scintillation efficiency, optical losses, resolution and count rates. Instrumental and analytical issues, such as the effects of resolution on signal-to-noise ratio and on the performance of spectroscopy analysis software, were not formally considered in the Phase I design. These issues are important to the overall performance of a long-term monitoring system, and are being considered in the design of the Phase III system.

Based on the results of the Phase II testing, it is concluded that the LPRMS probe as tested can detect and quantify uranium isotopes at levels of 100 pCi/g total U, but cannot reliably detect and quantify uranium isotopes at levels of 50 pCi/g total U or less. U-235 can be identified and quantified at 2 pCi/g or less, but with a 2 sigma measurement uncertainty of nearly 40%; U-238 can be identified and quantified at about 45 pCi/g with a 2 sigma uncertainty of about 40%. Count times of 30 minutes or more, and special analysis techniques (including disabling of some statistical tests) were required to achieve this level of performance. At higher activity levels, reliability of detection increased and uncertainty decreased. At the highest activity levels tested, 2 sigma uncertainties as low as 6% were achieved (30 minute count times) with standard analysis techniques, for both U-235 and U-238. For comparison, the B&W Survey Probe detected and quantified uranium isotopes at 50 pCi/g with count times of 30 minutes or greater; the 2 sigma uncertainties were about 40% for U-235 at <1 pCi/g and U-238 at about 20 pCi/g. At 100 pCi/g total U, the 2 sigma uncertainties were about 25%, dropped to about 8% at 300 pCi/g total U, and were less than 5% at the highest activity levels.

The LPRMS probe designed in Phase I and tested in Phase II was not capable of identifying and quantifying uranium isotopes at activities near concern levels of 35 pCi/g total U (17 pCi/g U-238, 0.85 pCi/g U-235). To detect and monitor these isotopes at such activities, significant improvements in resolution, peak-to-total ratio, or both will be required. Based on the results obtained with the B&W Survey Probe, it is believed that a resolution of

7.5 to 8.0% (at 662 keV) will be adequate, with some improvement in peak-to-total ratio. We have considered options to accomplish this (discussed below), and have concluded that a workable approach is readily available, employing a butt-coupled scintillator/PMT probe. This approach retains the benefits of low installed cost, serviceability, CPT installation and minimal potential for cross-contamination both during installation and in service.

### 7.1 Resolution Effects

In general, for any given test configuration, it was more difficult for the analysis software to locate peaks for the LPRMS count data than for the B&W Survey Probe. When the peaks were located in the spectra, more difficulty was encountered in identifying nuclides. For identified nuclides, the uncertainties in the calculated activities were larger. This was due primarily to the poorer resolution of the LPRMS, even though the count rates with the LPRMS probe were 10 to 40 percent higher than with the B&W Survey Probe.

The effect of resolution on the energy spectrum is illustrated in **Figure 7-1**, which shows counts of a calibration source performed with the LPRMS and B&W Survey Probes. The cal source and count times were the same for both probes. The resolution of the LPRMS probe is about 11.8%, the B&W Survey Probe resolution is about 7.3% (at 662 keV). The peaks for the LPRMS probe (dotted line) are lower and broader than those for the B&W Survey Probe (solid line), although they contain about the same or greater number of counts. The net height of the Cs-137 peak at 662 keV is roughly 7500 counts for the LPRMS probe and 12000 counts for the B&W Survey Probe. The signal-to-noise ratio (net peak height/continuum) for this peak is about 4 for the B&W Survey Probe and less than 2 for the LPRMS probe. The functional result of this is a significant increase in the minimum detectable activity (MDA): small peaks, either from low activities or from low yield isotopes, cannot be separated from the statistical variation of the continuum count rate.

The higher FWHM results in greater uncertainty in the location of the peak centroids, making peak identification more difficult. It also results in complications in separating multiple peaks and in determining their areas. For example, the Co-60 peaks in **Figure 7-1** are at 1173 and 1333 keV, separated by 160 keV. With the B&W Survey Probe, these peaks are cleanly resolved with little overlap, and the Compton edge of the 1333 keV peak (at 1119 keV) is below the Region of Interest (ROI) for the 1173 peak. With the LPRMS probe, these two peaks have significant overlap, and the Compton edge of the 1333 keV peak is within the 1173 keV peak. While these two peaks can still be separated, simple peak height analysis algorithms will have difficulty correctly determining the peak areas because of the relatively shallow valley between them and the presence of the Compton edge of one peak within the area of the other. More complex analysis routines using interactive Gaussian fits could do a better job of analyzing these peaks, but are more expensive, slower, and can require *a priori* knowledge of peak locations to be effective.

## 7.2 Sources of Resolution Loss

As discussed in Section 4.2.3, the controlling factor to the achievable resolution in a PMT/scintillator combination is statistical broadening, based on the number of photoelectrons emitted from the PMT photocathode. This quantity is controlled by the number of incident optical photons/gamma event and the quantum efficiency of the photocathode. In the LPRMS, both of these factors are important. The optical losses associated with using a lightguide reduce the number of optical photons incident at the photocathode, by about 9 dB, compared to a butt-coupled geometry. The spectral mismatch between the CsI(Tl) emission spectrum and the photocathode response spectrum introduces an additional loss of about 3.5 dB, compared to a bialkali PMT and NaI(Tl) scintillator. All other losses, such as gamma attenuation by the steel scintillator window, are minor compared to these.

The losses associated with the lightguide are primarily due to the limited view angle of the lightguide into the scintillator, a function of its numerical aperture. The lightguide chosen has an NA of about 0.65. Significantly increasing the lightguide numerical aperture to increase the view angle is not practical, because transparent materials with the required higher index of refraction are not readily available. The CsI(Tl) scintillator emission spectrum minimizes the throughput losses in the lightguide; changing the scintillator to improve the spectral match to a PMT would result in a greater increase in the throughput losses than could be gained in a better spectral match. Changing the lightguide to a material with lower losses in the emission spectrum of NaI(Tl) would result in a lower NA and consequently greater view angle losses than would be gained by the decrease in spectral losses.

## 7.3 Potential Solutions

Since a simple change of the scintillator or lightguide cannot be used to improve the resolution, a number of other potential solutions to the resolution problem have been considered and are discussed in the following subsections.

### 7.3.1 Use Gross Count Rate

Since the problems resulting from resolution are primarily those involved with identifying and quantifying nuclides (spectroscopic problems), the concept of monitoring based on gross count rate was considered. This approach has the advantage of using both peak and continuum counts, increasing the count rate. If the energy window is sufficiently large, the relatively small changes anticipated in system gain over time are unimportant. The gross count rates are high enough that relatively short count times are adequate for obtaining good count statistics. The lowest activity drum, 51 pCi/g total U, had a gross count rate of 731 CPS, resulting in more than 130,000 counts in a 3 minute count. For ten 3 minute counts, the standard deviation was 1.25 CPS, for a 2 sigma uncertainty of about 0.3%. Longer counts had the expected lower standard deviations: 0.18% at ten minutes and 0.1% at 30 minutes.

When using gross count rate, the rate includes the counts from the isotopes of concern, normal background isotopes (K-40, Ra-226, Th-232), plus any background counts from the PMT and electronics which are not discriminated away. Relatively small differences in background isotopes with high yields can obscure larger differences in low yield isotopes like uranium. The table below shows the gross count rate data for the drummed soils tests and their nominal activities. Using spectroscopy, the differences in the uranium are clearly seen, while the gross count rate data can show decreases with increasing uranium, or nonproportional increases. In tests 2A and 2B, the same soil was tested in the natural moisture and the saturated condition; this change in soil moisture resulted in a gross count rate decrease of about 12% (as expected).

**Gross Count Rate Data from Drummed Soil Tests**

| Test | Activity | Gross Count Rate (CPS) |
|---|---|---|
| 1B | 51 pCi/g U | 731 |
| 1D | 95 pCi/g U | 691 |
| 1C | 162 pCi/g U | 692 |
| 1E | 311 pCi/g U | 887 |
| 1F | 95 pCi/g U | 470 |
| 1G | 162 pCi/g U | 562 |
| 1H | 311 pCi/g U | 817 |
| 2A (dry) | 1750 pCi/g U | 2109 |
| 2B (sat) | 1750 pCi/g U | 1850 |

This data points out two major drawbacks of using gross count rate for monitoring of uranium isotopes:

- it cannot differentiate between small changes in big yield or background isotopes and big changes in small yield isotopes,
- it cannot differentiate between changes in isotope activity levels and soil moisture changes.

Water percolation is the major source of movement for isotopes in the vadose zone; an increase in activity accompanied by an increase in soil moisture content could not be reliably discerned, and a decrease in soil moisture alone would register as an increase in gross count rate and thereby an increase in activity level. These problems could be handled by an independent measure of soil moisture, and allowance for the additional attenuation by calculation. This method cannot allow for changes from other sources. Using spectroscopy, a moisture measurement is not required: since changes in the activity of a background isotope like K-40 would not be expected, apparent changes in the K-40 peak can be used to normalize the energy spectrum for soil moisture changes, and changes from other sources are unimportant.

### 7.3.2 Change Analysis Approach

An analysis approach is available which uses both the peak and continuum counts from a detector to quantify nuclides. This approach was developed before scintillation crystals with good uniformity, resolution and peak-to-total ratio were available. This approach requires an independent calibration count for each unknown and background isotope; the contributions of each isotope to the peaks and continuum are then separated in the analysis using this calibration matrix. This approach can work well in the controlled conditions of a counting lab, provided that all the isotopes are known in advance, that there are not too many unknowns and that the calibration geometry accurately reflects the measurement geometry. This method works best when the main problem is an adverse peak-to-total ratio rather than poor resolution.

With the large number of potential unknowns at DOE sites, the calibration task is formidable with this approach. The calibration specimens would need to be approximately the size of a 55 gallon drum, and one would be needed for every unknown and background isotope expected. The expected isotopes for any given site would need to be identified; the appropriate calibration specimens could then be used to develop the site specific calibration matrix. If the number of isotopes were too large, it would be expected that this method would not work very well, but the maximum number is presently unknown. Given the likelihood of 3-5 background isotopes and 5 to 10 unknowns at any given site, plus the uncertainty in how well this method would work, this is not a preferred approach to solving the resolution problem.

### 7.3.3 Change Detector Type

The possibility of changing the detector type to one with a higher quantum efficiency was considered. Both silicon photodiodes and mercuric iodide photodiodes have QE of nearly 90% over the CsI(Tl) spectral range. Resolution calculations showed that even an increase to 90% would not improve the resolution by the needed amount because of the dominance of the lightguide losses. In addition, the currently available detectors of these types have larger noise levels than PMTs at GEEs below about 500 keV, where many of the gamma lines are found. PMTs are now available with extended green response which could potentially improve the QE by about 50% in the CsI(Tl) spectral range, increasing it from about 10% to about 15%. As with the photodiodes, while this would be an improvement, it would not be sufficient.

### 7.3.4 Use Down-hole PMT

To overcome the shortcomings of the above approaches, the possibility of modifying the probe concept to use a down-hole PMT was considered. In this approach, the probe would be configured with a PMT directly butt-coupled to the scintillator, much like the B&W Survey Probe tested in Phase II. The losses associated with the lightguide NA would be eliminated, and the scintillation crystal could be changed to NaI(Tl) to eliminate the spectral mismatch losses. Based on the results of the Phase II testing, there is little doubt that the needed resolution could be obtained with this approach. With this approach, the advantages of the lightguide approach would be lost.

The major advantages originally seen for the lightguide were that it could provide low cost transmission of the scintillation signal and that it would eliminate the need for removal of the entire probe in order to service the PMT. In the original concept, the signal would be carried on relatively small diameter optical fiber to a central location, and optically multiplexed to a single detection electronics set. This would place the temperature sensitive components and those which might require periodic service in a controlled and accessible environment, and make all of the below-ground components passive and highly reliable.

Because the probe was to be permanently installed using CPT, it was desirable to have passive and reliable components below ground to minimize the possibility of cross-contamination which could result from probe removal.

During Phase I, it was found that the scintillator needed to be larger than originally anticipated in order to have sufficient absorption of the anticipated gamma flux, and that the use of a small diameter fiber was not possible; the lightguide needed to be as large as the scintillator to minimize optical losses. To avoid the cost and difficulty of running the larger diameter lightguides over long distances, the Phase II probe design incorporated the optical detection in the probe. The probe was designed so that if service of the PMT was required, it could be performed without removing the probe from the ground.

During the planning for the Phase II testing, it was learned that the capability had been developed and demonstrated for using CPT trucks to push 1-1/2 inch PVC plastic well casings. A demonstration of this capability at the FEMP was included during the CPT demonstration test. It was decided to test the Phase II LPRMS probe in such plastic casings to minimize the need for de-contamination procedures, and to simplify installing and removing the probe during the in-situ tests. The two temporary borings in the Southfield were installed using the SCAPS truck, and were subsequently tested with the LPRMS probe and the B&W Survey Probe.

With the capability of pushing PVC well casings available, the benefits which prompted the use of the lightguide should now be attainable with a down-hole PMT. By installing a water-tight PVC casing, a butt-coupled probe like the B&W Survey Probe can be installed simply by lowering it into the casing. Should the probe require service, it can be retrieved simply with no risk of cross-contamination, and without the need for a CPT rig to re-install it. This approach provides a number of other benefits, as well.

- The plastic casing can be pushed as rapidly as the CPT truck can push, without being slowed down by the assembly of the one meter probe sections, thereby reducing installation costs.

- The probe does not require heavy structure to permit it to be pushed with CPT, resulting in lower probe cost; this reduction alone more than offsets the cost of the PVC casing.

- The probe window thickness can be minimized, reducing the backscatter peak at 200-250 keV and increasing the count rate at lower energies.

- The probe does not require lightguide, reducing probe cost.

- Without lightguide, the scintillator can be NaI(Tl), reducing probe cost.

- The PMT and scintillator will both be in an essentially isothermal environment once installed, minimizing gain drift and spectral shifts.

- The PMT will be shielded from cosmic ray background by the soil.

- Butt-coupled PMT/scintillator combinations are already readily commercially available, minimizing cost and functional uncertainty.

- Multiple probes can potentially be installed in the same casing at different elevations, provided the casing bore is large enough.

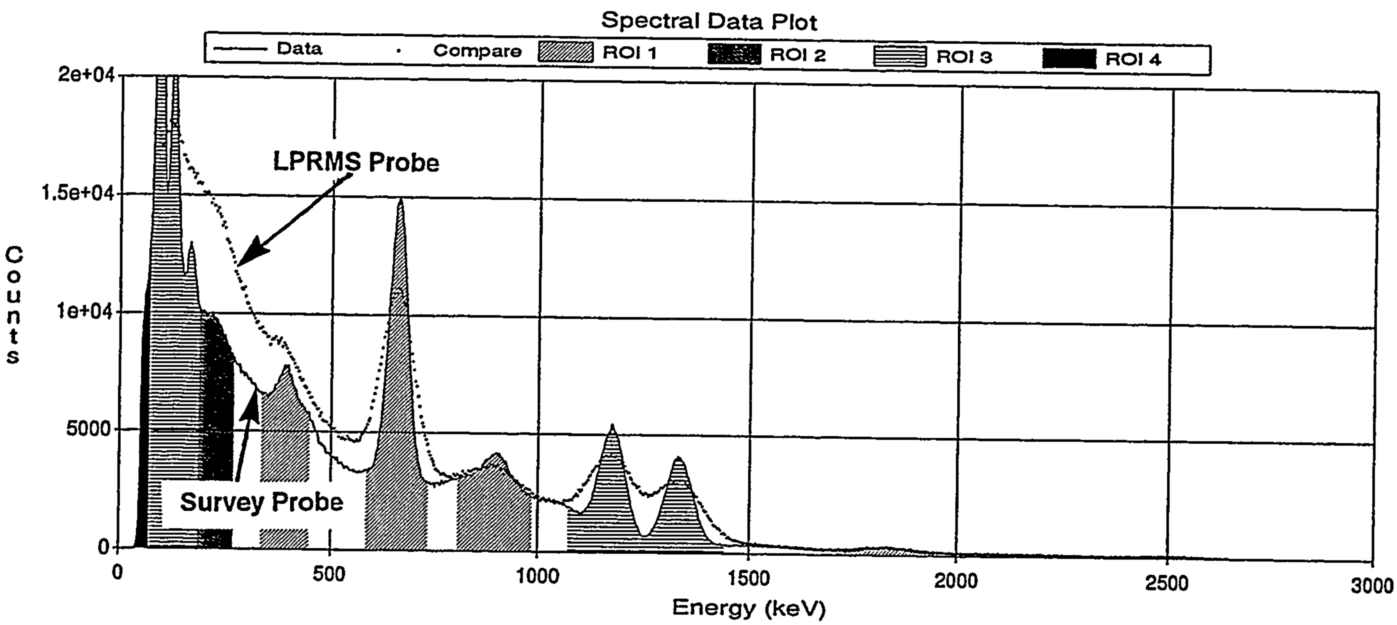
- During installation, the probe can be used to profile activity with depth before being set at its final monitoring position.

The use of this approach does depend on CPT technology for pushing PVC casing. At present, pushing of sizes larger than 1-1/2 inches has not been demonstrated, although it is not believed that this will be a serious limitation. Cobbly Western soils will require higher push forces, but this presents essentially the same problems for both steel probes or PVC. It is believed that new techniques, such as preloading of the PVC and sonic excitation, should permit the necessary depths to be reached.

Another concern with this approach is that the gamma absorption of NaI(Tl) is somewhat lower than that of CsI(Tl); for a given crystal size, NaI(Tl) will capture less of the incident gamma and will have a lower peak-to-total ratio because of this. In spite of this, the NaI(Tl) B&W Survey Probe worked reasonably well, nearly achieving the required performance. We believe that increasing the crystal diameter somewhat to increase peak-to-total ratio will offset the decreased absorption characteristics and overcome this problem.

The approach of using a butt-coupled scintillator/PMT in a CPT- installed PVC casing can provide the resolution and sensitivity needed for long-term monitoring of low activity, low yield nuclides, while retaining the benefits originally envisioned for the lightguide coupled scintillator. The monitoring system would be readily adaptable to either active or closed waste sites, and could also be readily applied in existing monitoring wells. We, therefore, have selected this approach as the basis for the system for the Phase III demonstration.

## Figure 7-1 Comparison of Calibration Spectra




**Reference Spectrum**

| | | | |
|---|---|---|---|
| Datasource: | N1F-CAL.CNF | | |
| Live Time: | 1800 sec | | |
| Real Time: | 1831 sec | | |
| Acq. Start: | 11-08-94 8:26:10 AM | | |
| Start: | 1 | : | 27.03 (keV) |
| Stop: | 1024 | : | 2805.65 (keV) |

**Compare Spectrum**

| | |
|---|---|
| Datasource: | D1F-CAL.CNF |
| Live Time: | 1800 sec |
| Real Time: | 1828 sec |
| Acq. Start: | 11-07-94 10:36:13 AM |
| Start: | 5 |
| Stop: | 809 |

# 8.0 Phase III Design

Based on the analyses and Phase II test results, a design for the Phase III system has been developed. This system incorporates all of the features expected to be needed in a commercial long-term post-closure radiation monitor, including multiple probes, multiplexing, off-site data access and unattended operation. The design is based on a butt-coupled NaI(Tl) scintillator/PMT, as discussed in section 7.2.4. Monitoring will be performed using periodic counting (once per day) and spectroscopic analysis. The probes will be placed in 2 inch Sch 80 PVC casing which will be installed by pushing with a CPT truck. Virtually all of the components required for the system are commercially available. With the architecture chosen for this system, a fully expanded and implemented system may include hundreds of remote detector/MCA stations, all electronically connected to the on-site data concentrator, which in turn is connected to the off-site host computer where data evaluation and trending is performed. **Figure 8-1** shows a conceptual drawing of an installed 5 probe system.

## 8.1 System Architecture

The overall architecture of the Phase III system is shown in **Figure 8-2**. The system consists of remote stations at each probe location which are linked to a central data concentrator by RF data links. The data concentrator is connected to an off-site host computer by a phone line modem.

Each remote station is in a standby (battery save) mode, until it receives a command from the data concentration computer to begin data acquisition. The electronics and PMT are warmed up for about 20 minutes, and a 90 minute count is performed. The resulting energy spectrum is transmitted to the data concentration computer, and the remote station is returned to the standby mode.

The data concentration computer contains the software to initiate and control acquisition of each remote station, to monitor for presets reached, to receive the data from each remote station and to interface and transmit data to the off-site host via a phone line modem.

The off-site host computer contains the software and procedures to receive the acquired data from the on-site data concentrator, to analyze the uploaded spectral data for nuclide specific information, to extract specified information and place this in a database organized by location and by time (secondary key).

## 8.2 Data Concentrator and Host Computers

The on-site data concentrator and off-site host are anticipated to be Pentium class personal computers with 16 Mb RAM and a minimum 500 Mb hard drives. The data concentrator will include basic spectroscopy software, serial ports to the radio modems, the radio modems to the remotes, phone line modem and dial-up capability and the software routines needed to control data acquisition and transmit data to the host. The host computer will include gamma analysis, nuclide identification and database software, and a phone line modem with dial-up capability. All MCA and gamma analysis software to be used are demonstrated commercially available programs; some data handling procedures will be written specifically for this application using a demonstrated software package (REXX) which is already integrated with both the hardware and gamma analysis software.

## 8.3 Remote Stations

Each probe location will comprise a stand-alone remote location, capable of unattended operation; up to five remotes will be used in the Phase III demonstration. In addition to the down-hole probe, each remote location will consist of:

InSpector gamma spectroscopy MCA system set-up for direct connection to battery power,

RS-232 radio modem for data communication to the data concentration computer, Environmental enclosure suitable for maintaining internal temperature and humidity conditions within the operating specifications of the InSpector and radio gear,

Solar panel, charger and storage cell assembly of sufficient power capacity to power the InSpector and radio hardware.

These components will be procured and integrated by the supplier to complete the remote stations as standalone units.

### 8.4 Probe Design

The down-hole probe for the Phase III system is shown in **Figure 8-3**. The probe consists of a 1.5 inch diameter by 6 inch long NaI(Tl) scintillator in a hermetic housing. The scintillator is directly butt-coupled to a 1.5 inch PMT housed in the probe body. The probe body is a hermetically-sealed thin-wall stainless steel cylinder, which also houses the voltage divider base, and provides feedthroughs for the high voltage (HV) and signal cables. No other electronics are used down-hole. The HV and signal cables extend to the surface, where they are connected to a high voltage power supply and a signal preamp, respectively. The probes required for the Phase III demonstration will be procured as complete commercial assemblies.

### 8.5 Evaluations

Two types of evaluations will be performed in Phase III: a 12 month field demonstration and laboratory evaluations. The field demonstration will include tests of up to 5 probe channels installed in PVC borings at depths of up to 60 feet. This test will demonstrate the long-term reliability and stability of the installed system for monitoring in-situ contamination, and its ability to cope with annual weather changes and seasonal ground water changes. Laboratory tests will be performed to characterize the system Data Quality (DQ): MDA (minimum detectable activity), precision and bias. The laboratory tests will be performed using a calibration source or sources with known activity levels. The entire system, including the RF links, will be subjected to these tests before field installation. Some or all of these tests may also be repeated after the 12 month demonstration test to assess the post-test condition of the system. The proposed tests are described in more detail in Appendix B.

### 8.6 System Installed Costs

Based on cost estimates obtained for the Phase III demonstration system, the system installed costs have been estimated. These costs do not include any reduction in cost for quantity, marketplace competition or increased maturity of the system technology, and thus can be considered as typical of the costs for the first installed system. The system costs include the costs for hardware, software and quality assurance (to ISO 9001), as well as the project management costs for deploying the system. Costs are not included for site specific activities such as determination of monitoring locations and depths, project specific health and safety plans, permitting and other similar activities.

The system components include those which are required for each monitoring location (probes and remote stations), those which are required for each site monitored (data concentrator) and those which are required for the system as a whole (host computer). For comparison purposes, a system with 12 monitoring locations at 20 meter depth has been assumed. This system requires a single data concentrator and a single host computer. It has been assumed that the host computer is dedicated to this one system, although in actuality, a single host can provide analysis and trending for numerous sites.

#### 8.6.1 Per Point Costs

The costs per monitored point include the cost of PVC casing installation (by CPT), the cost of completion of the boring, the down hole probe, preamp, MCA, and the enclosure (including RF transceiver and solar power supply).

| | |
|---|---|
| Casing & Installation | 1325 |
| Completion | 450 |
| Scintillation Probe | 1450 |
| Preamp | 450 |
| MCA/software | 10680 |
| Enclosure | 5800 |
| Installation/debug | 800 |
| Total/Location | $20955 |

### 8.6.2 Per Site Costs

The costs per site include the costs of deployment and training for installation of the casing, the master transceiver, the data concentrator and its software. The costs for space and utilities (electric and phone line) are considered incidental and are not included.

| | |
|---|---|
| Deployment/training | 5900 |
| Transceiver | 2750 |
| Data Concentrator | 25445 |
| Site setup/debug | 4375 |
| Total per Site | $38470 |

### 8.6.3 Per System Costs

The per system costs include the costs of the host computer, its software and licenses and the costs to install and configure the system.

| | |
|---|---|
| Host & software | 37185 |
| Configuration/debug | 7000 |
| | $44085 |

### 8.6.4 Total System Cost

The total system cost for a single system to monitor 12 points, with a dedicated host computer is shown below.

| | |
|---|---|
| Per Point Costs | 241860 |
| Per Site Costs | 38470 |
| Per System Costs | 44085 |
| | $324415 |

### 8.6.5 Comparison Costs

Costs for performing conventional sampling and analysis were estimated by FERMCO personnel for samples taken from a depth of 25 feet and analyzed for total Uranium. The estimate did not include costs for project specific health and safety plans, health and safety oversight personnel, radiological control technicians, sample shipping or surveying required. The total costs per sample were estimated to be $3000 per sample based on current rates. Information from Rocky Flats, found in DOE Technology Transfer '95 indicated that these analyses could cost approximately $3500 or more, and require 60 to 400 days. For the present cost comparison, $3500 per analysis sample was assumed. The costs of conventional sampling and analysis were evaluated using a simple annuity (present worth) type of calculation, assuming an interest rate of 5% compounded annually. The effects of inflation were ignored in this cost analysis.

If it assumed that each of 12 locations must be sampled and analyzed only once annually for a period of 25 years, the cost per location per year is $3500, and the cost for the site is $42000 per year. From the annuity tables, the "w" factor for 25 years for 5% interest is 14.094. The present capital (C) which is equivalent to $42000/year (Y) for 25 years can then be calculated from

$$C = Y \times w.$$
$$= \$42000 \times 14.094$$
$$= \$591948$$

roughly 1.8 times the cost of the installed system. Use of the LPRMS thus results in roughly a 45% cost savings.

If it is assumed that each of the locations must be sampled and analyzed quarterly, the cost savings are much larger. The cost per year using conventional sampling and analysis is $168000, and the present capital equivalent of 25 years of this sampling is $2,367,792, and the savings with the LPRMS system is approximately 87%.

**Figure 8-1 Conceptual Drawing of Installed System**

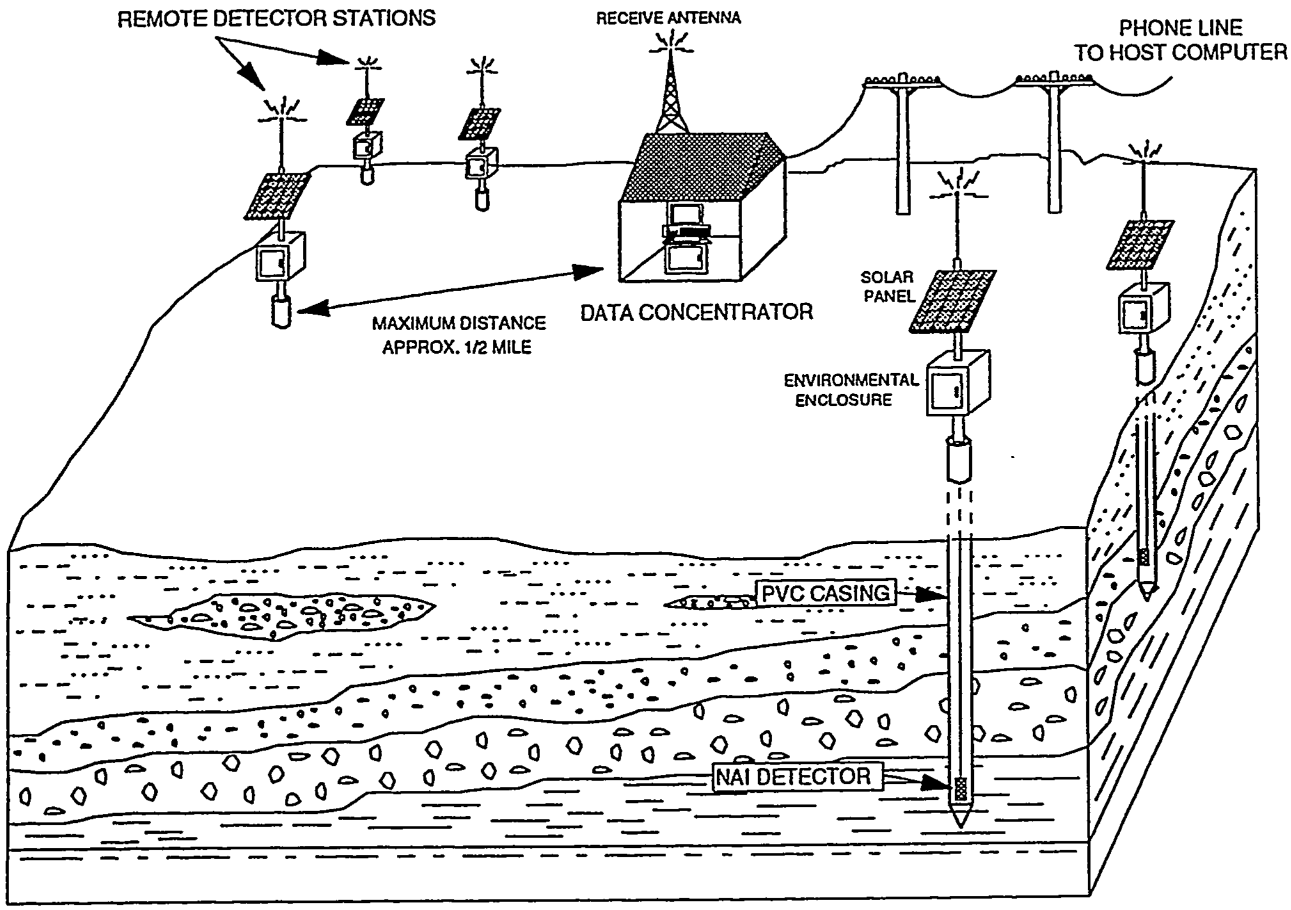


**Figure 8-2 System Architecture**

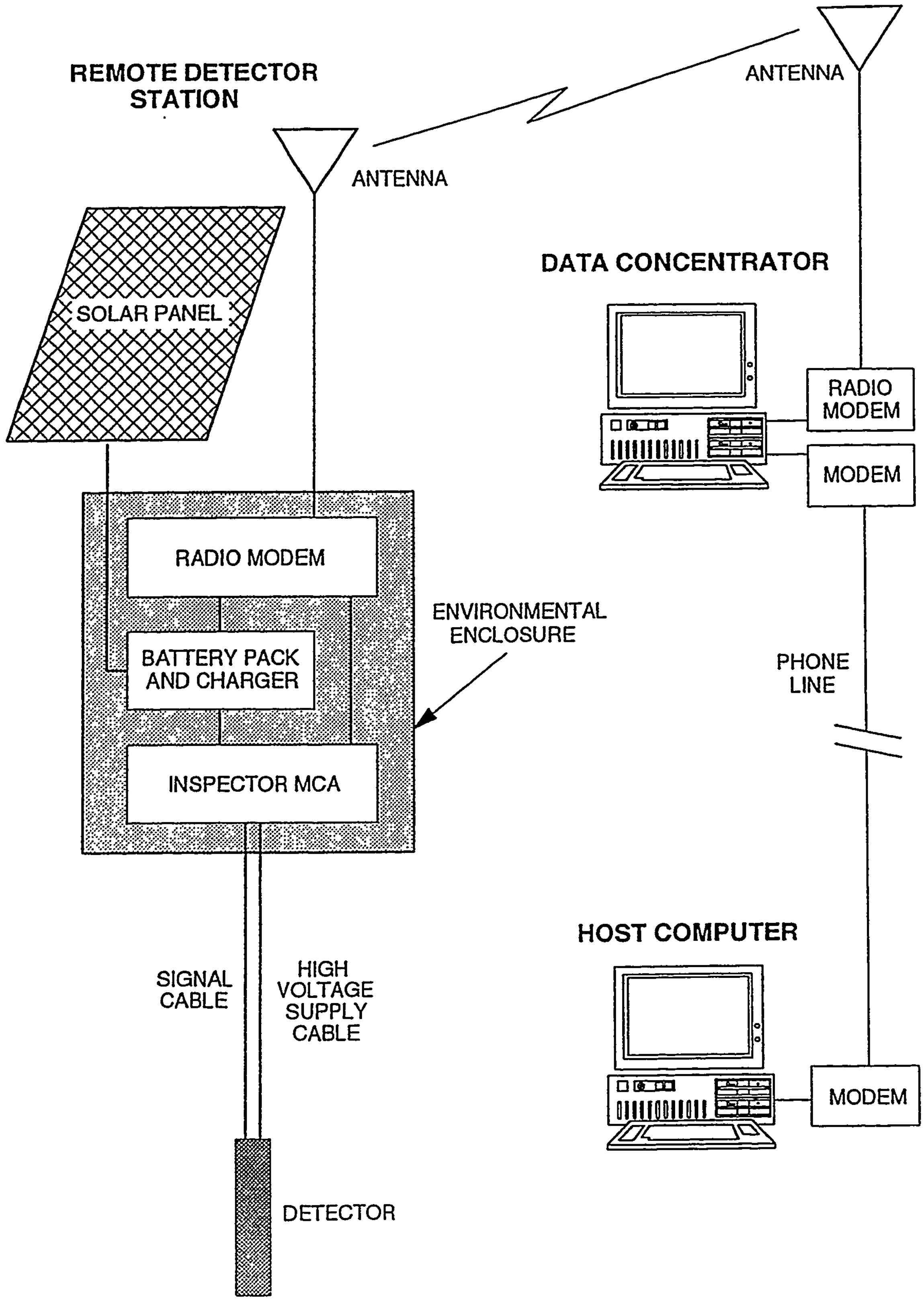
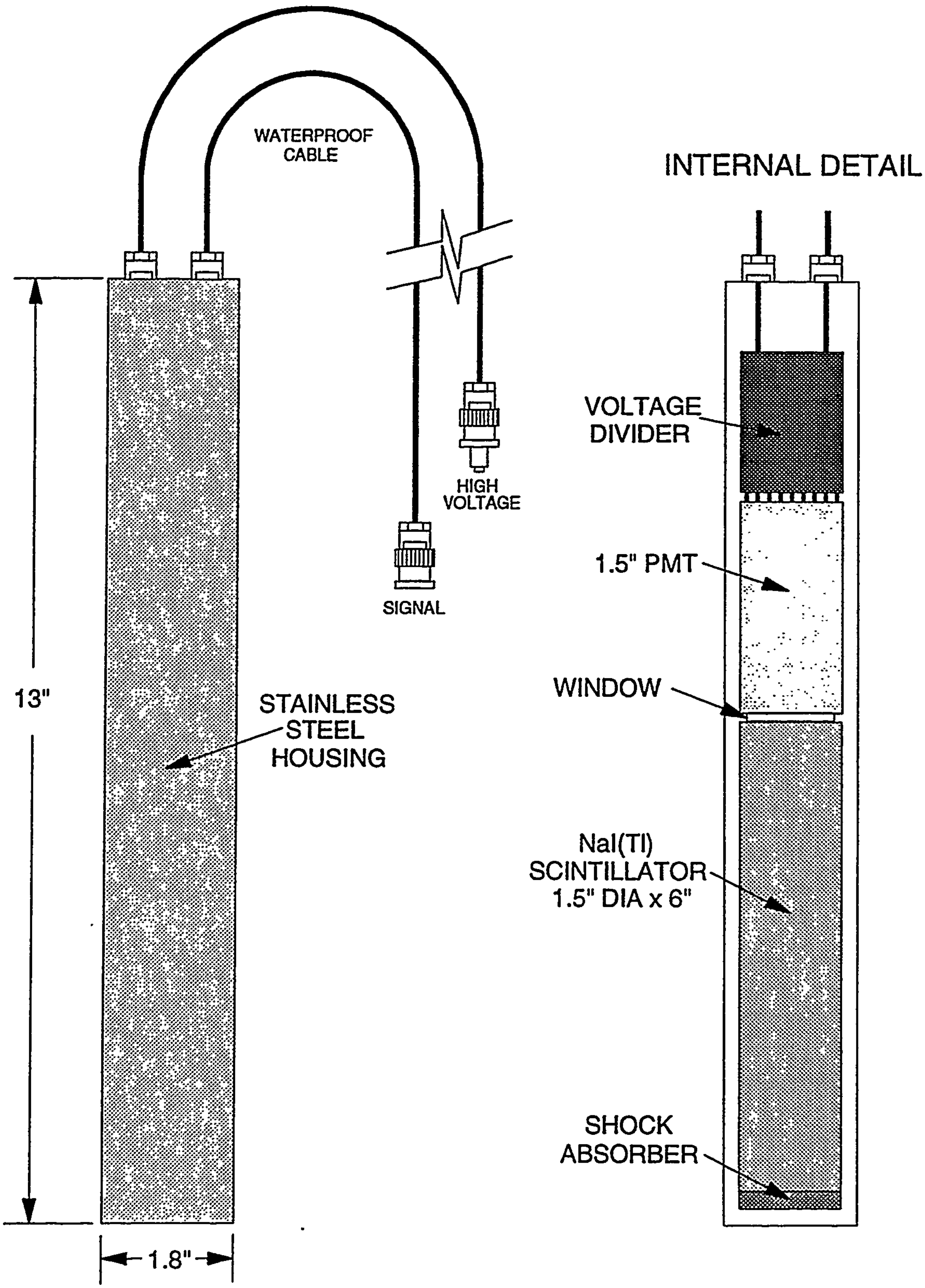


**Figure 8-3 Probe Design**



# Appendix A

Reanalysis Results

User ROIs, LPRMS Data

# Figure A-1 Results Summary: Test 1B (51 pCi/g Total U)

## User ROI Analysis

Test D1BU: Nominal Activity = 51.1 pCi/g Total U    Effic. from 01/30/95

| Count USID | K-40 +- | U-235 +- 0.923 0.41 | U-238a +- | U-238b +- 21.803 8.38 | Ra-226a +- | Ra-226b +- | Th-232b +- | Th-232d +- |
|---|---|---|---|---|---|---|---|---|
| C01 | 11.18 2.15 | <4.5 | 163.91 48.69 | <263 | | | | |
| C02 | 11.62 2.16 | <4.4 | 152.23 45.66 | <262 | | | | |
| C03 | 9.80 2.10 | <4.4 | 158.29 48.09 | <262 | | | | |
| C04 | <17.3 | <4.4 | 153.22 46.96 | <261 | | | | |
| C05 | 12.82 2.20 | <4.4 | 165.05 48.60 | <260 | | | | |
| C06 | 11.62 2.14 | <4.4 | 175.42 54.02 | <262 | | | | |
| C07 | 8.86 2.12 | <4.4 | 162.33 50.01 | <262 | | | | |
| C08 | <16.9 | <4.4 | 170.45 49.46 | <261 | | | | |
| C09 | <17.0 | <4.4 | 161.79 50.96 | <262 | | | | |
| C10 | 12.71 2.17 | <4.4 | 174.39 51.57 | <260 | | | | |
| C11 | 14.19 1.21 | <2.4 | 157.88 47.73 | <142 | | | | |
| C12 | 15.30 1.19 | <2.4 | 167.04 49.56 | <142 | | | | |
| C13 | 12.04 1.18 | <2.4 | 160.18 48.14 | <142 | | | | |
| C14 | 13.34 1.20 | <2.4 | 163.75 49.01 | <143 | | | | |
| C15 | 16.28 1.20 | <2.4 | 162.98 49.19 | <142 | | | | |
| C16 | 11.58 0.70 | <1.4 | 173.49 50.60 | <82 | | | | |
| C17 | 11.97 0.71 | <1.4 | 166.30 49.46 | <82 | | | | |
| Avg | 12.38 1.90 | | 164.04 6.57 | | | | | |

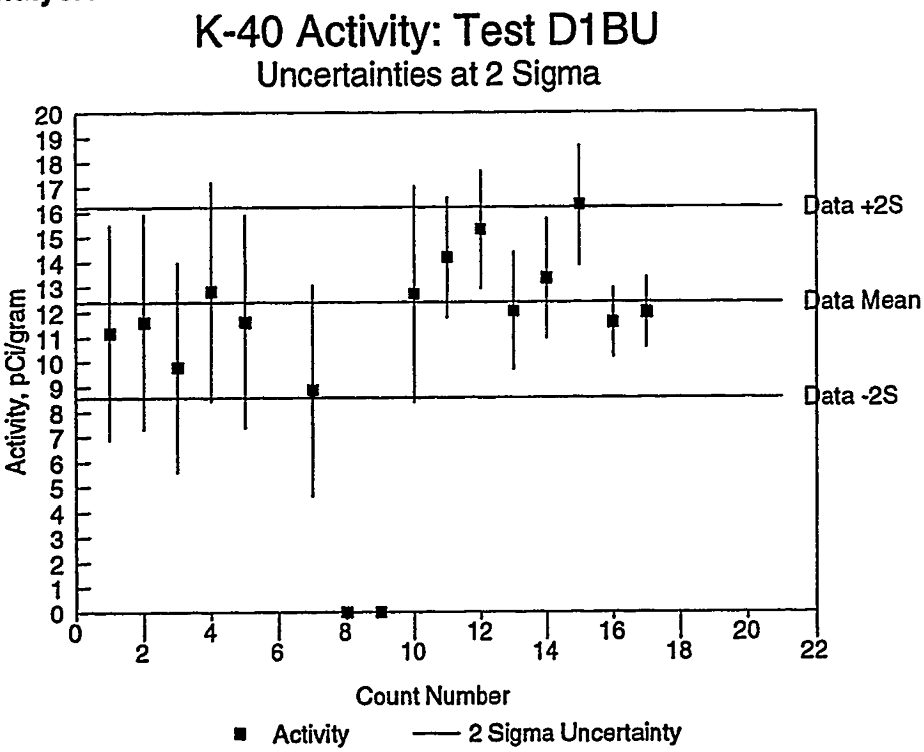
## Library Analysis

Test D1B: Nominal Activity = 51.1 pCi/g Total U    Efficiencies from 01/30/95

| Count USID | K-40 +- | U-235 +- 0.923 0.41 | U-238a +- | U-238b +- 21.803 8.38 | Ra-226a +- | Ra-226b +- | Th-232b +- | Th-232d +- |
|---|---|---|---|---|---|---|---|---|
| C01 | <17.2 | <4.4 | <87 | <263 | | | | |
| C02 | 11.42 2.16 | <4.4 | <87 | <262 | | | | |
| C03 | <17.1 | <4.4 | <87 | <262 | | | | |
| C04 | <17.3 | <4.4 | <87 | <261 | | | | |
| C05 | 12.87 2.20 | <4.4 | <87 | <260 | | | | |
| C06 | 11.74 2.14 | <4.4 | <87 | <262 | | | | |
| C07 | <16.8 | <4.4 | <87 | <262 | | | | |
| C08 | <16.9 | <4.4 | <87 | <261 | | | | |
| C09 | <17.0 | <4.4 | <87 | <262 | | | | |
| C10 | 12.70 2.18 | <4.4 | <87 | <260 | | | | |
| C11 | 14.11 1.21 | <2.4 | <48 | <142 | | | | |
| C12 | 15.17 1.19 | <2.4 | <48 | <142 | | | | |
| C13 | 11.87 1.19 | <2.4 | <48 | <142 | | | | |
| C14 | 13.34 1.20 | <2.4 | <48 | <143 | | | | |
| C15 | 16.28 1.20 | <2.4 | <48 | <142 | | 0.74 0.22 | | 1.19 0.13 |
| C16 | 11.57 0.70 | <1.4 | <28 | <82 | | | | |
| C17 | 11.96 0.71 | <1.4 | <28 | <82 | | | | |
| C18 | | | | | | | | |
| C19 | | | | | | | | |
| C20 | | | | | | | | |
| Avg | 13.00 1.52 | | | | | 0.74 0.00 | | 1.19 0.00 |

**Figure A-2 K-40 Activity: Test 1B (51 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

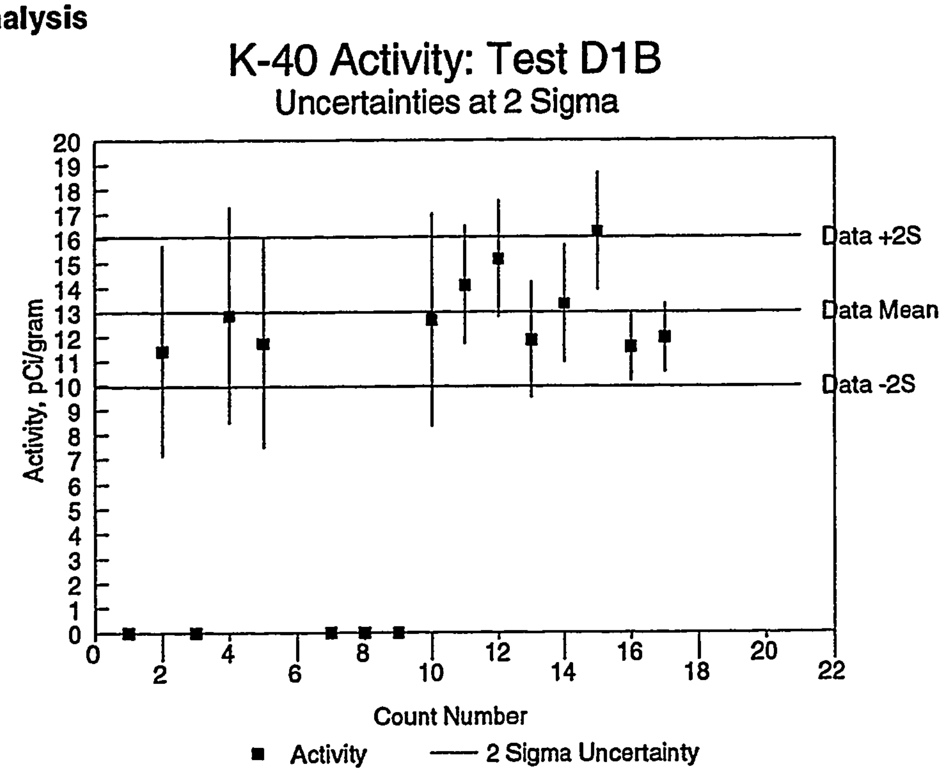
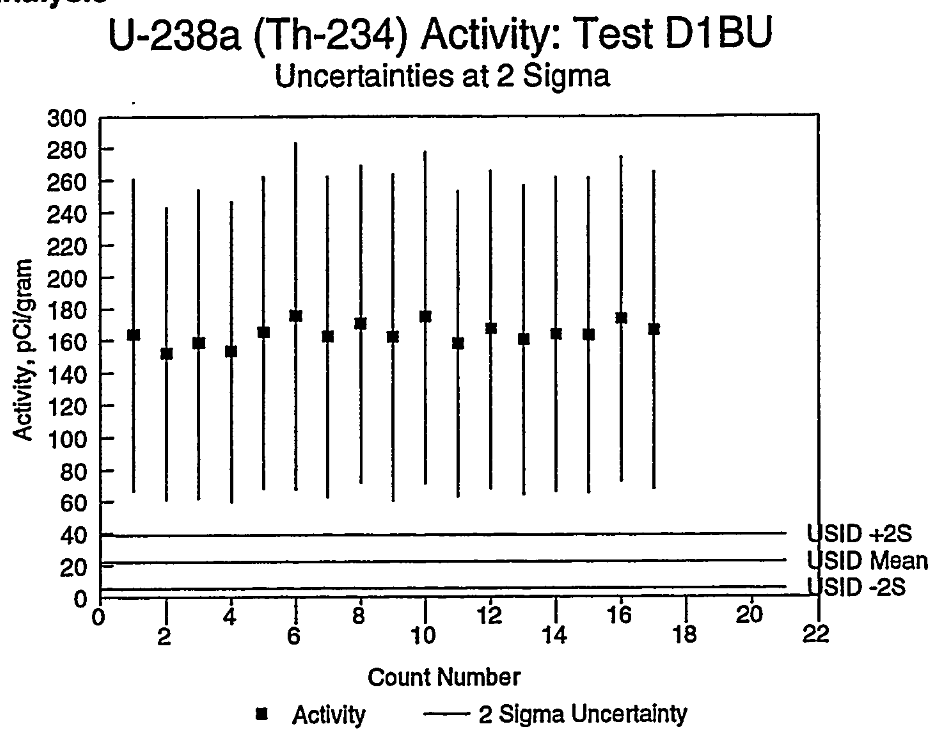
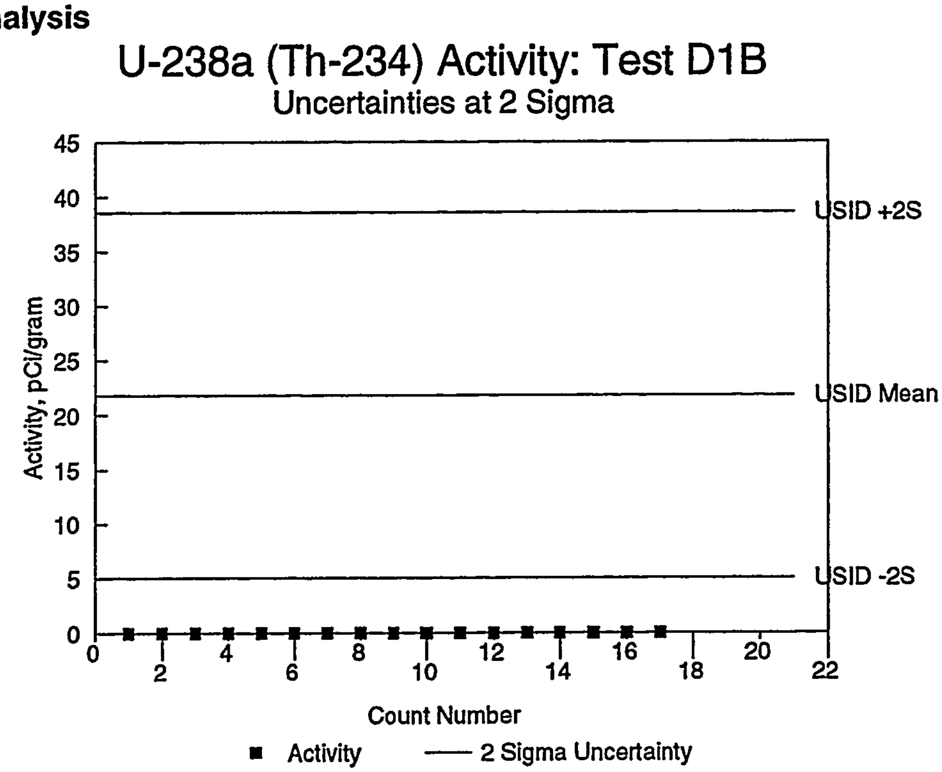


**Figure A-3 U-238a (Th-234) Activity: Test 1B (51 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**



## Figure A-4 Results Summary: Test 1D (95 pCi/g Total U)

### User ROI Analysis

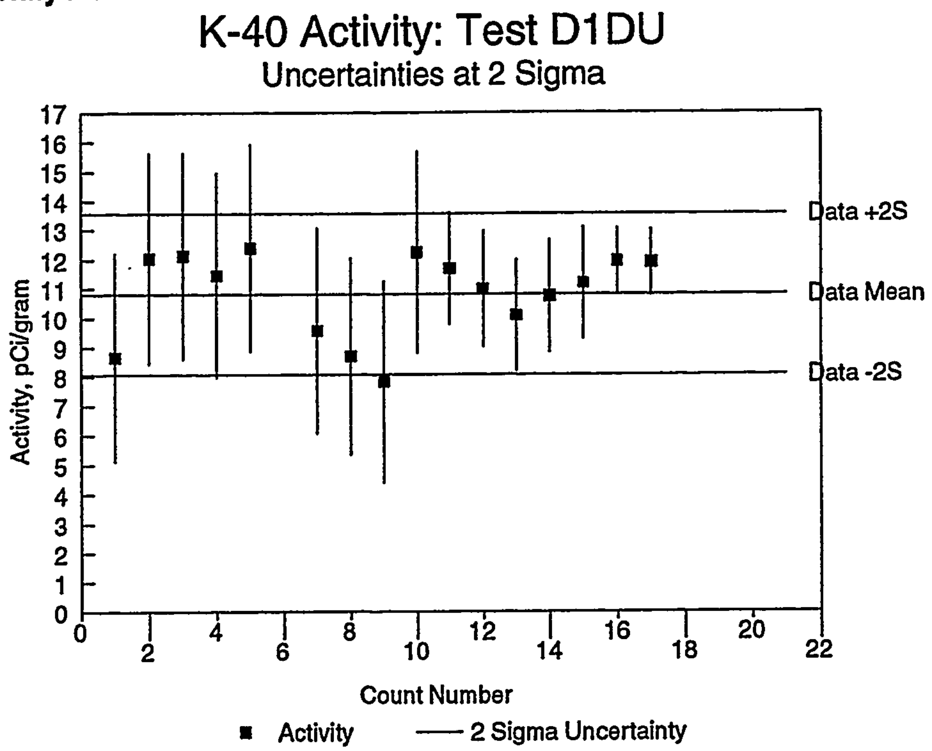
| Test D1DU: Nominal Activity = 94.6 pCi/g Total U | | | | | Effic. from 01/30/95 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Count | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
| USID | | | 2.05 | 0.16 | | | 44.636 | 3.18 | | | | | | | | |
| C01 | 8.66 | 1.78 | 3.79 | 1.41 | 224.25 | 65.84 | <216 | | | | | | | | | |
| C02 | 12.03 | 1.80 | 4.60 | 1.40 | 217.88 | 67.82 | <216 | | | | | | | | | |
| C03 | 12.12 | 1.77 | 4.12 | 1.40 | 234.50 | 68.67 | <216 | | | | | | | | | |
| C04 | 10.30 | 1.73 | 5.02 | 1.45 | 226.58 | 66.77 | <216 | | | | | | | | | |
| C05 | 11.45 | 1.76 | 4.24 | 1.41 | 235.31 | 68.33 | <213 | | | | | | | | | |
| C06 | 12.39 | 1.77 | 4.74 | 1.40 | 202.16 | 63.60 | <216 | | | | | | | | | |
| C07 | 9.56 | 1.76 | <3.9 | | 216.27 | 66.42 | <214 | | | | | | | | | |
| C08 | 8.70 | 1.69 | 5.99 | 1.40 | 242.09 | 71.18 | <215 | | | | | | | | | |
| C09 | 7.82 | 1.72 | 5.13 | 1.40 | 247.41 | 71.42 | <216 | | | | | | | | | |
| C10 | 12.23 | 1.73 | 5.25 | 1.41 | 209.12 | 66.08 | <215 | | | | | | | | | |
| C11 | 11.69 | 0.97 | 4.31 | 0.81 | 233.68 | 67.07 | <117 | | | | | | | | | |
| C12 | 10.99 | 1.00 | 4.60 | 0.94 | 226.58 | 66.47 | 52.79 | 14.20 | | | | | | | | |
| C13 | 10.09 | 0.96 | 3.15 | 0.95 | 218.88 | 66.46 | <117 | | | | | | | | | |
| C14 | 10.74 | 0.97 | 3.12 | 0.98 | 221.96 | 66.40 | 46.53 | 14.02 | | | | | | | | |
| C15 | 11.19 | 0.97 | 4.12 | 1.10 | 221.59 | 66.70 | <117 | | | | | | | | | |
| C16 | 11.94 | 0.57 | 4.08 | 0.64 | 224.86 | 66.75 | 35.70 | 8.18 | | | | | | | | |
| C17 | 11.90 | 0.57 | 3.76 | 0.64 | 221.60 | 66.67 | 43.28 | 8.20 | | | | | | | | |
| C18 | | | | | | | | | | | | | | | | |
| C19 | | | | | | | | | | | | | | | | |
| C20 | | | | | | | | | | | | | | | | |
| Avg | 10.81 | 1.37 | 4.38 | 0.73 | 224.98 | 10.96 | 44.58 | 6.16 | | | | | | | | |

### Library Analysis

| Test D1D: Nominal Activity = 94.6 pCi/g Total U | | | | | Efficiencies from 01/30/95 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Count | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
| USID | | | 2.05 | 0.16 | | | 44.636 | 3.18 | | | | | | | | |
| C01 | 8.13 | 1.76 | <3.9 | | <79 | | <216 | | | | | | | | | |
| C02 | 11.76 | 1.79 | <3.9 | | <79 | | <216 | | | | | | | | | |
| C03 | 11.66 | 1.76 | <3.9 | | <79 | | <216 | | | | | | | | | |
| C04 | 10.39 | 1.73 | <3.9 | | <79 | | <216 | | | | | | | | | |
| C05 | 11.96 | 1.77 | 6.19 | 1.79 | <79 | | <213 | | | | | | | | | |
| C06 | 12.66 | 1.75 | <3.9 | | <79 | | <216 | | | | | | | | | |
| C07 | 9.42 | 1.75 | <3.9 | | <79 | | <214 | | | | | | | | 1.53 | 0.49 |
| C08 | 8.99 | 1.68 | <3.9 | | <79 | | <216 | | | | 1.02 | 0.33 | | | | |
| C09 | <13.6 | | <3.9 | | <79 | | <216 | | | | | | | | | |
| C10 | 12.14 | 1.72 | <3.9 | | <79 | | <215 | | | | | | | | | |
| C11 | 11.66 | 0.97 | <2.1 | | <43 | | <117 | | | | | | | | | |
| C12 | 11.17 | 1.00 | <2.1 | | <43 | | <117 | | | | | | | | | |
| C13 | 10.08 | 0.95 | <2.1 | | <43 | | <117 | | | | | | | | | |
| C14 | 10.64 | 0.97 | <2.1 | | <43 | | <117 | | | | | | | | | |
| C15 | 11.19 | 0.97 | <2.1 | | <43 | | <117 | | | | 0.74 | 0.22 | | | 1.19 | 0.13 |
| C16 | 11.94 | 0.57 | <1.2 | | <25 | | <68 | | | | | | | | | |
| C17 | 11.89 | 0.58 | <1.2 | | <25 | | <68 | | | | 0.55 | 0.15 | | | 0.95 | 0.11 |
| C18 | | | | | | | | | | | | | | | | |
| C19 | | | | | | | | | | | | | | | | |
| C20 | | | | | | | | | | | | | | | | |
| Avg | 10.98 | 1.23 | 6.19 | 0.00 | | | | | | | 0.77 | 0.19 | | | 1.22 | 0.24 |

**Figure A-5 K-40 Activity: Test 1D (95 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

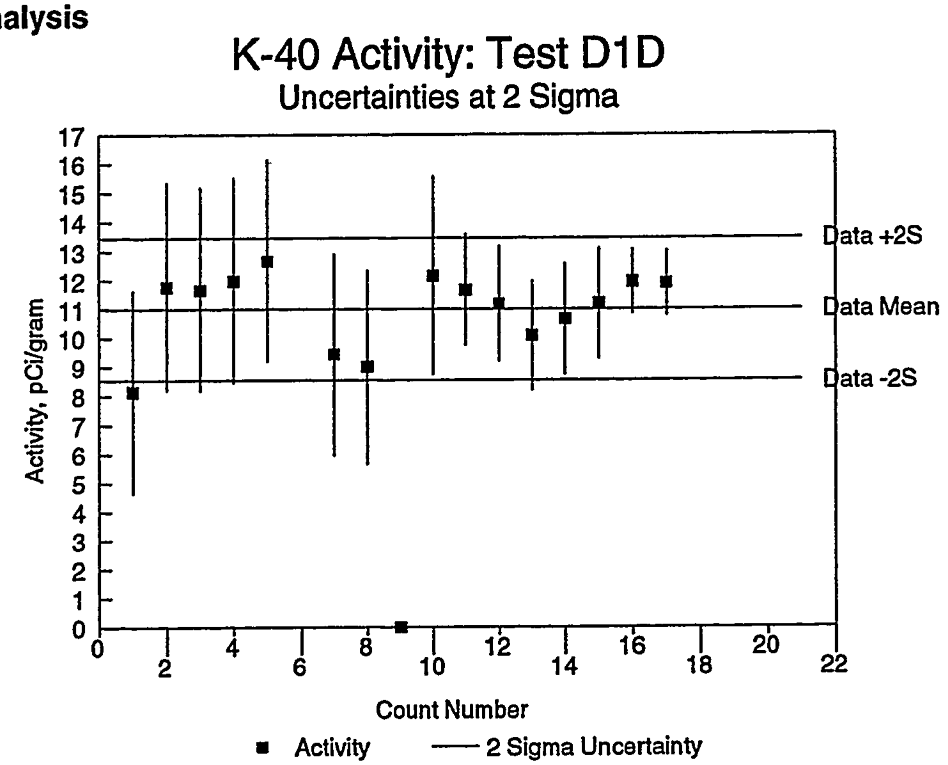
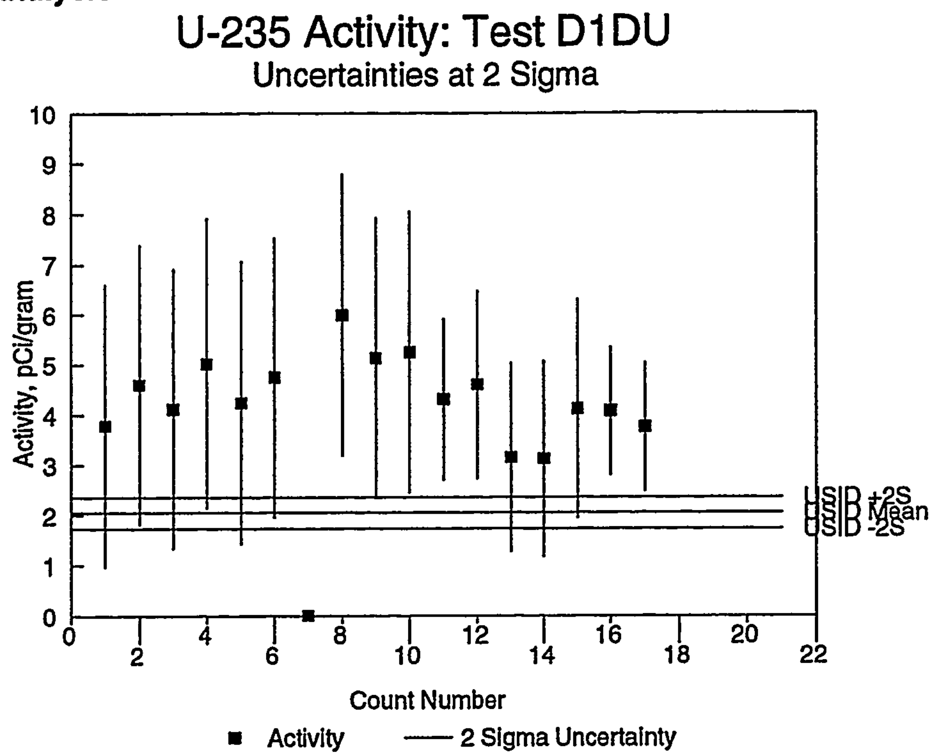


**Figure A-6 U-235 Activity: Test 1D (95 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

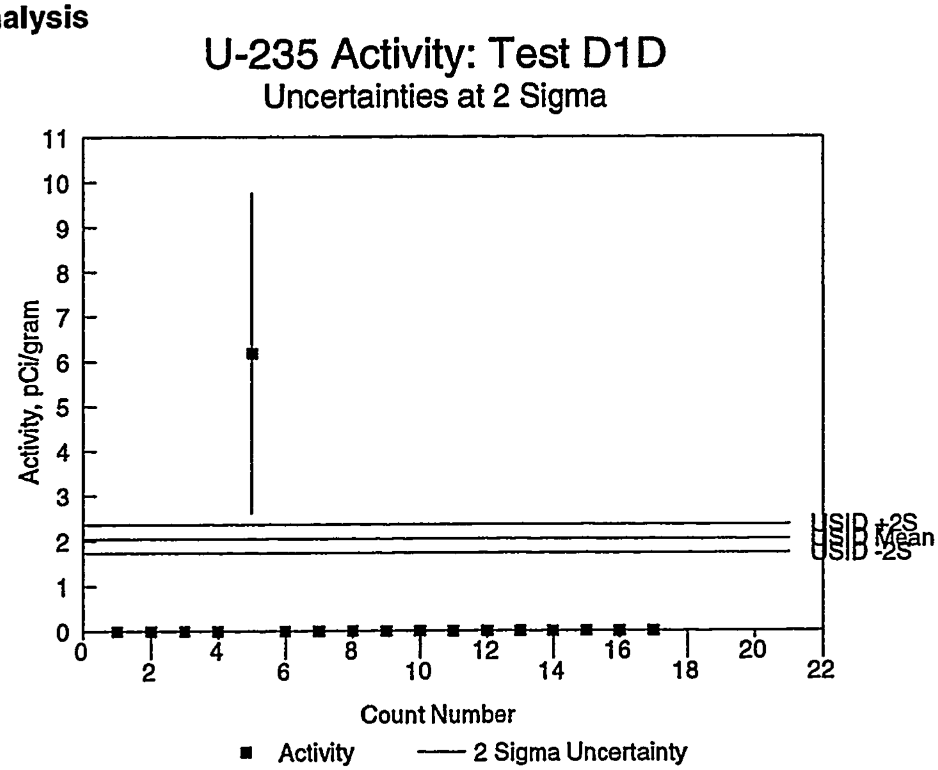
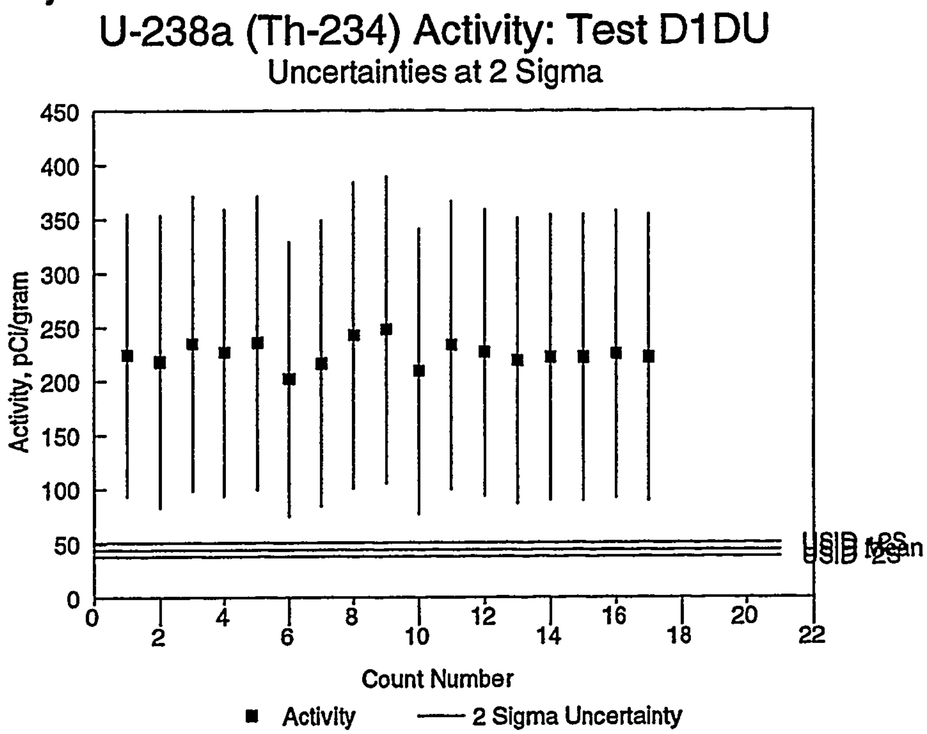


**Figure A-7 U-238a (Th-234) Activity: Test 1D (95 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

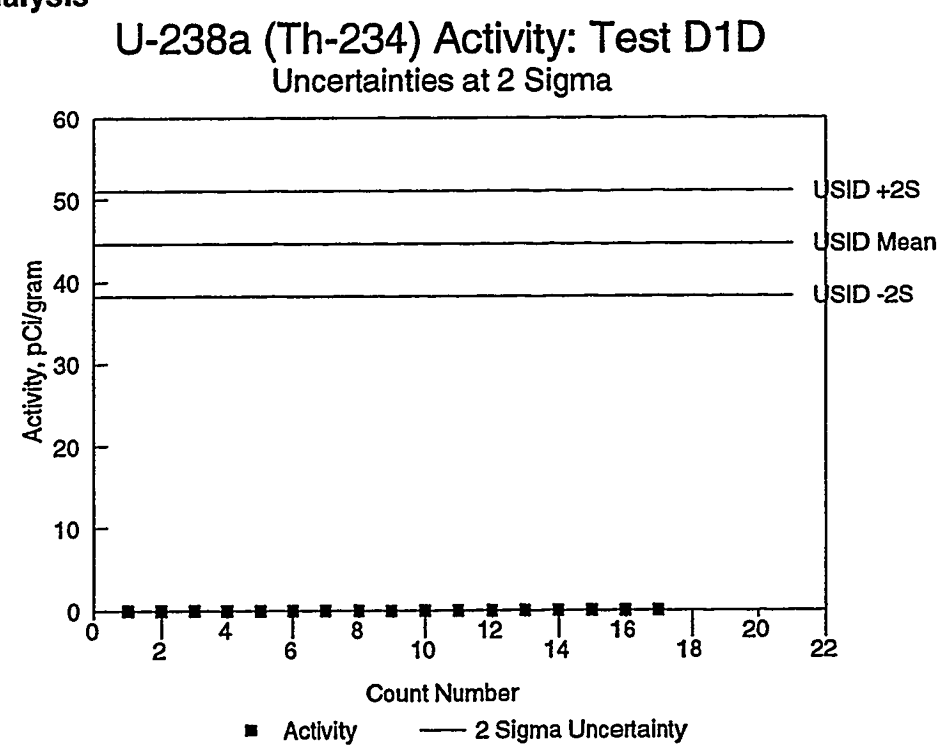
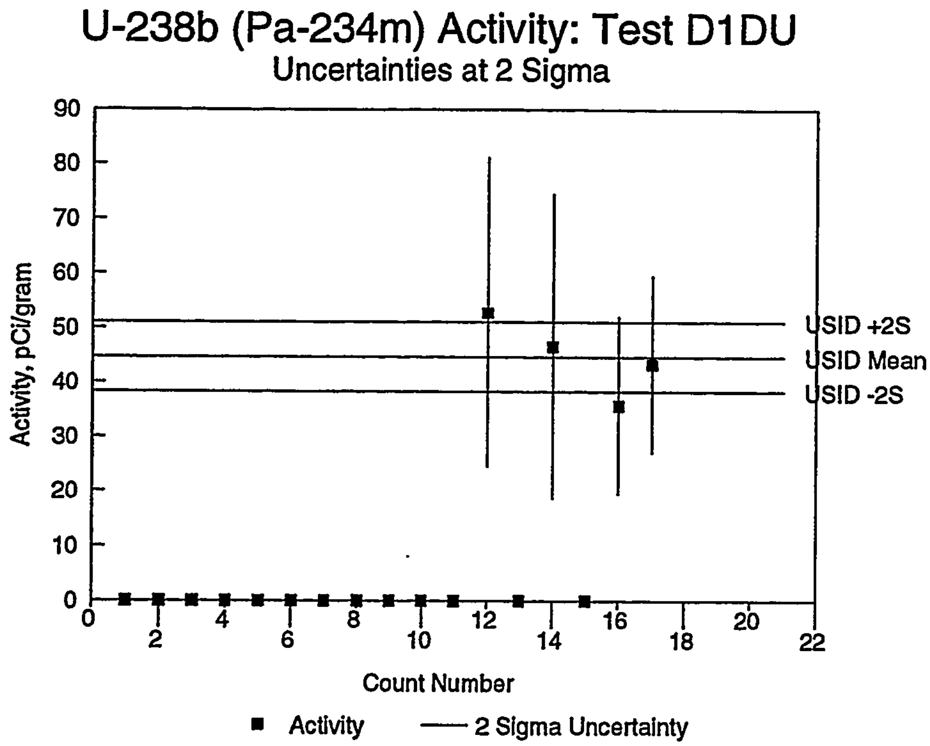
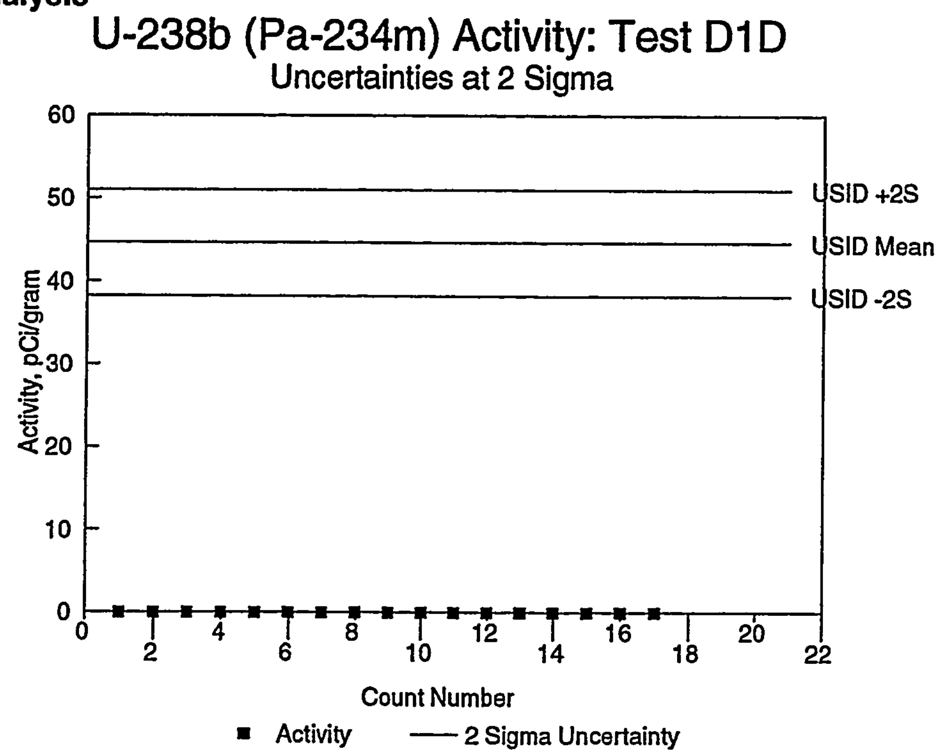


**Figure A-8 U-238b (Pa-234m) Activity: Test 1D (95 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**



## Figure A-9 Results Summary: Test 1F (95 pCi/g Total U)

### User ROI Analysis

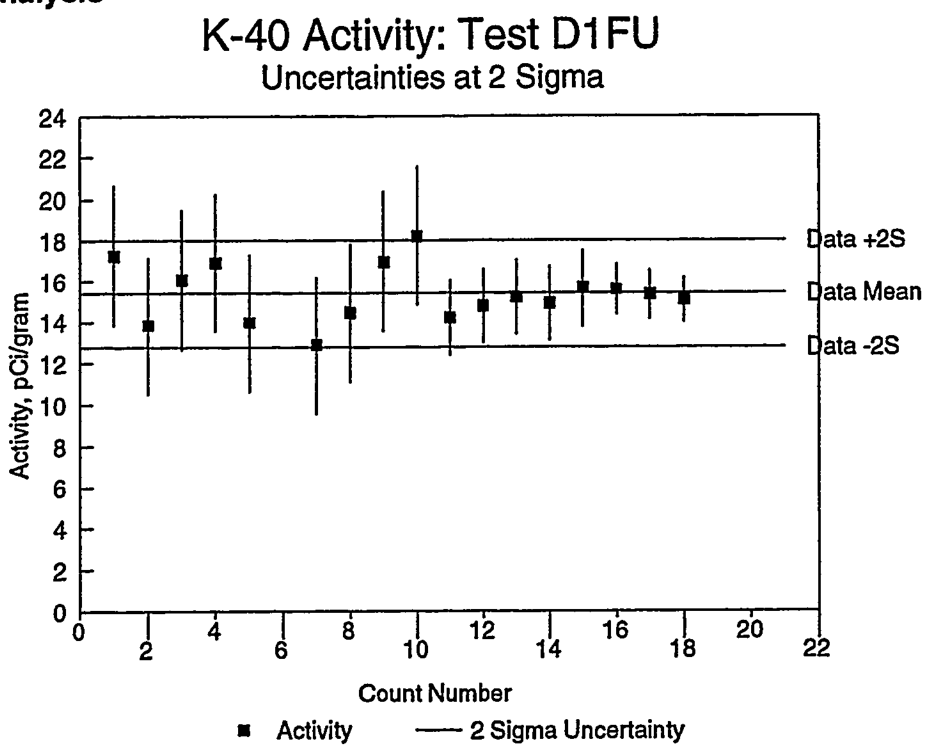
| Test D1FU: Nominal Activity = 94.6 pCi/g Total U | | | Effic. from 01/12/95 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Count | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
| USID | | | 2.05 | 0.16 | | | 44.636 | 3.18 | | | | | | | | |
| C01 | 17.26 | 1.71 | 3.79 | <3.6 | 172.22 | 47.13 | | <199 | | | | | | | | |
| C02 | 13.83 | 1.67 | 5.65 | 1.22 | 197.11 | 51.19 | | <201 | | | | | | | | |
| C03 | 16.07 | 1.73 | 2.82 | 1.25 | 190.56 | 50.71 | | <199 | | | | | | | | |
| C04 | 15.92 | 1.69 | 5.02 | <3.6 | 223.97 | 57.00 | | <200 | | | | | | | | |
| C05 | 16.89 | 1.69 | 4.24 | <3.6 | 196.39 | 52.87 | | <198 | | | | | | | | |
| C06 | 13.96 | 1.68 | 5.87 | 1.42 | 183.97 | 49.68 | | <200 | | | | | | | | |
| C07 | 12.87 | 1.66 | 6.29 | 1.32 | 193.46 | 50.74 | | <201 | | | | | | | | |
| C08 | 14.46 | 1.69 | 5.99 | <3.6 | 200.21 | 52.71 | | <196 | | | | | | | | |
| C09 | 16.95 | 1.72 | 4.12 | 2.21 | 195.25 | 50.16 | | <197 | | | | | | | | |
| C10 | 18.20 | 1.69 | 3.48 | 1.22 | 187.79 | 49.17 | | <200 | | | | | | | | |
| C11 | 14.21 | 0.93 | 4.34 | 0.80 | 196.71 | 50.57 | 46.98 | 13.61 | | | | | | | | |
| C12 | 14.76 | 0.92 | 4.02 | 0.89 | 189.47 | 49.75 | 52.79 | <108 | | | | | | | | |
| C13 | 15.21 | 0.92 | 3.69 | 0.69 | 200.44 | 51.79 | | <108 | | | | | | | | |
| C14 | 14.90 | 0.93 | 3.80 | 0.85 | 206.42 | 53.16 | 46.53 | <108 | | | | | | | | |
| C15 | 15.66 | 0.94 | 4.20 | 0.80 | 195.35 | 50.66 | | <109 | | | | | | | | |
| C16 | 15.57 | 0.62 | 4.45 | 0.72 | 192.41 | 49.95 | 40.13 | 8.32 | | | | | | | | |
| C17 | 15.33 | 0.61 | 3.89 | 0.68 | 191.11 | 50.36 | 52.49 | 7.90 | | | | | | | | |
| C18 | 15.07 | 0.56 | 3.50 | 0.59 | 187.17 | 49.47 | 48.45 | 7.84 | | | | | | | | |
| C19 | | | | | | | | | | | | | | | | |
| C20 | | | | | | | | | | | | | | | | |
| Avg | 15.40 | 1.31 | 4.40 | 0.95 | 194.45 | 10.16 | 47.90 | 4.25 | | | | | | | | |

### Library Analysis

| Test D1F: Nominal Activity = 94.6 pCi/g Total U | | | Efficiencies from 01/12/95 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Count | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
| USID | | | 2.05 | 0.16 | | | 44.636 | 3.18 | | | | | | | | |
| C01 | 17.58 | 1.71 | 5.39 | 1.73 | | <73 | | <199 | | | | | | | | |
| C02 | 11.76 | <12.6 | 1.41 | 0.57 | | <72 | | <201 | | | | | | | | |
| C03 | 16.07 | 1.73 | | <3.6 | | <73 | | <199 | | | | | | | | |
| C04 | 15.72 | 1.68 | | <3.6 | | <73 | | <200 | | | | | | | | |
| C05 | 16.57 | 1.70 | 6.19 | <3.6 | | <73 | | <198 | | | | | | | | |
| C06 | 13.94 | 1.69 | | <3.6 | | <73 | | <200 | | | | | | | | |
| C07 | 12.62 | 1.68 | | <3.6 | | <73 | | <201 | | | | | | | 1.53 | 0.49 |
| C08 | 14.38 | 1.69 | | <3.6 | | <73 | | <196 | | | 1.02 | 0.33 | | | | |
| C09 | 16.97 | 1.73 | | <3.6 | | <73 | | <197 | | | | | | | | |
| C10 | 18.12 | 1.69 | | <3.6 | | <73 | | <200 | | | | | | | | |
| C11 | 14.22 | 0.93 | | <2.0 | | <40 | | <108 | | | 0.50 | 0.17 | | | | |
| C12 | 14.76 | 0.92 | | <2.0 | | <40 | | <108 | | | | | | | 1.06 | 0.24 |
| C13 | 15.20 | 0.92 | | <2.0 | | <40 | | <108 | | | | | | | 0.72 | 0.24 |
| C14 | 14.93 | 0.93 | 3.85 | 0.98 | | <40 | | <108 | 1.17 | 0.74 | | | 5.17 | 1.71 | 0.70 | 0.13 |
| C15 | 15.63 | 0.94 | | <2.0 | | <40 | | <109 | | | 0.74 | 0.22 | | | 0.80 | 0.24 |
| C16 | 15.59 | 0.62 | 3.30 | 0.75 | | <23 | | <62 | | | | | | | 0.49 | 0.19 |
| C17 | 15.31 | 0.61 | | <1.1 | | <23 | | <62 | | | 0.55 | 0.15 | | | 1.10 | 0.10 |
| C18 | 15.05 | 0.56 | 2.40 | 0.65 | | <23 | | <62 | | | | | | | 0.84 | 0.22 |
| C19 | | | | | | | | | | | | | | | | |
| C20 | | | | | | | | | | | | | | | | |
| Avg | 15.25 | 1.54 | 3.76 | 1.64 | | | | | 1.17 | 0.00 | 0.70 | 0.20 | 5.17 | 0.00 | 0.91 | 0.30 |

**Figure A-10 K-40 Activity: Test 1F (95 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

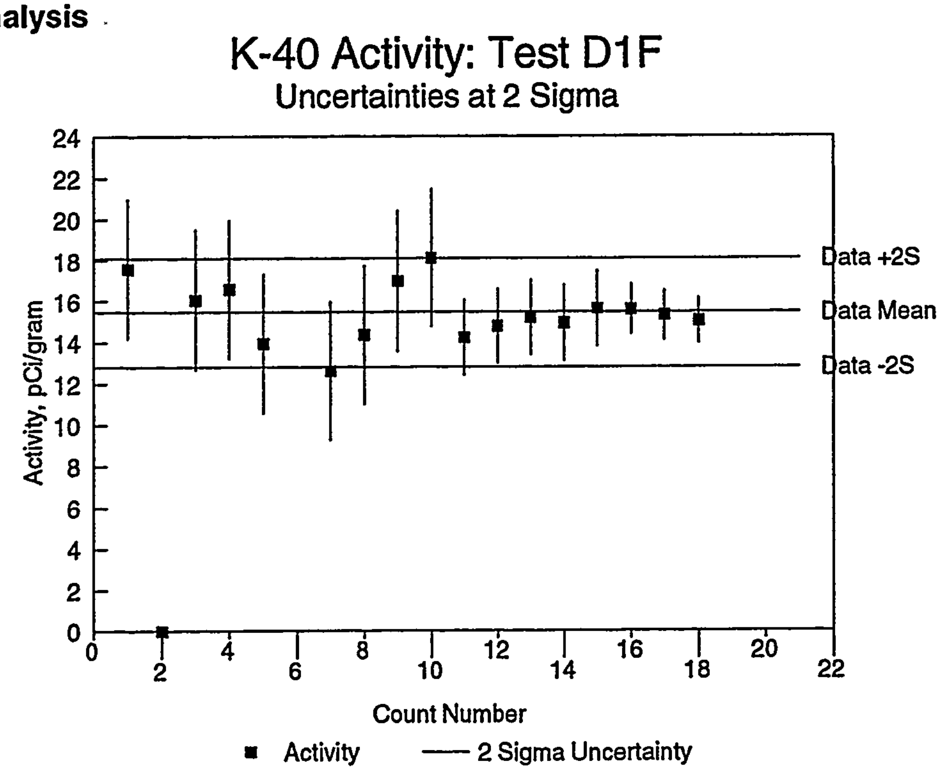
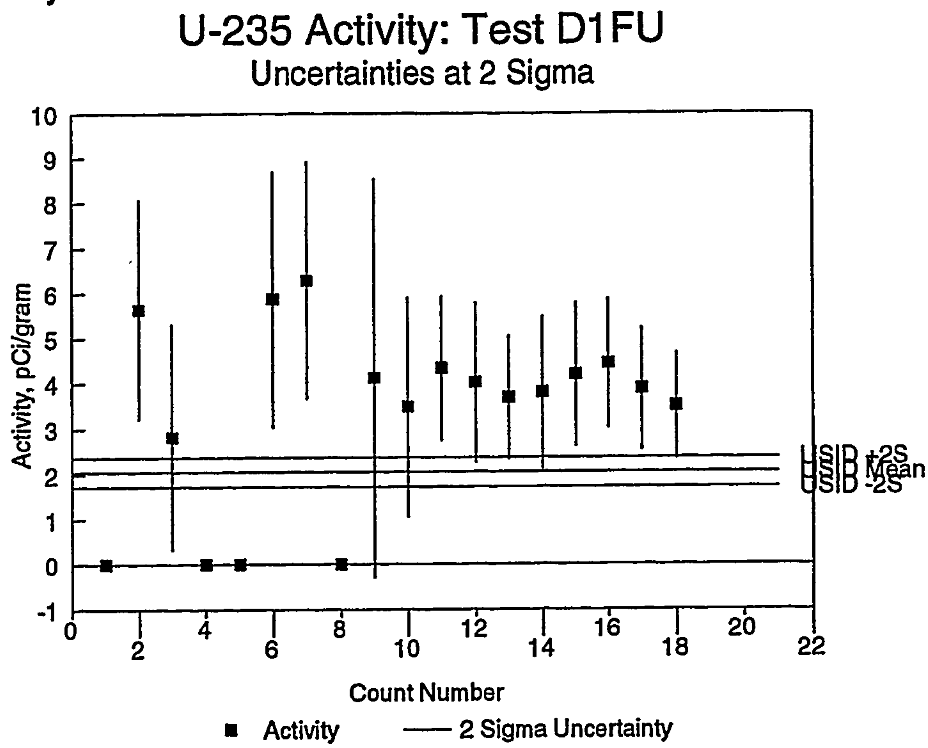


**Figure A-11 U-235 Activity: Test 1F (95 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

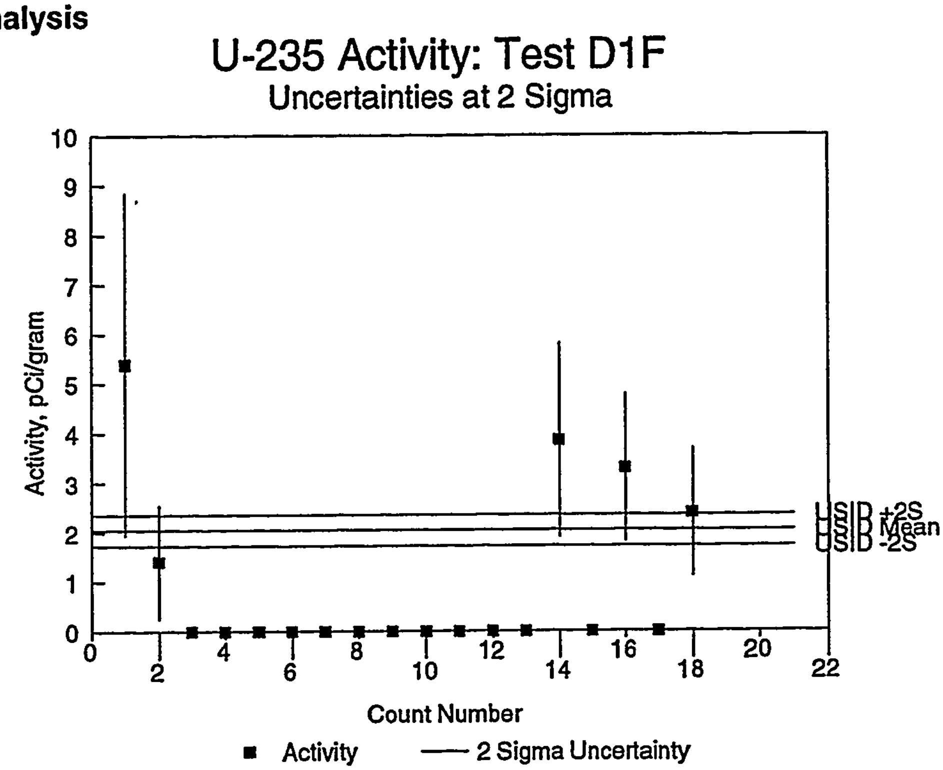
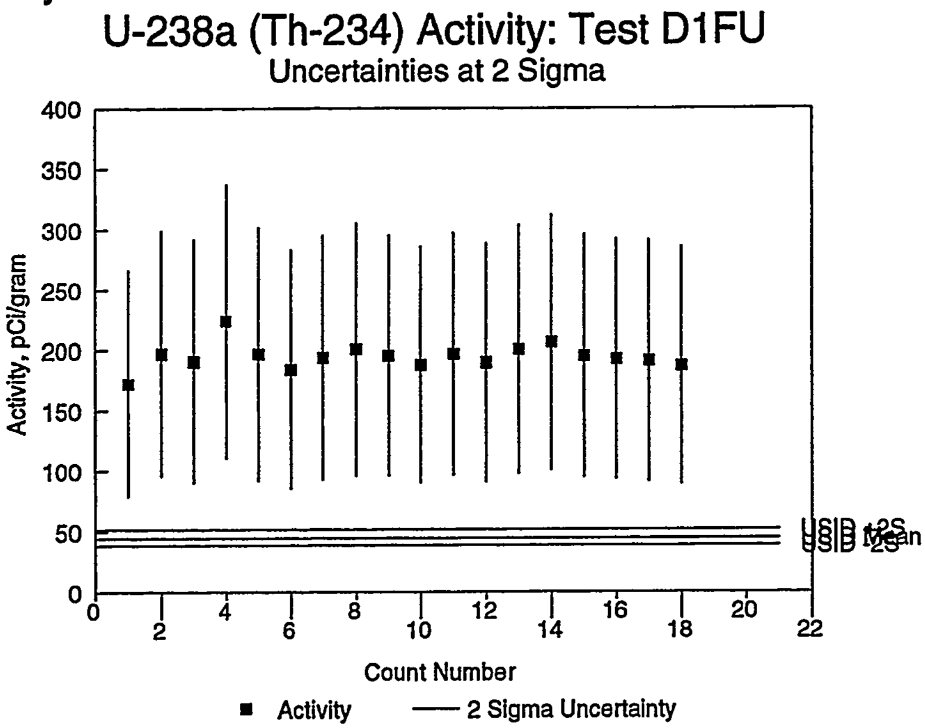


**Figure A-12 U-238a (Th-234) Activity: Test 1F (95 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

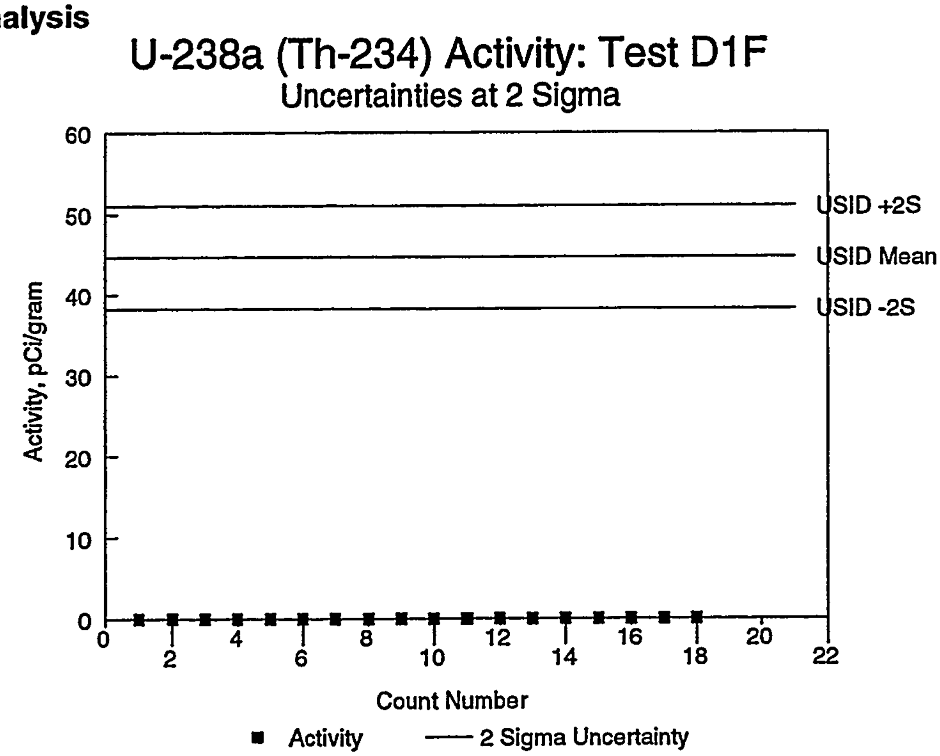
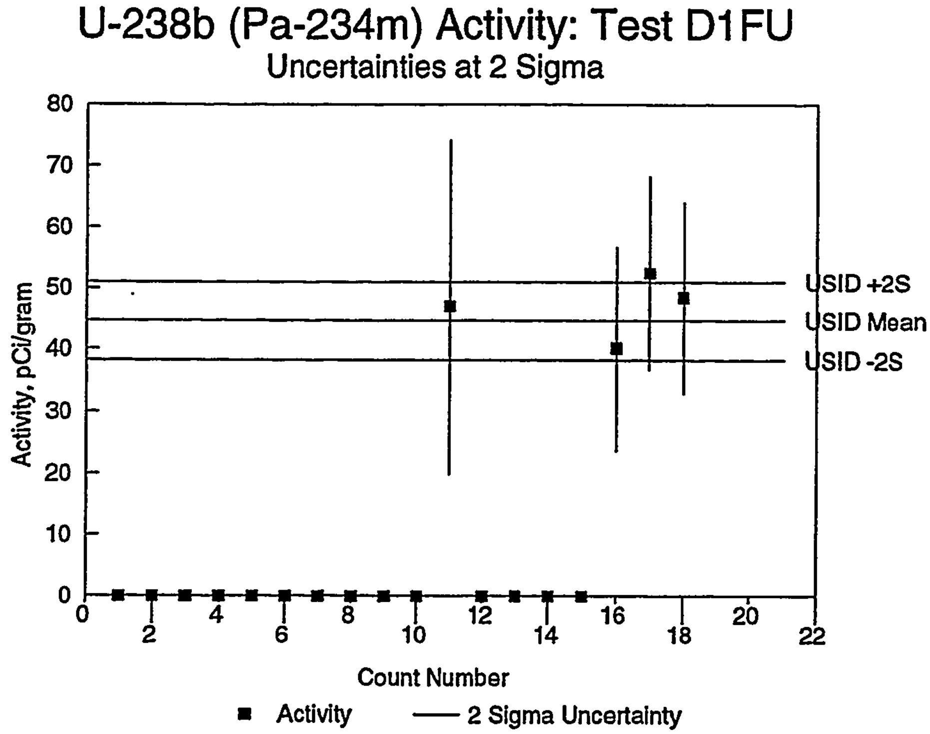
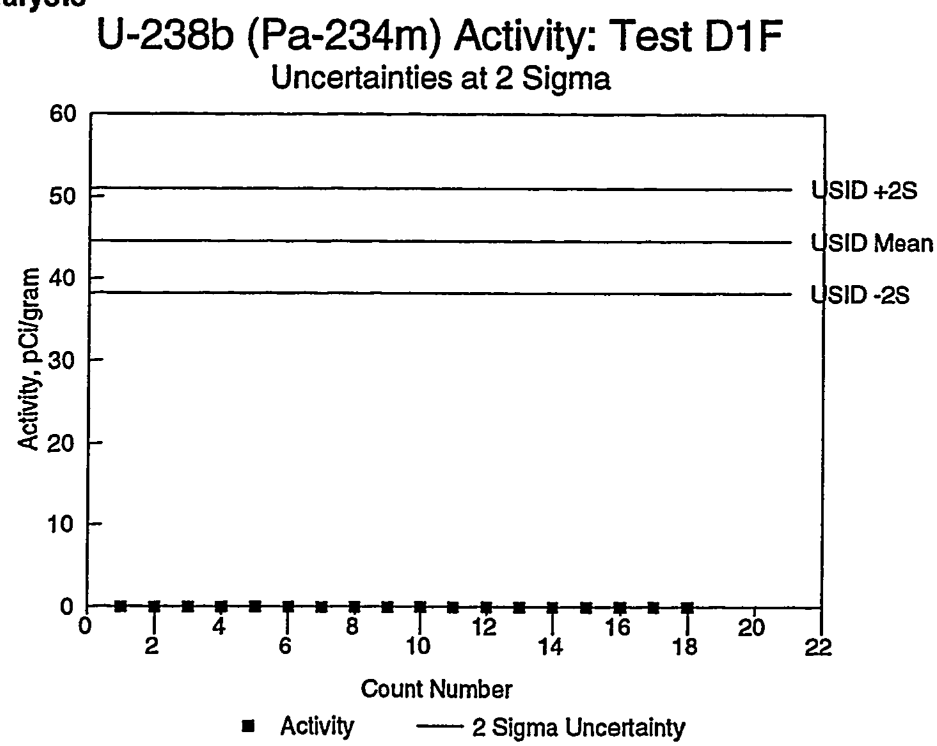


**Figure A-13 U-238b (Pa-234m) Activity: Test 1F (95 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**



## Figure A-14 Results Summary: Test 1C (162 pCi/g Total U)

### User ROI Analysis

Test D1CU: Nominal Activity = 162.2 pCi/g Total U Effic. from 01/30/95

| Count | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| USID | | | 3.451 | 1.56 | | | 79.241 | 33.2 | | | | | | | | |
| C01 | 13.22 | 1.92 | 3.79 | <4.4 | 255.37 | 63.03 | | <244 | | | | | | | | |
| C02 | 14.90 | 1.85 | 5.65 | <4.4 | 270.42 | 67.51 | | <243 | | | | | | | | |
| C03 | 13.62 | 1.92 | 1.84 | 0.68 | 222.76 | 57.25 | | <245 | | | | | | | | |
| C04 | 13.50 | 1.89 | 5.02 | <4.4 | 267.40 | 65.98 | | <244 | | | | | | | | |
| C05 | 13.66 | 1.92 | 7.71 | 1.74 | 255.27 | 62.41 | | <244 | | | | | | | | |
| C06 | 17.30 | 1.97 | 5.87 | <4.4 | 271.63 | 66.40 | | <243 | | | | | | | | |
| C07 | 14.66 | 1.90 | 7.78 | 1.66 | 257.46 | 63.11 | | <245 | | | | | | | | |
| C08 | 14.46 | <15.5 | 1.47 | 0.64 | 256.30 | 64.43 | | <245 | | | | | | | | |
| C09 | 12.72 | 1.93 | 2.15 | 0.71 | 266.97 | 65.53 | | <243 | | | | | | | | |
| C10 | 16.86 | 1.96 | 3.48 | <4.4 | 249.36 | 61.20 | | <246 | | | | | | | | |
| C11 | 14.73 | 1.08 | 4.34 | <2.4 | 257.68 | 62.64 | 63.26 | 16.15 | | | | | | | | |
| C12 | 15.64 | 1.07 | 5.82 | 1.19 | 276.14 | 66.89 | 80.16 | 16.29 | | | | | | | | |
| C13 | 15.69 | 1.06 | 5.25 | 1.34 | 246.83 | 59.83 | | <134 | | | | | | | | |
| C14 | 14.12 | 1.06 | 4.12 | 1.38 | 246.69 | 60.57 | 65.68 | 16.11 | | | | | | | | |
| C15 | 14.67 | 1.07 | 1.11 | 0.43 | 266.67 | 65.02 | 82.47 | 15.92 | | | | | | | | |
| C16 | 14.28 | 0.75 | 5.56 | 1.08 | 248.51 | 60.74 | 58.85 | 9.30 | | | | | | | | |
| C17 | 15.05 | 0.80 | 5.07 | 0.94 | 263.44 | 63.94 | 48.69 | 9.59 | | | | | | | | |
| C18 | 15.07 | 0.56 | 3.50 | 0.59 | 187.17 | 49.47 | 48.45 | 7.84 | | | | | | | | |
| C19 | | | | | | | | | | | | | | | | |
| C20 | | | | | | | | | | | | | | | | |
| Avg | 14.68 | 1.15 | 4.42 | 1.89 | 253.67 | 20.14 | 63.94 | 12.58 | | | | | | | | |

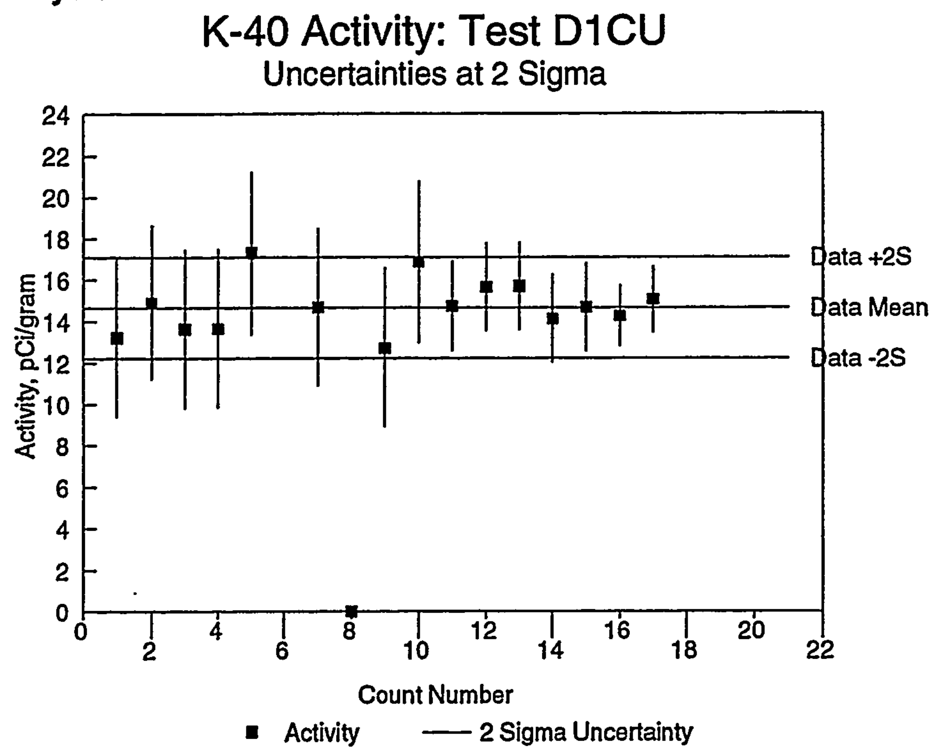
### Library Analysis

Test D1C: Nominal Activity = 162.2 pCi/g Total U Efficiencies from 01/30/95

| Count | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| USID | | | 3.451 | 1.56 | | | 79.241 | 33.2 | | | | | | | | |
| C01 | 13.72 | 1.91 | 5.39 | <4.4 | | <88 | | <244 | | | | | | | | |
| C02 | 15.11 | 1.85 | 2.49 | 1.78 | | <88 | | <243 | | | | | | | | |
| C03 | 16.07 | <15.5 | | <4.4 | | <88 | | <245 | | | | | | | | |
| C04 | 13.51 | 1.89 | | <4.4 | | <89 | | <244 | | | | | | | | |
| C05 | 13.78 | 1.92 | 6.19 | <4.4 | | <89 | | <244 | | | | | | | | |
| C06 | 17.68 | 1.96 | | <4.4 | | <89 | | <243 | | | 1.31 | 0.36 | | | | |
| C07 | 12.62 | <15.5 | | <4.4 | | <89 | | <245 | | | | | | | 1.53 | 0.49 |
| C08 | 13.12 | 1.91 | | <4.4 | | <89 | | <245 | | | 1.02 | 0.33 | | | | |
| C09 | 13.75 | 1.94 | | <4.4 | | <88 | | <243 | | | | | | | | |
| C10 | 16.87 | 1.96 | | <4.4 | | <89 | | <246 | | | | | | | | |
| C11 | 14.58 | 1.08 | | <2.4 | | <48 | | <134 | | | 0.63 | 0.20 | | | | |
| C12 | 15.29 | 1.07 | 2.08 | 1.26 | | <49 | 82.09 | 16.38 | | | | | | | 1.06 | 0.24 |
| C13 | 15.77 | 1.07 | | <2.4 | | <49 | | <134 | | | | | | | 0.72 | 0.24 |
| C14 | 14.32 | 1.07 | 3.85 | <2.4 | | <49 | | <133 | 1.17 | 0.74 | | | 5.17 | 1.71 | 0.70 | 0.13 |
| C15 | 14.83 | 1.07 | | <2.4 | | <49 | | <133 | | | 0.74 | 0.22 | | | 0.80 | 0.24 |
| C16 | 14.55 | 0.73 | 2.02 | 1.15 | | <28 | | <77 | | | | | | | 0.76 | 0.20 |
| C17 | 14.99 | 0.81 | 1.46 | 0.78 | | <28 | | <76 | | | 0.55 | 0.15 | | | 0.58 | 0.17 |
| C18 | 15.05 | 0.56 | 2.40 | 0.65 | | <23 | | <62 | | | | | | | 0.84 | 0.22 |
| C19 | | | | | | | | | | | | | | | | |
| C20 | | | | | | | | | | | | | | | | |
| Avg | 14.76 | 1.26 | 3.24 | 1.62 | | | 82.09 | 0.00 | 1.17 | 0.00 | 0.85 | 0.28 | 5.17 | 0.00 | 0.87 | 0.28 |

**Figure A-15 K-40 Activity: Test 1C (162 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

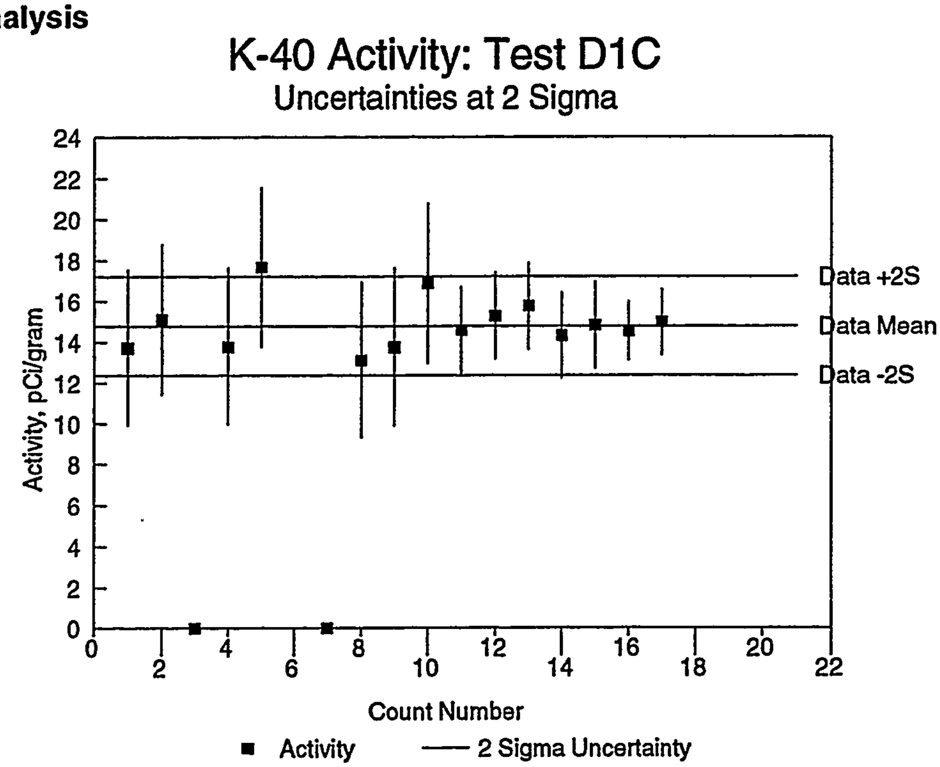
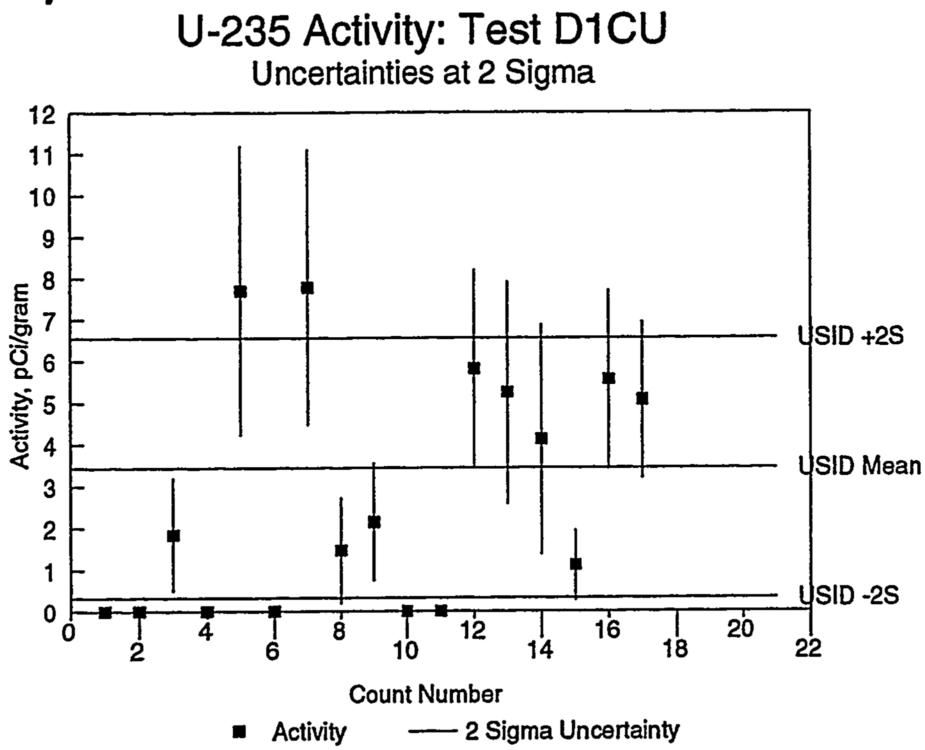


**Figure A-16 U-235 Activity: Test 1C (162 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

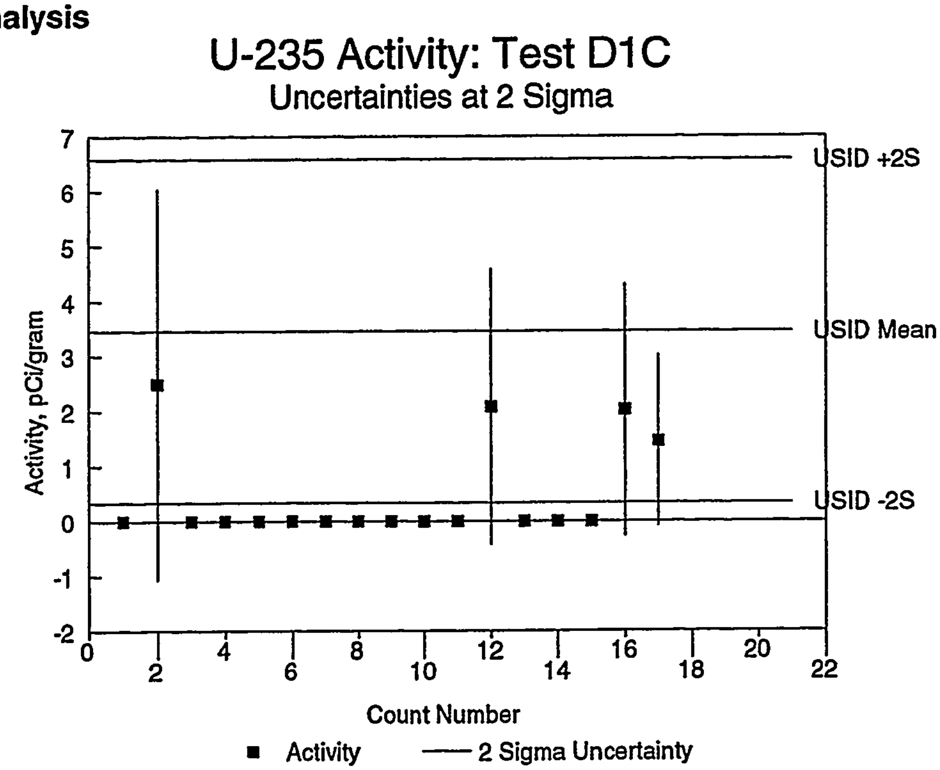
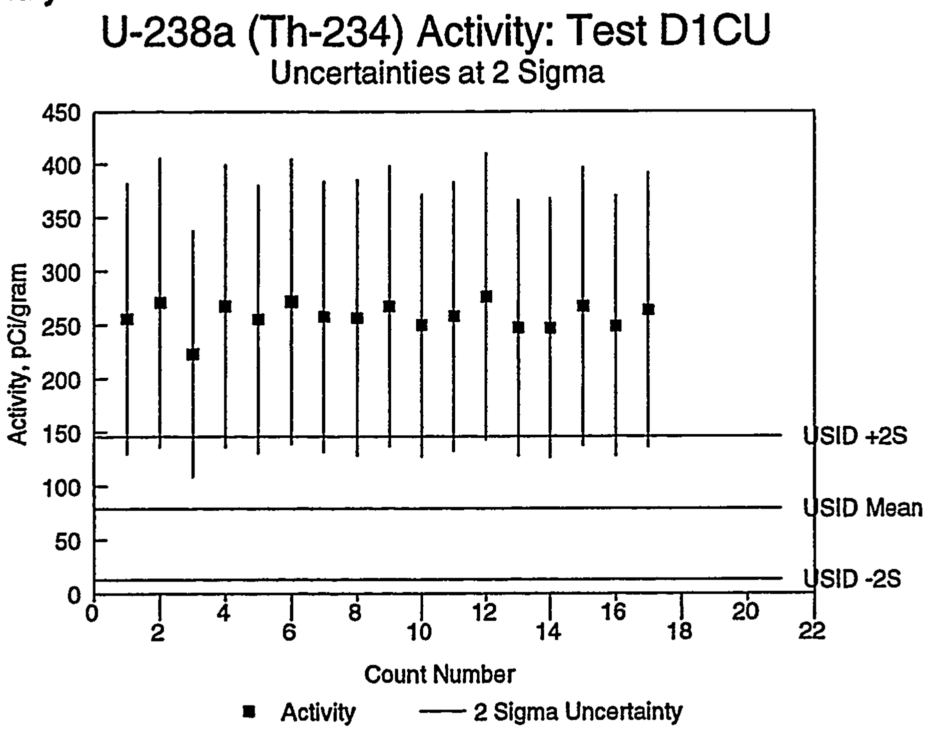


**Figure A-17 U-238a (Th-234) Activity: Test 1C (162 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

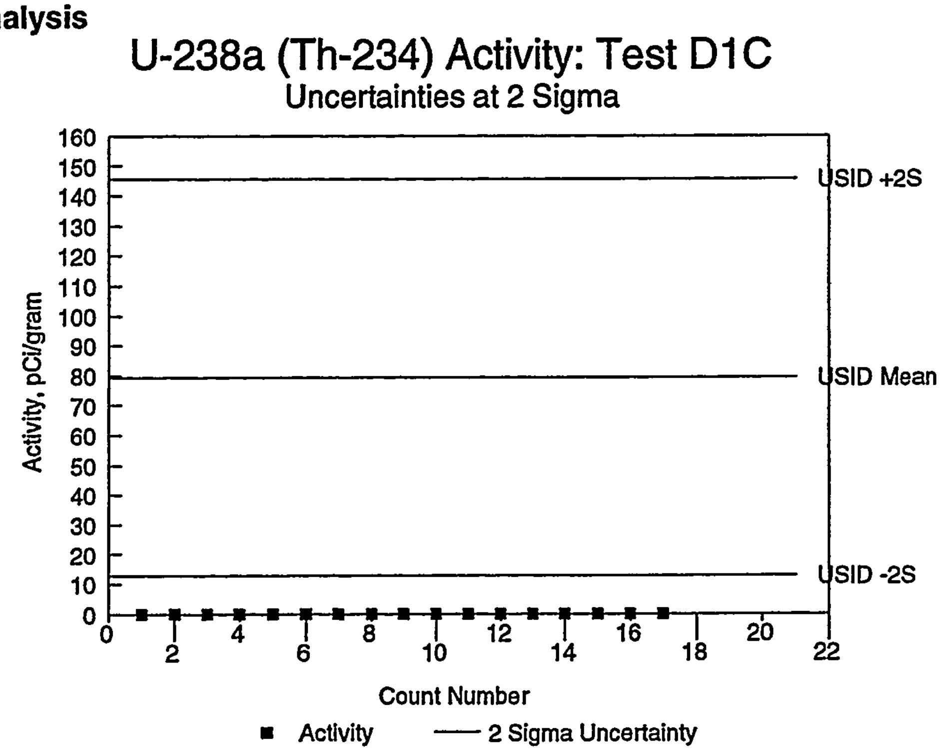
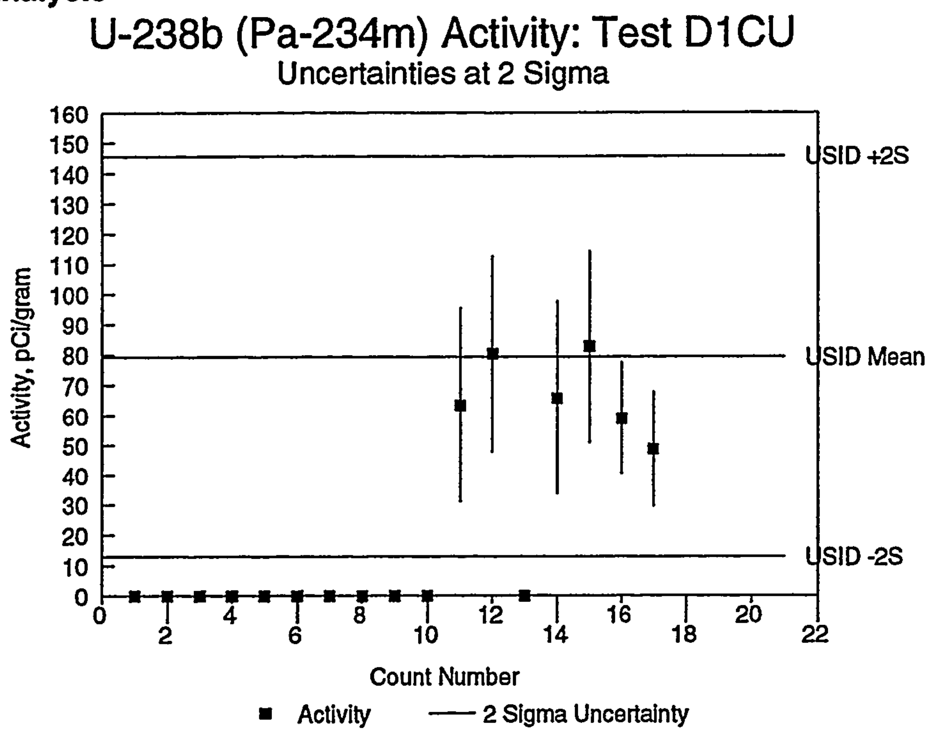
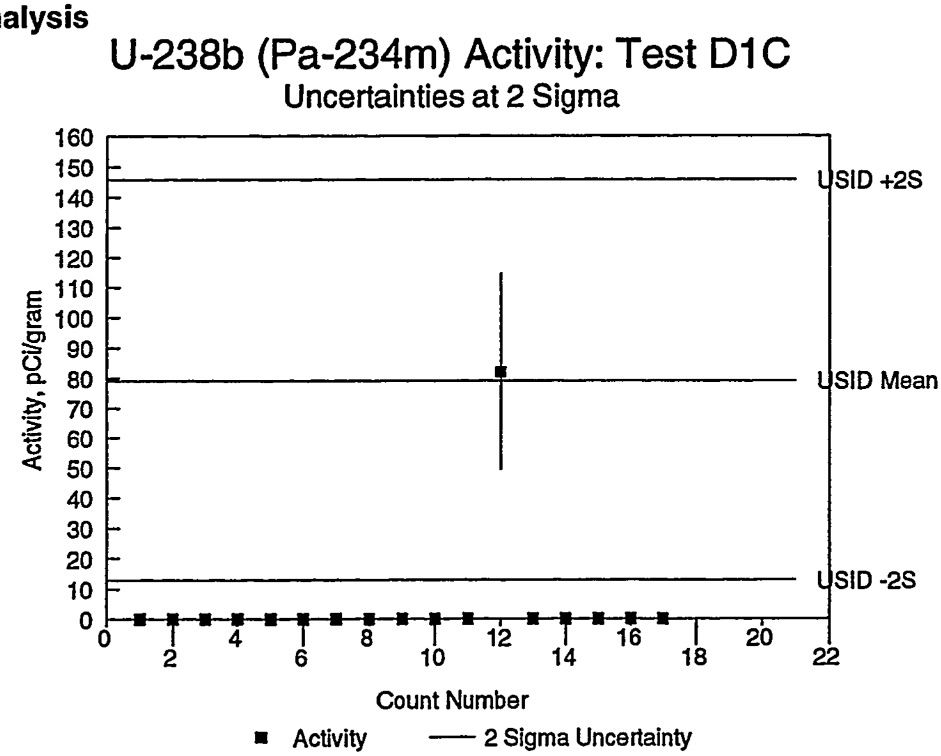


**Figure A-18 U-238b (Pa-234m) Activity: Test 1C (162 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**



## Figure A-19 Results Summary: Test 1G (162 pCi/g Total U)

### User ROI Analysis

Test D1GU: Nominal Activity = 162.2 pCi/g Total U     Effic. from 01/12/95

| Count USID | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 3.451 | 1.56 | | | 79.241 | 33.2 | | | | | | | | |
| C01 | 16.01 | 1.57 | 3.79 | <3.4 | 171.89 | 43.21 | | <183 | | | | | | | | |
| C02 | 10.87 | 1.47 | 1.51 | 0.49 | 184.67 | 44.09 | | <180 | | | | | | | | |
| C03 | 12.43 | 1.54 | 2.65 | 0.96 | 158.60 | 38.93 | 81.04 | 24.56 | | | | | | | | |
| C04 | 12.00 | 1.59 | 1.72 | 0.52 | 152.35 | 38.23 | | <181 | | | | | | | | |
| C05 | 11.08 | 1.57 | 1.10 | 0.48 | 183.18 | 45.34 | 81.48 | 22.87 | | | | | | | | |
| C06 | 11.60 | 1.51 | 3.80 | 1.37 | 171.49 | 41.53 | | <180 | | | | | | | | |
| C07 | 14.19 | 1.49 | 7.78 | <3.3 | 154.42 | 38.33 | 78.66 | 22.77 | | | | | | | | |
| C08 | 10.18 | 1.54 | 1.47 | <3.3 | 162.81 | 39.99 | | <182 | | | | | | | | |
| C09 | 12.57 | 1.50 | 1.17 | 0.49 | 165.22 | 41.39 | | <183 | | | | | | | | |
| C10 | 15.55 | 1.59 | 1.56 | 0.49 | 174.00 | 43.60 | | <181 | | | | | | | | |
| C11 | 11.70 | 0.86 | 1.67 | 0.31 | 177.39 | 42.74 | 69.72 | 13.21 | | | | | | | | |
| C12 | 10.44 | 0.85 | 1.45 | 0.32 | 171.65 | 41.74 | 56.00 | 12.95 | | | | | | | | |
| C13 | 10.70 | 0.91 | 5.25 | <1.8 | 176.68 | 42.48 | 52.04 | 13.88 | | | | | | | | |
| C14 | 11.17 | 0.88 | 2.83 | 0.93 | 180.05 | 43.58 | 50.22 | 12.71 | | | | | | | | |
| C15 | 11.74 | 0.89 | 0.96 | 0.34 | 181.88 | 44.24 | 82.47 | <98 | | | | | | | | |
| C16 | 11.06 | 0.72 | 1.01 | 0.34 | 180.22 | 43.36 | 45.61 | 7.95 | | | | | | | | |
| C17 | 10.94 | 0.70 | 1.07 | 0.29 | 183.64 | 44.23 | 43.32 | 8.12 | | | | | | | | |
| C18 | 11.66 | 0.64 | 0.99 | 0.31 | 177.33 | 42.98 | 45.25 | 9.06 | | | | | | | | |
| C19 | | | | | | | | | | | | | | | | |
| C20 | | | | | | | | | | | | | | | | |
| Avg | 11.99 | 1.61 | 2.32 | 1.77 | 172.64 | 9.81 | 62.35 | 15.58 | | | | | | | | |

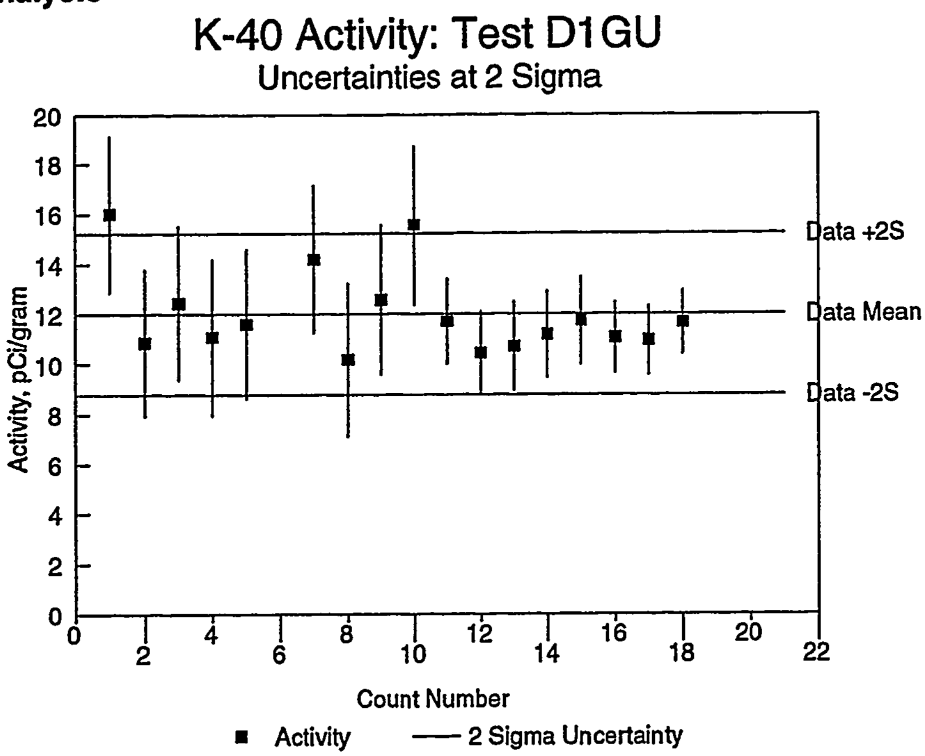
### Library Analysis

Test D1G: Nominal Activity = 162.2 pCi/g Total U     Efficiencies from 01/12/95

| Count USID | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 3.451 | 1.56 | | | 79.241 | 33.2 | | | | | | | | |
| C01 | 16.03 | 1.56 | | <3.4 | | <69 | | <183 | | | | | | | | |
| C02 | 11.12 | 1.49 | | <3.3 | | <69 | | <180 | | | | | | | | |
| C03 | 12.40 | 1.54 | 1.48 | 0.49 | | <69 | | <181 | | | | | | | | |
| C04 | 11.98 | 1.59 | 1.86 | 0.49 | | <69 | | <181 | | | 1.09 | 0.28 | | | | |
| C05 | 11.10 | 1.58 | | <3.3 | | <69 | 82.48 | 22.73 | | | | | | | | |
| C06 | 11.73 | 1.52 | 1.74 | 0.54 | | <69 | | <180 | | | | | | | | |
| C07 | 14.33 | 1.50 | | <3.3 | | <69 | | <178 | | | | | | | | |
| C08 | | <11.1 | | <3.3 | | <69 | | <182 | | | | | | | | |
| C09 | 12.69 | 1.52 | 3.20 | 0.98 | | <69 | | <183 | | | | | | | | |
| C10 | 15.54 | 1.58 | 1.57 | 0.49 | | <69 | | <181 | | | | | | | | |
| C11 | 12.41 | 0.86 | | <1.8 | | <38 | | <100 | | | 0.46 | 0.15 | | | | |
| C12 | 10.77 | 0.84 | | <1.8 | | <38 | 59.15 | 12.86 | | | | | | | 0.73 | 0.22 |
| C13 | 10.73 | 0.91 | | <1.8 | | <38 | | <98 | | | | | | | 0.92 | 0.23 |
| C14 | 11.17 | 0.88 | 2.60 | 0.96 | | <38 | | <98 | | | | | | | | |
| C15 | 11.70 | 0.90 | 1.04 | 0.36 | | <38 | | <98 | | | | | | | 0.70 | 0.22 |
| C16 | 10.58 | 0.74 | 1.01 | 0.34 | | <22 | | <56 | | | 0.52 | 0.10 | | | | |
| C17 | 10.82 | 0.71 | | <1.1 | | <22 | | <56 | | | | | | | 0.68 | 0.13 |
| C18 | 11.64 | 0.65 | 1.06 | 0.34 | | <22 | | <57 | 0.51 | 0.10 | 0.48 | 0.09 | | | | |
| C19 | | | | | | | | | | | | | | | | |
| C20 | | | | | | | | | | | | | | | | |
| Avg | 12.16 | 1.60 | 1.73 | 0.70 | | | 70.82 | 11.67 | 0.51 | 0.00 | 0.64 | 0.26 | | | 0.76 | 0.10 |

## Figure A-20 K-40 Activity: Test 1G (162 pCi/g total U)

### User ROI Analysis




### Library Analysis

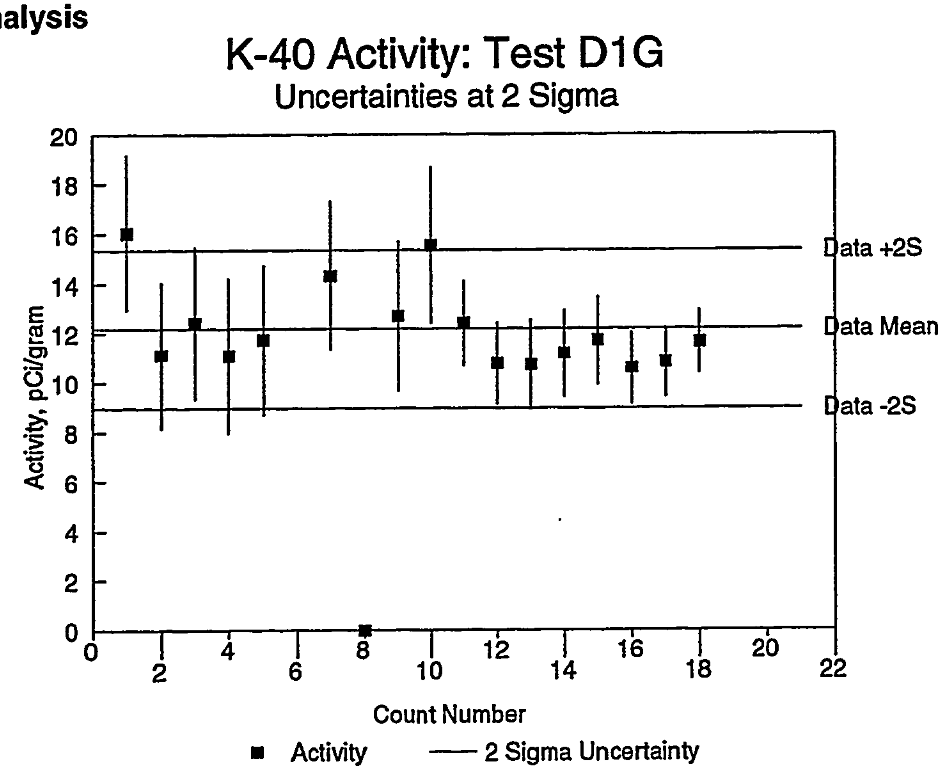
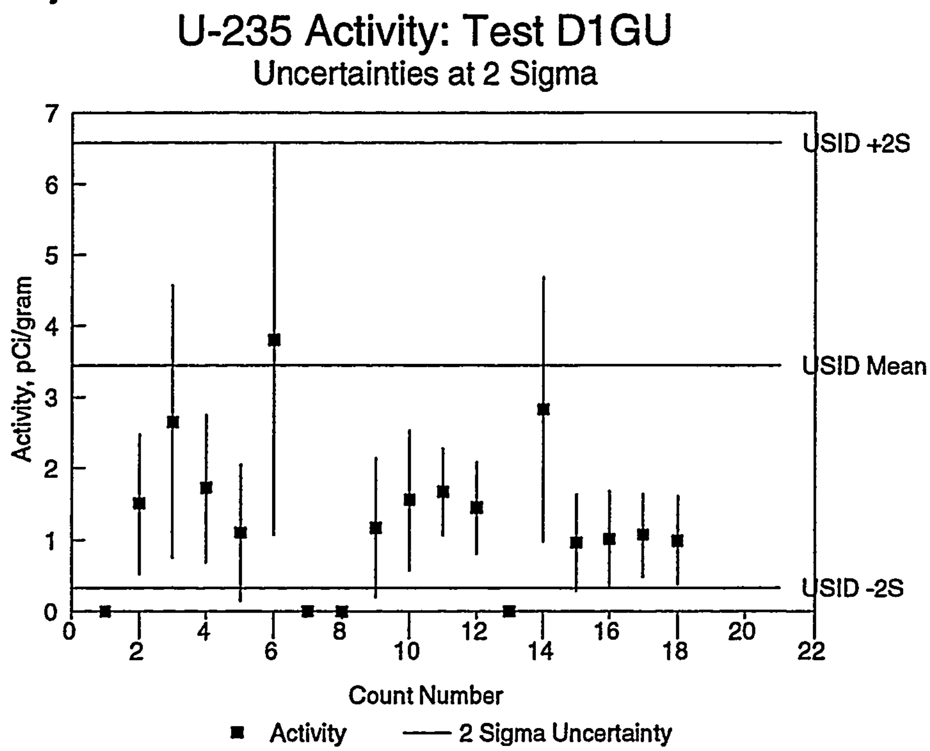


**Figure A-21 U-235 Activity: Test 1G (162 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

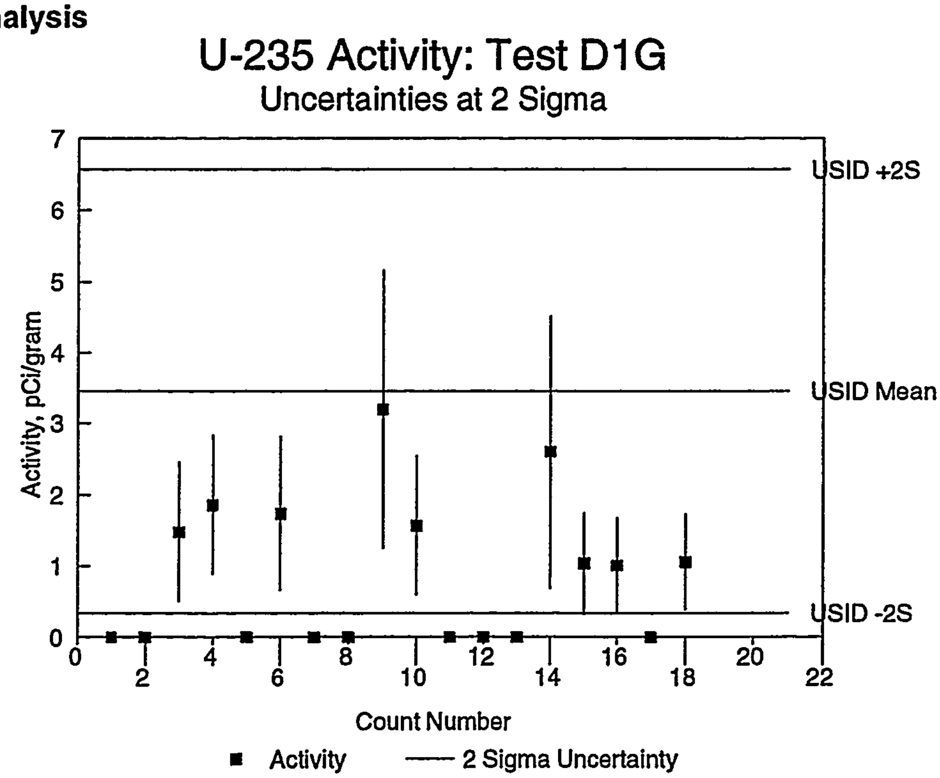
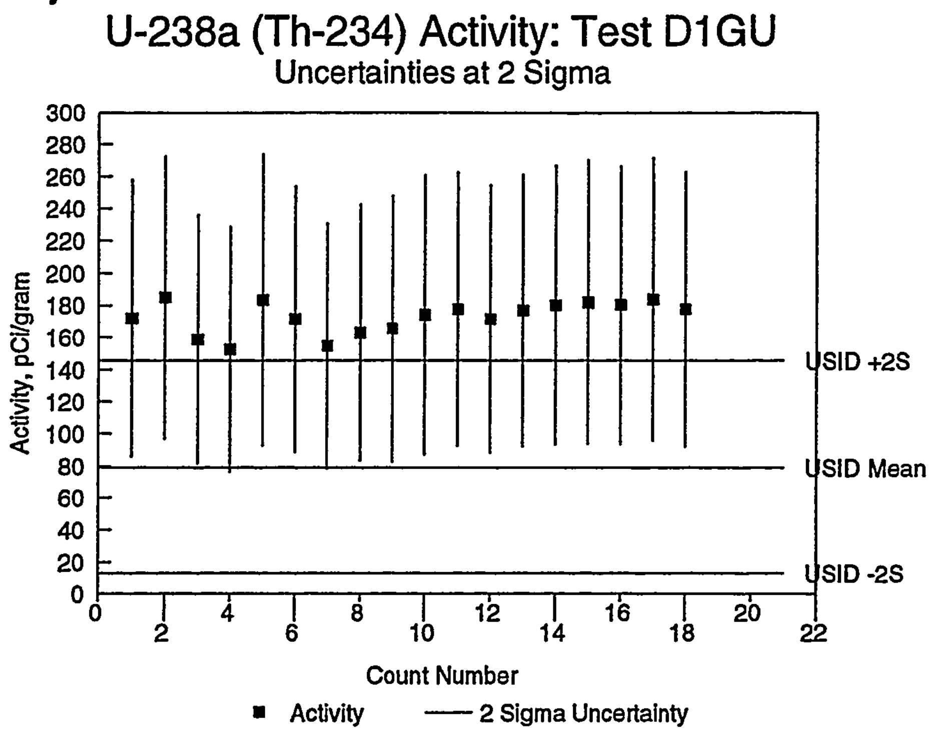


**Figure A-22 U-238a (Th-234) Activity: Test 1G (162 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

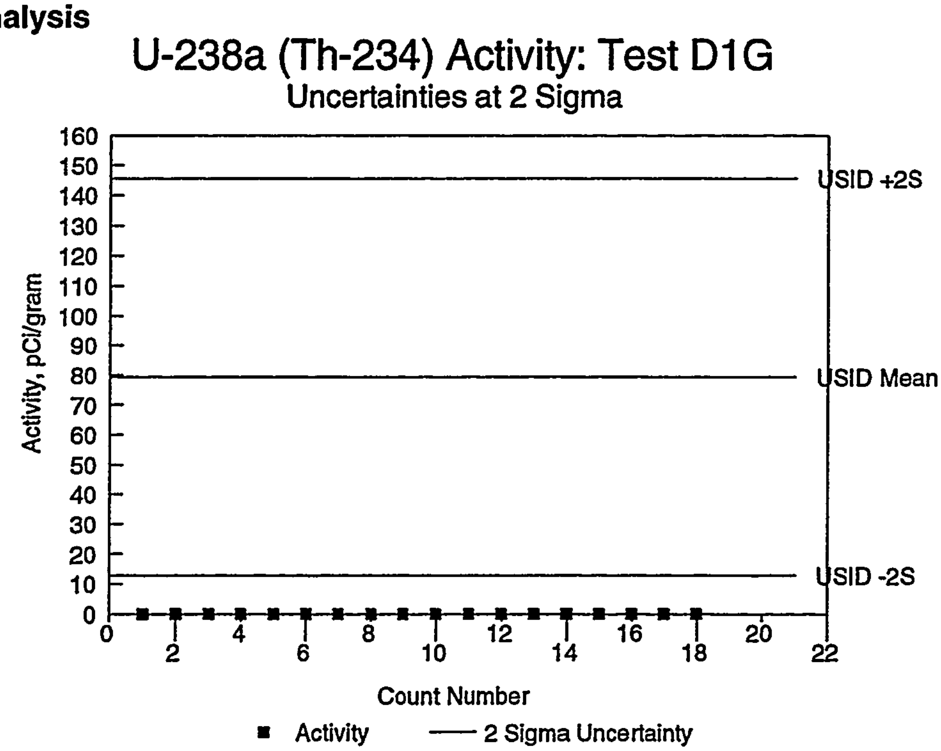
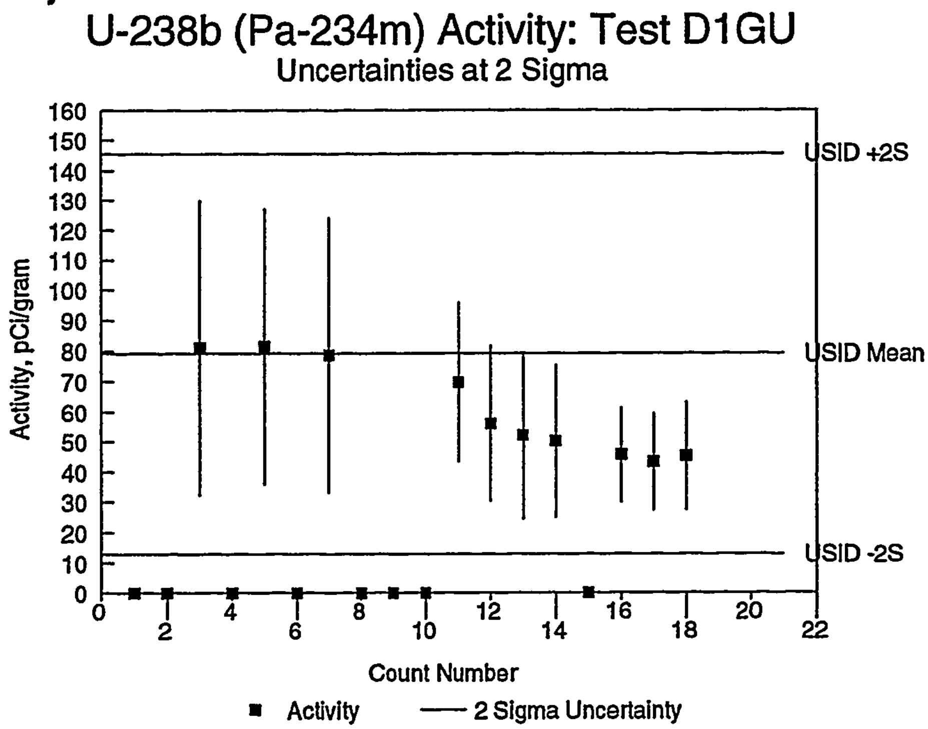
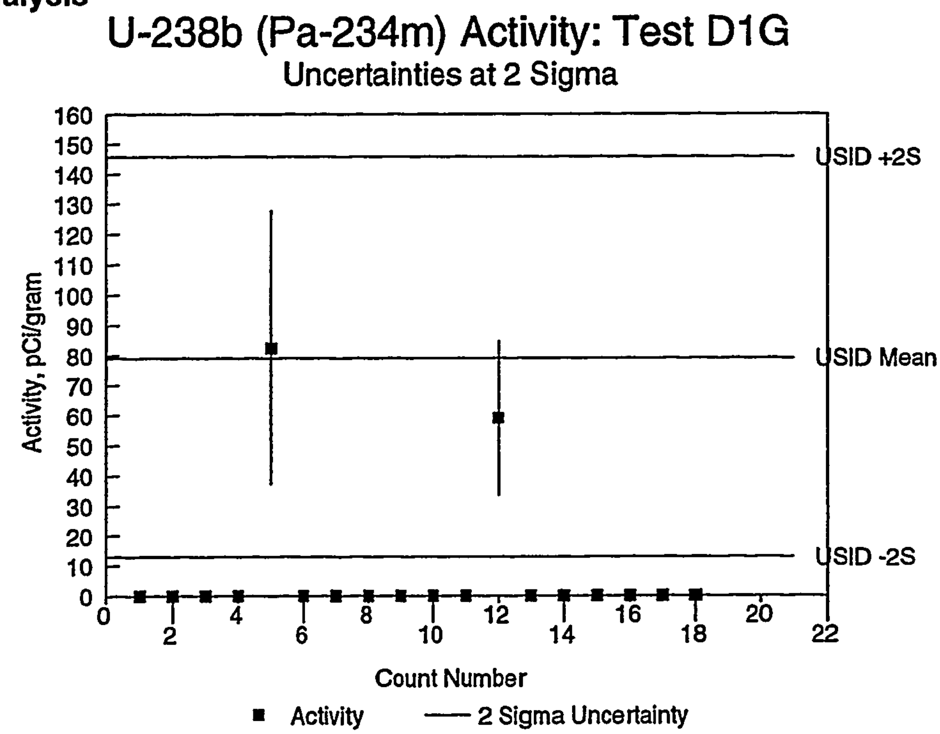


**Figure A-23 U-238b (Pa-234m) Activity: Test 1G (162 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**



## Figure A-24 Results Summary: Test 1E (311 pCi/g Total U)

### User ROI Analysis

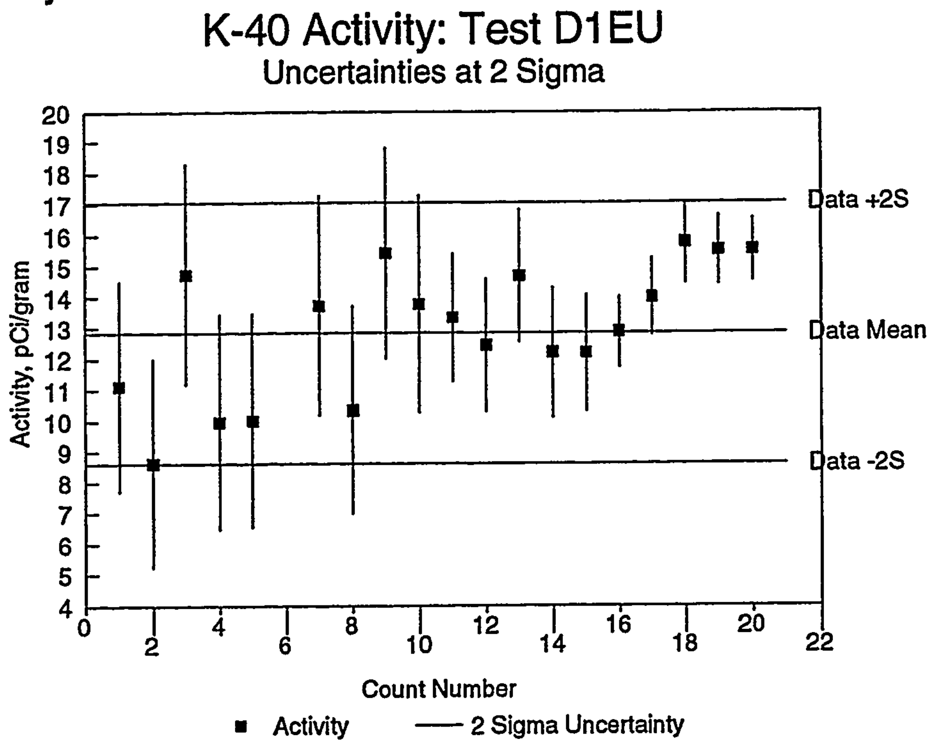
| Test D1EU: Nominal Activity = 311.8 pCi/g Total U | | | | | Effic. from 01/30/95 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Count | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
| USID | | | 6.693 | 0.95 | | | 155.6 | 15.5 | | | | | | | | |
| C01 | 11.11 | 1.71 | 5.71 | 0.71 | 401.51 | 103.8 | 169.27 | 29.19 | | | | | | | | |
| C02 | 8.63 | 1.69 | 2.74 | 0.84 | 367.95 | 95.3 | 166.17 | 27.30 | | | | | | | | |
| C03 | 14.72 | 1.79 | 5.32 | 0.72 | 388.01 | 99.4 | 192.86 | 27.63 | | | | | | | | |
| C04 | 10.54 | 1.75 | 4.44 | 0.88 | 367.85 | 97.1 | 140.45 | 28.79 | | | | | | | | |
| C05 | 9.95 | 1.75 | 5.51 | 0.72 | 379.31 | 99.2 | 181.33 | 29.14 | | | | | | | | |
| C06 | 10.00 | 1.74 | 5.14 | 0.71 | 380.27 | 98.5 | 188.95 | 28.57 | | | | | | | | |
| C07 | 13.72 | 1.78 | 4.02 | 0.85 | 363.69 | 95.7 | 199.11 | 29.21 | | | | | | | | |
| C08 | 10.34 | 1.70 | 4.95 | 0.87 | 379.77 | 96.9 | 139.07 | 28.55 | | | | | | | | |
| C09 | 15.41 | 1.71 | 4.92 | 0.69 | 396.92 | 101.3 | 200.88 | 29.03 | | | | | | | | |
| C10 | 13.76 | 1.76 | 4.35 | 0.78 | 365.88 | 96.3 | 140.82 | 29.20 | | | | | | | | |
| C11 | 13.32 | 1.04 | 5.36 | 0.53 | 391.00 | 100.0 | 162.79 | 18.21 | | | | | | | | |
| C12 | 12.44 | 1.08 | 4.54 | 0.59 | 372.39 | 96.9 | 171.44 | 15.23 | | | | | | | | |
| C13 | 14.67 | 1.08 | 5.36 | 0.55 | 371.66 | 97.8 | 155.80 | 15.16 | | | | | | | | |
| C14 | 12.20 | 1.06 | 4.87 | 0.51 | 375.13 | 96.8 | 150.76 | 14.67 | | | | | | | | |
| C15 | 12.19 | 0.95 | 4.43 | 0.61 | 382.80 | 98.7 | 163.69 | 16.13 | | | | | | | | |
| C16 | 12.87 | 0.58 | 4.77 | 0.45 | 378.42 | 98.2 | 169.66 | 9.00 | | | | | | | | |
| C17 | 13.98 | 0.63 | 4.84 | 0.47 | 368.39 | 96.2 | 189.49 | 9.71 | | | | | | | | |
| C18 | 15.76 | 0.67 | 2.93 | 0.40 | 329.77 | 80.8 | 196.57 | 9.33 | | | | | | | | |
| C19 | 15.50 | 0.55 | 2.78 | 0.48 | 332.46 | 81.2 | 202.76 | 8.10 | | | | | | | | |
| C20 | 15.52 | 0.51 | 2.92 | 0.50 | 332.89 | 81.4 | 210.04 | 7.27 | | | | | | | | |
| Avg | 12.83 | 2.11 | 4.50 | 0.92 | 371.30 | 19.3 | 174.60 | 21.81 | | | | | | | | |

### Library Analysis

| Test D1E: Nominal Activity = 311.8 pCi/g Total U | | | | | Efficiencies from 01/30/95 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Count | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
| USID | | | 6.693 | 0.95 | | | 155.6 | 15.5 | | | | | | | | |
| C01 | 16.03 | <13.7 | 5.37 | 0.78 | | <93 | 90.04 | 39.73 | | | | | | | | |
| C02 | 8.63 | 1.70 | 2.47 | 0.89 | | <93 | | <233 | | | | | | | | |
| C03 | 14.86 | 1.79 | 1.48 | <4.6 | | <94 | 192.96 | 27.68 | | | | | | | | |
| C04 | 10.67 | 1.75 | 4.18 | 0.89 | | <93 | | <235 | | | 1.09 | 0.28 | | | | |
| C05 | 11.10 | <13.8 | 13.85 | 1.98 | | <94 | 82.48 | <235 | | | | | | | | |
| C06 | 9.82 | 1.75 | 5.03 | 0.70 | | <93 | | <234 | | | | | | | | |
| C07 | 13.41 | 1.78 | | <4.6 | | <94 | | <234 | | | | | | | | |
| C08 | | <13.7 | 4.64 | 0.95 | | <93 | | <232 | | | | | | | 1.57 | 0.53 |
| C09 | 15.44 | 1.71 | 5.06 | 0.82 | | <93 | | <233 | | | | | | | | |
| C10 | 13.78 | 1.76 | 4.08 | 0.82 | | <93 | 190.60 | 60.60 | 1.95 | 0.40 | | | | | | |
| C11 | 13.33 | 1.04 | 5.39 | 0.59 | | <51 | 162.21 | 18.00 | | | 0.46 | 0.15 | | | | |
| C12 | 12.19 | 1.08 | 4.28 | 0.63 | | <51 | 59.15 | <127 | | | | | | | 0.91 | 0.29 |
| C13 | 14.68 | 1.08 | 5.10 | 0.60 | | <51 | | <128 | | | 0.76 | 0.22 | | | 0.92 | 0.23 |
| C14 | 12.02 | 1.06 | 4.67 | 0.55 | | <51 | | <127 | | | | | | | | |
| C15 | 11.84 | 0.96 | 4.20 | 0.65 | | <51 | | <128 | | | | | | | 0.70 | 0.22 |
| C16 | 12.82 | 0.58 | 1.01 | <1.5 | | <29 | 154.51 | 10.26 | | | 0.45 | 0.13 | | | | |
| C17 | 13.99 | 0.63 | 11.93 | 0.87 | | <29 | 163.75 | 12.16 | | | 0.47 | 0.13 | | | 0.68 | 0.13 |
| C18 | 15.76 | 0.67 | 2.86 | 0.35 | | <29 | 149.16 | 13.02 | 0.51 | 0.10 | 0.49 | 0.14 | | | | |
| C19 | 15.49 | 0.55 | 2.70 | 0.40 | | <20 | 155.60 | 8.98 | | | 0.58 | 0.06 | | | | |
| C20 | 15.51 | 0.51 | 2.85 | 0.42 | | <17 | 156.71 | 7.70 | | | | | | | 0.68 | 0.07 |
| Avg | 13.23 | 2.10 | 4.80 | 3.06 | | | 141.56 | 42.16 | 1.23 | 0.72 | 0.61 | 0.22 | | | 0.91 | 0.31 |

**Figure A-25 K-40 Activity: Test 1E (311 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

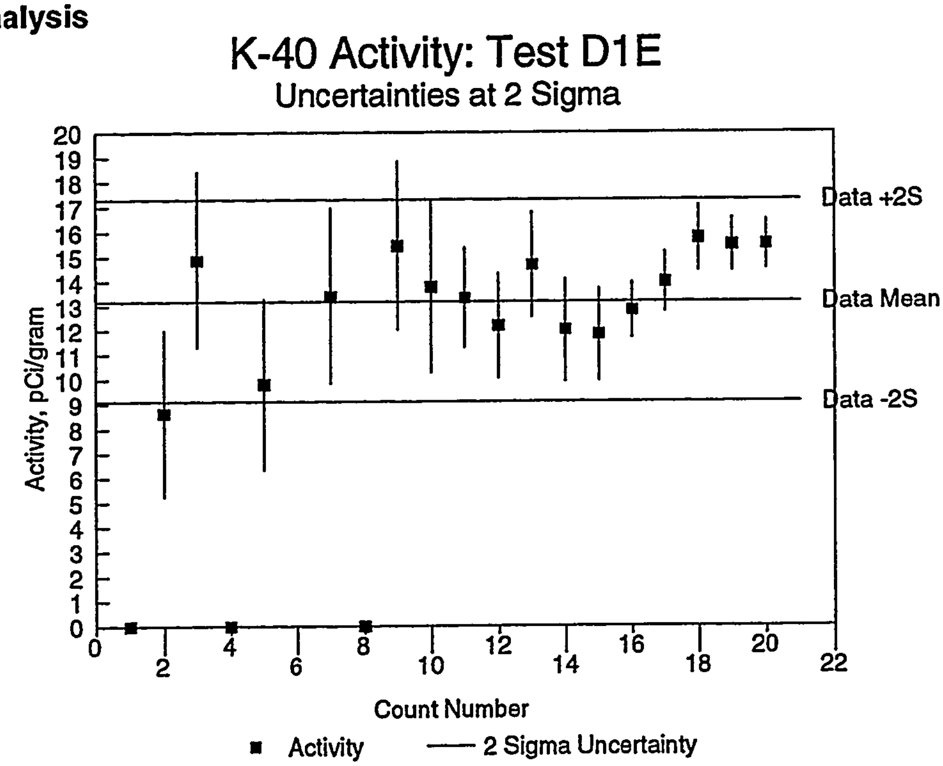
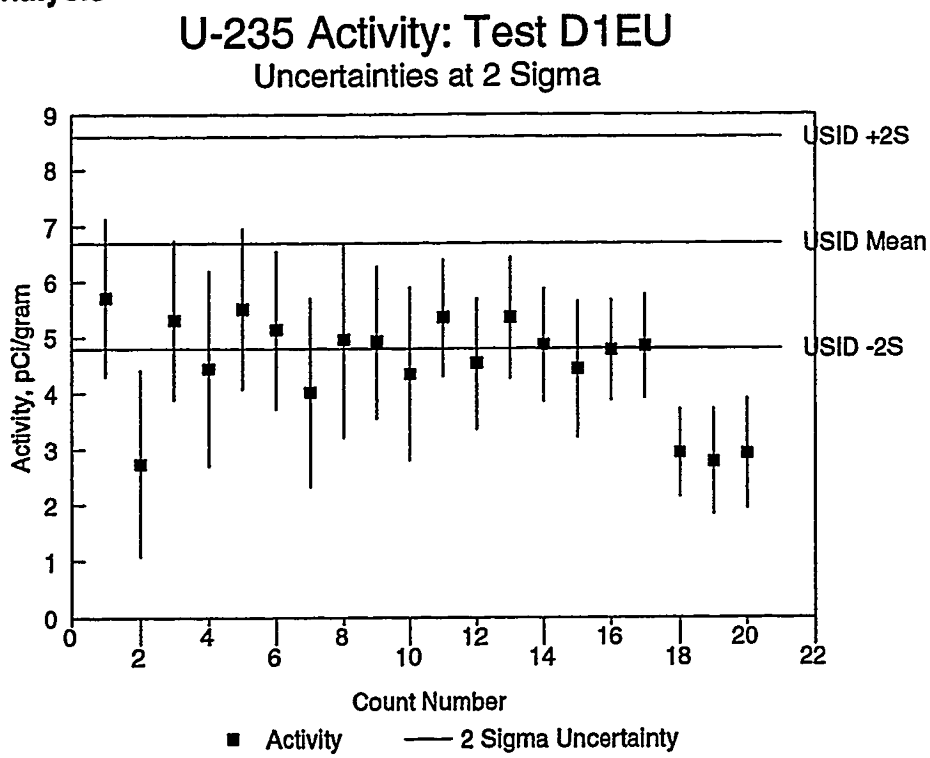


**Figure A-26 U-235 Activity: Test 1E (311 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

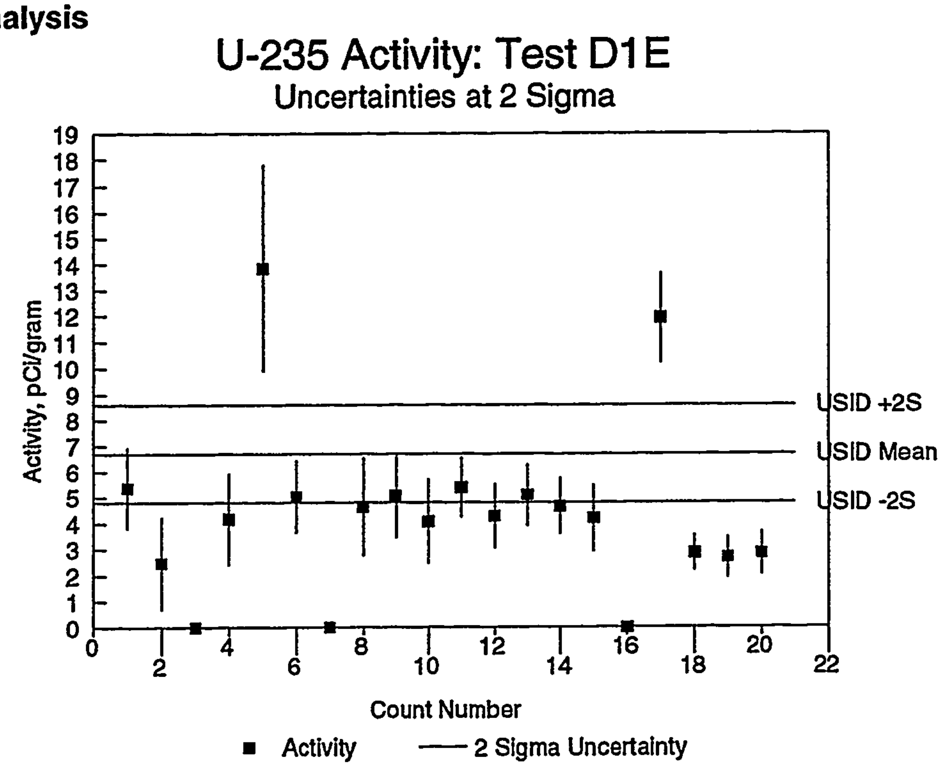
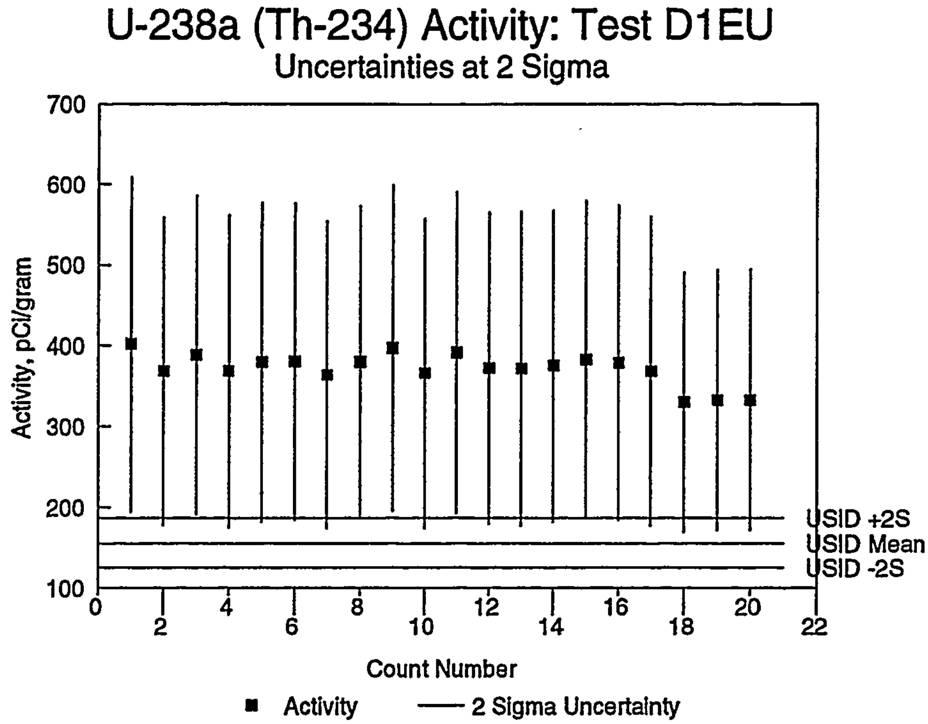


**Figure A-27 U-238a (Th-234) Activity: Test 1E (311 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

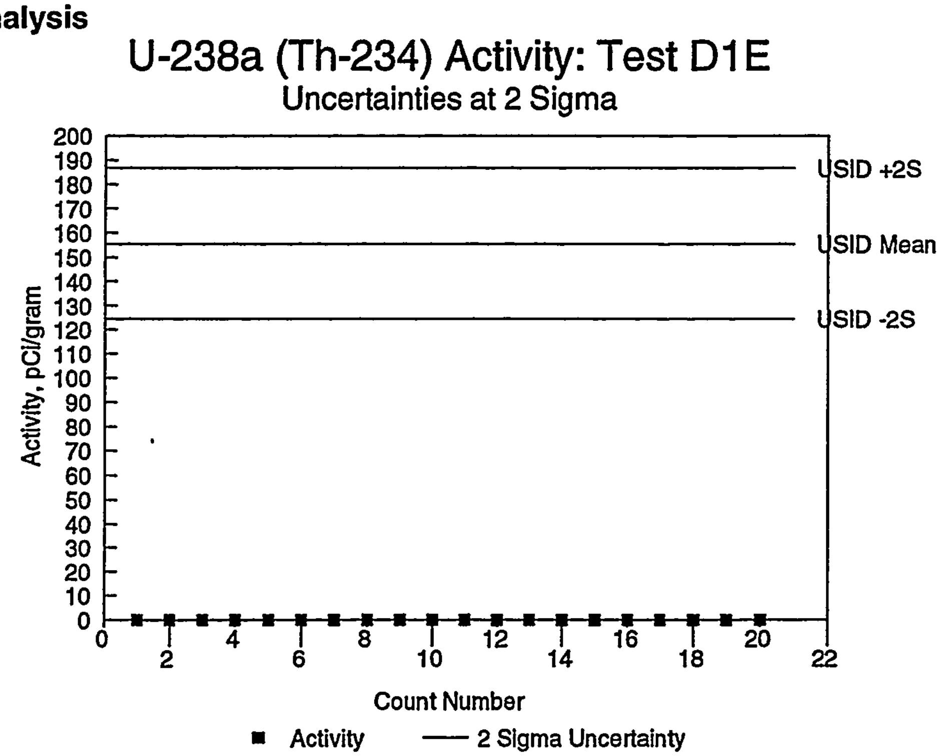
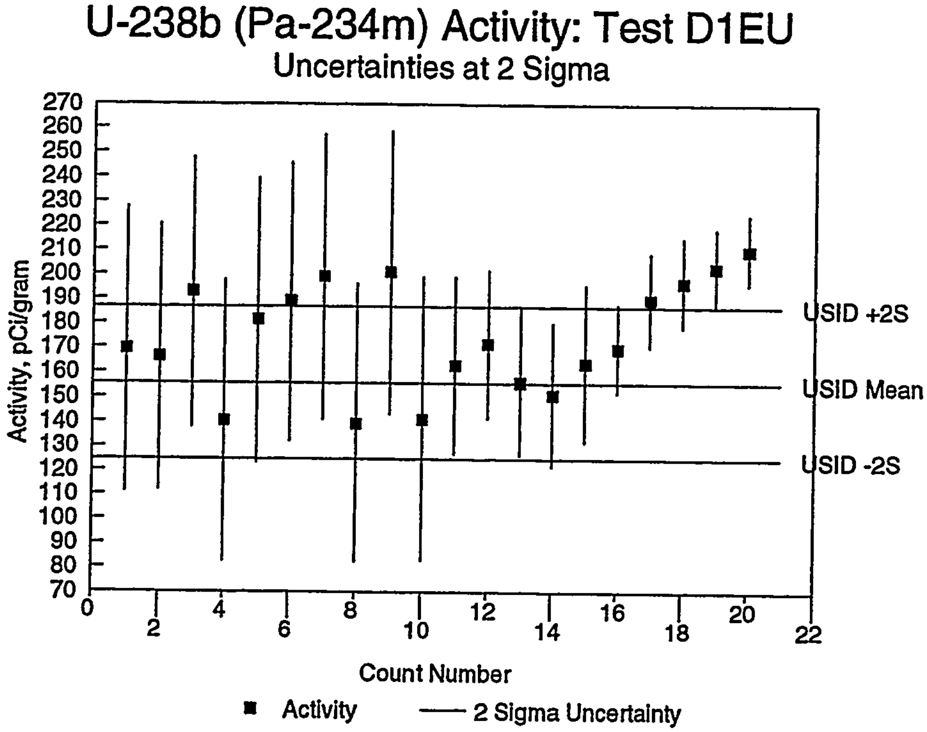
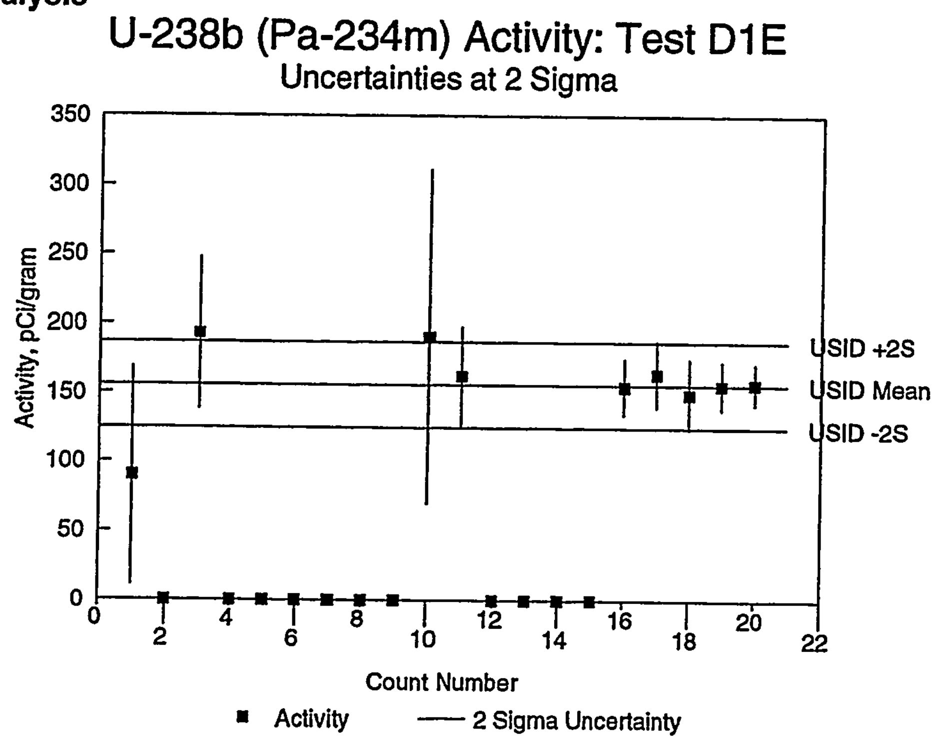


**Figure A-28 U-238b (Pa-234m) Activity: Test 1E (311 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**



## Figure A-29 Results Summary: Test 1H (311 pCi/g Total U)

### User ROI Analysis

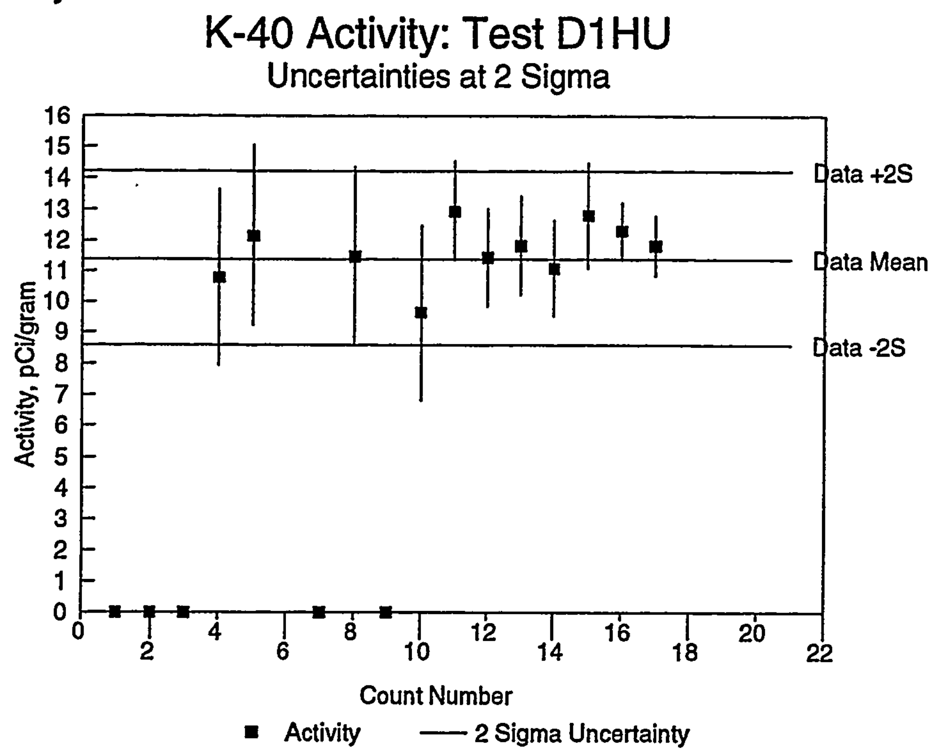
| Test D1HU: Nominal Activity = 311.8 pCi/g Total U | | | Effic. from 01/12/95 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Count USID | K-40 | +- | U-235 6.693 | +- 0.95 | U-238a | +- | U-238b 155.6 | +- 15.5 | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
| C01 | 11.11 | <11.5 | 2.90 | 0.62 | 327.38 | 82.08 | 150.03 | 24.32 | | | | | | | | |
| C02 | 8.63 | <11.5 | 3.63 | 0.56 | 348.31 | 85.86 | 99.12 | 24.44 | | | | | | | | |
| C03 | 14.72 | <11.3 | 3.08 | 0.70 | 330.44 | 82.16 | 137.16 | 23.89 | | | | | | | | |
| C04 | 7.50 | 1.42 | 3.60 | 0.87 | 336.08 | 84.10 | 146.31 | 24.35 | | | | | | | | |
| C05 | 10.78 | 1.43 | 3.44 | 0.71 | 333.19 | 82.66 | 181.33 | <195 | | | | | | | | |
| C06 | 12.14 | 1.46 | 3.27 | 0.70 | 338.61 | 84.64 | 158.70 | 24.17 | | | | | | | | |
| C07 | 13.72 | <11.2 | 3.38 | 0.74 | 365.75 | 89.14 | 114.70 | 23.99 | | | | | | | | |
| C08 | 11.46 | 1.45 | 4.45 | 0.70 | 365.74 | 88.69 | 89.02 | 24.17 | | | | | | | | |
| C09 | 15.41 | <11.3 | 3.41 | 0.73 | 352.06 | 87.51 | 146.63 | 24.27 | | | | | | | | |
| C10 | 9.64 | 1.43 | 3.24 | 0.68 | 342.99 | 83.92 | 139.43 | 22.72 | | | | | | | | |
| C11 | 12.94 | 0.80 | 3.03 | 0.59 | 357.13 | 87.06 | 153.94 | 12.36 | | | | | | | | |
| C12 | 11.45 | 0.80 | 8.00 | 0.95 | 361.88 | 87.82 | 158.19 | 13.42 | | | | | | | | |
| C13 | 11.82 | 0.81 | 3.48 | 0.73 | 365.81 | 88.13 | 153.38 | 12.32 | | | | | | | | |
| C14 | 11.09 | 0.78 | 2.68 | 0.65 | 367.51 | 88.94 | 155.91 | 12.27 | | | | | | | | |
| C15 | 12.80 | 0.85 | 2.51 | 0.71 | 356.76 | 86.53 | 149.09 | 12.47 | | | | | | | | |
| C16 | 12.30 | 0.47 | 9.12 | 0.94 | 375.90 | 90.08 | 148.95 | 7.63 | | | | | | | | |
| C17 | 11.81 | 0.50 | 8.43 | 0.97 | 365.59 | 88.07 | 151.03 | 7.41 | | | | | | | | |
| C18 | 12.37 | 0.47 | 8.55 | 1.00 | 376.18 | 90.36 | 140.70 | 8.33 | | | | | | | | |
| C19 | 15.50 | 0.55 | 2.78 | 0.48 | 332.46 | 81.19 | 202.76 | 8.10 | | | | | | | | |
| C20 | 15.52 | 0.51 | 2.92 | 0.50 | 332.89 | 81.38 | 210.04 | 7.27 | | | | | | | | |
| Avg | 12.14 | 2.11 | 4.30 | 2.16 | 351.63 | 15.80 | 149.32 | 27.85 | | | | | | | | |

### Library Analysis

| Test D1H: Nominal Activity = 311.8 pCi/g Total U | | | Efficiencies from 01/12/95 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Count USID | K-40 | +- | U-235 6.693 | +- 0.95 | U-238a | +- | U-238b 155.6 | +- 15.5 | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232d | +- |
| C01 | 16.03 | <11.5 | 5.37 | <3.6 | | <74 | 90.04 | <195 | | | | | | | | |
| C02 | 8.63 | <11.5 | 3.64 | 0.56 | | <74 | 94.25 | 24.41 | | | | | | | | |
| C03 | 14.86 | <11.3 | 1.48 | <3.6 | | <74 | 192.96 | <193 | | | | | | | | |
| C04 | 10.67 | <11.3 | 4.18 | <3.6 | | <74 | 136.81 | 24.32 | | | 1.09 | 0.28 | | | | |
| C05 | 11.10 | <11.4 | 13.85 | <3.6 | | <73 | 82.48 | <195 | | | | | | | | |
| C06 | 9.82 | <11.3 | 5.03 | <3.6 | | <74 | | <193 | | | | | | | | |
| C07 | 10.03 | 1.45 | | <3.6 | | <74 | | <194 | | | | | | | | |
| C08 | 10.29 | 1.45 | 4.64 | <3.6 | | <74 | | <195 | | | | | | | 1.57 | 0.53 |
| C09 | 15.44 | <11.3 | 3.64 | 0.80 | | <74 | | <194 | | | | | | | | |
| C10 | 8.87 | 1.43 | 4.08 | <3.6 | | <74 | 139.87 | 23.40 | 1.95 | 0.40 | | | | | | |
| C11 | 12.31 | 0.81 | 3.38 | 0.64 | | <40 | 152.67 | 12.36 | | | 0.46 | 0.15 | | | | |
| C12 | 10.89 | 0.79 | 4.28 | <2.0 | | <40 | 160.91 | 13.40 | | | | | | | 0.91 | 0.29 |
| C13 | 11.34 | 0.81 | 12.29 | 1.50 | | <40 | 162.16 | 12.37 | | | 0.80 | 0.19 | 1.28 | 1.20 | 0.92 | 0.23 |
| C14 | 10.85 | 0.78 | 4.67 | <2.0 | | <41 | 137.55 | 17.56 | | | 0.70 | 0.19 | | | | |
| C15 | 12.62 | 0.87 | 4.20 | <2.0 | | <41 | | <104 | | | | | | | 0.70 | 0.22 |
| C16 | 12.29 | 0.47 | 13.32 | 0.97 | | <23 | 125.99 | 10.27 | | | 0.39 | 0.11 | 0.85 | 0.65 | | |
| C17 | 11.81 | 0.50 | 8.10 | 0.76 | | <23 | 163.75 | <60 | | | 0.52 | 0.11 | | | 0.68 | 0.13 |
| C18 | 12.36 | 0.47 | 7.31 | 0.79 | | <29 | 113.08 | 8.84 | 0.51 | 0.10 | 0.49 | 0.14 | | | 0.85 | 0.07 |
| C19 | 15.49 | 0.55 | 2.70 | 0.40 | | <20 | 155.60 | 8.98 | | | 0.58 | 0.06 | | | | |
| C20 | 15.51 | 0.51 | 2.85 | 0.42 | | <17 | 156.71 | 7.70 | | | | | | | 0.68 | 0.07 |
| Avg | 12.06 | 2.23 | 5.74 | 3.53 | | | 137.66 | 30.26 | 1.23 | 0.72 | 0.63 | 0.21 | 1.07 | 0.22 | 0.90 | 0.29 |

**Figure A-30 K-40 Activity: Test 1H (311 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

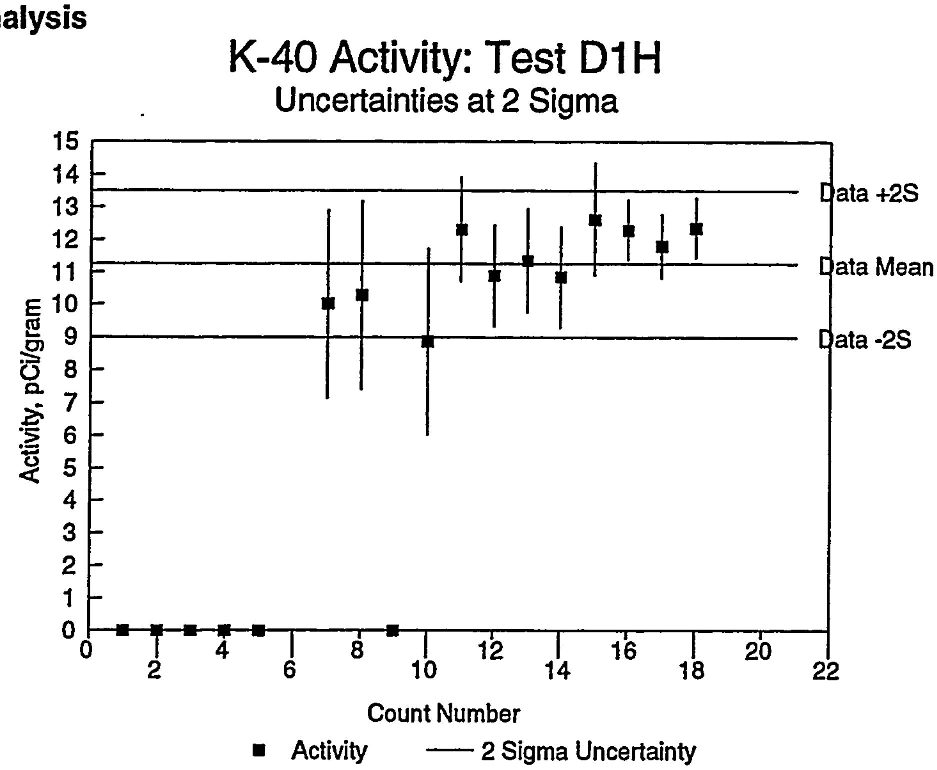
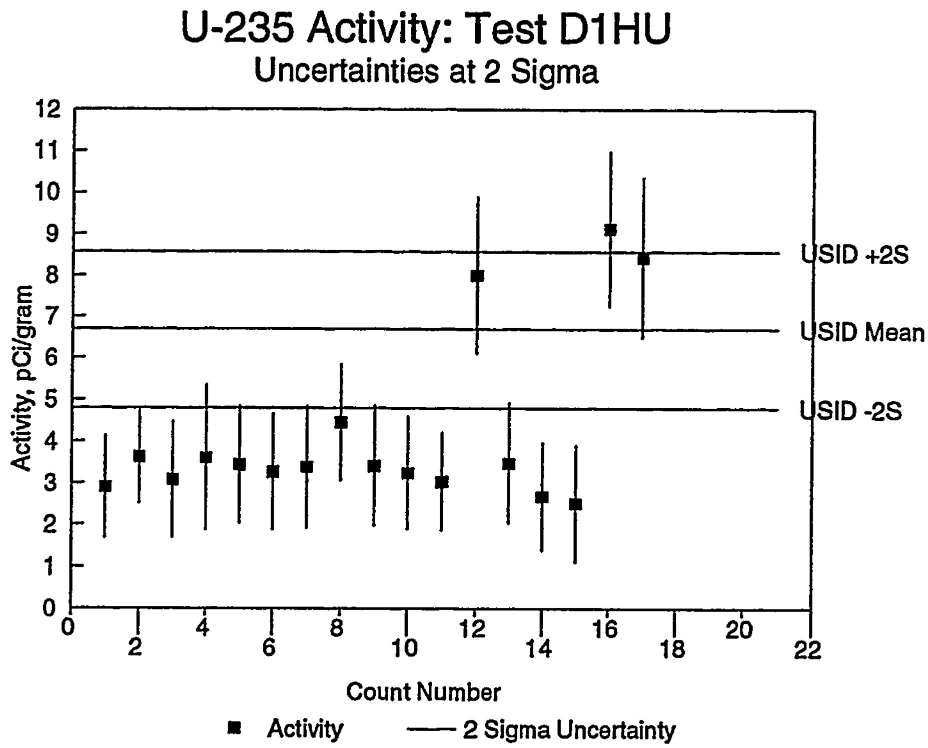


**Figure A-31 U-235 Activity: Test 1H (311 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

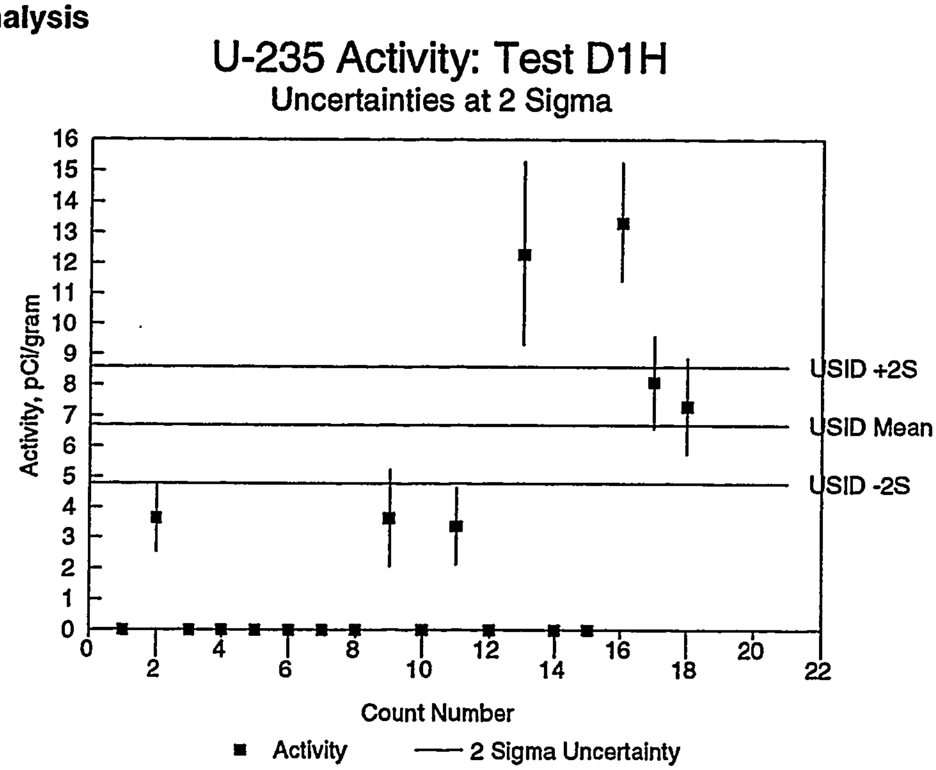
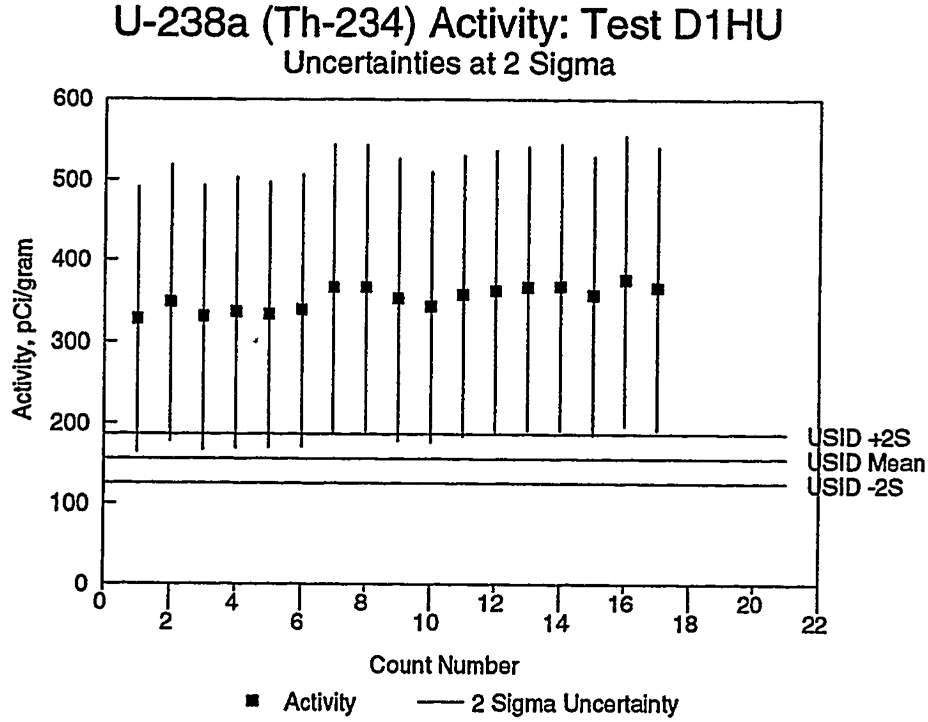


**Figure A-32 U-238a (Th-234) Activity: Test 1H (311 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

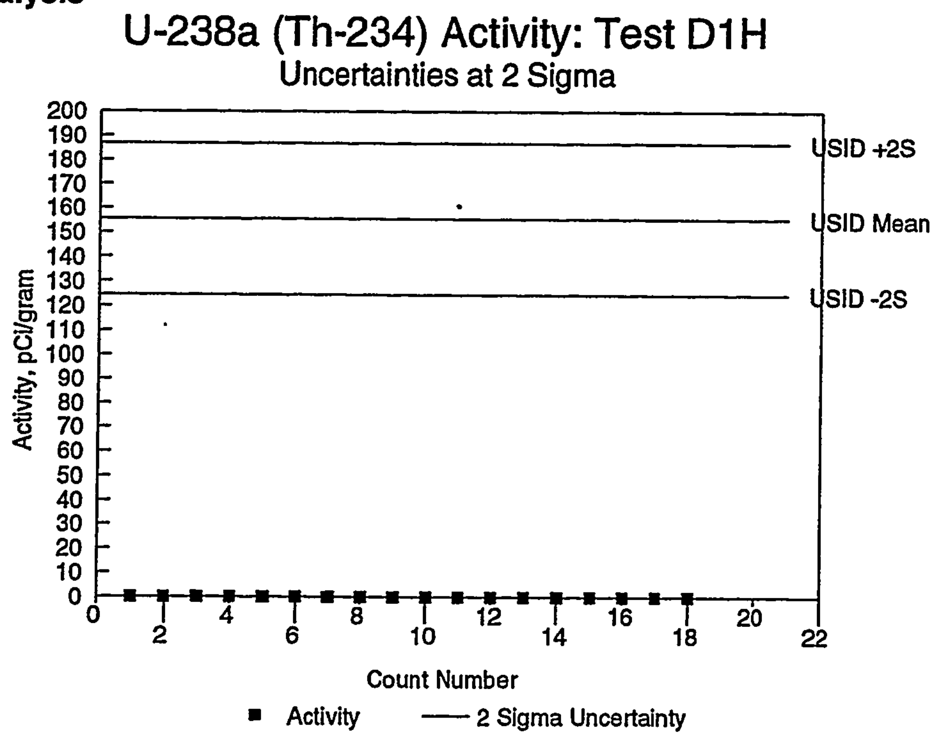
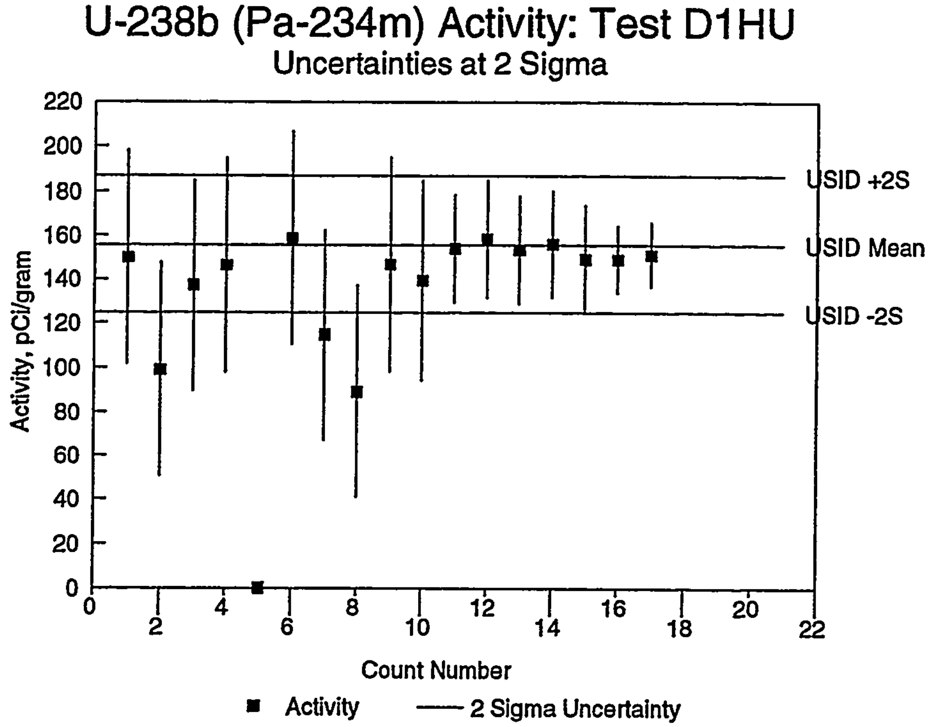
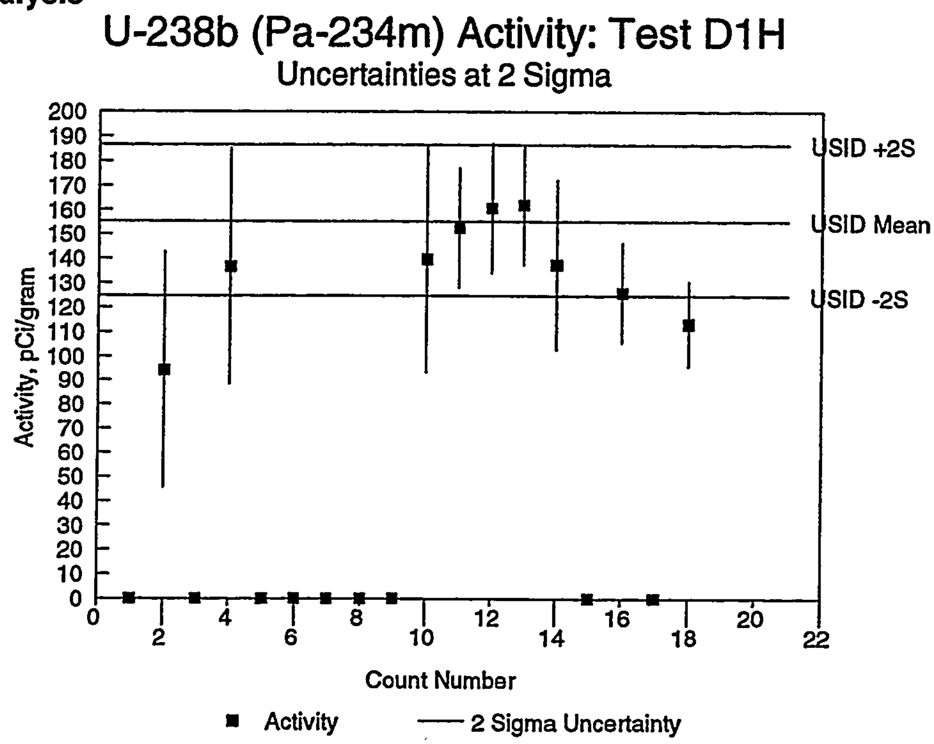


**Figure A-33 U-238b (Pa-234m) Activity: Test 1H (311 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**



## Figure A-34 Results Summary: Test 2A (>1000 pCi/g U)

### User ROI Analysis

Test D2AU: Nominal Activity = 1750 pCi/g Total U Effic. from 01/30/95

| Count USID | K-40 | +- | U-235 36.26 | +- 0 | U-238a (Th-234) | +- | U-238b 824.25 | +- 0 | Ra-226a (Pb-214) | +- | Ra-226b | +- | Th-232b | +- | Th-232c (Bi-212) | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C01 | 12.74 | 2.42 | 17.59 | 1.57 | 1310.21 | 317.0 | 761.31 | 46.12 | | | | | | | | |
| C02 | 11.20 | 2.35 | 17.52 | 1.21 | 1225.68 | 298.6 | 659.17 | 49.33 | | | | | | | | |
| C03 | 9.25 | 2.38 | 20.89 | 1.63 | 1226.63 | 300.2 | 718.78 | 52.48 | | | | | | | | |
| C04 | 16.69 | 2.4 | 22.20 | 1.45 | 1223.23 | 297.8 | 684.61 | 51.66 | | | | | | | | |
| C05 | 13.67 | 2.35 | 20.55 | 1.20 | 1206.21 | 296.4 | 656.42 | 46.70 | | | | | | | | |
| C06 | 11.54 | 2.36 | 20.37 | 1.20 | 1133.06 | 278.9 | 595.72 | 48.80 | | | | | | | | |
| C07 | 9.09 | 2.40 | 21.13 | 1.20 | 1157.07 | 284.3 | 717.21 | 52.37 | | | | | | | | |
| C08 | 12.57 | 2.39 | 21.36 | 1.20 | 1117.06 | 276.1 | 614.23 | 49.81 | | | | | | | | |
| C09 | 8.06 | 2.38 | 19.67 | 1.25 | 1185.98 | 292.4 | 735.15 | 50.45 | | | | | | | | |
| C10 | 11.53 | 2.38 | 19.84 | 1.22 | 1194.88 | 294.0 | 687.72 | 49.82 | | | | | | | | |
| C11 | 8.96 | 1.31 | 19.57 | 0.93 | 1169.67 | 287.4 | 697.79 | 34.72 | | | | | | | | |
| C12 | 10.75 | 1.42 | 19.48 | 0.87 | 1158.81 | 284.0 | 682.80 | 34.71 | | | | | | | | |
| C13 | 12.99 | 1.33 | 18.99 | 0.76 | 1121.84 | 276.8 | 697.97 | 39.10 | | | | | | | | |
| C14 | 10.28 | 1.44 | 19.85 | 0.97 | 1153.11 | 285.6 | 718.40 | 35.18 | | | | | | | | |
| C15 | 10.68 | 1.57 | 18.93 | 0.93 | 1141.44 | 281.3 | 666.99 | 34.60 | | | | | | | | |
| C16 | 12.13 | 0.92 | 19.98 | 0.84 | 1136.36 | 279.4 | 747.42 | 28.55 | | | | | | | | |
| C17 | 11.41 | 0.88 | 20.39 | 0.70 | 1140.92 | 280.0 | 754.06 | 25.11 | | | | | | | | |
| C18 | 11.51 | 0.86 | 19.87 | 0.78 | 1118.16 | 275.6 | 754.55 | 24.55 | | | | | | | | |
| C19 | 15.50 | 0.55 | 2.78 | 0.48 | 332.46 | 81.2 | 202.76 | 8.10 | | | | | | | | |
| C20 | 15.52 | 0.51 | 2.92 | 0.50 | 332.89 | 81.4 | 210.04 | 7.27 | | | | | | | | |
| Avg | 11.80 | 2.23 | 18.19 | 5.23 | 1089.28 | 256.5 | 648.16 | 153.5 | | | | | | | | |

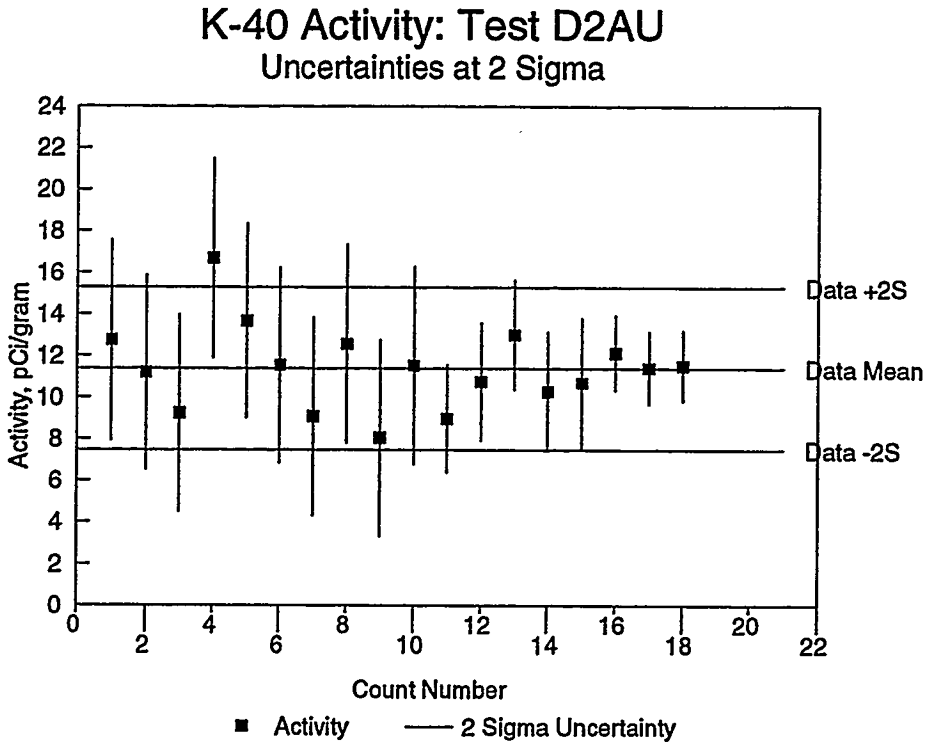
### Library Analysis

Test D2A: Nominal Activity = 1750 pCi/g Total U Efficiencies from 01/30/95

| Count USID | K-40 | +- | U-235 36.26 | +- 0 | U-238a (Th-234) | +- | U-238b 824.25 | +- 0 | Ra-226a (Pb-214) | +- | Ra-226b | +- | Th-232b | +- | Th-232c (Bi-212) | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C01 | 13.14 | 2.44 | 17.39 | 1.57 | <155 | | 90.04 | <381 | | | | | | | | |
| C02 | 10.96 | 2.36 | 17.45 | 1.17 | <155 | | 94.25 | <382 | | | | | | | | |
| C03 | 14.86 | <21 | 20.79 | 1.60 | <154 | | 738.95 | 51.68 | | | | | | | | |
| C04 | 16.88 | 2.41 | 23.03 | 1.24 | <154 | | 695.20 | 51.11 | 3.36 | 0.65 | 1.09 | 0.28 | | | | |
| C05 | 13.90 | 2.35 | 20.54 | 1.13 | <154 | | 668.78 | 49.22 | | | | | | | | |
| C06 | 9.82 | <21 | 21.34 | 1.21 | <153 | | 603.19 | 48.05 | | | | | | | | |
| C07 | 10.03 | <21 | 21.12 | 1.13 | <153 | | 729.98 | 52.73 | | | | | | | | |
| C08 | 12.67 | 2.40 | 21.37 | 1.14 | <153 | | 624.95 | 49.21 | | | | | | | 1.57 | 0.53 |
| C09 | 8.22 | 2.39 | 20.21 | 1.25 | <153 | | 737.92 | 49.84 | | | | | | | | |
| C10 | 11.50 | 2.38 | 19.85 | 1.17 | <153 | | 687.50 | 49.51 | 1.95 | 0.40 | | | | | | |
| C11 | 9.10 | 1.31 | 19.70 | 0.88 | <84 | | 697.79 | 34.32 | | | 0.46 | 0.15 | | | | |
| C12 | 10.89 | 1.41 | 23.92 | 2.32 | <84 | | 681.83 | 34.54 | | | | | | | 0.91 | 0.29 |
| C13 | 12.95 | 1.33 | 18.98 | 0.70 | <84 | | 698.70 | 38.92 | | | 0.80 | 0.19 | 1.28 | 1.20 | 0.92 | 0.23 |
| C14 | 10.41 | 1.43 | 20.01 | 0.91 | <84 | | 718.78 | 34.98 | | | 0.70 | 0.19 | | | | |
| C15 | 10.71 | 1.57 | 18.22 | 0.93 | <84 | | 666.14 | 34.82 | | | | | | | 0.70 | 0.22 |
| C16 | 12.10 | 0.93 | 20.96 | 0.66 | <48 | | 747.73 | 28.86 | | | 0.39 | 0.11 | 0.85 | 0.65 | | |
| C17 | 11.39 | 0.89 | 20.93 | 0.59 | <34 | | 753.22 | 25.32 | | | 0.40 | 0.14 | | | 0.68 | 0.13 |
| C18 | 11.46 | 0.86 | 18.99 | 0.57 | <28 | | 753.43 | 24.84 | 0.51 | 0.10 | 0.34 | 0.12 | | | 0.85 | 0.07 |
| C19 | 15.49 | 0.55 | 2.70 | 0.40 | <20 | | 155.60 | 8.98 | | | 0.58 | 0.06 | | | | |
| C20 | 15.51 | 0.51 | 2.85 | 0.42 | <17 | | 156.71 | 7.70 | | | | | | | 0.68 | 0.07 |
| Avg | 12.10 | 2.25 | 18.52 | 5.48 | | | 585.03 | 234.1 | 1.94 | 1.16 | 0.60 | 0.24 | 1.07 | 0.22 | 0.90 | 0.29 |

**Figure A-35 K-40 Activity: Test 2A (>1000 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

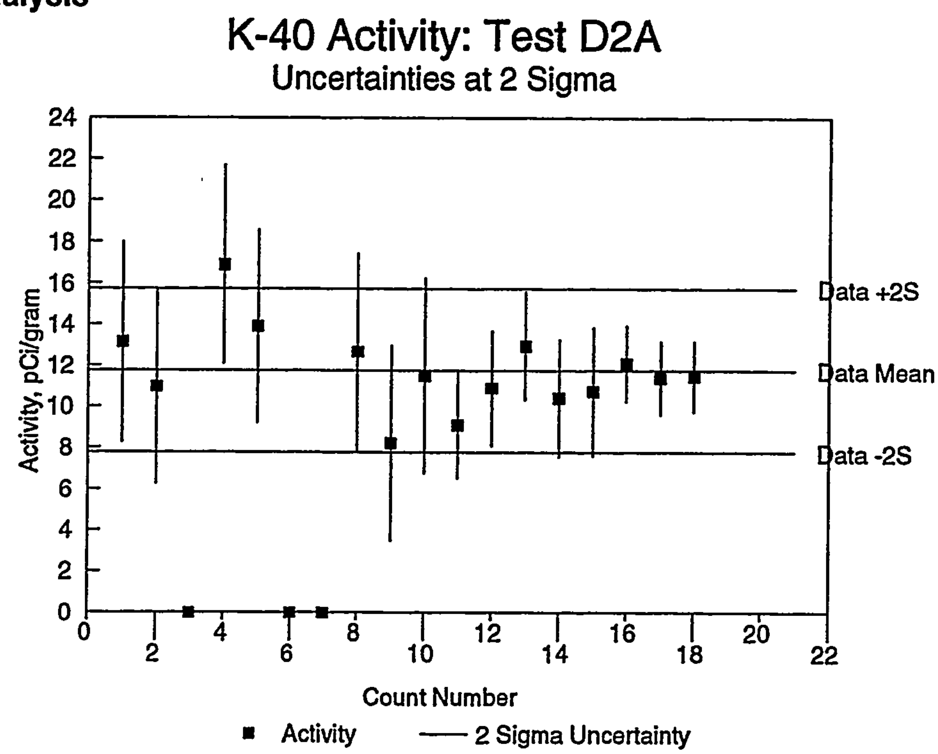
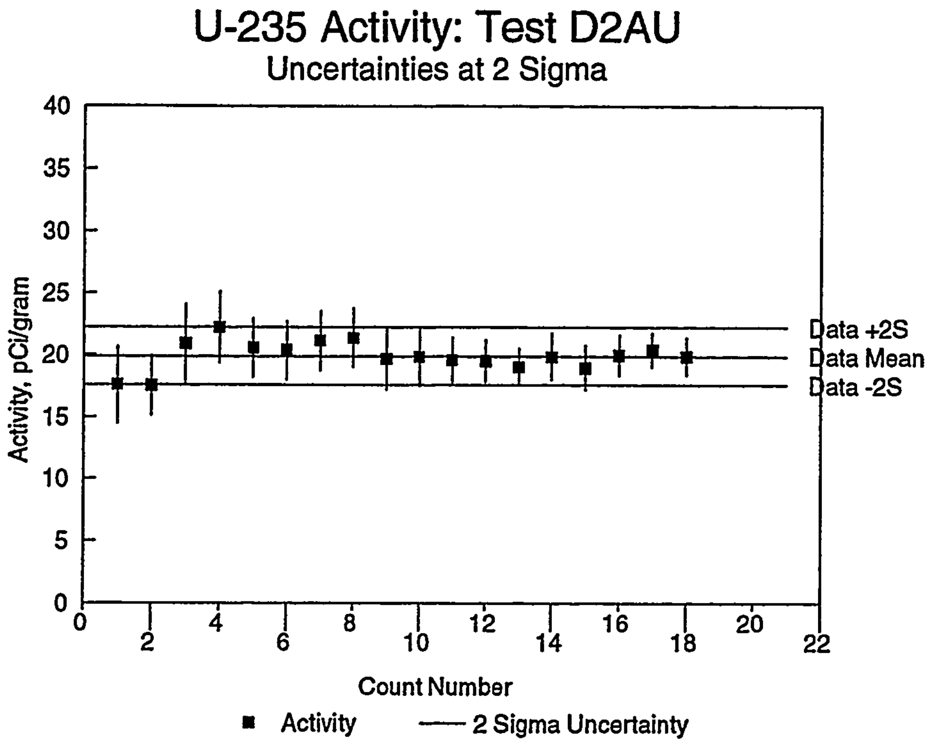


**Figure A-36 U-235 Activity: Test 2A (>1000 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

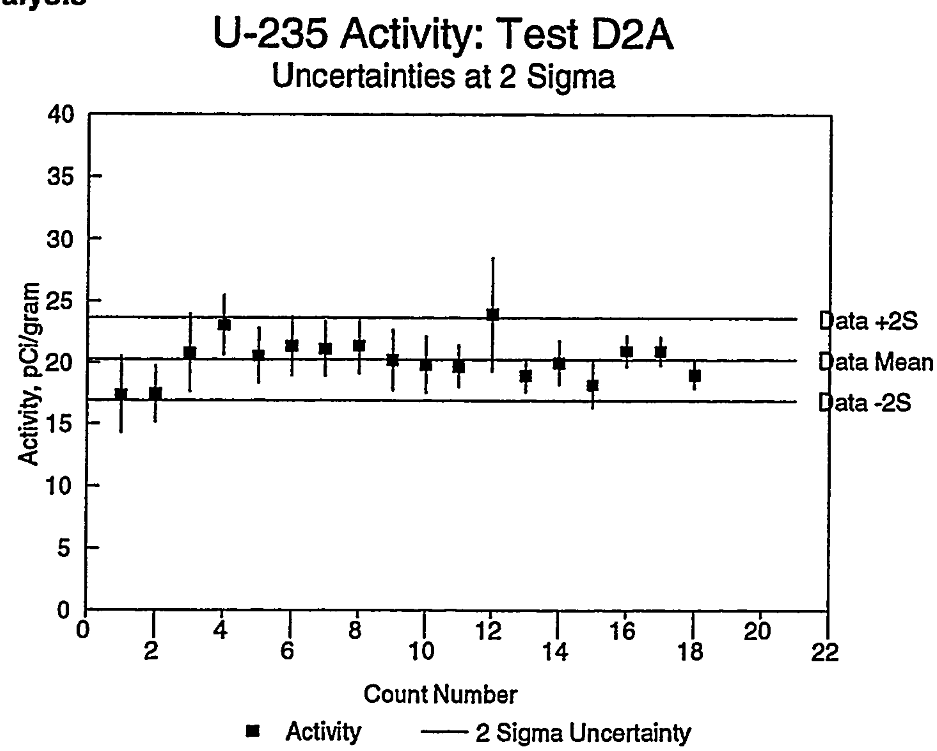
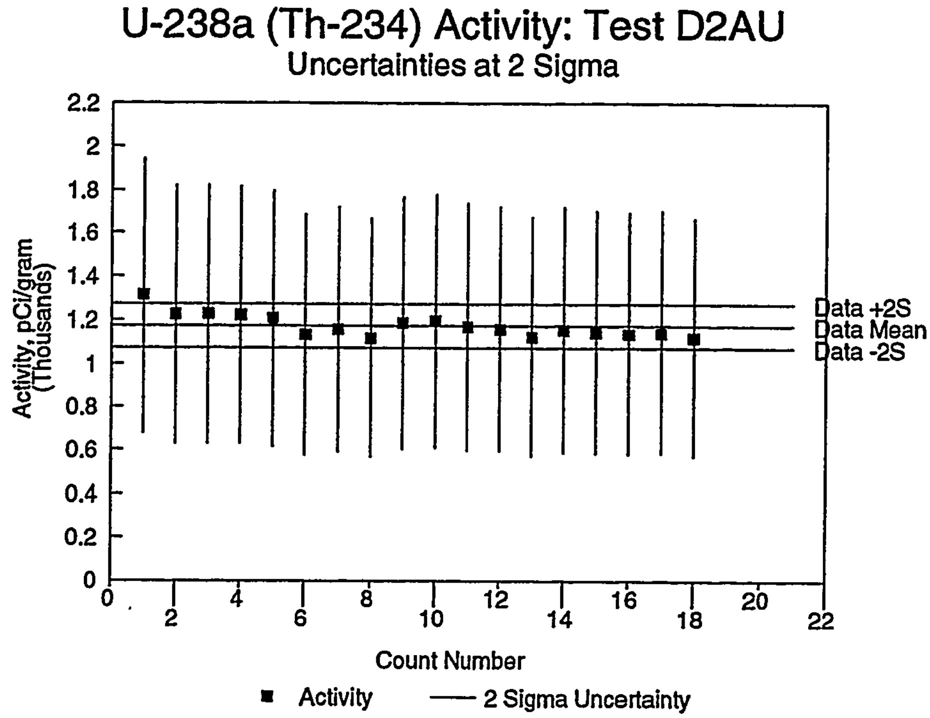


**Figure A-37 U-238a (Th-234) Activity: Test 2A (>1000 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

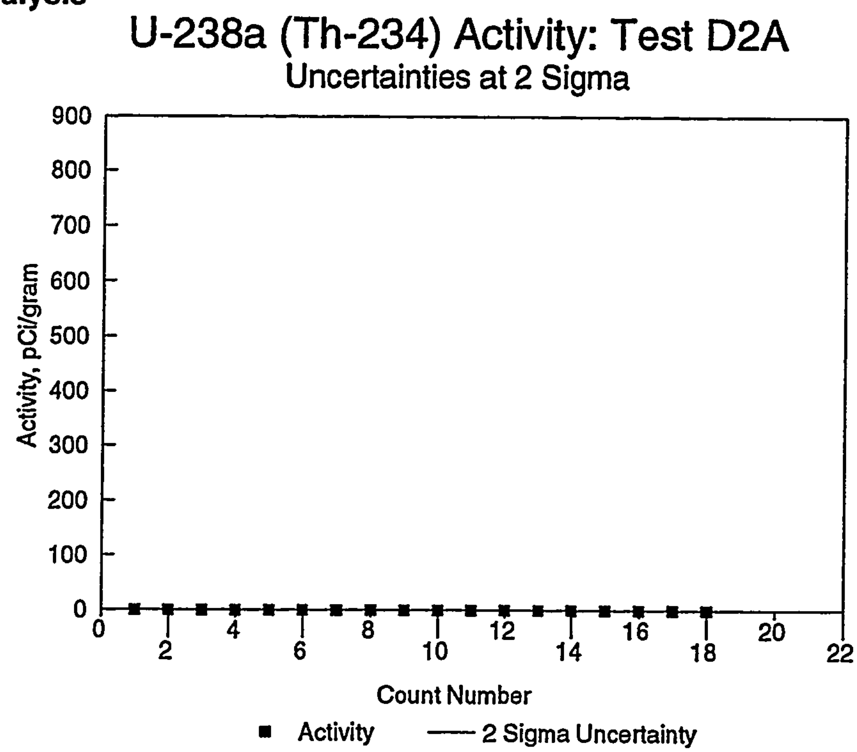
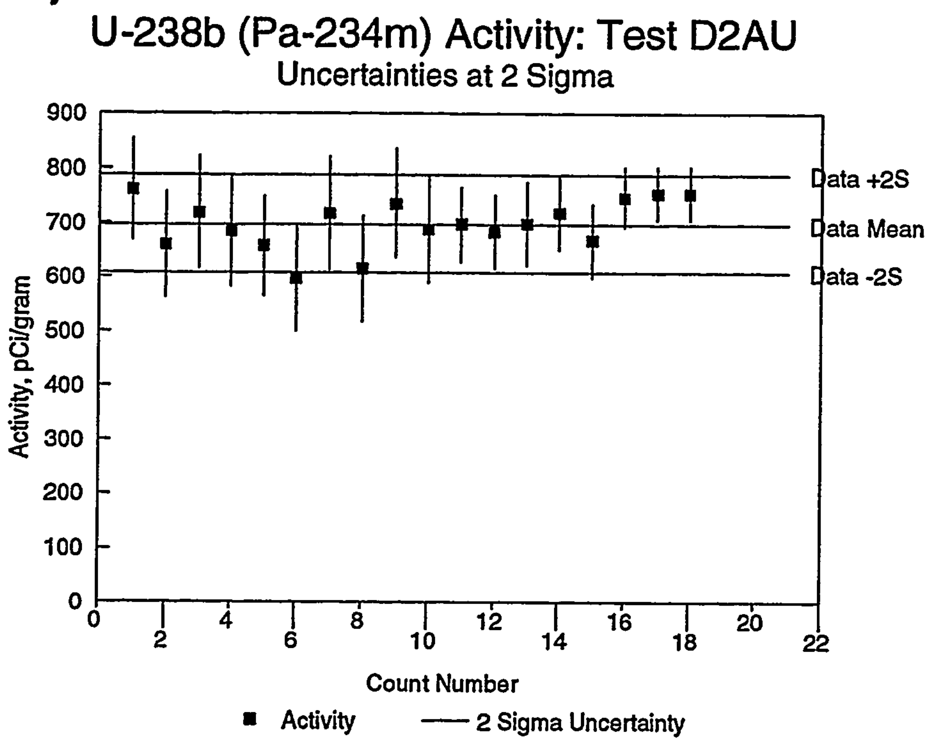
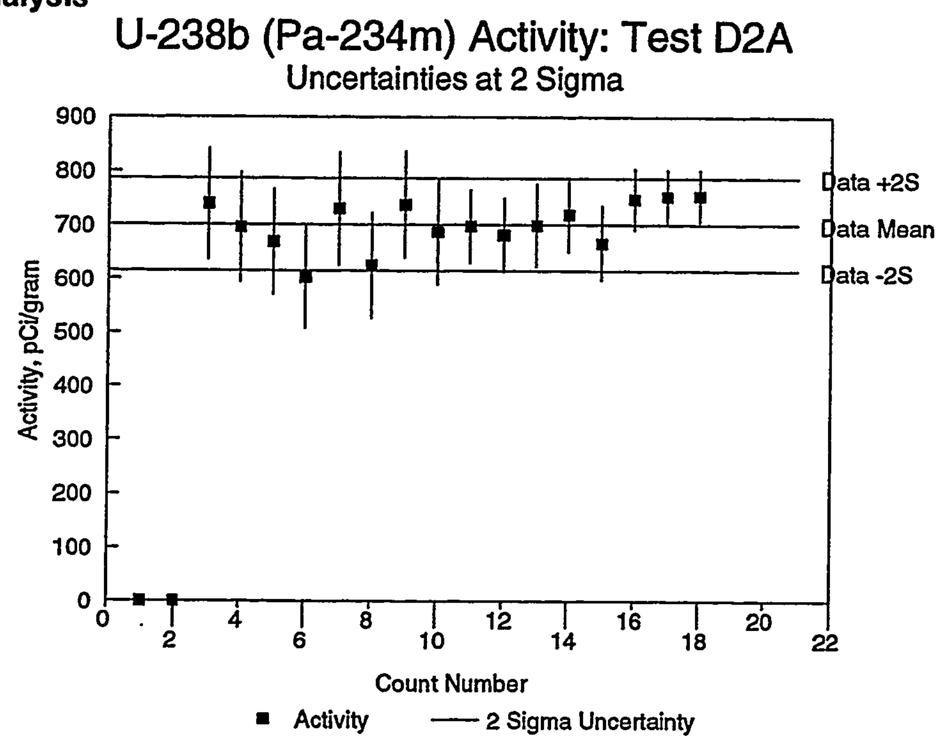


**Figure A-38 U-238b (Pa-234m) Activity: Test 2A (>1000 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**



# Figure A-39 Results Summary: Test 2B (>1000 pCi/g U)

## User ROI Analysis

Test D2BU: Nominal Activity = 1750 pCi/g Total U     Effic. from 01/30/95

| Count | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | (Pb-212) Th-232b | +- | (Bi-212) Th-232c | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D2AU | 11.39 | 1.95 | 19.9 | 1.15 | 1173.35 | 49.1 | 697.24 | 45.7 | 3.36 | 0.65 | | | | | 12.23 | 1.69 |
| C01 | 17.81 | 2.33 | 15.31 | 2.01 | 1403.34 | 335.8 | 707.75 | 44.77 | | | | | | | | |
| C02 | 12.80 | 2.32 | 14.50 | 1.82 | 1388.81 | 330.4 | 810.94 | 45.28 | | | | | | | | |
| C03 | 11.11 | 2.26 | 15.65 | 2.01 | 1366.82 | 326.3 | 747.31 | 45.12 | | | | | | | | |
| C04 | 12.64 | 2.28 | 16.34 | 1.86 | 1435.68 | 342.9 | 682.37 | 44.78 | | | | | | | | |
| C05 | 18.67 | 2.32 | 15.05 | 1.87 | 1381.42 | 327.5 | 629.27 | 45.24 | | | | | | | | |
| C06 | 16.11 | 2.32 | 15.44 | 1.74 | 1374.93 | 324.8 | 783.15 | 44.97 | | | | | | | | |
| C07 | 10.30 | 2.24 | 15.30 | 1.53 | 1380.92 | 326.3 | 717.33 | 44.77 | | | | | | | | |
| C08 | 11.91 | 2.27 | 16.84 | 1.72 | 1370.65 | 325.6 | 703.79 | 44.84 | | | | | | | | |
| C09 | 17.48 | 2.33 | 19.48 | 1.64 | 1328.35 | 314.4 | 664.09 | 45.45 | | | | | | | | |
| C10 | 13.34 | 2.31 | 18.54 | 1.41 | 1354.38 | 320.9 | 683.06 | 44.67 | | | | | | | | |
| C11 | 13.83 | 1.29 | 18.32 | 1.41 | 1358.72 | 322.3 | 734.74 | 24.58 | | | | | | | | |
| C12 | 15.69 | 1.29 | 18.22 | 1.27 | 1326.35 | 313.4 | 663.26 | 25.08 | | | | | | | | |
| C13 | 12.83 | 1.27 | 17.83 | 1.28 | 1332.01 | 316.6 | 696.68 | 25.62 | | | | | | | | |
| C14 | 14.18 | 1.27 | 16.38 | 1.38 | 1381.53 | 328.4 | 726.51 | 24.59 | | | | | | | | |
| C15 | 13.39 | 1.28 | 17.68 | 1.49 | 1333.60 | 317.5 | 729.45 | 25.22 | | | | | | | | |
| C16 | 15.08 | 0.76 | 16.84 | 1.49 | 1361.80 | 323.3 | 764.78 | 15.55 | | | | | | | | |
| C17 | 15.31 | 0.56 | 16.68 | 1.50 | 1355.26 | 321.6 | 796.57 | 11.81 | | | | | | | | |
| C18 | 15.36 | 0.48 | 16.95 | 1.45 | 1359.57 | 322.8 | 778.20 | 11.35 | | | | | | | | |
| C19 | 15.50 | 0.55 | 2.78 | 0.48 | 332.46 | 81.2 | 202.76 | 8.10 | | | | | | | | |
| C20 | 15.52 | 0.51 | 2.92 | 0.50 | 332.89 | 81.4 | 210.04 | 7.27 | | | | | | | | |
| Avg | 14.44 | 2.16 | 15.35 | 4.36 | 1262.97 | 311.2 | 671.60 | 161.8 | | | | | | | | |
| D2B/D2 | 1.27 | | 0.77 | | 1.08 | | 0.96 | | | | | | | | | |

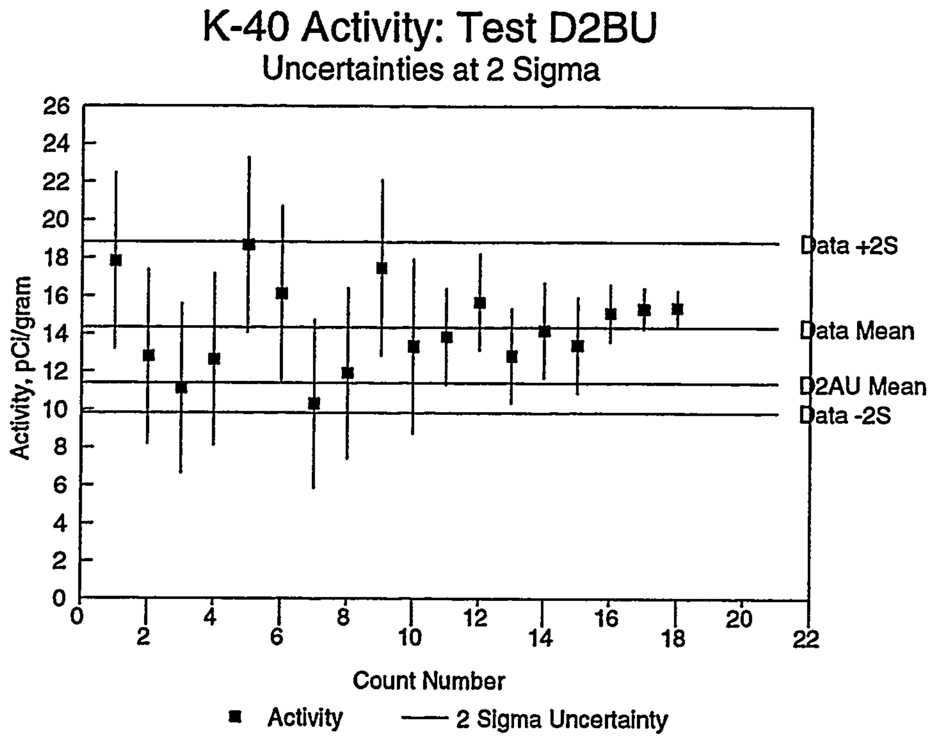
## Library Analysis

Test D2B: Nominal Activity = 1750 pCi/g Total U     Efficiencies from 01/30/95

| Count | K-40 | +- | U-235 | +- | U-238a (Th-234) | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | (Pb-212) Th-232b | +- | (Bi-212) Th-232c | +- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D2A | 11.75 | 1.99 | 20.27 | 1.66 | | | 700.26 | 43.2 | 3.36 | 0.65 | | | | | 12.23 | 1.69 |
| C01 | 17.44 | 2.33 | 13.77 | 2.28 | <154 | | 90.04 | <372 | | | | | | | 22.72 | 4.08 |
| C02 | 12.79 | 2.31 | 32.29 | 4.64 | <154 | | 515.09 | 63.07 | | | | | | | 14.51 | 5.07 |
| C03 | 10.57 | 2.31 | 14.64 | 2.48 | <153 | | 571.34 | 61.18 | | | | | | | | |
| C04 | 12.65 | 2.28 | 36.70 | 3.92 | <153 | | 695.20 | <375 | 3.36 | 0.65 | 1.09 | 0.28 | | | | |
| C05 | 18.37 | 2.32 | 30.21 | 4.39 | <153 | | 668.78 | <375 | | | | | | | | |
| C06 | 15.87 | 2.32 | 31.83 | 4.12 | <153 | | 758.19 | 48.31 | | | | | | | | |
| C07 | 10.03 | <19.8 | 13.81 | 1.59 | <153 | | 729.98 | <377 | | | | | | | | |
| C08 | 11.63 | 2.27 | 33.89 | 4.09 | <153 | | 697.43 | 44.83 | | | | | | | 1.57 | 0.53 |
| C09 | 17.41 | 2.33 | 34.52 | 3.71 | <152 | | 668.09 | 45.17 | | | | | | | | |
| C10 | 11.50 | <19.9 | 32.66 | 3.38 | <153 | | 687.50 | <377 | 1.95 | 0.40 | | | | | | |
| C11 | 13.89 | 1.28 | 19.70 | <4.2 | <84 | | 677.81 | 33.98 | | | 0.46 | 0.15 | | | | |
| C12 | 15.68 | 1.29 | 32.12 | 3.32 | <84 | | 617.24 | 33.80 | | | | | | | 0.91 | 0.29 |
| C13 | 12.97 | 1.27 | 16.92 | 1.21 | <83 | | 696.21 | 25.70 | | | 0.80 | 0.19 | 1.28 | 1.20 | 0.92 | 0.23 |
| C14 | 14.17 | 1.27 | 20.01 | <4.2 | <84 | | 677.85 | 33.87 | | | 0.70 | 0.19 | | | | |
| C15 | 13.39 | 1.28 | 34.70 | 3.56 | <83 | | 684.58 | 34.54 | | | | | | | 0.70 | 0.22 |
| C16 | 15.08 | 0.76 | 15.29 | 1.73 | <48 | | 775.09 | 17.87 | | | 0.39 | 0.11 | 0.85 | 0.65 | | |
| C17 | 15.30 | 0.56 | 15.81 | 1.91 | <34 | | 787.17 | 14.26 | | | 0.40 | 0.14 | | | 0.68 | 0.13 |
| C18 | 15.41 | 0.48 | 33.13 | 1.69 | <28 | | 751.43 | 14.26 | 0.51 | 0.10 | 0.34 | 0.12 | | | 0.85 | 0.07 |
| C19 | 15.49 | 0.55 | 2.70 | 0.40 | <20 | | 155.60 | 8.98 | | | 0.58 | 0.06 | | | | |
| C20 | 15.51 | 0.51 | 2.85 | 0.42 | <17 | | 156.71 | 7.70 | | | | | | | 0.68 | 0.07 |
| Avg | 14.26 | 2.25 | 23.38 | 10.71 | | | 603.07 | 207.0 | 1.94 | 1.16 | 0.60 | 0.24 | 1.07 | 0.22 | 4.84 | 7.62 |
| D2B/D2 | 1.21 | | 1.15 | | | | 0.86 | | | | | | | | 0.40 | |

**Figure A-40 K-40 Activity: Test 2B (>1000 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

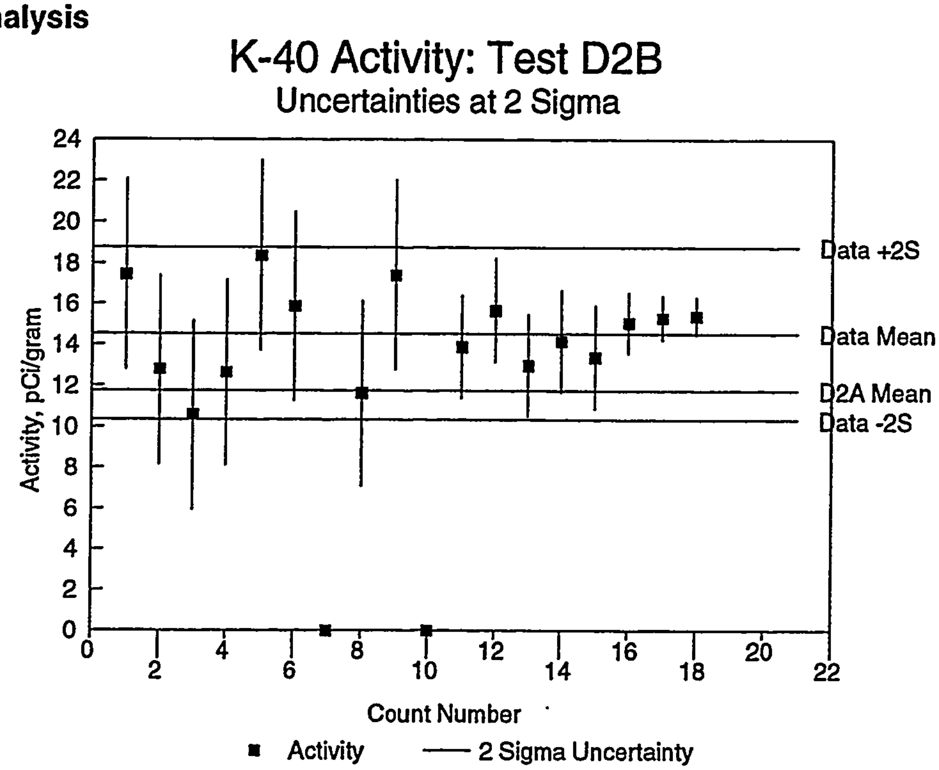
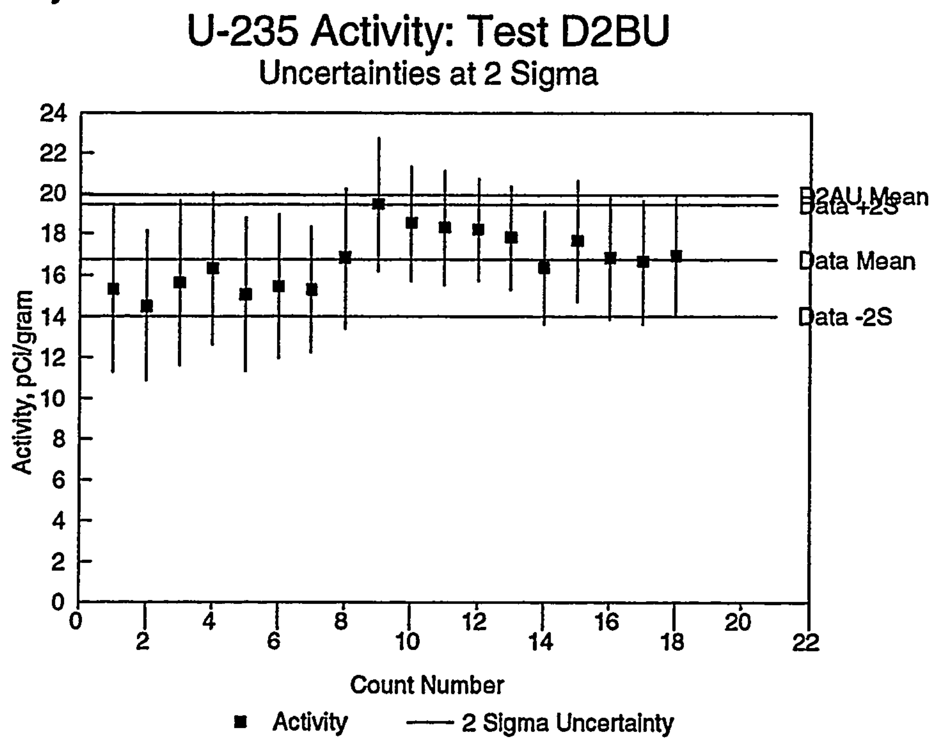


**Figure A-41 U-235 Activity: Test 2B (>1000 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

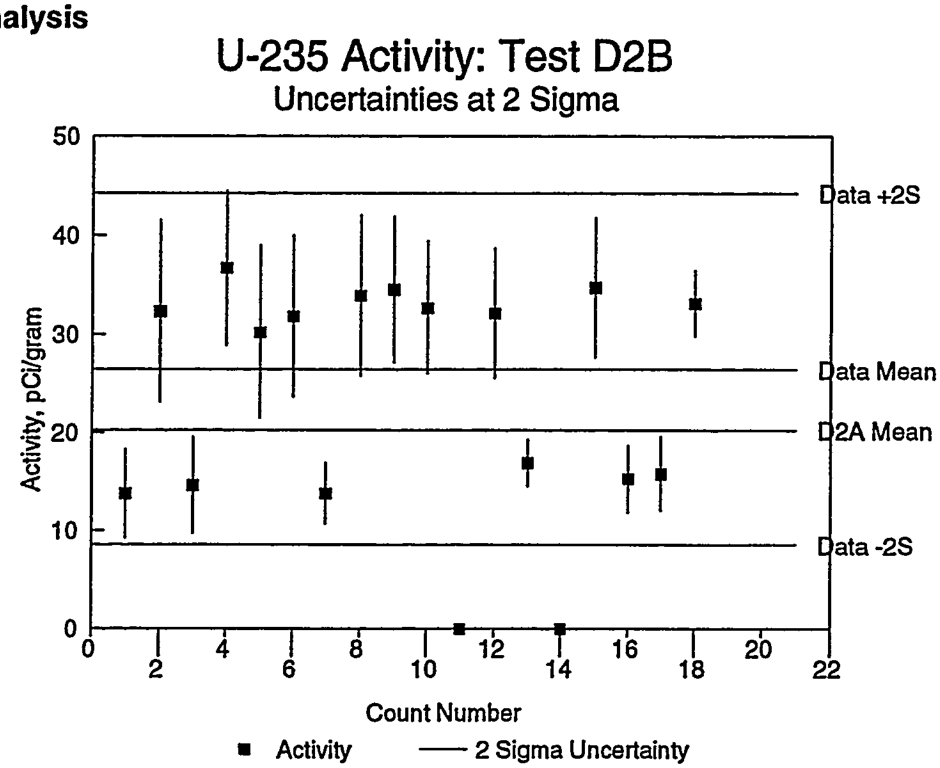
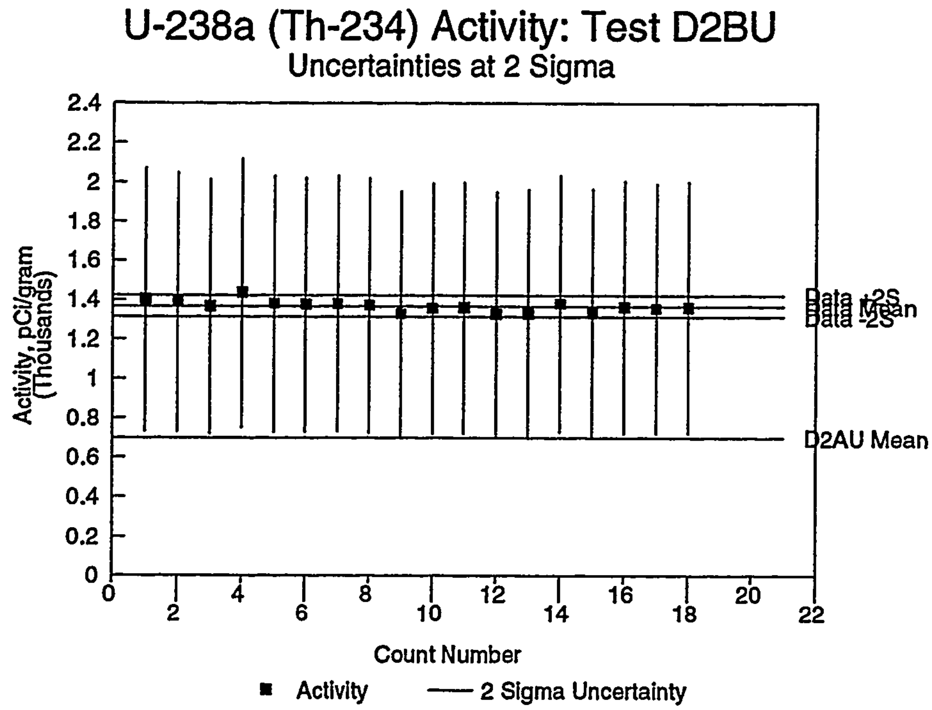


**Figure A-42 U-238a (Th-234) Activity: Test 2B (>1000 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**

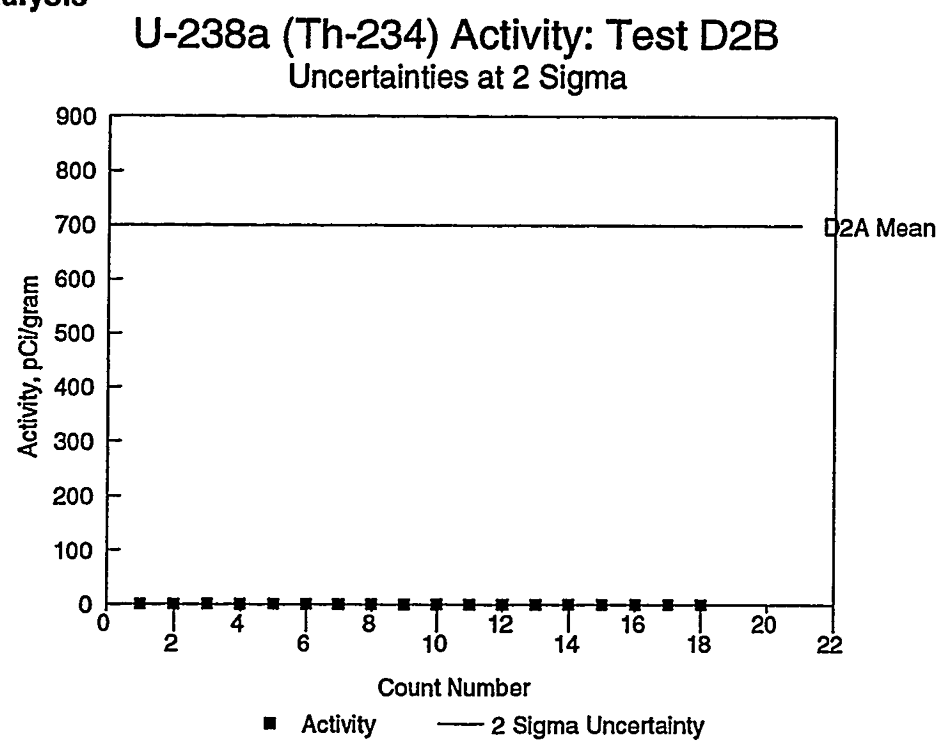
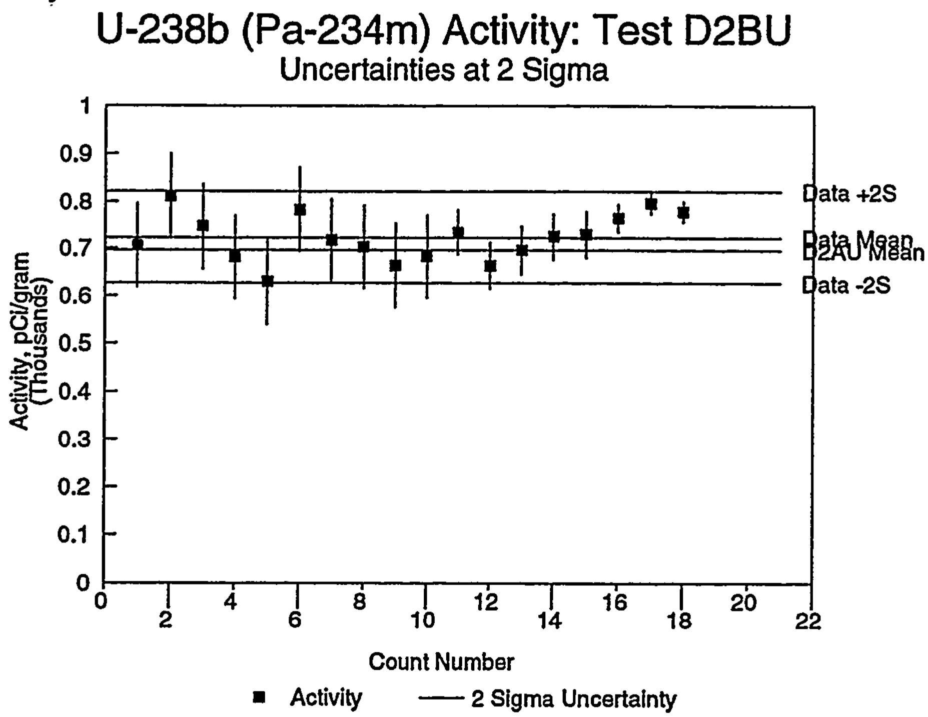
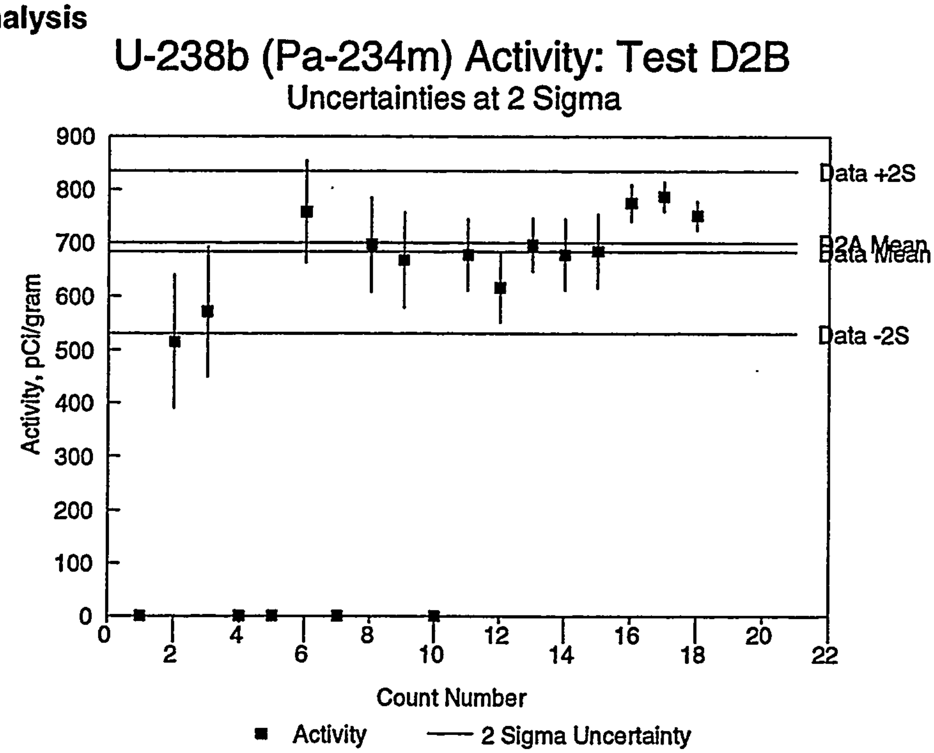


**Figure A-43 U-238b (Pa-234m) Activity: Test 2B (>1000 pCi/g total U)**

**User ROI Analysis**




**Library Analysis**



## Figure A-44 Results Summary: Test 5B (STP In situ)

### User ROI Analysis

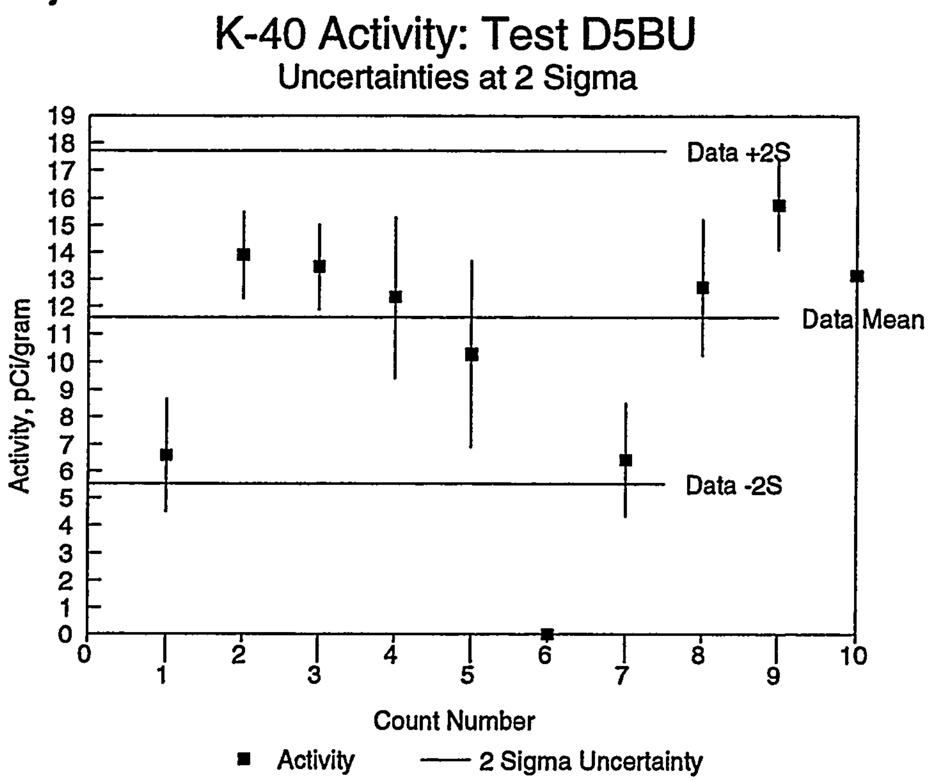
| Test D5BU: Nominal Activity = ???: STP Well 1441 | | | | | | | | | (Pb-214) | | (Bi-214) | | (Pb-212) | | (Bi-212) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Count | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232c | +- |
| C01 | 6.59 | 1.05 | <6.7 | | <242 | | <102 | | | | | | | | | |
| C02 | 13.90 | 0.81 | 4.59 | 1.88 | <236 | | <108 | | | | | | | | | |
| C03 | 13.46 | 0.79 | 8.71 | 2.42 | <238 | | <106 | | | | | | | | | |
| C04 | 12.35 | 1.47 | 10.14 | 3.13 | <415 | | <178 | | | | | | | | | |
| C05 | 10.27 | 1.70 | 6.86 | 2.63 | <417 | | <177 | | | | | | | | | |
| C06 | <8.5 | | 9.18 | 2.64 | <420 | | <176 | | | | | | | | | |
| C07 | 6.42 | 1.05 | <4.7 | | <168 | | <72 | | | | | | | | | |
| C08 | 12.71 | 1.25 | 7.67 | 3.21 | <406 | | <183 | | | | | | | | | |
| C10 | 15.74 | 0.82 | <4.7 | | <163 | | <80 | | | | | | | | | |
| C11 | 13.14 | 1.39 | <12 | | <399 | | <196 | | | | | | | | | |
| Avg | 11.62 | 3.05 | 7.86 | 1.80 | | | | | | | | | | | | |

### Library Analysis

| Test D5B: Nominal Activity = ???: STP Well 1441 | | | | | Efficiencies from 1/30/9 | | | | (Pb-214) | | (Bi-214) | | (Pb-212) | | (Bi-212) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Count | K-40 | +- | U-235 | +- | U-238a | +- | U-238b | +- | Ra-226a | +- | Ra-226b | +- | Th-232b | +- | Th-232c | +- |
| C01 | 2.75 | 0.76 | <6.7 | | <242 | | <102 | | | | | | | | | |
| C02 | 13.91 | 0.81 | <6.8 | | <236 | | <108 | | | | 3.17 | 0.24 | | | | |
| C03 | 13.40 | 0.80 | <6.8 | | <238 | | <106 | | | | 5.23 | 0.33 | 2.47 | 2.22 | | |
| C04 | 12.34 | 1.47 | <12 | | <415 | | <178 | | | | 6.69 | 0.64 | | | | |
| C05 | 9.59 | 1.72 | <12 | | <417 | | <177 | | 4.82 | 0.73 | 5.47 | 0.63 | 6.65 | 1.92 | 7.77 | 3.75 |
| C06 | <8.5 | | <12 | | <420 | | <176 | | | | 4.13 | 0.92 | | | 9.78 | 4.16 |
| C07 | 6.35 | 1.05 | <4.7 | | <168 | | <72 | | | | | | | | | |
| C08 | 12.72 | 1.25 | <12 | | <406 | | <183 | | | | 2.85 | 0.56 | | | | |
| C10 | 15.66 | 0.83 | <4.7 | | <163 | | <80 | | 1.25 | 0.59 | 1.35 | 0.19 | | | | |
| C11 | 12.86 | 1.41 | <12 | | <399 | | <196 | | | | | | | | | |
| Avg | 11.06 | 3.88 | | | | | | | 3.04 | 1.79 | 4.13 | 1.68 | 4.56 | 2.09 | 8.78 | 1.00 |

**Figure A-45 K-40 Activity: Test 5B (STP In situ)**

**User ROI Analysis**




**Library Analysis**

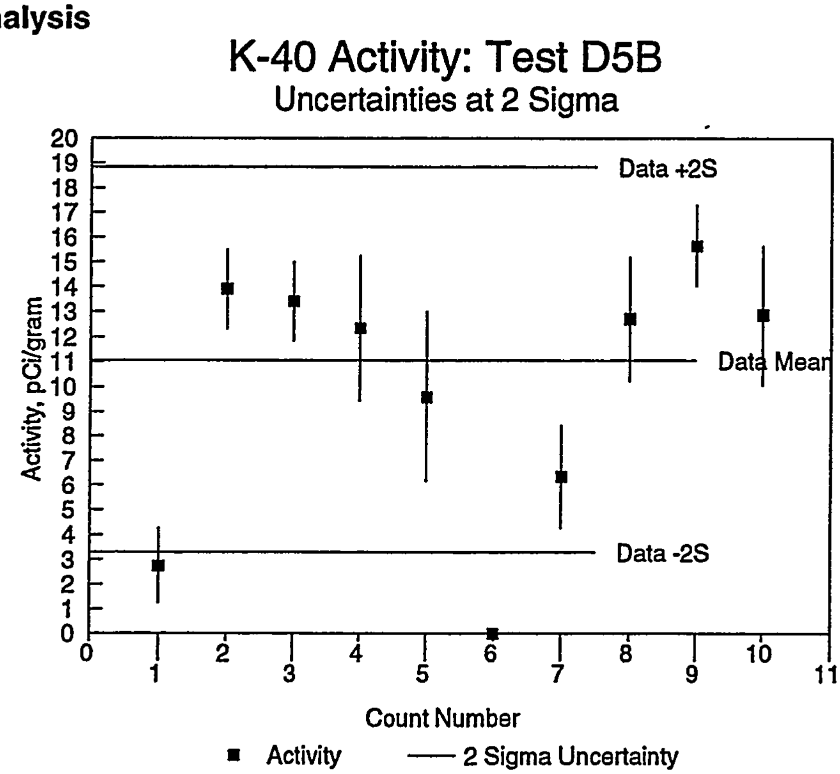
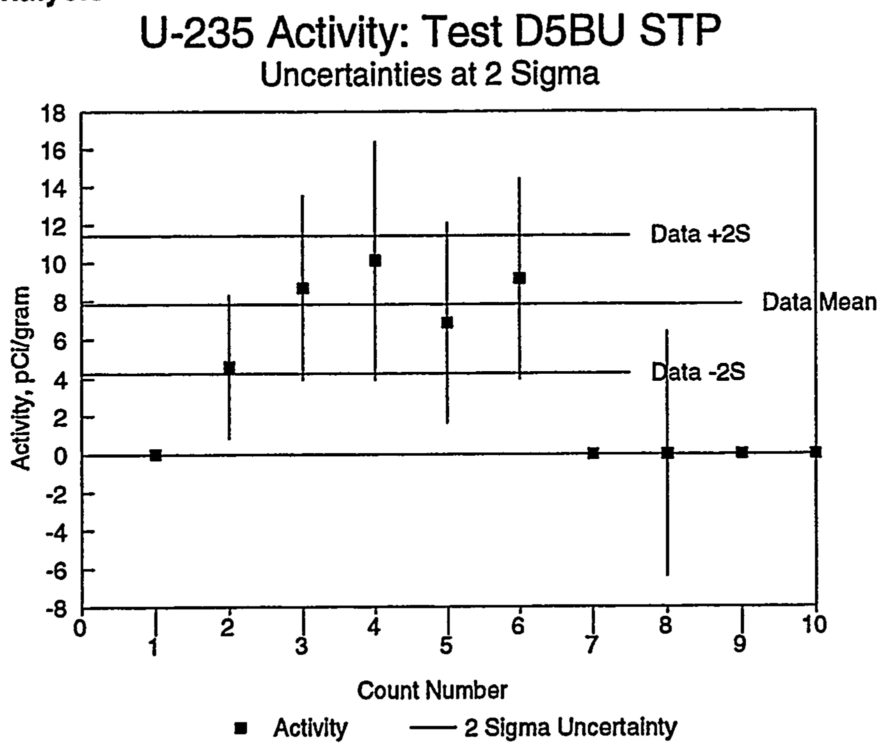
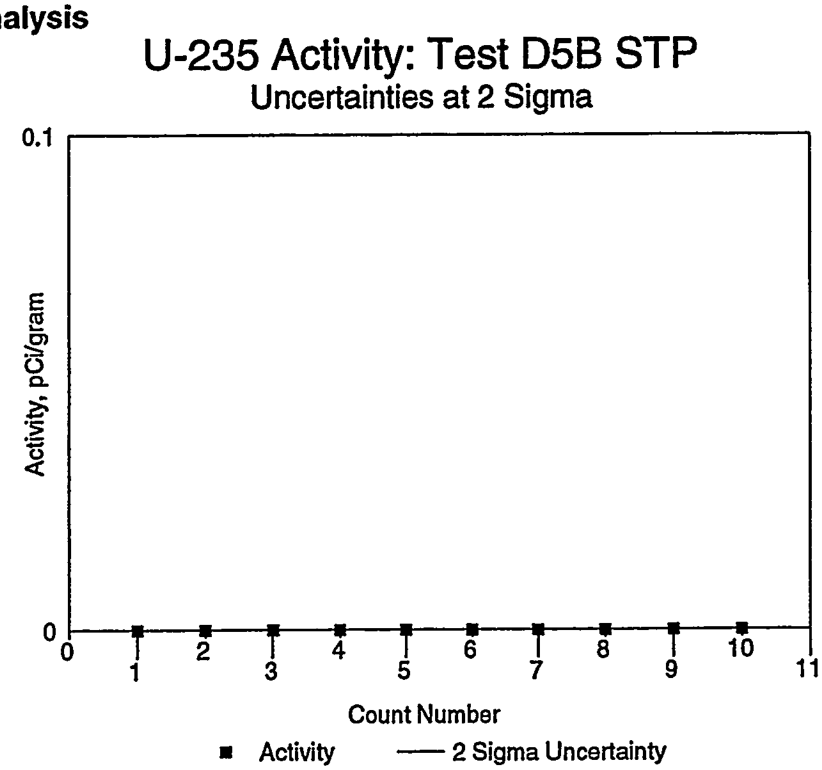


**Figure A-46 U-235 Activity: Test 5B (STP In situ)**

**User ROI Analysis**




**Library Analysis**



## Figure A-47 Results Summary: Test 5A (Southfield 11423)

### User ROI Analysis

| Run No. | Depth (ft) | K-40 | + - | U-235 | + - | U-235 Wtd Avg | U-238a | + - | U-238b | + - | U-238 Wtd Avg |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Test D5AU: Southfield Boring 11423. Probe in 1 meter Configurations | | | | | | | | | | | |
| D5A-C09 | 2.25 | 8.84 | 0.37 | | | | | | | | |
| D5A-C10 | 2.25 | 7.32 | 0.55 | | | | | | | | |
| D5A-C11 | 2.25 | 7.83 | 0.58 | | | | | | | | |
| D5A-C12 | 2.25 | 8.44 | 0.6 | | | | | | | | |
| Test D5AU: Southfield Boring 11423. Probe in 3 meter Configuration | | | | | | | | | | | |
| D5A-C16 | 9 | 5.96 | 0.64 | 1.97 | 0.3 | 1.970 | 117.1 | 32 | | | 117.100 |
| D5A-C17 | 9 | 5.59 | 0.51 | 1.92 | 0.26 | 1.920 | 116.35 | 31.7 | 32.6 | 7.15 | 48.017 |
| D5A-C18 | 9 | 4.94 | 0.47 | 2.19 | 0.24 | 2.190 | 109.98 | 30.2 | 34.45 | 5.85 | 46.696 |
| D5A-C19 | 9 | 7.32 | 0.66 | 5.6 | 0.41 | 5.600 | 445.56 | 119 | | | 445.560 |
| D5A-C20 | 9 | 6.98 | 0.47 | 5.59 | 0.37 | 5.590 | 449.55 | 119 | 36.25 | 7.51 | 60.800 |
| D5A-C21 | 9 | 7.07 | 0.38 | 5.71 | 0.37 | 5.710 | 445.74 | 119 | 34.93 | 6.14 | 55.140 |
| D5A-C22 | 5.5 | 4.97 | 0.64 | 4.33 | 0.39 | 4.330 | 308.31 | 86.6 | | | 308.310 |
| D5A-C23 | 5.5 | 4.78 | 0.44 | 4.23 | 0.37 | 4.230 | 308.64 | 86.7 | | | 308.640 |
| D5A-C24 | 5.5 | 4.71 | 0.36 | 4.16 | 0.38 | 4.160 | 317.58 | 88.2 | | | 317.580 |
| D5A-C25 | 5.5 | 5.6 | 0.63 | | | | 297.06 | 84.2 | | | 297.060 |
| D5A-C26 | 5.5 | 5.13 | 0.45 | | | | 295.56 | 84.6 | | | 295.560 |
| D5A-C27 | 5.5 | 5.32 | 0.36 | | | | 299.24 | 85.1 | | | 299.240 |

### Library Analysis

| Run No. | Depth (ft) | K-40 | + - | U-235 | + - | U-235 Wtd Avg | U-238a | + - | U-238b | + - | U-238 Wtd Avg |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Test D5A: Southfield Boring 11423. Probe in 1 meter Configuration | | | | | | | | | | | |
| D5A-C09 | 2.25 | 8.86 | 0.36 | | | | | | | | |
| D5A-C10 | 2.25 | 7.32 | 0.55 | | | | | | | | |
| D5A-C11 | 2.25 | 7.59 | 0.59 | | | | | | | | |
| D5A-C12 | 2.25 | 8.45 | 0.6 | | | | | | | | |
| Test D5A: Southfield Boring 11423. Probe in 3 meter Configuration | | | | | | | | | | | |
| D5A-C16 | 9 | | | | | | | | | | |
| D5A-C17 | 9 | | | | | | | | | | |
| D5A-C18 | 9 | | | | | | | | | | |
| D5A-C19 | 9 | | | 8.35 | 0.58 | 10.067 | | | | | |
| D5A-C20 | 9 | | | | | | | | | | |
| D5A-C21 | 9 | | | 9.05 | 0.66 | 9.050 | | | | | |
| D5A-C22 | 5.5 | 4.92 | 0.64 | | | | | | | | |
| D5A-C23 | 5.5 | 4.72 | 0.44 | | | | | | | | |
| D5A-C24 | 5.5 | 4.64 | 0.36 | | | | | | | | |
| D5A-C25 | 5.5 | 5.58 | 0.63 | 6.58 | 0.97 | 6.580 | | | | | |
| D5A-C26 | 5.5 | 5.02 | 0.45 | | | | | | | | |
| D5A-C27 | 5.5 | 5.23 | 0.37 | | | | | | | | |

# Appendix B

Data Quality Tests

(Phase III)

## Characterization Tests

### 1.0 Purpose

The purposes of the Characterization Tests are to verify that system components meet the required performance specifications, to obtain the initial system setup parameters, to individually calibrate and characterize the performance of the three individual probes and to obtain supporting information for subsequent tests. These tests will include measurement of background count rate and measurement of resolution (at 662 keV) for each of the probes.

### 2.0 Approach

To obtain data on the performance of the individual probes and identify the contribution of probe construction materials to the background, these tests will be performed in a shield to reduce background from terrestrial and cosmogenic background.

### 3.0 Test Setup

The Characterization Tests will be performed with the detectors inside a lead shield with a minimum of two inches thickness. A copper or stainless steel shield liner may also be used to minimize the contribution of secondary lead X-rays. The tests will be performed with the probe axis horizontal to minimize the absorption path in the scintillator and the projected cross-section of the PMT faceplate for cosmogenic radiation.

The tests will be performed in the B&W ARC Rad Lab, under laboratory conditions. Radioactive source material to be used for these tests includes two sealed point sources: a mixed nuclide gamma reference standard with gamma lines covering the range of 60 to 1836 keV (for calibration) and a Cs-137 source (for resolution measurement).

Analyses will be performed using the gamma spectroscopy software to be used in the Phase III demonstration tests. Peaks will be located and identified using a library peak locate, with an unknown search.

### 4.0 Test Preparation

Prior to the start of the tests, each probe and MCA will be powered up for a period of 100 to 200 hours to burn in the PMTs to obtain representative background count rates. This burn-in will be performed either by the probe supplier or in the B&W ARC Rad Lab. The MCAs will initially be connected to the data concentrator with the RF modems and the data concentrator connected to the host with a null modem.

The high voltage power supplies for each channel will be set up for the normal operating voltage for the PMTs, approximately 900 VDC. The amplifier gains will be set-up to produce an energy range of about 50 to 2000 keV. The lower level discriminator (LLD) will be set at or below the energy for 1/10 maximum amplitude for the Am-241 peak at 59.5 keV. The upper level discriminator (ULD) will be set at or above the energy for 1/10 maximum amplitude for the Y-88 peak at 1836 keV. The MCAs will be configured for 1024 channels.

## 5.0 Test Matrix

The following tests will be performed for each of the three probe/MCA channels, with the probe in the lead shield.

- o Count the calibration source; perform energy and efficiency calibrations for the probe (side-on, centered on length). 1 count/probe, 3 counts total; 1 probe, 5 additional counts.
- o Count background for 1-1/2 to 2 hours. 1 Count/probe, 3 counts total.
- o Count the Cs-137 source for a minimum of 40,000 net counts to determine resolution at 662 keV. 1 count/probe, 3 counts total.
- o Install a null modem in one probe channel and repeat the background and calibration counts. 1 probe, 1 count each type.

## 6.0 Test Results

The results of these tests are expected to show that the three probes have background count rates and resolutions which are acceptable for the Phase III tests, that the variations from probe to probe are minor and negligible for subsequent testing, and that the results obtained with the RF modem are the same as the results with a null modem. Results to be reported are:

- o Background count rate for each probe (3 total)
- o Resolution for each probe (3 total)
- o Analysis results for cal source (9 total)
    - - Nuclide identification (9)
    - - Precision (9)
    - - Bias (4)
- o Background and resolution with null modem (1 total)

MDA Tests

## 1.0 Purpose

MDA (Minimum Detectable Activity), based on Detection Limit, is a statistically determined measure of the minimum activity which can be reliably quantified in a particular measurement situation. The purpose of the MDA Tests is to determine the MDA for each of the DOE identified isotopes of interest under representative measurement conditions, using the Phase III LPRMS (Long-Term Post-Closure Radiation Monitoring System).

## 2.0 Approach

The MDA for a particular isotope in a given measurement situation is primarily affected by the presence of interference, the continuum counts and the count rate for the activity of interest. Other significant parameters in calculating the MDA value are the degree of statistical confidence required, the yield of the isotope, count time and detector efficiency. Since all of the isotopes in an analyte contribute to the Compton continuum, it is unique for each measurement, and MDAs are generally calculated for each measurement.

To obtain an estimate of the detection limits for the system, the MDAs for each isotope will be determined for measurements obtained from a "blank", a sample which duplicates the geometric and attenuation characteristics and interferences expected in the actual measurements, but with no activity from the isotopes of interest. For in-situ soil measurements, K-40 (10.67% yield at 1.46 MeV) is the only significant potential interferant. The MDAs will be calculated using the gamma analysis software, which uses the method of Currie for this calculation. A separate MDA will be calculated for each analytically significant gamma line; the MDA for each nuclide of interest will be the lowest MDA for any of its gamma lines.

## 3.0 Test Article

The MDA Tests will be performed in a blank. This blank will consist of a 55 or 85 gallon drum of non-contaminated soil (obtained locally). A section of 2" schedule 80 PVC typical of that to be used in the Phase III field tests will be positioned in the center of the drum, extending from the bottom of the drum out through the lid. The soil will be used at natural moisture (air dried), and will be compacted to produce a mean density in the range of 1.5 to 2.3 g/cc. The actual mean density of the blank will be calculated from the soil volume (determined from the drum dimensions and the fill height) and its net weight. It is anticipated that this soil will contain background K-40 at an activity between 5 and 15 pCi/g and Th-232 and Ra-226 at activities of 1 pCi/g or less, plus incidental quantities of uranium isotopes. If the soil has K-40 activity of less than 5 pCi/g, as measured with the LPRMS probe using the efficiency calibration and analysis quantities developed in Phase II, the soil will be spiked with potassium chloride to increase the K-40 activity to between 5 and 15 pCi/g. If the K-40 activity is greater than 15 pCi/g, the soil will be blended with sufficient clean sand (or other inert filler) to decrease the K-40 activity to between 5 and 15 pCi/g. The activities of other background isotopes will not be adjusted.

## 4.0 Test Preparation

These tests will be performed after the completion of the characterization tests. After the blank is fabricated, it will be moved to the ARC Rad Lab and allowed to come to thermal equilibrium. Prior to testing, the energy calibration of each probe will be checked by counting the calibration source. The calculated efficiency values which will be used for in-situ measurements in the demonstration testing will be used in determination of the MDA values as well. The PMT high voltage and amplifier gains will be set up as in the characterization tests. The MCA will be set up for 1024 channels, with an energy range of about 50 to 2000 MeV; LLD and ULD will be set at 0.1 max of the Am-241 (59.5 keV) and Y-88 (1836 keV) peaks as described in the characterization tests. The tests will be performed with the blank and probe at thermal equilibrium.

## 5.0 Test Matrix

The following tests will be performed to characterize the MDA for the LPRMS. The tests will be performed after the probe has been warmed up for 20 to 30 minutes.

- o After the probe has been installed in the blank and warmed up, perform a 1-1/2 to 2 hour count of the blank. 3 probes, 1 count each.
- o For the last probe tested, turn off the HV for a minimum of 1/2 hour. Turn on the HV and allow the probe to warm up for 20 minutes. Count the blank for 1-1/2 to 2 hours. Repeat this sequence for 5 counts. 1 probe, 5 counts.

## 6.0 Test Results

These tests will quantify the expected MDA for the LPRMS for each of the DOE radioisotopes of concern. The results are expected to show that there are only minor variations in the MDA from count to count and from probe to probe. The results to be reported will be a list of the system MDA by isotope and comparisons from probe to probe and count to count.

## Precision and Bias Tests

### 1.0 Purpose

Precision is a statistically determined measure of the how closely the activity of a nuclide can be determined in a particular measurement situation; it is synonymous with measurement uncertainty. Precision is primarily a function of detector configuration and count statistics, including background count rate, interferences and system noise. Bias is a measure of how closely the analytically determined mean activity value approximates the true activity value for the analyte. Bias is influenced by count statistics, but is primarily influenced by analysis parameters, efficiency calibration and error in the analysis quantity.

For the LPRMS, good characterization of precision is critical; in a monitoring application, precision is the parameter which indicates how small a change in activity can be reliably detected and quantified. Bias is somewhat important in this application, but is not as critical as precision provided that it is consistent with time. In the actual in-situ measurement environment, it is not likely that soil density, soil moisture content, soil attenuation characteristics or spatial distribution of contaminants will be accurately known when the probes are installed. Uncertainty in these parameters contributes directly to uncertainty in the determination of absolute activities; thus, the actual system bias will include a contribution from error or uncertainty in these parameters. Provided that the bias inherent in the system remains constant, variability in environmental parameters such as soil moisture or density can be compensated by scaling to changes in the soil K-40 peak; this significantly reduces the contribution of this variability to measurement precision.

The purpose of the Precision and Bias Tests is to determine the precision and bias for activity measurements of uranium isotopes made with the LPRMS under representative measurement conditions, and to quantify the count-to-count stability of bias with time.

### 2.0 Approach

The generally accepted approach for characterizing the precision and bias of a radiological measurement system is to make measurements using a phantom which simulates the geometry, absorption characteristics, background nuclides and analyte nuclide activities expected in measurements of unknowns. The measurements are made using the same protocols to be used for making measurements of unknowns. Bias and precision are typically determined and stated at activities which are a minimum of ten times the MDA for the analyte isotopes. The adequacy (representativeness) of the phantom simulation and accurate knowledge of the isotope activities are central to obtaining good results with this approach; the simulation adequacy affects both bias and precision, the isotope activity mainly affects the bias measurement. Typically, the measurements are made using NIST Standard Reference Materials (SRMs) or standards directly compared to SRMs. Precision and bias can be calculated for a single measurement or for a series of measurements; for a system characterization the general practice is to base the calculations on the average of a minimum of 5 measurements.

Because of the large integration volume of the probe (about 100,000+ cc), obtaining either a representative calibration source or phantom is problematic. During the Phase II demonstration testing, a small point source was used to establish the energy calibration and calculated values were used for the efficiency calibration and analysis quantities. Based on the results from the drum tests in Phase II, this approach worked reasonably well, and this approach will be used for the energy and efficiency calibrations for the Phase III tests. For characterizing the precision and bias performance of the system, test articles are needed which are representative of the actual measurement conditions. A small point source close to the probe can provide representative count rates, but does not test the adequacy of the calculated efficiency calibration or the analysis quantity without further assumptions and calculations.

To obtain estimates of the precision and bias of the system, a series of counts will be performed in 55 gallon drums of soil contaminated with uranium isotopes with a range of activity levels. The in-situ measurement protocols will be used for these counts. The counts will be analyzed to determine uranium activity levels for each isotope, using the system analysis software. For each count, the MDA by isotope, and the measurement uncertainty of the activity determinations will be calculated using the spectroscopy analysis software. Bias will be calculated for each count by comparing the activity from the spectroscopic analysis to activity levels from previous characterizations of the drummed soils.

## 3.0 Test Articles

The Precision and Bias Tests will be performed in four 55 gallon drums of uranium contaminated soil, plus the blank from the MDA testing. The drums of contaminated soil were fabricated during Phase II of this program, using characterized soils from the Uranium in Soils Integrated Demonstration (USID). Sampling and analysis were performed on the soils from which the drums were filled as part of the USID, but were not performed specifically on the drummed soils when the drum samples were fabricated. Test results from the Phase II LPRMS and Survey Probe testing indicated that the soil activities in the drums were reasonably close to those determined in the USID analyses.

The USID soil analyses are shown in Table 1, below. The first three drums will be used as they were fabricated, to provide activities approximately 3, 5 and 10 times the estimated MDAs for U-235 and U-238 isotopes. The soil in the fourth drum will be cut with clean sand (by FERMCO personnel) to increase the volume and reduce the activity. After it is homogenized, six samples will be taken from this soil by FERMCO for laboratory analysis of isotopic uranium content, using the same analysis protocols and ASL levels used for the previously performed USID analyses. The soil will then be placed in the test drum. The activity of this soil after the cut is estimated to be about 1000 pCi/g, or about 30 times the MDA.

**Table 1 Test Article Uranium Activities**

| Soil ID (Ph II test) | Total U | MDA Multiple | ID |
|---|---|---|---|
| P011-C389 (1f) | 95 pCi/g | 3 | A |
| P011-D389 (1g) | 162 pCi/g | 5 | B |
| P011-E388 (1h) | 311 pCi/g | 10 | C |
| P011-0380 (2a) | ~1600 pCi/g | - | |
| P011-0380 (cut) | ~1000 pCi/g | 30 | D |

A section of 2" schedule 80 PVC typical of that to be used in the Phase III field tests will be positioned in the center of each drum, extending from the bottom of the drum out through the lid. The soils will be used at natural moisture (air dried), compacted to a mean density in the range of 1.5 to 2.3 g/cc. The actual mean densities of the first three drums are available from the Phase II testing. The density of the fourth drum will be calculated from the soil volume (determined from the drum dimensions and fill height) and its net weight after the test drum is refilled following the cut.

The first three drums have K-40 activity between 11 and 13 pCi/g, as measured with the LPRMS in the Phase II demonstration test. It is anticipated that the soil for the fourth drum will contain background K-40 at an activity of about 9-10 pCi/g after the sand cut, assuming the sand contains no K-40. Since the original soil K-40 activity was about 14.5 pCi/g, the activity following the cut cannot exceed 15 pCi/g. The K-40 activity will thus not need to be adjusted to fall into the desired range of 5 to 15 pCi/g. The activities of other background isotopes (Ra-226 and Th-232) will not be adjusted in any of the drums.

## 4.0 Test Preparation

The three lowest activity level drums will be used as fabricated for the Phase II demonstration tests. The soil in the fourth drum will be cut with clean sand to increase the volume and reduce the activity. After it is homogenized, six samples will be taken from this soil for laboratory analysis of uranium content. The soil will then be placed in the test drum, and compacted to a density of 1.5 to 2.3 g/cc; this drum should be filled to within 6 inches of the top of the drum and the fill height measured to within 1/4 inch. The gross weights of all drums will be measured prior to overpacking; this will provide assurance that excessive moisture has not entered the three soil drums from the South field, and provide data needed for determining mean density for the fourth drum. The drums will then be placed in steel 85 gallon overpack drums for shipping to the B&W Alliance Research Center, with permanent markings on the outside clearly indicating the soil contained in each drum.

After receipt inspection of the drums by the Radiological Safety Officer at the ARC, the drums will be moved to the ARC Rad Lab in Building A. The drums will be positioned approximately 1 foot apart (minimum). The lid bands for the overpack drums will then be removed. The drums will be allowed to stabilize for several days to come to thermal equilibrium with the lab environment.

The Precision and Bias Tests will be performed after the Characterization and MDA Tests have been completed. The LPRMS gamma spectrometer system will be set up with 3 MCAs, the data concentrator computer and the host computer. The RF modems or a switched null modem will be used between each MCA and the data concentrator, and a null modem (RS-232C cable) between the data concentrator and the host. For these tests, the solar power supplies and RF transceivers will not be used. The measurement protocols to be used will be the same as those to be used for the field tests; this includes number of MCA channels, PMT voltages, amplifier gains, discriminator settings (LLD and ULD), gain stabilization and count times. These parameters will not be adjusted for the duration of the testing. Prior to the start of the Precision and Bias Tests, the PMTs in the probes to be tested will have been un-powered for a minimum of 1 hour.

## 5.0 Test Matrix

Each of the three probes will be tested in each of the five test articles (4 uranium soil drums plus 1 blank). The three probes will be installed in the five test articles as indicated in Table 2, below, and allowed to come to thermal equilibrium for one hour. The probes will then be powered up for the warm-up period (20 to 30 minutes), and the count cycles shown in Table 3 will begin. After the completion of 5 off/warm-up/count cycles, the probes will be moved to the next configuration and the count process repeated. After five counts have been performed for each probe in each of the five configurations, the probes will be returned to configuration 1 and a second counting iteration will be performed in each of the five configurations.

**Table 2 System Test Configurations**
(Five counts/probe for each configuration, two iterations)

| Drum | Config 1 | Config 2 | Config 3 | Config 4 | Config 5 |
|---|---|---|---|---|---|
| A | Probe 1 | Probe 2 | Probe 3 | ------ | ------ |
| B | Probe 2 | Probe 3 | ------ | ------ | Probe 1 |
| C | Probe 3 | ------ | ------ | Probe 1 | Probe 2 |
| D | ------ | ------ | Probe 1 | Probe 2 | Probe 3 |
| E | ------ | Probe 1 | Probe 2 | Probe 3 | ------ |

**Table 3 Count Cycle for Each Configuration**

| Count | Off | Warm-up | Count |
|---|---|---|---|
| 1 | 1 hr | 20 min | 2 hr |
| 2 | 1 hr | 20 min | 2 hr |
| 3 | 1 hr | 20 min | 2 hr |
| 4 | 1 hr | 20 min | 2 hr |
| 5 | 1 hr | 20 min | 2 hr |

## 6.0 Test Results

The data from each count will be analyzed for uranium (and daughter) activities using the library peak locate, peak area and activity calculation routines in the gamma spectroscopy software (anticipated to be Genie-PC). The nuclide MDA and uncertainties in the activities will also be calculated for each count. For each probe, the activity uncertainties for the five counts in each iteration will be averaged; this average will be divided by the activity to calculate the fractional precision for each count iteration. For each probe, the activities calculated for each isotope for each of the five counts in each iteration will be averaged; bias will be calculated by taking the difference between this calculated average and the average activity determined from the laboratory analyses of the soils, and dividing this difference by the activity. The precision and bias results from the two iterations will be statistically compared to identify any differences between them. Results to be reported include:

- Precision and bias at 10 times the MDA.
- Precision and bias as a function of activity (3 to 30 times the MDA).
- Precision and bias differences by iteration.

# Appendix C

System MDAs

LPRMS and Survey Probe

Library Listing Report 6-22-95 1:16:08 PM Page 1

```
****************************************************************************
*****          L I B R A R Y   L I S T I N G   R E P O R T            *****
****************************************************************************
```

Nuclide Library Title: MDA LIBRARY

Nuclide Library Description: MDA LIBRARY

| Nuclide Name | Half-Life (Seconds) | Energy (keV ) | Energy Uncert. (keV ) | Yield (%) | Yield Uncert.(Abs.+-) |
|---|---|---|---|---|---|
| Co-60 | 1.663E+08 | 1173.237 | 0.004 | 99.90 | 0.02 |
| | | 1332.501* | 0.005 | 99.98 | 0.00 |
| Ru-105 | 1.598E+04 | 469.370 | 0.100 | 17.50 | 0.60 |
| | | 676.360 | 0.080 | 15.70 | 0.50 |
| | | 724.300* | 0.030 | 47.30 | 0.50 |
| Rh-106 | 7.800E+03 | 511.700* | 0.100 | 86.00 | 5.00 |
| | | 717.200 | 0.100 | 28.90 | 1.60 |
| | | 1046.700 | 0.100 | 30.40 | 1.60 |
| Ru-106a | 3.180E+07 | 511.700* | 0.100 | 86.00 | 5.00 |
| | | 717.200 | 0.100 | 28.90 | 1.60 |
| | | 1046.700 | 0.100 | 30.40 | 1.60 |
| Cs-137 | 9.467E+08 | 661.660* | 0.003 | 85.21 | 0.07 |
| Ce-144 | 2.462E+07 | 80.120 | 0.005 | 1.36 | 0.06 |
| | | 133.515* | 0.002 | 11.09 | 0.20 |
| Pb-210 | 7.025E+08 | 46.503* | 0.002 | 4.05 | 0.02 |
| Ra-223 | 9.879E+05 | 81.070 | 0.020 | 15.00 | 0.40 |
| | | 83.780* | 0.020 | 24.80 | 0.70 |
| | | 94.900 | 0.005 | 11.30 | 0.40 |
| | | 269.410 | 0.030 | 13.60 | 0.30 |
| Ra-226 | 5.049E+10 | 186.100* | 0.100 | 3.50 | 0.05 |
| Ra-226a | 5.049E+10 | 295.213 | 0.008 | 18.50 | 0.30 |
| | | 351.921* | 0.008 | 35.80 | 0.50 |
| Ra-226b | 5.049E+10 | 609.312* | 0.007 | 44.80 | 0.50 |
| | | 1120.287 | 0.010 | 14.80 | 0.20 |
| | | 1764.494 | 0.014 | 15.36 | 0.20 |
| Ac-227 | 6.871E+08 | 115.350* | 0.020 | 0.10 | 0.00 |
| Ac-227a | 6.871E+08 | 50.200 | 0.100 | 8.50 | 1.80 |
| | | 236.000* | 0.080 | 11.20 | 2.40 |
| | | 256.250 | 0.050 | 6.80 | 1.50 |
| Ac-227b | 6.871E+08 | 81.070 | 0.020 | 15.00 | 0.40 |
| | | 83.780* | 0.020 | 24.80 | 0.70 |
| | | 94.900 | 0.005 | 11.30 | 0.40 |
| | | 269.410 | 0.030 | 13.60 | 0.30 |
| Th-230 | 2.379E+12 | 67.672* | 0.002 | 0.38 | 0.03 |
| Th-231 | 9.187E+04 | 84.214* | 0.003 | 6.60 | 0.50 |
| Th-232 | 4.433E+17 | 63.810* | 0.010 | 0.27 | 0.01 |
| Th-232a | 4.433E+17 | 911.205* | 0.004 | 26.60 | 0.70 |
| Th-232b | 4.433E+17 | 84.373* | 0.003 | 1.27 | 0.02 |
| | | 131.613 | 0.004 | 0.14 | 0.00 |
| | | 215.985 | 0.005 | 0.26 | 0.00 |
| Th-232c | 4.433E+17 | 240.987* | 0.006 | 3.97 | 0.04 |
| Th-232d | 4.433E+17 | 87.300 | 0.010 | 8.03 | 0.10 |
| | | 115.190 | 0.010 | 0.60 | 0.11 |
| | | 238.633* | 0.004 | 43.60 | 1.30 |
| | | 300.087 | 0.010 | 3.34 | 0.11 |

Library Listing Report 6-22-95 1:16:08 PM Page 2

Library Title: MDA LIBRARY

| Nuclide Name | Half-Life (Seconds) | Energy (keV ) | Energy Uncert. (keV ) | Yield (%) | Yield Uncert.(Abs.+-) |
|---|---|---|---|---|---|
| Th-232e | 4.433E+17 | 727.180* | 0.060 | 6.65 | 0.15 |
| | | 1620.560 | 0.070 | 1.51 | 0.05 |
| Th-232f | 4.433E+17 | 583.140 | 0.013 | 30.26 | 0.02 |
| | | 2614.533* | 0.013 | 35.63 | 0.02 |
| Pa-233 | 2.330E+06 | 94.665 | 0.002 | 10.90 | 0.40 |
| | | 98.439 | 0.002 | 17.70 | 0.60 |
| | | 312.170* | 0.020 | 38.60 | 0.40 |
| U-233 | 5.024E+12 | 114.510* | 0.005 | 0.18 | 0.00 |
| U-234 | 7.731E+12 | 53.200* | 0.050 | 0.12 | 0.01 |
| U-235 | 2.221E+16 | 89.953 | 0.002 | 2.80 | 0.90 |
| | | 93.350 | 0.002 | 4.50 | 1.40 |
| | | 105.000 | 0.000 | 2.10 | 0.70 |
| | | 109.160 | 0.020 | 1.50 | 0.20 |
| | | 143.760 | 0.020 | 10.90 | 0.23 |
| | | 163.330 | 0.020 | 5.00 | 0.12 |
| | | 185.715* | 0.005 | 57.50 | 1.10 |
| | | 205.311 | 0.010 | 5.00 | 0.21 |
| U-235a | 2.221E+16 | 84.214* | 0.003 | 6.60 | 0.50 |
| U-236 | 7.387E+14 | 68.212* | 0.001 | 0.11 | 0.00 |
| Np-237 | 6.753E+13 | 86.477* | 0.010 | 12.40 | 0.40 |
| | | 92.287 | 0.002 | 1.68 | 0.10 |
| | | 95.868 | 0.002 | 2.73 | 0.15 |
| Np-237a | 6.753E+13 | 94.660 | 0.002 | 10.90 | 0.40 |
| | | 98.430 | 0.002 | 17.70 | 0.60 |
| | | 312.170* | 0.020 | 38.60 | 0.40 |
| Pa-237 | 5.220E+02 | 529.400 | 0.200 | 14.90 | 2.10 |
| | | 853.700* | 0.200 | 34.00 | 4.00 |
| | | 865.000 | 0.200 | 15.50 | 2.20 |
| U-237 | 5.832E+05 | 59.536* | 0.003 | 34.50 | 0.70 |
| | | 64.830 | 0.003 | 1.18 | 0.70 |
| | | 101.070 | 0.040 | 25.40 | 0.80 |
| | | 208.000 | 0.010 | 21.14 | 0.23 |
| U-238a | 1.409E+17 | 63.290 | 0.020 | 4.50 | 0.90 |
| | | 92.590* | 0.030 | 5.20 | 1.20 |
| U-238b | 1.409E+17 | 765.000 | 0.500 | 0.21 | 0.00 |
| | | 1001.000* | 0.500 | 0.59 | 0.00 |
| Am-241 | 1.364E+10 | 59.537* | 0.001 | 35.90 | 0.40 |

* = key line

TOTALS: 36 Nuclides 82 Energy Lines

```
***************************************************************************
*****       G A M M A   S P E C T R U M   A N A L Y S I S            *****
***************************************************************************

Report Generated On              :  6-30-95  8:09:55 AM

Sample Title                     : N3A-C01
Sample Location                  : Biodenitrification
Sample Identification            : Sand/Gravel
Sample Type                      : Bio-d
Sample Geometry                  : DRUM 1.5" CASING

Peak Locate Threshold            :  5.00
Peak Locate Range (in channels)  :    8 -  1024
Peak Area Range (in channels)    :    8 -  1024
Identification Energy Tolerance  :    0.100 FWHM

Sample Size                      :    150670.00 gram

Acquisition Started              : 11-14-94  2:20:16 PM

Live Time                        :     1800.0 seconds
Real Time                        :     1801.6 seconds

              Energy Calibration Name                : N6C-C03C
              Energy Calibration Used Done On        :  2-01-95
              Efficiency Calibration Used Done On    :  1-30-95

          Peak Locate Tolerance                :    0.50 FWHM
          Peak Locate ROI File Name :
          NID Variable Energy Tolerance        :    0.10 FWHM
          NID Confidence Index Threshold       :    0.10
          NID % Confidence Level for MDA       :    5.00
          Nuclide Library Used : C:\GENIEPC\CAMFILES\MDA.NLB

          No area correction performed on this spectrum
          No background subtract performed on this spectrum
```

Nuclide MDA Report 6-30-95 8:10:03 AM Page 11

```
*****************************************************************************
*****                 N U C L I D E   M D A   R E P O R T               *****
*****************************************************************************
```

Detector Name: DET02
Sample Geometry: DRUM 1.5" CASING
Sample Title: N3A-C01
Nuclide Library Used: C:\GENIEPC\CAMFILES\MDA.NLB

| | Nuclide Name | Nuclide Type | Energy (keV) | Yield (%) | Line MDA (pCi/gram) | Nuclide MDA (pCi/gram) |
|---|---|---|---|---|---|---|
| | Co-60 | Direct | 1173.24 | 99.90 | 0.17 | 0.17 |
| | | | 1332.50 | 99.98 | 0.20 | |
| | Ru-105 | Direct | 469.37 | 17.50 | 0.77 | 0.28 |
| | | | 676.36 | 15.70 | 0.84 | |
| | | | 724.30 | 47.30 | 0.28 | |
| | Rh-106 | Direct | 511.70 | 86.00 | 0.16 | 0.16 |
| | | | 717.20 | 28.90 | 0.48 | |
| | | | 1046.70 | 30.40 | 0.57 | |
| | Ru-106a | Rh-106 | 511.70 | 86.00 | 0.15 | 0.15 |
| | | | 717.20 | 28.90 | 0.44 | |
| | | | 1046.70 | 30.40 | 0.53 | |
| | Cs-137 | Direct | 661.66 | 85.21 | 0.15 | 0.15 |
| | Ce-144 | Direct | 80.12 | 1.36 | 16.66 | 2.14 |
| | | | 133.51 | 11.09 | 2.14 | |
| | Pb-210 | Direct | 46.50 | 4.05 | 6.23 | 6.23 |
| | Ra-223 | Direct | 81.07 | 15.00 | 1.50 | 0.90 |
| | | | 83.78 | 24.80 | 0.90 | |
| | | | 94.90 | 11.30 | 2.02 | |
| | | | 269.41 | 13.60 | 1.37 | |
| | Ra-226 | Direct | 186.10 | 3.50 | 6.39 | 6.39 |
| + | Ra-226a | Pb-214 | 295.21* | 18.50 | 0.54 | 0.24 |
| | | | 351.92* | 35.80 | 0.24 | |
| | Ra-226b | Bi-214 | 609.31 | 44.80 | 0.27 | 0.27 |
| | | | 1120.29 | 14.80 | 1.12 | |
| | | | 1764.49 | 15.36 | 1.26 | |
| | Ac-227 | Direct | 115.35 | 0.10 | 235.07 | 235.07 |
| + | Ac-227a | Th-227 | 50.20 | 8.50 | 2.90 | 1.05 |
| | | | 236.00* | 11.20 | 1.05 | |
| | | | 256.25 | 6.80 | 2.85 | |
| | Ac-227b | Ra-223 | 81.07 | 15.00 | 1.50 | 0.90 |
| | | | 83.78 | 24.80 | 0.90 | |
| | | | 94.90 | 11.30 | 2.01 | |
| | | | 269.41 | 13.60 | 1.37 | |
| | Th-230 | | 67.67 | 0.38 | 59.09 | 59.09 |
| | Th-231 | Direct | 84.21 | 6.60 | 3.44 | 3.44 |
| | Th-232 | Direct | 63.81 | 0.27 | 87.63 | 87.63 |
| | Th-232a | Ac-228 | 911.21 | 26.60 | 0.53 | 0.53 |
| | Th-232b | Th-228 | 84.37 | 1.27 | 17.79 | 17.79 |
| | | | 131.61 | 0.14 | 169.84 | |
| | | | 215.99 | 0.26 | 80.59 | |
| | Th-232c | Ra-224 | 240.99 | 3.97 | 5.03 | 5.03 |
| + | Th-232d | Pb-212 | 87.30 | 8.03 | 2.78 | 0.27 |

Nuclide MDA Report 6-30-95 8:10:03 AM Page 12

| | Nuclide Name | Nuclide Type | Energy (keV) | Yield (%) | Line MDA (pCi/gram) | Nuclide MDA (pCi/gram) |
|---|---|---|---|---|---|---|
| + | Th-232d | Pb-212 | 115.19 | 0.60 | 39.19 | 0.27 |
| | | | 238.63* | 43.60 | 0.27 | |
| | | | 300.09 | 3.34 | 5.15 | |
| | Th-232e | Bi-212 | 727.18 | 6.65 | 1.93 | 1.93 |
| | | | 1620.56 | 1.51 | 12.69 | |
| | Th-232f | Tl-208 | 583.14 | 30.26 | 0.40 | 0.40 |
| > | | | 2614.53 | 35.63 | 0.00 | |
| | Pa-233 | | 94.67 | 10.90 | 2.07 | 0.44 |
| | | | 98.44 | 17.70 | 1.28 | |
| | | | 312.17 | 38.60 | 0.44 | |
| | U-233 | | 114.51 | 0.18 | 130.79 | 130.79 |
| | U-234 | | 53.20 | 0.12 | 207.81 | 207.81 |
| | U-235 | Direct | 89.95 | 2.80 | 8.16 | 0.39 |
| | | | 93.35 | 4.50 | 5.04 | |
| | | | 105.00 | 2.10 | 10.89 | |
| | | | 109.16 | 1.50 | 15.51 | |
| | | | 143.76 | 10.90 | 2.17 | |
| | | | 163.33 | 5.00 | 4.71 | |
| | | | 185.71 | 57.50 | 0.39 | |
| | | | 205.31 | 5.00 | 4.30 | |
| | U-235a | Th-231 | 84.21 | 6.60 | 3.42 | 3.42 |
| | U-236 | Direct | 68.21 | 0.11 | 207.48 | 207.48 |
| | Np-237 | Direct | 86.48 | 12.40 | 1.79 | 1.79 |
| | | | 92.29 | 1.68 | 13.57 | |
| | | | 95.87 | 2.73 | 8.30 | |
| | Np-237a | Pa-233 | 94.66 | 10.90 | 2.07 | 0.44 |
| | | | 98.43 | 17.70 | 1.28 | |
| | | | 312.17 | 38.60 | 0.44 | |
| | Pa-237 | Direct | 529.40 | 14.90 | 2.15 | 1.05 |
| | | | 853.70 | 34.00 | 1.05 | |
| | | | 865.00 | 15.50 | 2.33 | |
| | U-237 | Direct | 59.54 | 34.50 | 0.68 | 0.68 |
| | | | 64.83 | 1.18 | 19.48 | |
| | | | 101.07 | 25.40 | 0.90 | |
| | | | 208.00 | 21.14 | 1.02 | |
| | U-238a | Th-234 | 63.29 | 4.50 | 5.25 | 4.38 |
| | | | 92.59 | 5.20 | 4.38 | |
| | U-238b | Pa-234m | 765.00 | 0.21 | 62.97 | 26.41 |
| | | | 1001.00 | 0.59 | 26.41 | |
| | Am-241 | Direct | 59.54 | 35.90 | 0.65 | 0.65 |

+ = Nuclide identified during the nuclide identification
* = Energy line found in the spectrum
> = MDA value not calculated
@ = Half-life too short to be able to perform the decay correction

```
*****************************************************************************
*****        G A M M A   S P E C T R U M   A N A L Y S I S            *****
*****************************************************************************

Report Generated On                 :  6-22-95  1:20:18 PM

Sample Title                        : N3A-C03
Sample Location                     : Biodenitrification
Sample Identification               : Sand/Gravel
Sample Type                         : Bio-d
Sample Geometry                     : DRUM 1.5" CASING

Peak Locate Threshold               :  5.00
Peak Locate Range (in channels)     :     8 -  1024
Peak Area Range (in channels)       :     8 -  1024
Identification Energy Tolerance     :    0.100 FWHM

Sample Size                         :    150670.00 gram

Acquisition Started                 : 11-14-94  3:22:07 PM

Live Time                           :     5400.0 seconds
Real Time                           :     5404.8 seconds

              Energy Calibration Name                : N6C-C03C
              Energy Calibration Used Done On        :  2-01-95
              Efficiency Calibration Used Done On    :  1-30-95

          Peak Locate Tolerance              :    0.50 FWHM
          Peak Locate ROI File Name :
          NID Variable Energy Tolerance      :    0.10 FWHM
          NID Confidence Index Threshold     :    0.10
          NID % Confidence Level for MDA     :    5.00
          Nuclide Library Used : C:\GENIEPC\CAMFILES\MDA.NLB

          No area correction performed on this spectrum
          No background subtract performed on this spectrum
```

Nuclide MDA Report 6-22-95 1:20:27 PM Page 11

```
*****************************************************************************
*****              N U C L I D E   M D A   R E P O R T                  *****
*****************************************************************************
```

Detector Name: DET02
Sample Geometry: DRUM 1.5" CASING
Sample Title: N3A-C03
Nuclide Library Used: C:\GENIEPC\CAMFILES\MDA.NLB

| | Nuclide Name | Nuclide Type | Energy (keV) | Yield (%) | Line MDA (pCi/gram) | Nuclide MDA (pCi/gram) |
|---|---|---|---|---|---|---|
| | Co-60 | Direct | 1173.24 | 99.90 | 0.10 | 0.10 |
| | | | 1332.50 | 99.98 | 0.11 | |
| | Ru-105 | Direct | 469.37 | 17.50 | 0.48 | 0.18 |
| | | | 676.36 | 15.70 | 0.53 | |
| | | | 724.30 | 47.30 | 0.18 | |
| | Rh-106 | Direct | 511.70 | 86.00 | 0.11 | 0.11 |
| | | | 717.20 | 28.90 | 0.32 | |
| | | | 1046.70 | 30.40 | 0.38 | |
| | Ru-106a | Rh-106 | 511.70 | 86.00 | 0.09 | 0.09 |
| | | | 717.20 | 28.90 | 0.26 | |
| | | | 1046.70 | 30.40 | 0.30 | |
| | Cs-137 | Direct | 661.66 | 85.21 | 0.08 | 0.08 |
| | Ce-144 | Direct | 80.12 | 1.36 | 9.61 | 1.24 |
| | | | 133.51 | 11.09 | 1.24 | |
| | Pb-210 | Direct | 46.50 | 4.05 | 3.58 | 3.58 |
| | Ra-223 | Direct | 81.07 | 15.00 | 0.87 | 0.52 |
| | | | 83.78 | 24.80 | 0.52 | |
| | | | 94.90 | 11.30 | 1.16 | |
| | | | 269.41 | 13.60 | 0.79 | |
| | Ra-226 | Direct | 186.10 | 3.50 | 3.70 | 3.70 |
| + | Ra-226a | Pb-214 | 295.21 | 18.50 | 0.55 | 0.14 |
| | | | 351.92* | 35.80 | 0.14 | |
| + | Ra-226b | Bi-214 | 609.31* | 44.80 | 0.09 | 0.09 |
| | | | 1120.29* | 14.80 | 0.37 | |
| | | | 1764.49* | 15.36 | 0.25 | |
| | Ac-227 | Direct | 115.35 | 0.10 | 135.62 | 135.62 |
| + | Ac-227a | Th-227 | 50.20 | 8.50 | 1.67 | 0.61 |
| | | | 236.00* | 11.20 | 0.61 | |
| | | | 256.25 | 6.80 | 1.65 | |
| | Ac-227b | Ra-223 | 81.07 | 15.00 | 0.86 | 0.52 |
| | | | 83.78 | 24.80 | 0.52 | |
| | | | 94.90 | 11.30 | 1.16 | |
| | | | 269.41 | 13.60 | 0.79 | |
| + | Th-230 | | 67.67* | 0.38 | 20.10 | 20.10 |
| | Th-231 | Direct | 84.21 | 6.60 | 2.01 | 2.01 |
| | Th-232 | Direct | 63.81 | 0.27 | 50.52 | 50.52 |
| | Th-232a | Ac-228 | 911.21 | 26.60 | 0.31 | 0.31 |
| | Th-232b | Th-228 | 84.37 | 1.27 | 10.26 | 10.26 |
| | | | 131.61 | 0.14 | 98.09 | |
| | | | 215.99 | 0.26 | 46.57 | |
| | Th-232c | Ra-224 | 240.99 | 3.97 | 2.91 | 2.91 |
| + | Th-232d | Pb-212 | 87.30 | 8.03 | 1.61 | 0.16 |

Nuclide MDA Report 6-22-95 1:20:27 PM Page 12

| | Nuclide Name | Nuclide Type | Energy (keV) | Yield (%) | Line MDA (pCi/gram) | Nuclide MDA (pCi/gram) |
|---|---|---|---|---|---|---|
| + | Th-232d | Pb-212 | 115.19 | 0.60 | 22.61 | 0.16 |
| | | | 238.63* | 43.60 | 0.16 | |
| | | | 300.09 | 3.34 | 2.99 | |
| | Th-232e | Bi-212 | 727.18 | 6.65 | 1.12 | 1.12 |
| | | | 1620.56 | 1.51 | 7.27 | |
| | Th-232f | Tl-208 | 583.14 | 30.26 | 0.23 | 0.23 |
| > | | | 2614.53 | 35.63 | 0.00 | |
| | Pa-233 | | 94.67 | 10.90 | 1.19 | 0.26 |
| | | | 98.44 | 17.70 | 0.74 | |
| | | | 312.17 | 38.60 | 0.26 | |
| | U-233 | | 114.51 | 0.18 | 75.46 | 75.46 |
| | U-234 | | 53.20 | 0.12 | 119.64 | 119.64 |
| | U-235 | Direct | 89.95 | 2.80 | 4.71 | 0.23 |
| | | | 93.35 | 4.50 | 2.91 | |
| | | | 105.00 | 2.10 | 6.28 | |
| | | | 109.16 | 1.50 | 8.95 | |
| | | | 143.76 | 10.90 | 1.25 | |
| | | | 163.33 | 5.00 | 2.72 | |
| | | | 185.71 | 57.50 | 0.23 | |
| | | | 205.31 | 5.00 | 2.49 | |
| | U-235a | Th-231 | 84.21 | 6.60 | 1.97 | 1.97 |
| + | U-236 | Direct | 68.21* | 0.11 | 69.42 | 69.42 |
| | Np-237 | Direct | 86.48 | 12.40 | 1.03 | 1.03 |
| | | | 92.29 | 1.68 | 7.83 | |
| | | | 95.87 | 2.73 | 4.79 | |
| | Np-237a | Pa-233 | 94.66 | 10.90 | 1.19 | 0.26 |
| | | | 98.43 | 17.70 | 0.74 | |
| | | | 312.17 | 38.60 | 0.26 | |
| | Pa-237 | Direct | 529.40 | 14.90 | 3.42 | 1.66 |
| | | | 853.70 | 34.00 | 1.66 | |
| | | | 865.00 | 15.50 | 3.66 | |
| | U-237 | Direct | 59.54 | 34.50 | 0.39 | 0.39 |
| | | | 64.83 | 1.18 | 11.26 | |
| | | | 101.07 | 25.40 | 0.52 | |
| | | | 208.00 | 21.14 | 0.59 | |
| | U-238a | Th-234 | 63.29 | 4.50 | 3.03 | 2.53 |
| | | | 92.59 | 5.20 | 2.53 | |
| | U-238b | Pa-234m | 765.00 | 0.21 | 36.50 | 15.13 |
| | | | 1001.00 | 0.59 | 15.13 | |
| | Am-241 | Direct | 59.54 | 35.90 | 0.37 | 0.37 |

+ = Nuclide identified during the nuclide identification
* = Energy line found in the spectrum
> = MDA value not calculated
@ = Half-life too short to be able to perform the decay correction

```
***************************************************************************
*****       G A M M A   S P E C T R U M   A N A L Y S I S           *****
***************************************************************************

Report Generated On              :  6-30-95  8:13:27 AM

Sample Title                     : D3A-C01
Sample Location                  : BIODENITRIFICATION
Sample Identification            : Sand/Gravel
Sample Type                      : Clean
Sample Geometry                  : Drum 1.5" Casing

Peak Locate Threshold            :  5.00
Peak Locate Range (in channels)  :     8 -  1024
Peak Area Range (in channels)    :     8 -  1024
Identification Energy Tolerance  :    0.100 FWHM

Sample Size                      :    189473.00 gram

Acquisition Started              : 11-14-94 12:01:43 PM

Live Time                        :     1800.0 seconds
Real Time                        :     1802.7 seconds

          Energy Calibration Name                : D3A-C01C
          Energy Calibration Used Done On        :  1-24-95
          Efficiency Calibration Used Done On    :  1-30-95

     Peak Locate Tolerance              :     0.50 FWHM
     Peak Locate ROI File Name :
     NID Variable Energy Tolerance      :     0.10 FWHM
     NID Confidence Index Threshold     :     0.10
     NID % Confidence Level for MDA     :     5.00
     Nuclide Library Used : C:\GENIEPC\CAMFILES\MDA.NLB

     No area correction performed on this spectrum
     No background subtract performed on this spectrum
```

Nuclide MDA Report 6-30-95 8:13:34 AM Page 11

```
*****************************************************************************
*****            N U C L I D E   M D A   R E P O R T                    *****
*****************************************************************************
```

Detector Name: DET01
Sample Geometry: Drum 1.5" Casing
Sample Title: D3A-C01
Nuclide Library Used: C:\GENIEPC\CAMFILES\MDA.NLB

| | Nuclide Name | Nuclide Type | Energy (keV) | Yield (%) | Line MDA (pCi/gram) | Nuclide MDA (pCi/gram) |
|---|---|---|---|---|---|---|
| + | Co-60 | Direct | 1173.24* | 99.90 | 0.11 | 0.11 |
| | | | 1332.50 | 99.98 | 0.23 | |
| | Ru-105 | Direct | 469.37 | 17.50 | 1.23 | 0.38 |
| | | | 676.36 | 15.70 | 1.15 | |
| | | | 724.30 | 47.30 | 0.38 | |
| | Rh-106 | Direct | 511.70 | 86.00 | 0.25 | 0.25 |
| | | | 717.20 | 28.90 | 0.65 | |
| | | | 1046.70 | 30.40 | 0.69 | |
| | Ru-106a | Rh-106 | 511.70 | 86.00 | 0.23 | 0.23 |
| | | | 717.20 | 28.90 | 0.60 | |
| | | | 1046.70 | 30.40 | 0.64 | |
| | Cs-137 | Direct | 661.66 | 85.21 | 0.21 | 0.21 |
| | Ce-144 | Direct | 80.12 | 1.36 | 71.83 | 3.14 |
| | | | 133.51 | 11.09 | 3.14 | |
| + | Pb-210 | Direct | 46.50* | 4.05 | 3577.48 | 3577.48 |
| | Ra-223 | Direct | 81.07 | 15.00 | 6.17 | 1.86 |
| | | | 83.78 | 24.80 | 3.18 | |
| | | | 94.90 | 11.30 | 4.61 | |
| | | | 269.41 | 13.60 | 1.86 | |
| | Ra-226 | Direct | 186.10 | 3.50 | 8.58 | 8.58 |
| | Ra-226a | Pb-214 | 295.21 | 18.50 | 1.35 | 0.66 |
| | | | 351.92 | 35.80 | 0.66 | |
| | Ra-226b | Bi-214 | 609.31 | 44.80 | 0.40 | 0.40 |
| | | | 1120.29 | 14.80 | 1.38 | |
| | | | 1764.49 | 15.36 | 1.57 | |
| | Ac-227 | Direct | 115.35 | 0.10 | 390.96 | 390.96 |
| | Ac-227a | Th-227 | 50.20 | 8.50 | 639.20 | 2.27 |
| | | | 236.00 | 11.20 | 2.27 | |
| | | | 256.25 | 6.80 | 3.74 | |
| | Ac-227b | Ra-223 | 81.07 | 15.00 | 6.17 | 1.86 |
| | | | 83.78 | 24.80 | 3.17 | |
| | | | 94.90 | 11.30 | 4.61 | |
| | | | 269.41 | 13.60 | 1.86 | |
| | Th-230 | | 67.67 | 0.38 | 743.31 | 743.31 |
| | Th-231 | Direct | 84.21 | 6.60 | 11.81 | 11.81 |
| | Th-232 | Direct | 63.81 | 0.27 | 1700.14 | 1700.14 |
| | Th-232a | Ac-228 | 911.21 | 26.60 | 0.69 | 0.69 |
| | Th-232b | Th-228 | 84.37 | 1.27 | 60.63 | 60.63 |
| | | | 131.61 | 0.14 | 252.04 | |
| | | | 215.99 | 0.26 | 101.33 | |
| | Th-232c | Ra-224 | 240.99 | 3.97 | 6.42 | 6.42 |
| | Th-232d | Pb-212 | 87.30 | 8.03 | 8.32 | 0.58 |

Nuclide MDA Report 6-30-95 8:13:34 AM Page 12

| Nuclide Name | Nuclide Type | Energy (keV) | Yield (%) | Line MDA (pCi/gram) | Nuclide MDA (pCi/gram) |
|---|---|---|---|---|---|
| Th-232d | Pb-212 | 115.19 | 0.60 | 65.27 | 0.58 |
| | | 238.63 | 43.60 | 0.58 | |
| | | 300.09 | 3.34 | 7.49 | |
| Th-232e | Bi-212 | 727.18 | 6.65 | 2.61 | 2.61 |
| | | 1620.56 | 1.51 | 15.88 | |
| Th-232f | Tl-208 | 583.14 | 30.26 | 0.60 | 0.42 |
| | | 2614.53 | 35.63 | 0.42 | |
| Pa-233 | | 94.67 | 10.90 | 4.81 | 0.64 |
| | | 98.44 | 17.70 | 2.70 | |
| | | 312.17 | 38.60 | 0.64 | |
| U-233 | | 114.51 | 0.18 | 219.17 | 219.17 |
| U-234 | | 53.20 | 0.12 | 23320.33 | 23320.33 |
| U-235 | Direct | 89.95 | 2.80 | 21.44 | 0.52 |
| | | 93.35 | 4.50 | 12.05 | |
| | | 105.00 | 2.10 | 20.64 | |
| | | 109.16 | 1.50 | 27.60 | |
| | | 143.76 | 10.90 | 3.08 | |
| | | 163.33 | 5.00 | 6.40 | |
| | | 185.71 | 57.50 | 0.52 | |
| | | 205.31 | 5.00 | 5.39 | |
| U-235a | Th-231 | 84.21 | 6.60 | 11.73 | 11.73 |
| U-236 | Direct | 68.21 | 0.11 | 2436.38 | 2436.38 |
| Np-237 | Direct | 86.48 | 12.40 | 5.60 | 5.60 |
| | | 92.29 | 1.68 | 33.01 | |
| | | 95.87 | 2.73 | 18.56 | |
| Np-237a | Pa-233 | 94.66 | 10.90 | 4.81 | 0.64 |
| | | 98.43 | 17.70 | 2.70 | |
| | | 312.17 | 38.60 | 0.64 | |
| Pa-237 | Direct | 529.40 | 14.90 | 3.42 | 1.39 |
| | | 853.70 | 34.00 | 1.39 | |
| | | 865.00 | 15.50 | 3.07 | |
| U-237 | Direct | 59.54 | 34.50 | 24.76 | 1.27 |
| | | 64.83 | 1.18 | 338.78 | |
| | | 101.07 | 25.40 | 1.80 | |
| | | 208.00 | 21.14 | 1.27 | |
| U-238a | Th-234 | 63.29 | 4.50 | 107.33 | 10.55 |
| | | 92.59 | 5.20 | 10.55 | |
| U-238b | Pa-234m | 765.00 | 0.21 | 82.57 | 32.34 |
| | | 1001.00 | 0.59 | 32.34 | |
| Am-241 | Direct | 59.54 | 35.90 | 23.77 | 23.77 |

+ = Nuclide identified during the nuclide identification
* = Energy line found in the spectrum
> = MDA value not calculated
@ = Half-life too short to be able to perform the decay correction

```
*****************************************************************************
*****       G A M M A   S P E C T R U M   A N A L Y S I S              *****
*****************************************************************************

Report Generated On                   :  6-22-95  1:31:40 PM

Sample Title                          : D3A-C03
Sample Location                       : BIODENITRIFICATION
Sample Identification                 : Sand/Gravel
Sample Type                           : Clean
Sample Geometry                       : Drum 1.5" Casing

Peak Locate Threshold                 :  5.00
Peak Locate Range (in channels)       :    8 -  1024
Peak Area Range (in channels)         :    8 -  1024
Identification Energy Tolerance       :   0.100 FWHM

Sample Size                           :   189473.00 gram

Acquisition Started                   : 11-14-94  1:04:55 PM

Live Time                             :    5400.0 seconds
Real Time                             :    5407.9 seconds

              Energy Calibration Name                    : D3A-C01C
              Energy Calibration Used Done On            :  1-24-95
              Efficiency Calibration Used Done On        :  1-30-95

          Peak Locate Tolerance                 :    0.50 FWHM
          Peak Locate ROI File Name :
          NID Variable Energy Tolerance         :    0.10 FWHM
          NID Confidence Index Threshold        :    0.10
          NID % Confidence Level for MDA        :    5.00
          Nuclide Library Used : C:\GENIEPC\CAMFILES\MDA.NLB

          No area correction performed on this spectrum
          No background subtract performed on this spectrum
```

Nuclide MDA Report 6-22-95 1:31:48 PM Page 11

```
*****************************************************************************
*****              N U C L I D E   M D A   R E P O R T                  *****
*****************************************************************************
```

Detector Name: DET01
Sample Geometry: Drum 1.5" Casing
Sample Title: D3A-C03
Nuclide Library Used: C:\GENIEPC\CAMFILES\MDA.NLB

| | Nuclide Name | Nuclide Type | Energy (keV) | Yield (%) | Line MDA (pCi/gram) | Nuclide MDA (pCi/gram) |
|---|---|---|---|---|---|---|
| + | Co-60 | Direct | 1173.24* | 99.90 | 0.07 | 0.07 |
| | | | 1332.50 | 99:98 | 0.13 | |
| | Ru-105 | Direct | 469.37 | 17.50 | 0.76 | 0.24 |
| | | | 676.36 | 15.70 | 0.72 | |
| | | | 724.30 | 47.30 | 0.24 | |
| | Rh-106 | Direct | 511.70 | 86.00 | 0.17 | 0.17 |
| | | | 717.20 | 28.90 | 0.44 | |
| | | | 1046.70 | 30.40 | 0.46 | |
| | Ru-106a | Rh-106 | 511.70 | 86.00 | 0.13 | 0.13 |
| | | | 717.20 | 28.90 | 0.35 | |
| | | | 1046.70 | 30.40 | 0.37 | |
| | Cs-137 | Direct | 661.66 | 85.21 | 0.12 | 0.12 |
| | Ce-144 | Direct | 80.12 | 1.36 | 41.51 | 1.82 |
| | | | 133.51 | 11.09 | 1.82 | |
| + | Pb-210 | Direct | 46.50* | 4.05 | 2055.69 | 2055.69 |
| | Ra-223 | Direct | 81.07 | 15.00 | 3.57 | 1.07 |
| | | | 83.78 | 24.80 | 1.84 | |
| | | | 94.90 | 11.30 | 2.67 | |
| | | | 269.41 | 13.60 | 1.07 | |
| | Ra-226 | Direct | 186.10 | 3.50 | 4.96 | 4.96 |
| | Ra-226a | Pb-214 | 295.21 | 18.50 | 0.78 | 0.38 |
| | | | 351.92 | 35.80 | 0.38 | |
| + | Ra-226b | Bi-214 | 609.31* | 44.80 | 0.12 | 0.12 |
| | | | 1120.29 | 14.80 | 0.80 | |
| | | | 1764.49* | 15.36 | 0.36 | |
| | Ac-227 | Direct | 115.35 | 0.10 | 225.93 | 225.93 |
| | Ac-227a | Th-227 | 50.20 | 8.50 | 369.26 | 1.31 |
| | | | 236.00 | 11.20 | 1.31 | |
| | | | 256.25 | 6.80 | 2.16 | |
| | Ac-227b | Ra-223 | 81.07 | 15.00 | 3.57 | 1.07 |
| | | | 83.78 | 24.80 | 1.83 | |
| | | | 94.90 | 11.30 | 2.66 | |
| | | | 269.41 | 13.60 | 1.07 | |
| | Th-230 | | 67.67 | 0.38 | 429.54 | 429.54 |
| | Th-231 | Direct | 84.21 | 6.60 | 6.92 | 6.92 |
| | Th-232 | Direct | 63.81 | 0.27 | 982.46 | 982.46 |
| | Th-232a | Ac-228 | 911.21 | 26.60 | 0.40 | 0.40 |
| | Th-232b | Th-228 | 84.37 | 1.27 | 35.04 | 35.04 |
| | | | 131.61 | 0.14 | 145.65 | |
| | | | 215.99 | 0.26 | 58.58 | |
| | Th-232c | Ra-224 | 240.99 | 3.97 | 3.71 | 3.71 |
| | Th-232d | Pb-212 | 87.30 | 8.03 | 4.81 | 0.34 |

Nuclide MDA Report 6-22-95 1:31:48 PM Page 12

| Nuclide Name | Nuclide Type | Energy (keV) | Yield (%) | Line MDA (pCi/gram) | Nuclide MDA (pCi/gram) |
|---|---|---|---|---|---|
| Th-232d | Pb-212 | 115.19 | 0.60 | 37.72 | 0.34 |
| | | 238.63 | 43.60 | 0.34 | |
| | | 300.09 | 3.34 | 4.32 | |
| Th-232e | Bi-212 | 727.18 | 6.65 | 1.51 | 1.51 |
| | | 1620.56 | 1.51 | 9.13 | |
| Th-232f | Tl-208 | 583.14 | 30.26 | 0.35 | 0.24 |
| | | 2614.53 | 35.63 | 0.24 | |
| Pa-233 | | 94.67 | 10.90 | 2.78 | 0.37 |
| | | 98.44 | 17.70 | 1.56 | |
| | | 312.17 | 38.60 | 0.37 | |
| U-233 | | 114.51 | 0.18 | 126.65 | 126.65 |
| U-234 | | 53.20 | 0.12 | 13472.53 | 13472.53 |
| U-235 | Direct | 89.95 | 2.80 | 12.39 | 0.30 |
| | | 93.35 | 4.50 | 6.97 | |
| | | 105.00 | 2.10 | 11.93 | |
| | | 109.16 | 1.50 | 15.95 | |
| | | 143.76 | 10.90 | 1.78 | |
| | | 163.33 | 5.00 | 3.70 | |
| | | 185.71 | 57.50 | 0.30 | |
| | | 205.31 | 5.00 | 3.11 | |
| U-235a | Th-231 | 84.21 | 6.60 | 6.78 | 6.78 |
| U-236 | Direct | 68.21 | 0.11 | 1408.03 | 1408.03 |
| Np-237 | Direct | 86.48 | 12.40 | 3.24 | 3.24 |
| | | 92.29 | 1.68 | 19.07 | |
| | | 95.87 | 2.73 | 10.73 | |
| Np-237a | Pa-233 | 94.66 | 10.90 | 2.78 | 0.37 |
| | | 98.43 | 17.70 | 1.56 | |
| | | 312.17 | 38.60 | 0.37 | |
| Pa-237 | Direct | 529.40 | 14.90 | 5.37 | 2.18 |
| | | 853.70 | 34.00 | 2.18 | |
| | | 865.00 | 15.50 | 4.82 | |
| U-237 | Direct | 59.54 | 34.50 | 14.34 | 0.74 |
| | | 64.83 | 1.18 | 196.19 | |
| | | 101.07 | 25.40 | 1.04 | |
| | | 208.00 | 21.14 | 0.74 | |
| U-238a | Th-234 | 63.29 | 4.50 | 62.01 | 6.10 |
| | | 92.59 | 5.20 | 6.10 | |
| U-238b | Pa-234m | 765.00 | 0.21 | 47.62 | 18.55 |
| | | 1001.00 | 0.59 | 18.55 | |
| Am-241 | Direct | 59.54 | 35.90 | 13.73 | 13.73 |

+ = Nuclide identified during the nuclide identification
* = Energy line found in the spectrum
> = MDA value not calculated
@ = Half-life too short to be able to perform the decay correction

# Appendix D

Data Analysis

# APPENDIX D
# DATA ANALYSIS

All of the data analyses for this project were performed using GENIE-PC gamma analysis software, version 2.1 (Canberra Nuclear). The software package used included the S400 Basic Spectroscopy Software, the S401 Gamma Analysis Software and the S405 Quality Assurance Software. This software incorporates algorithms for performing most of the analyses normally encountered in gamma spectroscopy, including energy and efficiency calibrations, peak location, continuum correction, peak area determination, detector efficiency correction, nuclide identification, interference correction, nuclide activity and uncertainty calculation, and minimum detectable activity (MDA) calculation. The general analysis sequence followed for each of the counts from each of the tests performed at FEMP was:

- Energy calibrate the count spectrum (counts vs keV)
- Locate the peaks in the spectrum (in keV)
- Determine the net peak areas (in detected counts)
- Determine efficiency for each peak
- Identify nuclides by gamma lines (nuclide ID list)
- Calculate total activities and uncertainties, based on nuclide gamma yields and corrected areas (pCi)
- Normalize activities and uncertainties to analysis quantity (pCi/g)
- Interference correction (corrected nuclide ID list)
- Calculate minimum detectable activities (MDAs in pCi/g).

The energy calibration was performed manually for each test. The other analysis steps and parameters were incorporated into an analysis template which was subsequently used for all of the analyses. Each of these steps and the analysis parameters used for each are described in more detail below.

## D-1. Nuclide Library

For the data from the FEMP demonstration tests, the analyses were performed using a nuclide library. This library incorporated the unknown nuclides anticipated, a majority of the daughters which could be expected to be in secular equilibrium (those with significant gamma yield) and potential background nuclides (such as K-40) or interferences. For each nuclide, the library also contains the half- life of the isotope and their various gamma lines and yields. A listing of this library is shown on the following page. For daughters in secular equilibrium with a long half-lived parent, the half-life was adjusted to that of the parent; where there was branching between the daughters, the gamma yields were adjusted so that the activity calculated would be that of the parent - the nuclide of concern. The daughter nuclides were renamed with the name of the parent and a letter suffix: for example, Th-234 became U-238a and Pa-234m became U-238b when they were used to calculate U-238 activities. Many of the low yield gamma lines and daughters were not included in the library because they are not spectroscopically useful with a scintillation detector. Where multiple daughters with significant gamma yields were available for a single parent (such as U-238 and Ra-226), they were included in the library to permit a quantitative cross check and to evaluate their suitability for use in the LPRMS.

## D-2. Calibrations

To analyze the count data from the tests, three additional things are required: an energy calibration, an efficiency calibration and an analysis quantity. The energy calibration provides the relationship between count channels and gamma energy in keV. The efficiency calibration provides the relationship (as a function of energy) between the number of counts which are counted by the system and the total gamma flux in the integration volume of the detector. The analysis quantity (sample mass) is used to normalize the total activity calculated for a count to determine activity in pCi/g; the total activity is divided by the mass of the sample.

The first step in the analysis of the data from a test was to obtain the energy calibration, based on a count of the nine nuclide calibration source performed immediately after the test. The stored calibration source count spectrum was retrieved, and the peaks were located using a library search against a stored library of the nuclides, gamma lines and activities of the isotopes in the calibration source. The analysis software was then used to perform a third order polynomial curve fit between the locations (in channels) and the known gamma energies (in keV). The analysis software also determines the full width at half-maximum (FWHM) for each peak in the calibration spectrum and fits a second order polynomial to the FWHM vs energy data. These two curve fit results are stored as a test-specific calibration file, which is used in the analysis of all of the counts in a test.

The efficiency calibrations for the probes were based on calculated rather than measured values, as described in section 4.3.2. The soil model described in that section (and in more detail in the Phase I Topical Report) was used to predict the photopeak count rate at 18 different energy lines between 60 and 2400 keV, assuming a uniform distribution of the gamma sources in the soil. The activity of the gamma sources was arbitrarily set at 1 DPM/g with a yield of 1. The ratio between the photopeak count rate at each energy line to the disintegration rate of the gamma sources within the integration volume of the probe was then calculated to determine the peak efficiency vs energy. Four tables of efficiency vs energy were manually input to files in the GENIE-PC software for the LPRMS and Survey probes, two each. One of these files for each probe was for the in-situ sample geometry and the other was for the geometry of the KUTh source. These data points were curve fit in the GENIE-PC software using a dual polynomial curve fit. In this approach, separate curve fits are performed in the low and high energy regions, with a common "cross- over" point. For the low energy region, a second order polynomial was used; for the high energy region, a fifth order polynomial was used. The cross-over was between 200 to 300 keV. The efficiencies for the KUTh source were used only during the development of the correction factors for the in-situ efficiencies, as described in section 4.3.2. All analyses of the FEMP data from the drums and in-situ were performed using the efficiency calibrations for the in-situ geometry.

The analysis quantities were determined from the active volume of the probe and the soil densities. The analysis volume for each probe was determined from the same model used for determining the detector efficiencies. The active volume depends on both the effective radius (depending on attenuation of the soil) and on the angles above and below the scintillator which contribute significantly to the count rate of the probe. The effective view angles were estimated to be about 30 degrees from the geometry of the probe; at angles steeper than this, the probe structure provided significant additional attenuation and there was minimal contribution of increased angles. The effective radius was determined from the soil model, as that radius beyond which there was not a significant increase in the intercepted gamma with an increase in radius. This is discussed in some detail in the Phase I topical report [reference 1]. The effective radius (and "true" analysis quantity) is actually a function of gamma energy; it is smaller at low energies, and larger at high energies. The analysis software uses only a single analysis quantity; our approach was to use an analysis quantity which was large enough to accommodate the higher energy gamma for both the analysis quantity calculation and the efficiency calculation described above. Thus the overestimate of the analysis quantity for low energy gamma is offset in the efficiency correction, since the same geometry is assumed for both.

```
*************************************************************************
*****          L I B R A R Y   L I S T I N G   R E P O R T          *****
*************************************************************************
```

Nuclide Library Title: Parent Library (PARENT2D.NLB)

Nuclide Library Description: Parent Library based on Combined

| Nuclide Name | Half-Life (Seconds) | Energy (keV ) | Energy Uncert. (keV ) | Yield (%) | Yield Uncert.(Abs.+-) |
|---|---|---|---|---|---|
| K-40 | 4.030E+16 | 1460.750* | 0.060 | 10.6700 | 0.1100 |
| Ra-226a | 5.049E+10 | 295.213 | 0.008 | 18.5000 | 0.3000 |
| | | 351.921* | 0.008 | 35.8000 | 0.5000 |
| Ra-226b | 5.049E+10 | 609.312* | 0.007 | 44.8000 | 0.5000 |
| | | 1120.287 | 0.010 | 14.8000 | 0.2000 |
| | | 1764.494 | 0.014 | 15.3600 | 0.2000 |
| Th-232a | 4.433E+17 | 911.205* | 0.004 | 26.6000 | 0.7000 |
| Th-232ai | 4.433E+17 | 89.950 | 0.020 | 2.1300 | 0.5400 |
| | | 967.964* | 0.020 | 21.3100 | 0.5400 |
| Th-232b | 4.433E+17 | 87.300 | 0.010 | 8.0300 | 0.1000 |
| | | 115.190 | 0.010 | 0.6000 | 0.1100 |
| | | 238.633* | 0.004 | 43.6000 | 1.3000 |
| | | 300.087 | 0.010 | 3.3400 | 0.1100 |
| Th-232c | 4.433E+17 | 727.180* | 0.060 | 6.6500 | 0.1500 |
| | | 1620.560 | 0.070 | 1.5100 | 0.0500 |
| Th-232d | 4.433E+17 | 583.140 | 0.013 | 30.2600 | 0.0000 |
| | | 2614.533* | 0.013 | 35.6300 | 0.0000 |
| U-235 | 2.221E+16 | 109.140 | 0.020 | 1.5000 | 0.1000 |
| | | 143.760 | 0.020 | 10.9000 | 0.2300 |
| | | 185.715* | 0.005 | 57.5000 | 1.1000 |
| U-235i | 2.221E+16 | 89.950 | 0.002 | 2.7300 | 0.1000 |
| | | 93.350 | 0.002 | 4.5000 | 0.1000 |
| | | 163.330 | 0.020 | 5.0000 | 0.1200 |
| | | 205.311 | 0.010 | 5.0000 | 0.2100 |
| U-238a | 1.410E+17 | 63.290 | 0.020 | 4.5000 | 0.9000 |
| | | 92.590* | 0.030 | 5.2000 | 1.2000 |
| U-238b | 1.410E+17 | 765.000 | 0.000 | 0.2070 | 0.0000 |
| | | 1001.000* | 0.000 | 0.5900 | 0.0000 |

* = key line

TOTALS: 12 Nuclides 28 Energy Lines

**Figure D-1. Analysis Library (PARENTS2D.nlb)**

## D-3. Peak Locate

All of the peak locations in the analysis of the FEMP data were performed using a library (Gamma-M) locate, with the unknown search enabled. The first step in the peak location is to determine the continuum background. The Genie-PC software uses a peak erosion technique to determine the continuum, as described in Appendix B of Reference 3. The resulting continuum is subtracted from the spectrum to form a net spectrum. Based on the energies of the gamma lines of the nuclides in the library selected and the FWHM values from the energy calibration, the software fits the data with pure Gaussians, in a least squares fit. After the fit of the library peaks, the software searches the spectrum for unknown peaks using a digital filtering technique, also described in Reference 3. The located peaks are subjected to a number of validity tests before they are included as valid peaks.

- A library peak is rejected if it is too close to another library peak based on the expected FWHM.
- An unknown peak is rejected if it is within the selected energy tolerance of a library peak (0.5 FWHM).
- Either type of peak is rejected if it does not exceed an MDA rejection limit.
- Either type of peak is rejected if its height does not exceed the variance of its height.
- Either type of peak is rejected if the square of its height is less than the height of the background underneath it.

When using a "User Specified ROI" peak locate, such as was done for the results in Appendix A, these statistical tests are disabled. The locations for the peaks are specified by the user, and the peak location is determined by calculating the geometric center of the area under the net spectrum in this region.

## D-4. Peak Areas

The peak area calculations were performed using a Library (Gamma- M) calculation. In this calculation, the areas of the net peaks located in the peak locate step (assumed to be Gaussian) are calculated from the measured peak height (from the count spectrum) and the expected FWHM (from the energy calibration). The uncertainties of the located peak areas are also calculated in this step, based on the peak area, the peak height and the uncertainty in the peak height for the located peak and the areas, heights and uncertainties of the heights for any interfering peaks.

## D-5. Efficiency Correction

At this point, the detector efficiency and the variance of the efficiency for each of the located peaks are calculated. All efficiencies were calculated using a dual efficiency curve, based on the stored tables of efficiency values described above. The efficiencies are not applied to the data until the activity calculation stage.

## D-6. Nuclide Identification

The nuclide identification uses a matrix method similar to the one developed in SAMPO80. All of the lines in the nuclide library are considered, with their proper branching ratios. The program first builds a matrix of possible identifications by comparing each nuclide in the analysis library against the observed peaks. For each nuclide with at least one gamma line within a specified energy tolerance of an observed peak (0.1 FWHM), a nuclide confidence value is calculated. The confidence value starts at 1.0, and is multiplied by penalty factors which include the energy difference between the observed and known peaks (yield corrected), the number of gamma lines in the library which are not observed in the spectrum (yield corrected) and a decay time penalty for short half-life isotopes. If the confidence value is greater than the specified confidence threshold (0.1), the nuclides are classified as identified.

## D-7. Activity Calculation

The activities per unit mass of the nuclides identified are calculated by dividing the peak areas (from section D-4) by the following factors:

- the sample amount (section D-2),
- the efficiency (efficiency calibration - D-5),
- the line yield (from the analysis library)
- the count time
- a units constant to convert activity to pCi
- a correction factor for nuclide decay during counting

The activity per unit mass and its variance are calculated for each gamma line observed in the spectrum. For a nuclide with multiple gamma lines, the nuclide activity is then calculated based on the weighted mean average of the individual line activities, with the variance as the weighting function.

## D-8. Interference Correction

During the interference correction, the identified nuclides are searched for possible interference sets, two or more nuclides with at least one common peak which the peak search and area algorithms have not been able to resolve into separate peaks. The activities of these nuclides are calculated based on the solution to a linear least squares equation. This is accomplished by minimizing the square of the difference between the ratio of the observed peak area divided by the line efficiency at that peak and the product of the unknown activity times the line yield summed over all observed peaks and unknown nuclide activities.

## D-9. MDA Calculations

Minimum detectable activities are then calculated for both the nuclides which have and have not been found in the spectrum by the analyses. These calculation are calculated using the methods developed by Currie, the most commonly accepted methods in the US. All of the MDA calculations were performed with a confidence factor of 5%: there is a 5% probability of a false positive (deciding a peak is present when it is not) and a 5% probability of a false negative (failing to decide a peak is present when it is). In this method, the critical level $L_c$ is defined as the product of the standard deviation of the observed net signal and a k factor (the abscissa of a normalized Gaussian at the specified confidence; 2.576 at 5% confidence). From this, the detection limit $L_d$ can be calculated as the critical level plus k times the standard deviation of the net signal when the signal is equal to $L_d$. The detection limit is effectively the smallest peak area which can be reliably detected at 95% confidence. Thus, the MDA in activity per unit mass is calculated by dividing $L_d$ by the factors

- the sample amount (section D-2),
- the efficiency (efficiency calibration - D-5),
- the line yield (from the analysis library)
- the count time
- a units constant to convert activity to pCi
- a correction factor for nuclide decay during counting

The MDA for a nuclide with multiple gamma lines is the lowest MDA for any of its individual gamma lines. When the count being analyzed is performed in a blank, this MDA calculation method produces the value for the lower limit of detection, which the NRC refers to as the LLD (Reg Guide 4.16) but which is referred to as the lower detection limit (LDL) in this report.